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Quantitative response of greenhouse tomato yield and quality to water deficit at different growth stages

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ABSTRACT

Deficit irrigation is widely used in tomato production because of water shortage. Many studies indicate that tomato yield is reduced but the fruit quality is improved under certain degree of water deficit. In order to investigate the quantitative relationship between tomato yield, fruit quality and water deficit, two experiments with different irrigation treatments were conducted in solar greenhouse in an arid region of northwest China from winter in 2008 to spring in 2009 (2008–2009 season) and from winter in 2009 to spring in 2010 (2009–2010 season). Results showed that the application of 1/3 (T1) and 2/3 (T2) of full irrigation at seedling stage (Stage I) did not significantly influence greenhouse tomato water consumption, total yield and fruit quality. Tomato water consumption and total yield were decreased by the application of 1/3 (T3) of full irrigation at flowering and fruit development stage (Stage II), and 1/3 (T5) or 2/3 (T6) of full irrigation at fruit maturation stage (Stage III). But the fruit contents of total soluble solids (TSS), reducing sugars (RS), organic acids (OA) and vitamin C (VC) as well as fruit firmness (Fn), sugar/acid content ratio (SAR), color index (*CI*) and water use efficiency (WUE) were significantly increased. However, no significant effects were found on tomato yield and fruit quality in the application of 2/3 full irrigation at Stage II (T4). The relative yield (Y/Y_{CK}) had a significant positive correlation with relative seasonal evapotranspiration (ET/ET_{CK}), while negative correlations were found between the relative values of fruit quality parameters and ET/ET_{CK}. Tomato yield is sensitive to water deficit during Stage II and Stage III, but fruit quality is mainly affected by water stress during Stage III. The regression equations between tomato yield, fruit quality parameters and ET could provide important basis for making irrigation strategies with the compromise between tomato yield and fruit quality

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1. Introduction

Tomato is one of popular vegetables as well as an important source of antioxidants such as lycopene, phenolic and vitamin C in human diet (Toor et al., 2006). With the development of social economy and the improvement of people's living condition, people's demand on tomato is changing from quantity to quality gradually. Water is an important factor influencing tomato yield and fruit quality. A certain degree of water deficit reduces tomato yield but improves the fruit quality as well (Mitchell et al., 1991; Zegbe-Domínguez et al., 2003; Kirda et al., 2004; Favati et al., 2009; Patanè and Cosentino, 2010).

In the arid region of northwest China, limited water resources affect the development of sustainable agriculture. With development of irrigated agriculture and rapid population growth in the region, over-exploitation of water resources has led to gradually falling of groundwater table, shrinking of vegetation areas, soil salinization and desertification (Kang et al., 2004). Due to the abundant solar resource but limited precipitation and snow in winter in the region, solar greenhouse industry is developing rapidly to improve local famers' income as well as to protect the water

Abbreviations: FC, field water capacity ($cm^{-3}\,cm^{-3}$); CK, full irrigation in the whole growth season; T1, receiving 1/3 full irrigation at seedling stage; T2, receiving 2/3 full irrigation at seedling stage; T3, receiving 1/3 full irrigation at flowering and fruit development stage; T4, receiving 2/3 full irrigation at flowering and fruit development stage; T5, receiving 1/3 full irrigation at fruit maturation stage; T6, receiving 2/3 full irrigation at fruit maturation stage; Stage I, seedling stage; Stage II, flowering and fruit development stage; Stage III, fruit maturation stage; DAT, days after transplanting; Temp, mean air temperature (°C); Rs, solar radiation ($W\,m^{-2}$); RH, mean air relative humidity (%); ET, total evapotranspiration (mm); ET_{daily}, daily average evapotranspiration ($mm\,d^{-1}$); *Y*, total fruit yield ($t\,ha^{-1}$); WUE, water use efficiency ($kg\,m^{-3}$); FN, fruit number per plant; FW, average fruit weight (g); TSS, total soluble solids ($g\,100\,g\,FW^{-1}$); RS, reducing sugars ($g\,100\,g\,FW^{-1}$); OA, organic acids ($g\,100\,g\,FW^{-1}$); VC, vitamin C ($mg\,kg\,FW^{-1}$); Fn, fruit firmness ($kg\,cm^{-2}$); *CI*, fruit colour index; SAR, sugar/acid content ratio; Y_{CK}, total fruit yield for CK treatment ($t\,ha^{-1}$); TSS_{CK}, total soluble solids for CK treatment ($100\,g\,FW^{-1}$); RS_{CK}, reducing sugars for CK treatment ($g\,100\,g\,FW^{-1}$); OA_{CK}, organic acids for CK treatment ($g\,100\,g\,FW^{-1}$); VC_{CK}, vitamin C for CK treatment ($mg\,kg\,FW^{-1}$); Fn_{CK}, fruit firmness for CK treatment ($kg\,cm^{-2}$); CI_{CK}, fruit colour index for CK treatment; SAR_{CK}, sugar/acid content ratio for CK treatment; ET_{CK}, total evapotranspiration for CK treatment (mm); ET_2, evapotranspiration for Stage II (mm); ET_3, evapotranspiration for Stage III (mm).

