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Assessing the response of yield and comprehensive fruit quality of tomato grown in greenhouse to deficit irrigation and nitrogen application strategies

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ABSTRACT

In this study, the influence of deficit irrigation (*two watering levels: W1, full and W2, 2/3 deficit*) at early or later fruit maturation stages, and reduced nitrogen application (*two levels: N1, control and N2, 2/3 reduced*) from spring to summer in 2012 (*the spring-summer season, SS)* and from winter in 2012 to spring in 2013 (*the winter-spring season, WS*) on greenhouse-grown tomato (*Lycopersicon esculentum* Mill.) was identified. The treatments were set as: CK (*W1W1N1*), T1 (*W2W1N1*), T2 (*W1W2N1*), T3 (*W2W2N1*), T4 (*W2W1N2*), T5 (*W1W2N2*), T6 (*W2W2N2*) and T7 (*W1W1N2*). The results indicated that the fruit yields under deficit irrigation were reduced by 8.6–12.5% and 13.1–29.4% in the two seasons, respectively. The contents of TTS (*total soluble solids*), TSSC (*total soluble sugar content*), SAR (*sugar and organic acid content ratio*), VC (*vitamin C*), lycopene, and RS (*reducing sugar*) in the fruits of all the plants increased during the maturation in the WS season. Crop evapotranspiration (ET_c), contents of TTS, TSSC, SAR and VC were all increased in the treated fruits compared to the control ones (*CK*) in both seasons. According to the two-way ANOVA, the fruit quality was more sensitive to water than to N-fertilizer, but it was just the opposite for NC (*nitrate content*). GRA (gray *relational analysis method*) and PCA (*principal component analysis method*) were two suitable appraisement methods for fruit comprehensive quality analysis. Eventually, the combinational evaluation method showed that T3 (*W2W2N1*) was the best water and nitrogen management strategy for the fruit comprehensive quality and yields in tomato.

1. Introduction

With the rapid economy development, people's demands on food quality are getting higher. Tomato (*Lycopersicon esculentum* Mill.), one of the most popular vegetables all over the world, is a rich food source of minerals, vitamins, organic acids, essential amino acid and antioxidants (Toor et al., 2006; Savić et al., 2008; Erba et al., 2013). In recent years, consumption of tomato is also suggested as can lower the risk of getting some human diseases (Massot et al., 2010; Al-Amri, 2013). As water resource is short in the northwest China and the greenhouse industry is a good way to guarantee the farmers' income, a reasonable water and N-fertilizer management strategy that improves tomato quality and maintains yield is needed.

Both water and nitrogen-fertilizer (N-fertilizer) are essential factors for tomato growth and influence fruit quality (Ozbahce and Tari, 2010; Patanè and Cosentino, 2010; Chen et al., 2013; Martínez-Andújar et al., 2013; Sun et al., 2013). Although deficit irrigation could decrease tomato yield to some extent, the quality is improved (Costa et al., 2007; Patanè and Cosentino, 2010; Patanè et al., 2011; Chen et al., 2013). N-fertilizer is important for tomato growth and neutralizes the stress on yields, and has a positive impact on fruit quality if the amount is proper. Temporary stresses from water and

Abbreviations: ET_c, crop evapotranspiration (mm); *TSS*, total soluble solids content (°Brix); *VC*, vitamin C content (mg 100gFW^{-1}); *OA*, organic acids content (g 100gFW^{-1}); *TSSC*, total soluble sugar content (g 100gFW^{-1}); *RS*, reducing sugar (g 100gFW^{-1}); *NC*, nitrate content (mg kgFW^{-1}); *SAR*, sugar and organic acid content ratio; *AHP*, analytic hierarchy process method; *GRA*, grey relational analysis method; *PCA*, principal component analysis method; *SS*, season spring-summer season; *WS*, *season* winter-spring season; *Stage I*, seedling stage; *StageII*, blossoming and fruit-set stage; *Stage* III, first stage of fruit maturation; *Stage IV*, second stage of fruit maturation; *MG*, mature green; *V*, veraison; *RR*, red ripening.

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nitrogen shortage have significant influences on leaf area index, as well as the fresh and dry weights of the whole plants (Savić et al., 2008). Total nitrogen and nitrate concentration behaved differently in other tissues, including leaves, stems and fruits in tomato. Water soluble dry matter, protein and nitrate contents decreased with the increasing of the irrigation practice, while total acidity and ascorbic acid increased in tomato (Karaman et al., 2005). The major osmotic compounds accumulated in fleshy fruits are soluble sugars and acids (primarily malic and citric acids), which determine taste and represent more than half of the total dry matter in tomato (Ripoll et al., 2014). It has been proved that deficit irrigation at early fruit ripening stage could effectively increase TSS contents in processing tomato (Johnstone et al., 2005). Deficit irrigation applied near fruit ripening stage possesses the greatest positive influence on glucose and fructose accumulation in tomato fruits (Ripoll et al., 2014). Larger irrigation volumes have been reported to decrease melon fruit quality, especially TSS contents (Sensoy et al., 2007). Among the antioxidant compounds in tomato, the carotenoids lycopene and beta carotene, vitamin C (L-ascorbic acid) and flavonols are the most important ones (Leiva-Brondo et al., 2012). Appropriate deficit irrigation trends to increase contents of lycopene, vitamin C and beta-carotenoid in tomato fruits (Favati et al., 2009; Patanè and Cosentino, 2010). Long-term severe water deficit and nitrogen stress restrict growth and reduce yields. However, the quality could be much improved, though certain degree of water and nitrogen deficit reduced some yields (Favati et al., 2009; Chen et al., 2013). It was tested that deficit irrigation and N-fertilizer increased the contents of TSS in tomato and apricot (Helyes et al., 2012; Milošević et al., 2013; Akhtar et al., 2014; Kuşçu et al., 2014). Nitrogen is the most limiting nutrient for plant growth and potential biomass production during the whole growth season, however, excessive N-fertilizer application may also cause NO_3-N leaching and affect nitrate content in tomato fruits (Yang et al., 2006; Zotarelli et al., 2009a,b; Wang et al., 2012; Kuscu et al., 2014). The utilization of N fertilizers by crops is generally below 50% (Karaman et al., 2005). Therefore, it is reasonable that optimal water irrigation and fertilizer management would balance the improving of fruit quality and obtaining relative high yields (Rinaldi et al., 2007).

