Effects of Nutrient Solution EC, Plant Microclimate and Cultivars on Fruit Quality and Yield of Hydroponic Tomatoes (*Lycopersicon esculentum*)

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Keywords: lycopene, greenhouse, total soluble solid, gas exchange, vapor pressure deficit, fruit yield, cultivar, harvest

Abstract

Four cultivars (Blitz, Mariachi, Quest and Rapsodie) of tomato were grown hydroponically on rockwool in two microclimates (east and west) inside the greenhouse (Tucson, AZ) under two nutrient solution electrical conductivity (EC) levels (2.6 or 4.5 dS m^{-1}), adjusted by adding NaCl and $CaCl_2$ after the setting of first fruit truss. In all cultivars, total soluble solid (TSS, %Brix at 20^{o}C) and lycopene concentration of fruits increased by 12-23 % and 34-85 %, respectively, with increasing EC level. Fruits harvested from the east side of the greenhouse had higher TSS than those from the west side, due to the different plant microclimate varying by daily PPF (photosynthetic photon flux) and VPD (vapor pressure deficit). However, lycopene concentration in fruits was not significantly affected by plant microclimate regardless of cultivars or EC. The cultivar Mariachi had the strongest effect in response to nutrient solution EC levels regarding both TSS and lycopene concentration among the cultivars examined. The cumulative yield at 7 weeks had no significant differences between nutrient solution EC and locations, regardless of cultivars. The results indicated that value added tomato fruits could be produced by manipulating EC and plant microclimate in the greenhouse without causing yield reduction.

INTRODUCTION

Tomato is an important crop in fresh vegetable market around the world. Recently, there is great interest for growers to improve the fruit quality by introducing improved cultivation methods. Total soluble solid concentration (TSS, measured as %Brix) of tomato fruits is one of the important variables that determines the fruit flavor and quality because TSS is the most common index associated directly with sugars and organic acids concentrations in the juice (Stevens et al., 1977; Young et al., 1993). Manipulation of nutrient solution electrical conductivity (EC, dS m^{-1}) is a well known technique to grow flavor-enhanced tomato because the elevated salinity in nutrient solution restricts the water transport to fruits and thus increase the TSS (Adams, 1991; Mitchell et al., 1991; Cornish, 1992; Lin and Glass, 1999). However, too severe water stress from high EC nutrient solution may cause a significant yield reduction (Adams, 1991).

The aerial environmental factors influence fruit growth and quality, and they also interact with the nutrient solution EC effects on the plant. Increasing photosynthetic photon flux (PPF) significantly increased the leaf net photosynthetic rate and total carbon fixed by tomato plants (Schwarz et al., 2002). When the PPF was lower than 200 μmol m^{-2} s^{-1}, there was no effect on plant growth up to a nutrient solution EC of 8 dS m^{-1}; however, when the plants were grown at a higher light intensity (1000 μmol m^{-2} s^{-1}), the tomato plant growth was reduced by the same EC treatments (Xu et al., 1995). Vapor pressure deficit (VPD) in the greenhouse influences tomato plant growth, fruit quality and yield as well. Lowering VPD in the greenhouse by the use of a mist system increased the leaf stomatal conductance, plant growth and yield for tomato plant grown under salinity stress condition (Romero-Aranda et al., 2002). Increasing VPD contributes to the significant reduction of fresh fruit weight and fruit water content, but increased TSS of tomato fruits (Leonardi et al., 2000).

The regulation of lycopene formation in crop plants has become an area of considerable interest due to its antioxidant activity. The tomato fruit is the principle dietary source of lycopene; the ripening of tomato fruit is accompanied by a dramatic increase in the carotenoid content, especially a massive accumulation of lycopene (Fraser et al., 1994). In addition, red color development in fruits is due to carotenoid pigments, particularly lycopene, which is a major quality index for marketing. However, enhancing lycopene concentration in tomato fruits by crop management is rarely reported.

The aim of our study is to find the effects of nutrient solution EC and environmental conditions on fruit quality as well as fruit yield. In the present experiment, four tomato cultivars were grown hydroponically in two different microclimate conditions inside the greenhouse. The effects of EC level and plant microclimates in greenhouse on tomato fruit TSS, lycopene concentration, and yield were studied.

