Increased Electrical Conductivity in Nutrient Solution Management Enhances Dietary and Organoleptic Qualities in Soilless Culture Tomato

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Abstract. Greenhouse tomato production is shifting to meet emerging consumer needs. Increasing environmental concerns have pressured growers to supply high-quality vegetables using sustainable production methods. The utilization of adapting fertilization to production conditions and/or nutrient solutions of moderately high conductivity seems promising in providing high yields of superior quality while limiting the emission of nutrients to the environment in greenhouse tomato crops. A tomato crop was grown in soilless culture with various levels of electrical conductivity (EC), 2.2, 3.5, and 4.5 dS·m⁻¹, adjusting the final nutrient concentration and maintaining nutritional balance. The effect of nutrient solutions with moderately high EC on fertigation parameters and the emission of nutrients to the environment, total crop productivity, distribution of fruit sizes, and dietary and organoleptic qualities were measured. Nutrient solutions of moderately high EC decreased total and commercial yield, with an average reduction from 5% to 19% and 3% to 22%, respectively. A considerable decrease in extra large and large fruits, with an EC decreased total and commercial yield, with an average reduction from 5% to 19% and 3% to 22%, respectively. A considerable decrease in extra large and large fruits, with an average reduction from 5% to 42%, was also observed. Nonetheless, dietary-related metabolites were significantly increased at the highest EC values: lycopene (6.3%), ascorbic acid (8.8%), total phenolics content (8.3%), and total antioxidant activity (11.1%). EC values of 3.5 and 4.5 dS·m⁻¹ are not widely used in commercial production but are frequently measured in drainage solutions in open hydroponic systems and discarded solutions in closed systems, mainly because of the use of poor-quality water and the accumulation of excess nutrients.

The greenhouse industry is focused on the consumer market. Consumers demand a diverse array of high-quality vegetables. Among vegetables, tomato is the most important for its high consumption and dietary quality as it contains mainly health-influencing compounds (Canene-Adams et al., 2005; Elmiman et al., 2004; Liu, 2013; Nishино et al., 2004; Wilcox et al., 2003). The dietary and organoleptic quality of fresh tomatoes can be affected by many pre- and post-harvest factors, such as genetic characteristics, growing conditions, ripening stage at harvest, and cultural management (Arah et al., 2015; Dorais et al., 2001a, 2008; Erba et al., 2013; Iglesias et al., 2015; Leonardi et al., 2000; Passam et al., 2007; Urrestarazu et al., 2015). Many commercial greenhouses are forced to use poor-quality water with residual ions such as Cl⁻, Na⁺, SO₄²⁻, and Mg²⁺, but nutrient solutions of moderately high EC are sometimes achieved by adding NaCl or major nutrients. This cultural management provides excellent possibilities for achieving high dietary and organoleptic quality in fresh tomato fruit (Adams, 1991; Auerwald et al., 1999; Borgehei et al., 2011; Cliff et al., 2012; De Pascale et al., 2001; Dorais et al., 2001b; Krauss et al., 2006; Magán et al., 2008; Morales and Urrestarazu, 2013; Sonneveld, 2000). The physiological responses of tomato plants cultivated using poor-quality water have been characterized in many studies. However, fewer studies have been conducted using nutrient solutions of moderately high EC with the addition of nutrients. The maximum yields for substrate-grown tomato crops are obtained using EC from 2.5 to 2.9 dS·m⁻¹ (Sonneveld and Van der Burg, 1991). To improve the produce quality, nutrient concentrations are sometimes higher than necessary for optimum plant growth and yield, and there is limited information about the effects of increased EC nutrient solution management in soilless culture. Hence, this work aims to assess the effects of moderately high EC nutrient solutions with equal balance of macronutrients on fertigation parameters and nutrient emissions to the environment, total crop productivity, distribution of fruit size, and dietary and organoleptic qualities in an unheated greenhouse under conditions similar to those of a commercial crop.

Materials and Methods

Cultivation conditions. Cultivation was performed at the facilities of the School of Agronomy of the Pontificia Universidad Católica de Valparaíso in a multitunnel greenhouse (polyethylene cover thickness: 200 µm) with a natural ventilation system in the province of Quillota (32°50' S; 71°13' W, 120 masl) in the region of Valparaíso, Chile. Tomato seedlings were planted on 27 July 2015, when the plants had six or seven true leaves. The cultivar Patron (Syngenta, Basel, Switzerland) was grafted onto Emperor rootstock (Rijk Zwaan, De Lier, The Netherlands) and used with 2 plants/m². The cultivation was managed following methods commonly used in the Quillota area. All plants were topped above the seventh truss 192 d after transplanting.

