Effects of Fertigation Duration on the Pollution, Water Consumption, and Productivity of Soilless Vegetable Cultures

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Abstract. The management of water and nutrient ions, such as nitrate, has been studied extensively in recent decades. Increasingly efficient models have been developed for the use of water and nutrients through the automation of fertigation techniques. The application of a fertigation volume for a duration four times longer than applied on the control was evaluated. In Almería (Spain), one pepper crop and two tomato crops—with and without grafting—were grown between Oct. 2013 and June 2014 in a soilless system with a coir substrate. The effects on root growth, plant growth, production, and quality were measured. The following parameters for the fertigation of the nutrient solution and drainage were recorded: % drainage volume, electrical conductivity (EC) of the nutrient solution, pH, and concentration of nitrates and potassium. The absorption of potassium and nitrate, and the nitrate emissions of the drainage were estimated. The results showed an increase in the root volume and an improved distribution in the cultivation unit for the treatment application in the pepper crop. Slowing the applied fertigation improved the absorption of water and nitrates, and the production in the ungrafted tomato and pepper crops, while the grafted tomato crop was unaffected. Nitrate emissions were lower in the evaluated treatment of the pepper and ungrafted tomato crops. The fruit quality parameters were unaffected.

It is estimated that in the Spanish South-east, there is a soilless surface of ≈ 5500 ha (13,590.80 acres) (Urrestarazu, 2013) that consumes ≈ 500 to 700 L (109.98 to 153.98 gal) of water per square meter each year. Water use in soilless culture (Massa et al., 2010; Parry et al., 2005) and its efficiency in production (Patanè et al., 2011), the absorption of nutrient ions, such as nitrate and potassium (Cornillon and Fellahi, 1993; Topcu et al., 2007), and the pollution of nutrients released into the environment, especially that of nitrates (e.g., Gallardo et al., 2009; Min et al., 2012; Thompson et al., 2013; Urrestarazu et al., 2008a), are widely

studied. In recent decades, many studies have been conducted to improve fertigation methods for the automation of fertigation systems in soilless cultures (e.g., Cáceres et al., 2007; Rodríguez et al., 2015; Steidle et al., 2014). Fertigation methods and their automation are based on the following: 1) the fertigation frequency (f), 2) the provision of applied volume in every new fertigation (AV), 3) the rate of water consumption by the crop, which is a function of the daily primary absorption by the plants, 4) the characteristics of the substrate used, and 5) the fertigation elements used for the supply of nutrient solutions (Urrestarazu, 2004). A large number of these fertigation methods are based on each new irrigation process being performed when 10% of the easily available water in the substrate has been exhausted plus the volume necessary to produce between 15% and 25% of the drainage

(volume A , $\text{mL}\cdot\text{m}^{-2}$), which is the leaching fraction (LF) (e.g., Rodríguez et al., 2015). The LF usually varies between 0.15 and 0.25, depending on the water quality expressed by the salinity (e.g., Urrestarazu, 2004; Urrestarazu et al., 2005; Urrestarazu et al., 2008b). The amount provided in each fertigation (AV, $\text{mL}\cdot\text{m}^{-2}$) is equal to $A + \text{LF}$.

$$\text{AV} = A + \text{LF}$$

The number (n) of fertigation applications per unit time is f , which in turn depends on the fertigation demand that the crop requires. The time (t , in minutes) required to supply the AV amount (volume delivered per unit area, $\text{mL}\cdot\text{m}^{-2}$) will depend on the available fertigation system and is variable; it is a predetermined value in all fertigation applications. We will consider t_i the time in minutes between two consecutive irrigations. The time at which the fertigation infrastructure supplies an AV volume is t , while in this study, a device was determined that transforms t to a value that is four times greater (t_d , in minutes).

$$t_d = 4 \cdot t$$

The time t_d must be less than t_i for the supply of fertigation to be equal in both treatments and to not overlap.

The values of EC, pH, and LF in fertigation drainage are frequently used parameters for the practical control of soilless systems (e.g., Gorbe and Calatayud, 2010; Hayward and Long, 1943; Urrestarazu et al., 2008b).

No information is available on the effect of the time of application of a fertigation volume given to a crop compared with the standard time of a fertigation based on the elements used in each fertigation installation, i.e., the emission duration to deliver the AV volume. This would not change the delivered volume but would affect the time that the roots are subject to a lower matric potential for a given time and, thus, the energy required for water absorption.