MATERIALS AND METHODS

Four cultivars of tomatoes were used (Blitz (DeRuiter Seeds, USA), Mariachi (Rijk Zwann Seeds, Netherlands), Quest (DeRuiter Seeds) and Rapsodie (Roger's Seeds, USA)). Seeds were sown into 4×4 cm rockwool cubes covered with a thin layer of vermiculite on January 23, 2003 and germinated/grown under frequent water mist in the greenhouse. After the cotyledons were fully unfolded, the seedlings were sub-irrigated once a day with one-half strength modified Hoagland nutrient solution (EC 1.2 dS m^{-1}, pH 6.0). When four true leaves emerged, the nutrient solution EC was increased to about 2.4 dS m^{-1}.

The seedlings were transplanted to 10×10 cm rockwool cubes 3 weeks after seeding. Nine weeks after seeding, uniform seedlings were selected and transplanted in the rockwool hydroponic systems at the east and west sides of the greenhouse (North-south orientation, with pad and fan cooling system) located in the University of Arizona Campus Agriculture Center (Tucson, AZ). Nutrient solution of about 2.4 dS m^{-1} EC was supplied using a drip irrigation system. When the fruits at the first truss became visible, half of the plants were supplied with an EC about 4.5 dS m^{-1} which was achieved by adding NaCl and $CaCl_2$.

Leaf net photosynthetic and transpiration rates were measured 2 weeks after the EC treatment using a portable photosynthesis measurement system (CIRAS2, PPSystems Co., USA) at a 1500 µmol m^{-2} s^{-1} PPF and 400 µmol mol^{-1} CO_2.

We harvested and weighed fruits twice a week when the fruits reached the red ripening stage. The TSS of the harvested fruit juice was determined by a hand refractometer (Atago N-20E) and the measured values (%Brix) were converted to a standard temperature condition of 20^{o}C. Lycopene concentrations of tomato fruits were measured spectrophotometrically using a modified method based on Fish et al. (2002). Each sample was assayed in triplicate. Lycopene analysis was performed only for the last harvest of 10 weeks after EC treatment.

EC and pH levels of the inflow nutrient solution and drainage were recorded daily. The air temperatures of east and west sides of the greenhouse were monitored using a 0.5 mm Type-T thermocouple, connected to a datalogger (CR-10X, Campbell Scientific, USA) throughout the experiment. The thermocouple sensors were kept at the plant canopy height. Photosynthetic active radiation (PAR) and VPD of the east and west sides of the greenhouse were monitored during limited time in the experiment.

There were 4 blocks at each side of the greenhouse, each of which consisted of 9 plants growing in three 20×91 cm rockwool slabs. Cultivars were randomly distributed within each block. The EC treatment was alternately distributed within four blocks placed at each side of the greenhouse. Data obtained from the experiment were analyzed by JMP software (version 4.0.4 SAS Institute, USA). Treatment significances and significance among individual treatment levels were analyzed by analysis of variance (ANOVA) and

Tukey HSD test, respectively.

RESULTS AND DISCUSSION

Nutrient Solution EC/pH and Greenhouse Microclimates

The nutrient solution (input solution) of the low EC treatments had 2.6±0.2 dS m^{-1} EC with 6.7±0.2 pH throughout the experiment, while that of the high EC treatments had 4.5±0.8 dS m^{-1} EC with 6.7±0.2 pH. The drainage solution EC was 5.5±2.0 dS m^{-1} at pH 7.4±0.6, and 9.0±3.2 dS m^{-1} at pH 7.3±0.5 for the low and high EC treatments, respectively. Average drainage percentage was 29% for the low EC treatments and 33% for high EC treatments.