Treatment applied and unit crop. Tomatoes were cultivated in a greenhouse equipped for fertigation, which allowed the assessment of the effects of different levels of EC with the same nutritional balance (equal balance of macronutrients) (Table 1) but different nutrient concentrations. The unit crop was a 30 L Projar Golden Grow Hydropnics Balance (Valencia, Spain) coil growth bag (100 × 30 × 10 cm, L × H × W). Three drippers were used per growth bag. Each growth bag contained three plants, each trained with two leading shoots and fertigated by three drippers with a nominal flow rate of 4.0 L·h⁻¹.

The water quality in the area has an EC value of ≤0.7 dS·m⁻¹, and a level of EC = 2.2 dS·m⁻¹ was assumed for the control treatment (T₀). For the next two treatments, the target level was increased to T₁ = 3.5 dS·m⁻¹ and T₂ = 4.5 dS·m⁻¹. Nutrient solutions were sampled daily during the crop cycle and were within 0.2 dS·m⁻¹ of EC target levels.

For each treatment, two control points were used for fertigation control: 1) a control...
Table 1. Nutrient solutions of EC treatments used for tomato cultivation during the crop cycle.

| EC (dS·m⁻¹) | pH   | K⁺ | Ca²⁺ | Mg²⁺ | NO₃⁻ | H₂PO₄⁻ | SO₄²⁻ |
|-------------|------|----|------|------|-------|--------|-------|
| 2.2         | 5.8  | 5.0 | 5.0  | 1.8  | 12.5  | 2.0    | 1.75  |
| 3.5         | 5.8  | 8.3 | 5.1  | 2.1  | 16.2  | 3.0    | 2.4   |
| 4.5         | 5.8  | 11.5| 7.4  | 2.1  | 21.4  | 4.0    | 2.5   |

Data shown are the average of three replicates.

Table 2. Fertigation parameters and nutrient emissions to environment of nutrient solutions with different electrical conductivity (EC) levels (dS·m⁻¹) used for tomato cultivation during the crop cycle.

| Drainage (%) | Drainage EC (dS·m⁻¹) | Drainage pH | Water (L·m⁻²) | NO₃⁻ (mol·m⁻²) | K⁺ (mol·m⁻²) | NO₃⁻ (g·m⁻²) |
|--------------|----------------------|-------------|----------------|-----------------|--------------|---------------|
| 2.2          | 2.2                  | 4.5         | 2.2            | 4.5             | 2.2          | 2.2           |
| 3.5          | 3.5                  | 4.5         | 3.5            | 4.5             | 3.5          | 3.5           |
| 4.5          | 4.5                  | 4.5         | 4.5            | 4.5             | 4.5          | 4.5           |

Data shown are the average of three replicates. Different letters indicate significant differences according to Tukey’s test (P ≤ 0.05).
effects (adding NaCl) and the benefits of the increased EC with an equal balance of macronutrients. Their results for decreased water availability, and thus the reduction of root-pressure-driven xylem transport of water and solutes, are similar to the findings reported by Gallegos-Cedillo et al. (2016).

Nitrate and potassium uptake exhibited an opposite trend to that of water uptake, increasing in higher EC treatments. These results are similar to previous results showing that an increase in all nutrients in equal ratios in the root environment can lead to a gradually increased uptake of all cations (Sonneveld and Voogt, 2009) but not enough to achieve equal nutrient emissions to the environment.

Effect on total crop productivity and on distribution of fruit sizes. Total and commercial yield decreased considerably (Table 3), with an average reduction from 15% to 19% and from 19% to 22% in the medium and high EC treatments, respectively, compared with the low EC treatment, thus presenting significant differences. The distributions of fruit size for the extra large (GG) and large (G) sizes were significantly affected, with decreases from 69% to 39.5% and from 42% to 36.5% in the medium and high EC treatments, respectively, compared with the low EC treatment. Medium sizes (M, MM, and MMM) were unaffected, whereas small fruits (S) were significantly affected, with a trend opposite to that of large sizes and an average reduction of 69%.

However, the total and commercial numbers of fruits per area were unaffected between treatments. Distribution of number of fruit size per area corresponding to extra large (GG) and large (G) sizes was significantly affected, with decreases from 68% to 59.5% and from 62% to 35% in the medium and high EC treatments, respectively, compared with the low EC treatment. Medium sizes (M, MM, and MMM) were unaffected, whereas small size (S) was significantly affected, with an opposite trend to that seen in large sizes and an average reduction of 73%.

