Thermography Study of Moderate Electrical Conductivity and Nutrient Solution Distribution System Effects on Grafted Tomato Soilless Culture

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Abstract. In recent decades, salinity in the culture of tomatoes has been one of the most studied parameters. This study aimed to evaluate the effect of a moderate increase in salinity, fertigation distribution, and its control using thermography on a soilless culture of grafted tomato. A tomato crop (cv. Ramyle) grafted onto tomato rootstocks (cv. Emperor) was cultivated in coir crop units at the University of Almeria from Nov. 2012 to May 2013. A plot design subdivided with four blocks was used, with salinity values of 2.0 and 2.5 dS·m⁻¹ in the main plots and fertigation distribution systems with either one (DD₁) or four (DD₄) drip manifolds in the subplots. The crop productivity was measured using total crop yield, commercial value, and size. The quality parameters in the fruits were not significantly affected. Thermographies were used to aid the control of differential transpiration exerted by salinity. The difference in salinity did not significantly affect the total or commercial production. However, despite being grafted plants, there was a statistically significant effect ($P \leq 0.05$) on the fruit size distribution when the electrical conductivity (EC) of the nutrient solution was increased from 2.0 to 2.5 dS·m⁻¹, with a lower production (16%) of large fruits and an increased production of smaller fruits. The DD₄ system significantly increased large tomato production (22%) compared with DD₁, and the quality parameters in the fruits were not significantly affected. As a result of the improvement in tomato size, the DD₄ distribution system economically offset the required higher initial expenditure compared with the DD₁ system. Thermography was revealed to be a robust, simple, and quick tool for diagnosing the effect of salinity on transpiration.

Salinity is one of the most limiting studied factors in protected horticulture. The negative effect of increased osmotic pressure deviations from an optimal value in the culture medium and nutrient solution has been studied for a long time. Adapting the management of fertigation and salinity (expressed as ionic composition of the nutrient solution) to the production conditions is a highly influential factor in terms of an economic balance but is also an important factor for controlling the emission of pollutants into the environment (Massa et al., 2010; Urrestarazu et al., 2008a). From the 1930s and 1940s (Hayward and Long, 1943; Robbins, 1937) to the present (Adams, 1991; Adams and Ho, 1989; Cuartero and Fernández-Muñoz, 1998; Ho and Adams, 1995; Urrestarazu et al., 2005), two clear effects with increasing salinity have been described as follows: 1) productivity loss and 2) the increase of fruit quality parameters (e.g., total soluble solids, dry matter content, acidity, average fruit weight, and ionic concentration). To determine and quantify the production loss resulting from increased

radical osmotic pressure, several experimental protocols have been described since the 1970s (e.g., Hoffman, 1985; Jobes et al., 1981; Maas and Hoffman, 1977). Currently, these protocols have been modified and adapted by quadratic fit models considering salinity values starting at 0 dS·m⁻¹ (Sonneveld, 2004a, 2004b; Sonneveld and Voogt, 2009). These models have been widely used to describe and forecast production based on certain conditions of salinity. The vast majority of the information available in the literature has been published under conditions of large salinity differences in the treatments. However, studies evaluating the effects of using moderate salinities are scarce.

A non-uniform distribution of nutrients in the culture medium causes a significant effect on plant roots (Robinson, 1994; Schwarz et al., 1995). From the work of Heinen (1997), van Noordwijk (1978), and van Noordwijk and Raats (1980, 1981), models have been developed to determine the importance of the distribution of fertigation drip emitter outlets and the location of drainage points in crop container units, but there are few studies that evaluate production-related economic benefits by applying a better distribution of the nutrient solution with similar costs of localized irrigation infrastructure, including drippers and their manifolds.

Thermography is being used in all areas of scientific and technological research (Grinzato et al., 2010). Recently, studies on the application of thermography to soilless cultivation in relation to fertigation (Fernández-Bregón et al., 2013) or in relation to the salinity of fertigation (Urrestarazu, 2013) have been published.