The average day and night temperatures were 24.1±2.4 and 20.7±3.1, respectively, for the east and 23.7±2.2 and 20.8±2.9, respectively, for the west. Although the measurements were not complete throughout the experiment, the microclimate differences between the east and west locations seemed to be more pronounced in PAR and VPD, rather than air temperature. The PAR, monitored for May 16th-May 27th, 2003 (4-6 weeks after the start of EC treatment) and June 12th-June 21st, 2003 (8-9 weeks after the start of EC treatments), showed that the east location had a higher daily PAR (35.1±5.2 mol m^2) than that of the west location (32.9±6.1 mol m^2) during the day. The VPD, monitored from June 5th to June 11th, 2003 (7 weeks after the start of EC treatments) showed that the VPD during the day in the east location was also higher in the east (1.1±0.3 kPa) than in the west location (0.9±0.3 kPa) of the greenhouse. Generally, the higher daily PAR is responsible for a higher plant growth and net photosynthesis rate. VPD had reportedly small effects on the physiology and development of horticultural crops when it is ranged between 0.2 kPa to 1 kPa, but a higher VPD induced leaf water stress (Grange and Hand, 1987). An increase of VPD from 1.6 to 2.2 kPa increased the TSS in tomato fruits but reduced fruit fresh weight by about 10% (Leonardi et al., 2000).. In this experiment, the difference of PAR and VPD in different location in the greenhouse influenced the fruit quality.

Leaf Gas Exchange of the Plants

Both microclimate and cultivar did not have significant effects on leaf gas exchange rates measured 2 weeks after the start of EC treatments. The leaf net photosynthetic rate, transpiration rate and stomatal conductance were in a range between 19.4±6.6 to 27.2±6.7 µmol m^{-2} s^{-1}, 4.8±0.2 to 7.2±0.4 mmol m^{-2} s^{-1}, and 411±45 to 506±122 mmol m^{-2} $s^{-1,}$ respectively. The high EC level of 4.5 dS m^{-1} did not significantly reduce leaf net photosynthetic rate (P = 0.89) and leaf stomatal conductance (P = 0.40). However, there was a tendency suggested that transpiration rates of the plants decreased under high EC compared to under low EC (P = 0.07). Different results were reported regarding the nutrient solution EC effects on leaf gas exchange of plants. Xu et al (1995) tested the leaf photosynthetic rate of tomato plants grown both using a nutrient film technique (NFT) and a rockwool system at three nutrient solution EC levels (2.0, 4.0 and 5.5 dS m^{-1}), where they found EC could increase the photosynthetic rate in both growing systems. Schwarz et al., (2002) reported that an increase of EC up to 8.75 dS m^{-1} had no effect on leaf net photosynthetic rate; however, the whole plant photosynthesis was decreased due to the decreased leaf area. Those inconsistent findings may be caused by the interaction between the aerial environmental and cultural factors.

Total Soluble Solid Concentration and Yield of Fruits as Affected by Nutrient Solution EC and Greenhouse Microclimates

For all cultivars, fruits grown under high EC had a higher TSS than those grown under low EC level during 7 weeks of harvests (Table 1, Fig. 1). Plant microclimate of greenhouse also had an effect on TSS and the East location, which had a higher PAR and VPD, induced higher TSS. Mariachi cultivar had the highest TSS for plants grown under high nutrient EC at the east location of greenhouse (Fig. 1). The increase of TSS of all cultivars in response to nutrient solution EC was between 12-23 % whereas Rapsodie has the lowest increase and Mariachi has the highest.

In the present experiment, TSS of tomato fruits grown hydroponically on rockwool system in greenhouse increased in response to the increased EC level (2.6 - 4.5 dS m^{-1}), which generally agreed with the previous results reported by Adams (1991), Mitchell et al. (1991), Cornish (1992) and Lin and Glass (1999). Cuartero and Fernandez-Munoz (1999) found that TSS of two commercial tomato cultivars increased at a 10.5 % rate per dS m^{-1} when nutrient solution EC was increased from 2.5 to 8.0 dS m^{-1}.