The results of the present study showed that the fresh fruit yield of tomato was reduced by an increase in moderately high EC nutrient solutions with an equal balance of macronutrients, in accordance with other works in which increased EC was achieved (Adams, 1991; Borghesi et al., 2011; Sonneveld, 2000). Many researchers have tested various EC ranges, obtaining thresholds between 3 and 10 dS-m⁻¹ with no reduction in commercial yield (De Pascale et al., 2001; Krauss et al., 2006). In addition, Borghesi et al. (2011) stated that the influence of EC threshold value on yield is also

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Table 3. Effects of nutrient solutions with different electrical conductivity (dS-m⁻¹) levels on yield, size, and number of fruits per area.

| Size          | Yield (kg-m⁻²) | No. of fruits/m² |
|---------------|---------------|------------------|
|               | 2.2           | 3.5             | 4.5             | 2.2           | 3.5             | 4.5             |
| GG (82–102 mm)| 1.04 a        | 0.81 a          | 0.32 b          | 3.93 a        | 3.11 a          | 1.26 b          |
| G (81–67 mm)  | 5.45 a        | 4.99 a          | 3.17 b          | 30.96 b       | 29.33 a         | 19.11 b         |
| M (66–57 mm)  | 2.67 a        | 3.12 a          | 2.58 a          | 23.67 a       | 27.81 a         | 23.09 a         |
| MM (56–47 mm)| 1.89 a        | 1.74 a          | 2.24 a          | 27.96 a       | 26.25 a         | 32.72 a         |
| MMM (46–40 mm)| 0.79 a       | 0.76 a          | 0.84 a          | 17.78 a       | 17.78 a         | 18.81 a         |
| S (39–35 mm)  | 0.05 b        | 0.10 ab         | 0.16 a          | 1.48 b        | 3.19 ab         | 5.48 a          |
| Marketable yield | 11.89 a     | 11.52 a         | 9.31 b          | 105.78 a      | 107.46 a        | 100.48 a        |
| Total yield   | 16.66 a       | 15.86 a         | 13.49 b         | 154.07 a      | 157.69 a        | 149.96 a        |

Data shown are the average of three replicates. Different letters indicate significant differences according to Tukey’s test (P ≤ 0.05).

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Fig. 1. Effect of variations in electrical conductivity values (dS-m⁻¹) of the nutrient solution on dietary quality of tomato fruits. Data shown represent the average of three replicates. Different letters indicate significant differences according to Tukey’s test (P ≤ 0.05).
dependent on genetics (e.g., cultivar). Not all tomato cultivars decreased their fruit size to the same extent, and small-sized fruits were least affected by salinity, with a lower reduction in yield (Cuartero and Fernández-Munoz, 1999). As growers choose tomato varieties depending on the fruit size demanded by consumers, tomatoes chosen to grow under moderately high EC nutrient solutions with an equal balance of macronutrients could be adjusted to commercial standards.

**Effect on dietary quality of fruit.** Functional quality parameters of tomato fruits are presented in Fig. 1. All measured parameters significantly improved as EC treatment increased. The increased dietary value of fruits produced at the higher EC level can be attributed to a lower accumulation of water in fruits caused by an osmotic effect of the higher nutrient solution EC. The percentage increase in dry matter content provided evidence for this question.

Lycopene content was considerably enhanced (with an average growth of 6.3% between low and high EC treatment). These results are similar to those of other studies (Borghesi et al., 2011; De Pascale et al., 2001; Krauss et al., 2006; Kubota et al., 2012). However, EC reduced or had no effect on lycopene content, as previously reported (Ali and Ismail, 2014; Fernández-García et al., 2002; Van Meulebroek et al., 2012). It has been argued that lycopene content depends on genotype and climatic conditions rather than salinity stress; lycopene content is also negatively correlated with fruit size rather than an increase in biosynthesis (Ehret et al., 2013).

Ascorbic acid content increased, with an average increase of 8.8% between the low and high EC treatment. Previous work has reported similar results (De Pascale et al., 2001; Ehret et al., 2013; Zushi and Matsuzoe, 2015). Ali and Ismail (2014) reported a 7-fold increase in ascorbic acid content in plants subjected to severe salinity stress (10 dS·m⁻¹). These authors stated that specific genotype salinity sensitivity plays a key role in tomato plant behavior, and thus, contradictory results were reported (Fernández-García et al., 2002; Kubota et al., 2012).

Total phenolics content and total antioxidant activity content (11.1%). We emphasize that this increase was achieved at EC values that are frequently measured in drainage solutions in open hydroponic systems.

**Conclusions**

Moderate salinity decreased total and commercial yield, with an average reduction of 5% to 19% and 3% to 22%, respectively. An important decrease in extra large (GG) and large (G) fruits, with average reductions of 69% to 42%, respectively, was also observed. However, the impact on yield, size, and dietary-related metabolites significantly increased at the highest EC value, including lycopene (6.3%), ascorbic acid (8.8%), total phenolics contents (8.3%), and total antioxidant activity content (11.1%). We emphasize that this increase was achieved at EC values that are frequently measured in drainage solutions in open hydroponic systems.

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