Of note, the improvement of the spatial distribution of fertigation in the cultivation unit in turn improves the production (Morales and Urrestarazu, 2013). This increase in production is due to better utilization of the substrate unit volume causing improved availability of water and nutrients (Robinson, 1994), which results in increased root growth. By occupying a greater volume, the roots can access better physicochemical conditions that are distributed unevenly, depending on the fertigation method (De Rijk and Schrevens, 1998; Sonneveld and Voogt, 1990).

The aim of the present study was to evaluate the effect of time on the application of a fertigation volume on the parameters of fertigation, water consumption, emission of pollutants, root distribution, and production of a pepper and tomato crop in a soilless culture system.

Abbreviations and concepts used:

AV = Volume (mL) delivered in each fertigation.

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A = Volume consumed ($\text{mL} \cdot \text{m}^{-2}$) by the crop that corresponds to 10% of the readily available water consumed by the crop and must be replaced in cultivation units.
 LF = Proposed leaching fraction. Generally varies between 0.1 and 0.5.
 n = Number of fertigation applications.
 f = Frequency of fertigation applications. Number of fertigation applications per unit time.
 t = Time (in minutes) that a required applied volume (AV) lasts for a given system.
 t_i = Time (in minutes) elapsed between the start of two consecutive irrigations.
 t_d = Time added to t (minutes) by interposing a device that reduces the flow (four times) the system issues; it is placed between the drip emitter and the cultivation unit.
 EC = Electrical conductivity of the nutrient solution.

Materials and Methods

Three independent experiments were conducted.

Experiment 1. The pepper cultivation was performed at the facilities of the University of Almeria (Spain) in a thermic plastic greenhouse (200 mm thick and 7.87 in). The culture conditions are shown in Table 1.

Treatment. The control treatment (T0) consisted of a standard fertigation lasting 5 min with self-compensating drippers and $3 \text{ L} \cdot \text{h}^{-1}$ ($0.66 \text{ gal} \cdot \text{h}^{-1}$) antidrain valves. The evaluated treatment (T1) consisted of a simple container with a labyrinthine output similar to those used in multiple manifolds from a dripper (Wamser et al., 2014) that increased the time during which fertigation was incorporated into the cultivation unit by four times (Fig. 1).

Fertigation conditions and fertigation sampling. For each treatment, one fertigation

control was established consisting of a control dripper and a drain pan that served as points of measurement for the monitoring of the supplied fertigation and its absorption response. In these locations, the volume of the nutrient solution and the pH, and EC of the fertigation input and the drainage were measured on a daily basis. These feedback data supplied the fertigation scheduling program. An automatic system to measure the volume of drainage was used, as reported by Rodríguez et al. (2015).

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 the drainage (Urrestarazu, 2004; Urrestarazu et al., 2005, 2008a). The duration of each irrigation process was selected by adjusting the volume to be supplied to each cultivation unit depending on the substrate water release curve obtained

Fig. 1. Fertigation hydrograph. The solid blue line is the control treatment (T0). The dashed red line is the evaluated treatment (T1), which extended the fertigation duration by four times. Right bars indicate total volume of fertigation to each watering.

Fig. 2. Nitrate (top) and potassium (bottom) content in the drainages of the pepper crop. The solid blue line is the control treatment (T0). The dashed red line is the evaluated treatment (T1), which extended the fertigation duration by four times. Right Bars indicate mean values.

of the substrate (Morales and Urrestarazu, 2013). The cultivation unit was a Pelemix GB1002410 coir grow bag (100 × 25 × 10 cm, L × H × W), (39.37 × 9.84 × 3.93 in, L × H × W) with a cultivation volume of 25 L (5.5 gal). The nutrient solution used was recommended by Sonneveld and Straver (1994). Three drippers were used per cultivation unit.

The nitrate and potassium content in the drainage was measured weekly by ion chromatography (Urrestarazu et al., 2008b). With the concentration and volume of the drained fertigation, the absorption of nitrates, and potassium was quantified in mmol·m⁻² and their emissions were quantified in g·m⁻².

During the first month of cultivation, the nitrate and potassium content of the drainage from daily fertigation were continuously monitored. The data are shown in Fig. 2.