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resource in recent years. Tomato has quickly become one of major vegetables grown in solar greenhouse in these regions because of its high potential yield and large profitability. According the investigation of a local government (Agriculture and Animal Husbandry Bureau of Minqin city), planting area of tomato grown in solar greenhouses is above 60% in 2009–2010. The irrigation management of tomato grown in greenhouse is controlled by farmers' experience to get maximum yield, which may lead to water wasting and poor fruit quality in tomato production. However the maximum yield does not result in a better financial return due to the low price of poor quality tomato fruit and high cost for the irrigation. In order to improve the fruit quality, efficient irrigation was proposed based on the response of fruit quality to water (Du and Kang, 2011). To obtain high quality tomato and maintain a satisfactory yield simultaneously, an irrigation scheduling that allows a compromise between tomato yield and fruit quality need to be formulated. The traditional insufficient irrigation scheduling pursues maximum crop yield or minimum yield loss with limited water resource. It is generally developed based on crop water production functions and suitable for cereal crops, e.g. wheat and maize (Shang and Mao, 2006; Igbadun et al., 2007). However, only the yield is considered and the quality is neglected in the irrigation scheduling, which cannot meet the requirement of irrigation management for high quality tomato production.

Some studies have as a goal to define irrigation strategies with the best compromise between tomato yield and fruit quality through experiments both in open field and greenhouse conditions. Cahn et al. (2001) reported that a good compromise between quality and quantity of tomato fruit was achieved when irrigation water was reduced to amounts ranging from 70 to 85% of crop evapotranspiration during berry growth either by cutting off irrigation 2 weeks earlier than conventional cut-off dates or by applying deficit irrigation. In a typical Mediterranean environment, the best management strategy to optimize yield and quality of processing tomato fruit was achieved by extending the irrigation interval in the whole growing season (irrigation was carried out when the cumulative crop evapotranspiration minus effective rain was 40 or 60 mm) and a 50% irrigation volume reduction during the second part of the tomato crop cycle which starts from berry veraison (Favati et al., 2009). Deficit irrigation applied to tomato appears to be beneficial not only for its well-known positive effects on water use efficiency, but also for improving the tomato fruit quality (Favati et al., 2009). However, before considering and taking advantages from deficit irrigation strategies, an extended knowledge of the effects of water deficit at different growth stages on tomato yield and fruit quality should be investigated.