Tomato fruit quality is a comprehensive concept and a sum of the interaction among the different individual quality attributes (Wang et al., 2011). There are many ways to classify the fruit quality, regarding the fruits' external appearance, size, texture and taste as the important characteristics of organoleptic quality (Ripoll et al., 2014). And the fruit quality is also generally classified as external (size, uniformity, shape and color), taste (TSS, sugar and organic acid), nutritional (lycopene and vitamin C) and storage (fruit firmness and fruit water content) qualities (Viskelis et al., 2008). Many methods have been adopted to evaluate fruit quality, e.g. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), GRA (Gray Relational Analysis) and PCA (Principal Component Analysis) methods (Wang, 2011), with each possessing its feature and applicability for a certain kind of requirement. The GRA method, effectively adopted for solving the complicated interrelationship among the designated performance characteristics, is a powerful tool for analyzing processes with multiple performance characteristics (Lu et al., 2009; Wang et al., 2013a; Wang et al., 2013b; Tamrin et al., 2014). PCA method, included in most of the standard statistical software packages (Lan et al., 2014), is useful in feature extraction and data reduction that the source of variance still can be accurately identified after the dimensionality reduction (Lu et al., 2009; Lan et al., 2014; Zabalza et al., 2014). However, all these methods are begun with AHP (Analytic Hierarchy Process) (Zhu and Xu, 2014) method for calculating the weight of each index. AHP is a popular and powerful technique for decision making, which is built on people's intrinsic ability to structure his/her perceptions or ideas hierarchically (Zhu and Xu, 2014).

The main limiting factor in crop production in arid region of northwest China is the lack of water resource (Du et al., 2008). Typically, the average annual rainfall in the Shiyang River Basin is below 200 mm and the irrigation water is mainly from melted glacier (Tong et al., 2007). Deficit irrigation is the normal water-saving irrigation strategy in these areas (Li et al., 2010). Tomato is one of the major crops grown in northwest China (Chen et al., 2013). Since the growth condition in greenhouse is much easier to control than these in open field, the greenhouse industry is developing rapidly in northwest China. Different from the conventional management method in field, much less amounts of water and N-fertilizer were required for crop growth in greenhouse (Sun et al., 2013). So, it is of great importance and urgent to optimize a water and N-fertilizer management strategy for tomato grown in greenhouse to balance the fruit quality and yields.

There are many studies about the tomato yield and fruit quality response to water deficit and N-fertilizer, but the relationship between the fruit comprehensive quality and the water irrigated and N-fertilizer in the greenhouse is needed to be identified. Few studies about the most suitable method for tomato fruit comprehensive quality appraisement are reported. So, the present study is aimed to (1) explore the yield and fruit comprehensive quality response to deficit irrigation and nitrogen fertilization; (2) find a most suitable appraisement method to appraise the tomato fruit comprehensive quality; and (3) establish a reasonable water and nitrogen management strategy for the tomato grown in greenhouse in northwest China.

2. Materials and methods

2.1. Experimental site

The experiment was conducted in the greenhouse in two consecutive growth seasons (2012 spring-summer and 2012–2013 winter-spring) at Shiyanghe Experimental Station of China Agricultural University, located in Wuwei City, Gansu Province of northwest China (latitude 37°52′ N, longitude 102°50′ E, altitude 1581 m). The site has a typical temperate continental climate with annual precipitation of 164.4 mm, pan evaporation of 2000 mm, mean temperature of 8.8 °C. Average groundwater table is below 25 m, mean sunshine duration is 3000 h and frost-free period is 150 d. The greenhouse that is 76 m long, 8 m wide with total planting area of 405 m^2 has an east-west orientation, with crop rows aligned north-south. The greenhouse has no temperature control system. In order to maintain the interior temperature at night during the winter, straw mats are spread on the surface of the thermal polyethylene sheet; and the interior temperature during the daytime is controlled by an arrow ventilation system on the roof. More details of the solar greenhouse were described by Qiu et al. (2011). The soil inside is silt loam with the field water capacity of 0.364 cm^3/cm^3 for two years. The average soil dry bulk density is 1.64 g/cm^3 in the 0–50 cm depth soil layer for the 2012 spring-summer and 1.45 g/cm^3 in the 0–60 cm depth soil layer for the 2012–2013 winter-spring season. The mineral nitrogen content in the soil before planting is 1452.68–1502.05 kg/ha and 1422.94–1500.15 kg/ha for both seasons, respectively.

2.2. Crop management

Tomato plants (*Lycopersicon esculentum* Mill. cv. 004024) were transplanted on February 28 and uprooted on July 10, 2012 in the SS season and November 2, 2012 and uprooted on May 10, 2013 in the WS season. The agronomic measures were the same in the two seasons. Tomato seedlings were evenly transplanted along each edge of the raised bed which was 5.6 m long and 0.75 m wide. The