This study had the following two objectives: 1) to evaluate the effect of moderate salinity and the type of fertigation distribution on a tomato crop; and 2) to evaluate the potential of thermography as a diagnostic tool of the effect of moderate salinity expressed through plant transpiration.

Materials and Methods

Cultivation conditions. Cultivation was performed at the facilities of the University of Almeria (Spain) in a plastic greenhouse (200 µm thick). Grafted seedlings were planted on 9 Nov. 2012 during a stage in which the plants had six and seven true leaves. We used the Emperor F1 cv. rootstock and the Ramyle F1 cv. tomato graft. The cultivation management was made following methods commonly used in the cultivation area.

For each treatment, two controls were established for fertigation control consisting of a control dripper and a drain pan that served as points of measurement and monitoring of supplied fertigation and its absorption response. In these locations, the volume of the nutrient solution as well as the pH and EC of the fertigation input and the drainage was measured on a daily basis. These feedback data supplied the fertigation scheduling program.

Each new irrigation process was performed when 10% of the readily available water in the substrate had been exhausted plus the volume necessary to produce between 15% and 25% of drainage (Urrestarazu, 2004; Urrestarazu et al., 2005, 2008b). The duration of each irrigation process was selected by adjusting the volume to be supplied to each cultivation unit depending on the soil water release curve obtained (Fig. 1). To obtain the water release curve of the coir substrate, the following volumes were calculated (vol:vol): total porosity, air volume (aeration capacity), readily available water, reserve water, and scarcely available water (AENOR, 2012). The physical analysis of the substrate was performed in triplicate. The cultivation unit was a Pelemix GB1002410® coir grow bag (100 × 25 × 10 cm) with a cultivation volume of 25 L.

Treatments applied. Two sources of variation were considered. The first source of variation was the salinity of the nutrient solution with an EC value of either 2.0 or 2.5 dS·m⁻¹. The nutrient solution was prepared with concentrated solutions of macronutrients in the proportions indicated in Table 1. The second source of variation was the number of supply outlets delivering the nutrient solution with one (DD₁) or four (DD₄) microtube drip manifolds. Each microtube was 4 mm in diameter and 60 cm in length. The distribution of the three or 12 pegs (or stabilizers)

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Fig. 1. Water release curve for the coir as a function of the water tension at the receiving substrate expressed in units of centimeters of water column (based on De Boodt et al., 1974).

Fig. 2. (A) Reference image of the two tomato leaves corresponding to the salinity treatments of $EC_{2.0}$ and $EC_{2.5}$ (EC values of 2.0 and 2.5 $dS \cdot m^{-1}$, respectively). (B) Thermography corresponding to the different salinity treatments. (C) Detail of the method for measuring the temperature in a leaflet. (D) Method applied to all of the leaflets of each leaf. EC = electrical conductivity; AVG = average temperature considered in a thermograph.

Fig. 3. Effect of the electrical conductivity (EC) ($dS \cdot m^{-1}$) of the nutrient solution, namely, 2.0 ($EC_{2.0}$; dashed line) and 2.5 ($EC_{2.5}$; solid line) and the distribution of the nutrient solution with one (DD_1 ; dashed line) and four (DD_4 ; solid line) dripper outlets on tomato plant production size ($kg \cdot m^{-2}$) according to equatorial diameter and total commercial size. * and ns indicate significant differences in the analysis of variance at $P \leq 0.05$ and nonsignificant, respectively.

Fig. 4. Average temperature of tomato crop leaves with nutrient solution treatments with electrical conductivity (EC) values of 2.0 and 2.5 $dS \cdot m^{-1}$, respectively (average data of all three leaflets per treatment). Average temperatures measured by thermography of a 3 to 5 cm^2 surface area of each leaflet and leaf (see Fig. 2).

was done in a uniform manner throughout the culture unit.