The cumulative yield per plant for the 7 weeks of harvest ranged between 4.0 kg to 6.5 kg per plant. However, there was no significant difference for fruit yield between EC levels, cultivars and greenhouse microclimates. The results showed that an increase of nutrient solution EC up to 4.5 dS m^{-1} improved the fruit quality regarding TSS level without reducing the total fruit yield. For effects of the nutrient solution EC on the yield, Adam (1991) reported that an EC about 8 dS m^{-1} decreased the tomato yield from 4% to 5% per dS m^{-1}, whereas the EC about 12 dS m^{-1} decreased the tomato yield from 6% to 8% per dS m^{-1}. The results indicated that a further increase of EC could decrease the fruit yield significantly.

Water accounts for more than 90% of the total weight of ripe tomato fruit. Therefore, the water uptake of fruits is very important to both fruit quality and yield. In previous research, the higher nutrient solution EC increased the phloem sap concentration and the ratio of phloem water to xylem water (Ho et al., 1987). In this experiment, the EC level up to 4.5 dS m^{-1} increased the TSS of tomato fruit with no significant reduction of yield. The transpiration rate of tomato plants also had no significant difference under increased nutrient solution EC. In addition, minimal or no incidence of blossom-end rot was observed during the experimental period, which is related to calcium deficiency cause by the reduced amount of water flow to the fruit. All these data supported that the water uptake in tomato fruit grown under an increased nutrient solution EC of 4.5 dS m^{-1} was not greatly reduced. Increasing nutrient solution EC to a moderate level may contribute to the increased concentration in phloem sap and thus improve the total soluble solid in fruit without yield reduction.

The relatively higher VPD and PAR inside the greenhouse increased the TSS of most cultivars tested in the experiment. It suggested that fruit quality could be enhanced by controlling the aerial environments in addition to nutrient solution EC. The higher VPD could also provide a water stress to the plants (Grange and Hand, 1987); therefore this method is effective for enhancing the TSS of fruits.

Lycopene Concentration of Fruits as Affected by Nutrient Solution EC

Nutrient solution EC had a significant effect on lycopene concentration of tomato fruits. For all cultivars, the lycopene concentration increased significantly for fruits grown under high nutrient solution EC; however, greenhouse microclimate had no effect on the lycopene concentration (Table 1). The increase of lycopene concentration for all cultivars was between 34-85 %, ranging between 31.4 to 73.7 mg kg^{-1} FW (Fig. 2). The reported fresh tomato quantified lycopene concentration was between 31 to 77 mg kg^{-1} FW from several cultivars quantified by a reversed-phase HPLC (Nguyen and Schwartz, 1999).

Nutrient solution EC manipulation is a technique to grow sweet tomato fruits. Our experiment indicates that the lycopene concentration could be also enhanced by increasing the nutrient solution EC in the experiment. Enhancing lycopene concentration in the fruits has been a major interest in plant breeding using both conventional method and genetic engineering; however, there is minimal research to increase lycopene levels by plant production management as far as we know. The increase of VPD had no effect on enhancing the fruit color (Leonardi et al., 2000). It indicates that the VPD has no effect on lycopene concentration in tomato fruit since lycopene is the major pigment in the ripening tomato fruit. This may also indicate that lycopene enhancement observed in high EC treatments was not associated with altered water balance (less water) of the fruits, but with salinity level induced under high EC and related metabolisms in the fruit, which remained unclear in the present experiment.

Lycopene is a major carotenoid present in the human diet, in which tomato and tomato products are the predominant sources. It is an effective antioxidant, twice as effective as β-carotene, associated with reducing the risk of cancer and cardiovascular disease (Gerster, 1997; Stahl and Sies, 1997; Giovanucci, 1999). Lycopene can not be synthesized de novo in the human body and must be acquired from the diet. The lycopene-enriched tomato has an important nutritional value.

CONCLUSION

From the overall results, a crop management technique by nutrient solution EC manipulation is a potential method to grow high quality tomatoes rich in TSS and lycopene. The results indicate that the fruit quality can be significantly enhanced when plants were grown under moderate water stress conditions, in terms of TSS and lycopene in the fruit with no significant yield loss. The greenhouse microclimate could influence the TSS of fruit but not lycopene. The enhancement of lycopene and TSS contribute to the overall improvement of tomato quality, either in nutritional values or flavor.