Vegetative growth and harvest sampling. From the beginning of the harvest, the culture was sampled weekly. From each harvest, a subsample of three pepper fruits was used to make a homogenized solution to measure the total soluble solids (expressed as °Brix), which were measured with a digital hand-held refractometer (manufactured for Atago PAL-1).

After the peppers were dried in a forced air oven at 85 °C (185 °F) for 72 h, the dry matter mass was obtained by weighing three peppers to an accuracy of 0.01 g (2.2 × 10⁻⁵ lb).

For each treatment, at the end of cultivation, four complete cultivation units per treatment were sampled. The fresh weights of the roots, stem, and leaves for each cultivation unit were measured. Subsequently, the dry weights were quantified for each sample using the same procedure as for the fruits.

Furthermore, to calculate the harvest index during deleafing for pruning formation and tutored management, the dry and fresh weights of the discarded plant material were quantified. The harvest index was calculated by dividing the dry fruit weight by the dry weight of the whole plant.

Consistent sampling was performed from the roots of the bags of each treatment to extract a cylinder of 3.5 cm (1.38 inches) diameter and 20 cm (7.87 inches) long perpendicular to the cultivation unit and at 3 cm from the last location of the pick of the dripper. This substrate volume was divided into three sections depending on the depth of

the container (Fig. 3). These measurements were performed in duplicate. The separation of the roots from the substrate was manually performed, aided by the color difference between the substrate and the root. Only roots with diameters less than 1 mm were considered. The root surface area was measured using our image analysis program, expressing the results in cm² of the roots, with cm⁻³ of the substrate as an uptake unit from root.

Experiment 2. The harvest of individual fruits was performed 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).

In the samples of the tomato fruits, the juice pH and EC were also measured.

The other culture parameters were the same as experiment 1. Sampling of the roots was not considered.

Experiment 3. Experiment 3 was similar to experiments 1 and 2, but the application period of the treatment lasted only two months during the period of full production (Table 1).

For experiments 2 and 3, vegetative growth was not recorded.

Table 1. Experimental crop parameters.

Expt.	Crop	Plant/m ²	Date		
			Transplant	Start harvest	Final crop
1	Sweet pepper cv. <i>Padua</i> F1	2	14 Oct. 2013	10 Jan. 2014	16 May 2014
2	Tomato cv. <i>Zynac</i> F1 rootstock with graft <i>Maxifort</i>	1	18 Feb. 2014	22 Apr. 2014	26 May 2014
3	Tomato cv. <i>Caniles</i> F1	1.8	20 Aug. 2013	5 Feb. 2014 ^a	01 Apr. 2014

^aAlso indicates the date that the treatment was applied for this experiment.

Fig. 3. Sampling distribution scheme of the roots in a pepper crop as a function of the position of drippers and drainage points in the cultivation unit.

Fig. 4. Fertigation drainage hydrographs. The solid blue line is the control treatment (T0). The dashed red line is the evaluated treatment (T1), which extended the duration of the fertigation by four times. The mean values obtained by averaging four different drainages during the first month at different dates of pepper (top) and grafted tomato (bottom) cultivation.

Fig. 5. Sweet pepper root distribution in the vertical section of a coir soilless cultivation unit near a dripper. *, **, and ns indicate significant differences at $P < 0.05$ and $P < 0.01$ and differences that were not significant, respectively. The solid blue line is the control treatment (T0). The dashed red line is the evaluated treatment (T1), which extended the fertigation duration by four times. Bars indicate total root surface.

Experimental design and statistical analysis. The experiments were all conducted using a split-plot design (Little and Hill, 1978; Petersen, 1994) with four plot blocks. Analysis of variance and the corresponding separation of mean values were performed accordingly. The mathematical

treatment of the data was performed using Statgraphics Centurion® 16.1.15 and Microsoft Office 2010. The experimental unit consisted of three coir grow bags. Student's t test was used to calculate the mean separation of the values obtained from the treatment.

Results and Discussion

Effect on water consumption, other fertigation parameters, and polluting emissions to the environment. Figure 4 shows drainage hydrographs of experiments 1 and 2. In both cases, there was delayed output of drainage

Table 2. Absorption and release of a nutrient solution into the environment of the coir culture as a function of the time used to provide the same volume of fertigation.