Harvest sampling. The harvest took place during a period spanning from 14 Mar. to 15 May 2012. The harvest of individual fruits was done on a weekly basis for tomatoes in the state of maturity corresponding to a uniform red color of the tomato skin. The tomatoes were sized according to their equatorial diameter and the prevailing commercial fruit category (DO, 2000). The yield of each size was clustered throughout the culture, and the median values are shown in Table 2. From each harvest, a subsample of three tomato fruits was taken and used to make a homogenized solution to measure pH, EC, and total soluble solids (expressed as $^{\circ}Brix$), which were measured with a digital handheld refractometer (Atago PAL-1). After drying the tomatoes in a forced-air oven at 85 $^{\circ}C$ for 72 h, the dry matter was obtained by weighing three tomatoes with an accuracy of one hundredth of a gram.

Sampling and analysis of the thermographies. At full production of the tomato crop, three thermographies for each EC treatment were taken by sampling the eighth fully expanded leaf located at the end of the plant (Fig. 2). The average temperatures were measured in an area of between 3 and 5 cm^2 for each leaflet following the procedure described by Fernández-Bregón et al. (2013) and Urrestarazu (2013). The thermographies were taken the same day at 1200 hr following the criteria of Fernández-Bregón et al. (2013) and Möller et al. (2007).

Infrared thermography images were obtained with a Fluke[®] Ti32 thermal imaging scanner (Janesville, WI) with an infrared spectrum measuring range of 7.3 to 13 μm and a temperature range of -40 to $+600$ $^{\circ}C$. The detector allows a resolution of 320×240 pixels with a minimum focal length of 0.3 m and a spatial resolution of 0.01 $^{\circ}C$. The thermal image processing was analyzed with the SmartView 3.2[™] Researcher Pro software (Fluke Thermography, Plymouth, MN), which allowed the determination of mean, maximum, and minimum temperatures in a particular surface area.

Experimental design and statistical analysis. The experiment was conducted using a split-plot design (Little and Hill, 1978; Petersen, 1994). The main plot had salinity (EC) as the

Table 1. Nutrient solutions used in the culture of tomato.

Electrical conductivity (dS·m ⁻¹)	Macronutrients (mm)							Micronutrients (μM)					
	pH	NO ₃ ⁻	H ₂ PO ₄ ²⁻	SO ₄ ²⁻	K ⁺	Ca ²⁺	Mg ²⁺	Iron	Manganese	Copper	Zinc	Boron	Molybdenum
2.00 ^z	5.80	10.25	1.50	1.75	4.75	5.00	1.51	15	10	0.75	5	30	0.5
2.50	5.80	12.81	1.88	2.19	5.95	6.25	1.89	15	10	0.75	5	30	0.5

^zBased on Sonneveld and Straver (1994).

source of variation. The secondary plot corresponded to the plot hosting the drip fertigation system (DD₁ and DD₄). The number of plot and subplot blocks was four. An analysis of variance and the corresponding separation of mean values were performed accordingly. The mathematical treatment of the data were performed using Statgraphics Centurion® 16.1.15 and Microsoft Office 2010 (Microsoft Inc., Redmond, WA). The experimental unit consisted of three coir grow bags. Each bag contained three plants fertigated with three dripper outlets with a nominal flow rate of 3 L·h⁻¹. A simple Student's *t* test was used to calculate the mean separation of temperature values obtained from the thermography imaging data.

Results and Discussion

Effect on total crop productivity. Table 2 shows the treatment data arranged per total productivity, commercial value, and size. In the total crop yield and total commercial value, no significant differences were observed for the following treatments: salinity and type of drip manifold (DD) used to distribute the nutrient solution. An increased production in the lower salinity (EC_{2.0}) treatment was not found compared with the higher salinity (EC_{2.5}) treatment described in the literature (Hoffman, 1985; Jobs et al., 1981; Maas and Hoffman, 1977; Sonneveld, 2004a; Sonneveld and Voogt, 2009).