AKNOWLEDGEMENTS

CEAC Paper #P-125929-14-04. Support provided by the Controlled Environment Agriculture Center (CEAC), College of Agriculture and Life Sciences, The University of Arizona, Tucson, AZ. Authors would like to thank Merle Jensen, Pat Rorabaugh, and Mark Kroggel for the assistance and support to conduct the analyses presented in this paper.

Literature Cited

Adams, P. 1991. Effects of increasing the salinity of the nutrients solution with major nutrients or sodium chloride on the yield, quality and composition of tomato grown in rockwool. J. Hort. Sci. 66:201-207.

Cornish, P.S. 1992. Use of high electrical conductivity of nutrients solution to improve the quality of salad tomatoes grown in hydroponic culture. J. Expt. Agr. 32:513-520.

Cuartero, J. and Rafael, F.M. 1999. Tomato and salinity. Scientia Hort., 78: 83-125.

Fish, W.W., Perkins-Veaziea, P. and Collins, J.K. 2002. A Quantitative Assay for Lycopene That Utilizes Reduced Volumes of Organic Solvent. J. Food Composition and Analysis, 15:309-317.

Fraser, F.D., Truesdale, M.R., Bird, C.R., Schuch, W. and Bramley, P. M. 1994. Carotenoid biosynthesis during tomato fruit development. Plant Physiol. 105:405-413.

Gerster, H. 1997. The potential role of lycopene for human health. J. Am. Coll. Nutr. 16:109-126.

Giovannucci, E. 1999. Tomatoes, tomato-based products, lycopene, and prostate cancer: review of the epidemiologic literatures. J. Natl Cancer Inst. 91:317-331.

Grange, R.I. and Hand, D.W. 1987. A review of the effects of atmospheric humidity on the growth of horticultural crops. J. Hort. Sci. 62:125-134.

Ho, L.C., Grange, R.I. and Picken, A.J. 1987. An analysis of the accumulation of water and dry matter in tomato fruit. Plant, Cell and Environment, 10:157-162.

Leonardi, C., Soraya, G.. and Nadia, B. 2000. High vapour pressure deficit influences growth, transpiration and quality of tomato fruits. Scientia Hort., 84:285-296.

Lin, W.C. and Glass, A.D.M. 1999. The effects of NaCl addition and macronutrient concentration on fruit quality and flavor volatiles of greenhouse tomatoes. Acta Hort. 481:487-491.

Mitchell, J.P., Shennan, C. and Grattan, S.R. 1991. Developmental changes in tomato fruit composition in response to water deficit and salinity. Physiol Planta. 83:177-185.

Nguyen, M.L. and Schwartz, S.J. 1999. Lycopene: Chemical and biological properties. Food Technology, 53: 38-45.

Romero-Aranda, R., Soria, T. and Cuartero, J. 2002. Greenhouse mist inproves yield of

tomato plants grown under saline conditions. J. Amer. Soc. Hort. Sci. 127:644-648.
Schwarz D., Klaring, H.P., Van Iersel, M.W. and Ingram, I.T. 2002. Growth and photosynthetic response of tomato to nutrient solution concentration at two light levels. J. Amer. Soc. Hort. Sci. 127:984-990.
Stahl, W. and Sies, H. 1996. Lycopene: a biologically important carotenoid for humans? Arch. Biochem. Biophy, 336:1-9.
Stevens, M.A., Kader, A.A. and Albright-Houlton, M. 1977. Intercultivar variation in composition of locular and pericarp portions of fresh market tomatoes. J. Amer. Soc. Hort. Sci. 102:689-692.
Xu, H.L., Gauthier, L. and Gosselin, A. 1995. Effects of fertigation management on growth and photosynthesis of tomato plant grown in peat, rockwool and NFT. Scientia Hort. 63:11-20.
Young, T.E., Juvik, J.A. and Sullivan, J.G. 1993. Accumulation of the components of total solids in ripening fruits of tomato. J. Amer. Soc. Hort. Sci. 118:286-292.