Pulupol et al. (1996) studied the effects of deficit irrigation on greenhouse tomato, and found that compared to well-watered crops, plant growth and fruit yield, size and number were reduced, but fruits had higher color intensity, lower water content, and higher concentration of sucrose, glucose, and fructose under water deficit. Liu and Chen (2002) reduced irrigation times for cherry tomato after the first three trusses fruit set and found that fruit size and yield were reduced, but the contents of total soluble solids, organic acids, vitamin C and sugar/acid content ratio as well as WUE were increased. Nuruddin et al. (2003) found that marketable yield and WUE were reduced, but fruit soluble solids and color index were increased by water stress during tomato fruit growth and fruit ripening stages. Johnstone et al. (2005) reported that the content of total soluble solids of processing tomato was increased by deficit irrigation at early fruit ripening stage. In Mediterranean climate condition appropriate deficit irrigation reduced processing tomato yield, but increased the fruit reddish and the contents of total soluble solids, reducing sugars, organic acids, vitamin C and lycopene (Favati et al., 2009). Moreover, some studies established quantitative relationship between tomato yield and evapotranspiration (Xu et al., 2001; Kirda et al., 2004; Patanè et al., 2011). However, few studies (Patanè and Cosentino, 2010) about quantitative relationship between tomato fruit quality and water deficit at different growth stages are reported. The quantitative relationship between tomato quality and water deficit at different growth stages is useful in formulating an irrigation schedule for high quality tomato production. In this study, two experiments with regulated deficit irrigation at different growth stages were conducted in solar greenhouses in an arid region of northwest China to (1) assess the water consumption pattern of tomato under water deficit at different growth stages; (2) evaluate the effects of water deficit at different growth stages on tomato yield, quality and WUE; and (3) establish quantitative relationship between tomato yield, fruit quality and evapotranspiration for the whole growth season as well as for different growth stages.

2. Materials and methods

2.1. Experimental site

Experiments were conducted in the solar greenhouse at the Wuwei Experimental Station of Crop Water Use, Ministry of Agriculture, P.R. China which is located in Wuwei, Gansu province of northwest China (latitude 37°52′N, longitude 102°51′E, altitude 1581 m), from winter 2008 to spring 2009 (2008–2009 season) and from winter 2009 to spring 2010 (2009–2010 season). The site has a typical continental temperate climate with annual precipitation of 164.4 mm, pan evaporation of 2000 mm, mean temperature of 8.8 °C, mean sunshine duration of 3000 h and frost-free period of 150 d. The groundwater table is below 25 m. The greenhouse is 76 m long and 8 m wide with planting area of 405 m^2. The greenhouse has no heating system and straw mats are spread on the surface of the thermal polyethylene sheet during the winter months to maintain the interior temperature at night. The greenhouse interior temperature during the daytime is controlled by a narrow ventilation system on the roof. More details of the solar greenhouse construction were described by Qiu et al. (2011). The soil inside is a desert sandy loam with a mean dry bulk density of 1.45 ± 0.01 g cm^{-3} and 1.46 ± 0.01 g cm^{-3}, field water capacity (Wilcox, 1965) of 0.340 ± 0.009 (cm^3 cm^{-3}) and 0.364 ± 0.011 (cm^3 cm^{-3}) at the 0–50 cm soil layer for 2008–2009 and 2009–2010 season, respectively. The dry bulk density and field water capacity were measured with two replications in both seasons. The crops were irrigated with groundwater and the electrical conductivity is 0.52 ds m^{-1}.

2.2. Crop management

Tomato plants (*Lycopersicon esculentum Mill*, cultivar Jinzuan-3) were transplanted on October 5, 2008 in the 2008–2009 season and tomato plants (*Lycopersicon esculentum Mill*, cultivar Taikong-1) were transplanted on September 22, 2009 in the 2009–2010 season. Both tomato cultivars were local leading varieties and belong to pink tomato series. Before transplanting, soil was rototilled and the beds were raised as Fig. 1 and 110 t ha^{-1} of decomposed organic manure (pig and sheep manure), 1200 kg ha^{-1} of diammonium phosphate (N 18%, P_2O_5 46%) and 350 kg ha^{-1} of compound fertilizer (N 18%, P_2O_5 15%, K_2O 12%) were broadcasted uniformly as basal fertilizer in the soil. After transplanting 300 kg ha^{-1} of urea (N 46.7%), 150 kg ha^{-1} of potassium sulfate (K_2O 52%) and 450 kg ha^{-1} of compound fertilizer (N 18%, P_2O_5 15%, K_2O 12%) were applied with irrigation events. Tomato seedlings were evenly transplanted along the edge of the furrow side with row spacing of 0.35 m and interplant spacing of 0.35 m in both seasons (Fig. 1). All plots were irrigated after transplanting with the same amount

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