It is well known that grafting contributes to increased plant vigor and greater tolerance to diseases (Miguel et al., 2004), salinity and water stress (e.g., Fernández-García et al., 2002; Lee, 1994; Lee and Oda, 2003; Schwarz et al., 2010). Therefore, grafting may have helped to prevent the loss of total production of the tomato crop.

Effect on the distribution of fruit sizes. Tomato fruit size was significantly affected by both the salinity and nutrient solution distribution system (DD) (Fig. 3). The nutrient solution with a lower EC value (EC_{2.0}) produced a statistically significant ($P \leq 0.05$) higher proportion of larger fruits (size MM; 16%) and a lower proportion of the smaller fruit size (P; 5%) and noncommercial size (34%). Because larger sizes tend to have a higher market value, the EC increase from 2 to 2.5 dS·m⁻¹ resulted in a loss of market value. These results were consistent with those obtained in a large number of studies, in which an increase in salinity has been reported to cause a reduction in mean fruit weight (Hayward and Long, 1943; Ho and Adams, 1995).

Similarly, increasing the number of drip outlets of the nutrient solution from one (DD₁) to four (DD₄) produced a variation in

Table 2. Total tomato crop yield (kg·m⁻²) arranged according to size and electrical conductivity (EC) of the nutrient solution and fertigation supply with one and four drip manifolds.

Size ^y	EC = 2.0 dS·m ⁻¹		EC = 2.5 dS·m ⁻¹	
	No. of outlet drip manifolds		No. of outlet drip manifolds	
	1	4	1	4
M (57–67 mm)	0.65 b ^z	1.03 a	0.91 ab	1.01 a
MM (47–57 mm)	3.69 ab	4.18 a	3.10 b	3.50 ab
MMM (40–47 mm)	2.03 a	1.70 bc	1.94 ab	1.65 c
P (35–40 mm)	1.83 a	1.50 c	1.76 ab	1.71 b
Noncommercial (< 35 mm)	0.75 c	0.82 bc	0.97 b	1.12 a
Total commercial	8.20 a	8.22 a	7.72 a	7.87 a
Total	8.96 a	9.05 a	8.69 a	9.00 a

^zDifferent letters between columns indicate significant differences at $P \leq 0.05$.^ySource: DO (2000).

Table 3. Some parameters of tomato fruits according to the different electrical conductivity (EC) values of the nutrient solution and fertigation system used (one and four outlet drip manifolds).

	EC (dS·m ⁻¹)		No. of drip manifolds	
	2.0	2.5	1	4
pH	4.21	4.27 NS	4.24	4.24 NS
EC	4.38	4.44 NS	4.43	4.39 NS
Total soluble solids (°Brix)	4.92	5.08 NS	5.11	4.89 *
Dry matter (%)	7.08	7.25 NS	7.20	7.13 NS

*Statistically significant differences between treatments at $P \leq 0.05$; NS = nonsignificant.Table 4. Economic balance based on usage of one (DD₁) or four (DD₄) outlet drip manifolds for each distribution system for tomato cultures grafted in coir bags considering only the yield and income generated by the production of larger tomatoes.

Sizes ^x	Yield (kg/m ² /culture)		Dripper price ^z (€/m ² /year)		Tomato price ^y (€/kg)	Income (€/m ² /culture)	
	DD ₁	DD ₄	DD ₁	DD ₄		DD ₁	DD ₄
M (57–67 mm)	0.78	1.03	0.12	0.42	1.12	0.87	1.15
MM (47–57 mm)	3.40	3.84	0.12	0.42	0.81	2.75	3.11
MMM (40–47 mm)	1.99	1.68	0.12	0.42	0.60	1.19	1.01
Total	6.17	6.55				4.82	5.27
Difference DD ₄ –DD ₁	0.38		0.30			0.45	