Tables

Table1. Main effects of EC, cultivar and plant microclimate (East and West) in the greenhouse on the total soluble solid concentration (TSS, %Brix at 20^oC) of fruits. The TSS was the average of 7 weeks of harvest; the first harvest was on 4th week after start of EC treatment (approximately 2.6 and 4.5 dS m^{-1} for low and high EC, respectively).

Factor	TSS (%Brix)
Nutrient solution EC	
High EC	5.8
Low EC	4.9
ANOVA	*
Cultivar	
Blitz	5.2c
Mariachi	5.6a
Quest	5.4b
Rapsodie	5.2c
ANOVA	*
Greenhouse microclimates	
East	5.6
West	5.2
ANOVA	*

Significant differences were determined by ANOVA at P=0.05. Means with the same letters are not significantly different according to a Tukey HSD test at P=0.05.

Figures

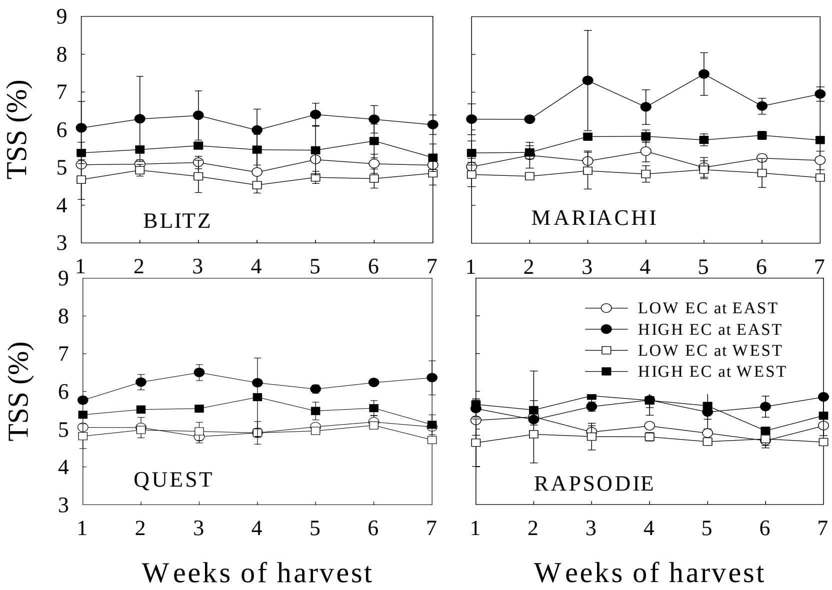

Fig. 1. Weekly changes in the total soluble solid concentrations (TSS, % Brix at 20^{o}C) of tomato fruits of four cultivars grown in the greenhouse as affected by nutrient solution EC (2.6 and 4.5 dS m^{-1}) and plant microclimates of different locations (west and east sides) inside the greenhouse. The data were obtained from 7 weeks harvests with the first harvest on 4th week after the start of EC treatment. Means are shown with standard deviations.

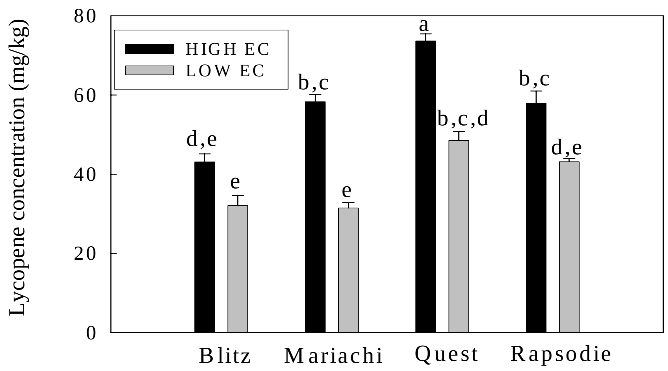

Fig. 2. The lycopene concentration (mg/kg FW) of fruits of four cultivars grown in the greenhouse under a high nutrient solution EC (approximately 4.5 dS m^{-1}) treatment. The data were obtained from the 10th week's harvest after start of EC treatment. Means with the same letters are not significantly different according to a Tukey HSD test at *P*=0.05.