Expt.	Drainage (%)		pH		Electrical conductivity (dS·m ⁻¹)		Water (L·m ⁻²)		Uptake				Emission	
	T0	T1	T0	T1	T0	T1	T0	T1	NO ₃ ⁻ (mol·m ⁻²)		K ⁺ (mol·m ⁻²)		NO ₃ ⁻ (g·m ⁻²)	
									T0	T1	T0	T1	T0	T1
1. Sweet pepper	43.26	39.01*	7.16	7.26NS	3.29	3.30NS	361.14	388.12*	4.51	4.76*	1.76	1.96*	99.23	83.78*
2. Grafted tomato	14.61	12.56NS	7.46	7.27NS	3.91	4.09NS	126.90	127.57NS	0.90	0.90NS	0.52	0.52NS	7.08	6.83NS
3. Ungrafted tomato	60.38	58.01NS	7.39	7.55NS	3.60	3.77NS	60.26	65.02*	0.30	0.36*	0.37	0.28*	72.72	69.02**

Notes: T0 = control treatment, T1 = quadrupled delivery time of fertigation to the cultivation unit.

*, **, and NS mean significant differences at $P \leq 0.05$ and $P \leq 0.01$ and differences that are not significant, respectively.

from the evaluated treatment relative to the control. For the peppers, the hydrographs of both treatments, however, lasted a similar time, while for the tomatoes, the drainage time of the control was much lower.

Figure 2 shows the nitrate and potassium contents of the drainage of the pepper crop; a much lower proportion for both was observed in T1. The concentration distribution was very similar throughout the drainage, suggesting that any samples taken diagnose the nutritional status of the crop.

Table 2 shows the most significant parameters for controlling fertigation: the % drained volume and the pH, and EC of the nutrient solution. In absolute values, they were similar to those recorded by Urrestarazu et al. (2008b) in similar circumstances in soilless culture in rock wool and coir. No significant differences were observed, except for the drainage percentage in the pepper crop, where a lower value was recorded for the treatment that quadrupled the time during which fertigation was delivered.

Increased water absorptions of 7% and 8% were recorded for the pepper and ungrafted tomato crops, respectively, favoring treatment T1. These data can be justified by the fact that a lower matric potential is maintained in the substrate for a longer period of time, and consequently, a lower suction pressure is required to absorb water. In experiment 2 (grafted tomato), increased water absorption was not recorded. This is most likely due to the vigor of the rootstock (e.g., Fernández-García et al., 2002; Lee, 1994; Lee and Oda, 2003; Schwarz et al., 2010), which may offset the benefit of absorbing water at lower suction pressures (Urrestarazu et al., 2008a).

Nitrate uptake had a very similar trend to that of water, increasing by 7% and 20% in treatment T1 for the pepper and ungrafted tomato crops, respectively. Potassium had no clear behavior for treatment T1. For the ungrafted tomato crop, it was reduced by 11%; however, it had no significant effect for the grafted tomato crop.

Nitrate emission into the environment was markedly reduced by 16% and 5% in the pepper and ungrafted tomato crops, respectively. The effect of the treatment on the grafted tomato was not significant.

These results are consistent with the known facts that improving the root conditions improves the absorption of water and nutrient ions (such as nitrates and potassium), as reported for the soilless tomato culture when improving the temperature of the

roots (e.g., Cornillon and Fellahi, 1993; Urrestarazu et al., 2008b) or the oxygenation (e.g., Ityel et al., 2014; Urrestarazu and Mazuela, 2005).

Effect on the distribution of roots and vegetative growth. The importance of the quantity and distribution of the roots inside the cultivation unit is well known. This depends on the relative position of the drippers with respect to drainage points and other fertigation parameters as was reported on tomato crop (De Rijk and Schrevels, 1998; Van Noordwijk and Raats, 1980), such as the type of substrate (rock wool vs. coir) (Cano, unpublished work). When the proportion of roots at various depths was measured according to the treatments used, a large significant difference was found (Fig. 5). A greater root absorption surface was recorded throughout the cultivation unit around the dripper in treatment T1. In addition, better distribution of the root absorption surface was also recorded in the upper layers of the substrate. It has also been demonstrated that better a distribution of fertigation from the dripper increases the productivity of the tomato crop in coir cultivation units (Morales and Urrestarazu, 2013).

Table 3 shows the vegetative growth and harvest index of the pepper crop. The root growth showed a significant mean increase (at $P \leq 0.01$) of 15% and 20% in treatment T1 for the fresh and dry roots, respectively. Only the fresh shoots, however, were significantly affected by 5% (at $P \leq 0.05$).