^zBased on average prices of two trading houses and the recommended average replacement time of drippers (10 years).^yBased on average prices received by farmers in agricultural cooperatives for the same culture dates. Source: H y hortalizas de Almería (2013) [Fruits and vegetables of Almería (2013)].^xSource: DO (2000).

the distribution of the tomato fruit sizes. The M and MM sizes increased significantly ($P \leq 0.05$) by an average of 30% and 13%, respectively. Moreover, the smaller sizes, namely MMM and P, decreased by 16% and 11%, respectively. Consequently, a better fertigation distribution system in the culture unit improved the production, as occurred with the lower saline treatment. These results were similar to those published by Robinson (1994), who reported productivity improvements when nutrients are properly distributed. Similar results have also been reported by Sonneveld and de Kreij (1999) and Sonneveld and Voogt (1990) about production of cucumber and tomato, respectively.

The use of grafted plants did not prevent a loss of large tomatoes in favor of smaller

tomatoes. Therefore, the vigor effect described for grafted plants was not positively expressed in the size distribution.

Effect on the production quality parameters. Table 3 shows some quality parameters of tomato fruits. The different treatments did not show significant differences in the evaluated fruit quality parameters, except for the total soluble solids in the treatments that decreased with increasing distribution of nutrient solution. An increase in salinity values has been related to a significant increase in the percentage of dry matter, acidity, total soluble solids (°Brix), and fruit osmotic concentration (Hayward and Long, 1943). However, in the present experiment, such a significant increase was not observed, which may have been the result of the following

Table 5. Economic balance based on nutrient solution selection (NS) with electrical conductivity (EC) values of 2.0 dS·m⁻¹ (EC_{2.0}) and 2.5 dS·m⁻¹ (EC_{2.5}) for tomato cultures grafted in coir bags considering only the yield and income generated by the production of larger tomatoes.

Sizes ^x	Yield (kg/m ² /culture)		Price NS ^z (€/m ² /culture)		Tomato price ^y (€/kg)	Income (€/m ² /culture)	
	EC _{2.0}	EC _{2.5}	EC _{2.0}	EC _{2.5}		EC _{2.0}	EC _{2.5}
M (57–67 mm)	0.84	0.96	0.69	1.10	1.12	0.94	1.08
MM (47–57 mm)	3.93	3.30	0.69	1.10	0.81	3.18	2.67
MMM (40–47 mm)	1.86	1.79	0.69	1.10	0.60	1.11	1.07
Total	6.63	6.05				5.23	4.82
Difference EC _{2.0} –EC _{2.5}	–0.58		–0.41			–0.41	

^xBased on the prices of each liter of the nutrient solution and the volume of the culture cycle used.

^yBased on average prices earned by farmers in the agricultural cooperatives for the same culture dates and area. Source: Frutas y Hortalizas de Almería (2013) [Fruits and vegetables of Almería (2013)].

^zSource: DO (2000).

reasons: 1) the small increase of EC that was considered; 2) the tolerant behavior of tomato compared with other horticultural crops, as previously described in pioneer studies (Maas and Hoffman, 1977); and 3) the potential contribution of the vigor provided by the rootstock against salinity (Lee and Oda, 2003). The higher stress caused by a worse distribution of fertigation (DD₄ vs. DD₁) could justify the increased value of total soluble solids. These results agreed with the idea suggested in the recent review by Rouphael et al. (2010) on the effect of grafting on fruiting vegetables. These authors indicated that further research is needed to gain insight into the role that the grafts play on fruit quality.

Effect on the economic balance. Table 4 shows the partial economic balance regarding the investment costs required depending on the selection of the DD₁ fertigation distribution system with respect to the DD₄ system. Only the revenues from the large tomatoes, which are those with greater commercial value, were considered. The differential value of a single year's tomato crop (0.30 €/m²/crop) would have offset the higher initial investment (from 0.45 €/m²/year) representing the DD₄ system with respect to the DD₁ system. Table 5 shows the partial economic balance regarding the economic cost involved in fertigation with a solution that has an EC value of 2.0 dS·m⁻¹ with respect to that performed with a solution that has an EC value of 2.5 dS·m⁻¹. These results showed a farmer's loss of income of 0.41 €/m² (8.5%) with a higher proportion of expenditure on fertilizers (0.41 €/m²) if the fertigation was performed with an EC_{2.5} solution. Consequently, as a function of the value of the fertilizers and the tomato market value on the basis of size, an extra value of 0.82 €/m² was obtained with the EC_{2.0} option compared with the EC_{2.5} option. However, the farmer sometimes chose this disadvantageous option for some of the following reasons: 1) to maintain an adequate harvest index by a moderate saline stress (maintaining an appropriate balance between the proportion of the vegetative and reproductive phase of the tomato); 2) to avoid increased susceptibility to plant health problems; 3) to increase the lifetime of post-harvest (Mizrahi, 1982; Mizrahi et al., 1988); and/or 4) to increase or improve the quality

parameters (total soluble solids and acidity) as well as to increase products that enhance the flavor or health beneficial nutrients (Cuartero et al., 1996; Rouphael et al., 2010; Sharaf and Hobson, 1986).

In both conditions, choosing DD₁ over DD₄ and/or EC_{2.5} over EC_{2.0}, there is an implied economic loss to the farmer. In both cases, the proportion of this loss depends on the difference in the market value of large tomatoes compared with smaller tomatoes with this difference being generally higher in North American markets compared with European markets. However, despite causing substantial economic loss in commercial farms that choose the EC_{2.5} option over EC_{2.0}, it is a common practice.

Role of thermography. The average temperatures measured on leaves treated with solutions with different EC values are shown in Figure 4. This small difference of transpiration vs. increment moderate increase EC of nutrient solution was sufficient to be captured, measured, and analyzed by thermography through adequate software. Although the temperature differences were small (less than 1 °C; ≈2%), the lowest recorded temperatures were significantly correlated with the treatment with the lowest EC value ($P \leq 0.001$). This method is based on an adequate measure of only an appropriate leaf fraction under similar environmental conditions (Fernández-Bregón et al., 2013; Urrestarazu, 2013) avoiding the disadvantages when 1) infrared thermography measures include other surfaces different from the desired area with consequent errors in estimated temperature (Jones et al., 2002; Moran et al., 1994); or 2) measuring the temperature of a single point on a leaf. These correlations and results were similar to that found by Oerke et al. (2006) in melons or by Urrestarazu (2013) in ornamental plants. Therefore, if thermography is properly handled, it can serve as a simple, rustic, nondestructive, and useful remote sensing tool for diagnosing a limiting factor such as poor transpiration resulting from a possible saline or water stress condition. Consequently, thermography could be incorporated into a remote sensing network for the control and monitoring of horticultural crops, as suggested by Álvaro et al. (2011) and Fernández-Bregón et al. (2012).

Conclusion

A moderate increase in EC (from 2.0 to 2.5 dS·m⁻¹) of nutrient solution did not exert a significant effect on crop yield in a grafted tomato crop or on fruit quality parameters (total soluble solids, dry weight content, or osmotic concentration of tomato juice). However, the effect of increase EC was reflected in the distribution of tomato sizes by significantly lowering the production of large tomatoes by 14% compared with smaller tomatoes.

A better distribution, four-outlet drip manifold in comparison with a one-outlet drip manifold of the nutrient solution on the culture unit did not improve the performance or the fruit quality parameters (total solids, soluble dry weight content, or osmotic concentration of tomato juice), but it significantly improved the percentage of larger fruits by more than 20%.

Distribution improvement and optimal EC in the nutrient solution increased the profitability of the crop because larger fruits have a higher market value.

Thermography may constitute a robust, fast, and non-destructive remote sensing tool for diagnosing a moderate salinity condition.

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