Effect on production and size. Table 4 shows the production of three crops. In the pepper crop, there was a significant increase of 11% (at $P \leq 0.01$) of the number of fruits, favoring the treatment. When treatment T1 was applied to ungrafted tomato for only 2 months, there was a significant increase in both the total production (11%) and the number of fruits (5%). These positively correlated results between higher water absorption and higher production are well known, and data have been collected for examples in studies such as those by Pulpol et al. (1996) in a tomato crop or by Urrestarazu and Mazuela (2005) in melon and cucumber crops.

When applying the treatment with a slower flow rate, a significant increase in the production and number of fruits of thicker size (M: 57–67 mm) (22.44–26.38 inches) were also found at 43% and 42%, respectively. In contrast, in the control treatment, smaller sized fruits (MMM: 40–47 mm) (15.75–18.50 inches) Increased significantly

Table 3. Vegetative growth parameters as a function of the time taken to provide the same volume of applied fertigation in a pepper crop (g/plant).

		T0	T1
Root	Fresh weight	148.25	175.50**
	Dry weight	19.47	26.16**
Shoot	Fresh weight	2475.50	2615.40*
	Dry weight	252.75	245.46NS
HI		0.48	0.50NS

T0 = control treatment, T1 = quadrupled delivery time of fertigation to the cultivation unit.

*, **, and NS mean significant differences at $P \leq 0.05$ and $P \leq 0.01$ and differences that are not significant, respectively. HI is the harvest index (dry fruit weight/total dry weight).

(at $P < 0.05$) by 11% and 15% for the production and the number of fruits, respectively. This increase in the production of the larger size fruits implies a significant economic benefit for the farmers, as demonstrated by Morales and Urrestarazu (2013) in their economic study working with coir and grafted tomato.

Of note, the production and size of the grafted tomato crop was unaffected. Therefore, the benefit of improved water and nutrient absorption caused by treatment T1 could be offset by the vigor of the rootstock (e.g., Fernández-García et al., 2002; Lee, 1994; Lee and Oda, 2003; Schwarz et al., 2010).

Effect on the quality of production. Table 5 shows the quality parameters of fruits of the three crops tested. Of all of the parameters measured, only the EC of the fruits and the dry matter of the ungrafted tomato crop showed a significant difference (5%) favoring the control treatment and longer treatment of applied fertigation, respectively. Except for these two parameters, all of the other measurements did not show significant differences. Similar results were obtained by Urrestarazu and Mazuela (2005), who demonstrated that improving the radical oxygenation benefitted the water absorption and production of melon and cucumber crops, but no improvement in the quality parameters of the fruits was found. Similar results were also found by Morales and Urrestarazu (2013) in a grafted tomato crop in which the root environment was improved with a better distribution of fertigation.

Conclusions

Applying fertigation for a longer time in the pepper crop increased the root growth by

Table 4. Production and size of the fruits in the coir culture as a function of the time taken to deliver the same volume of fertigation.

Crop	Size	kg·m ⁻²		Fruit/m ²	
		T0	T1	T0	T1
Sweet pepper		6.05	6.22	248	276**
Grafted tomato					
GG (> 82 mm)		2.91	3.02NS	9.83	9.54NS
G (67–82 mm)		2.31	2.10NS	13.29	12.21NS
M (57–67 mm)		1.01	1.01NS	8.58	8.54NS
MM (47–57 mm)		0.52	0.50NS	7.08	6.83NS
MMM (40–47 mm)		0.02	0.05**	0.54	1.33**
Total		6.78	6.68NS	39.33	38.46NS
Ungrafted tomato					
M (57–67 mm)		0.42	0.74*	4.28	7.43*
MM (47–57 mm)		1.82	2.33NS	22.52	28.72NS
MMM (40–47 mm)		2.31	2.08*	41.78	36.15NS
Total		4.55	5.15*	68.58	72.30NS

T0 = control treatment, T1 = quadrupled delivery time of fertigation to the cultivation unit.

*, **, and NS mean significant differences at $P \leq 0.05$ and $P \leq 0.01$ and differences that are not significant, respectively.

Table 5. Quality parameters of fruits in the coir culture as a function of the time taken to deliver the same volume of fertigation.

Crop	pH		Electrical conductivity (dS·m ⁻¹)		°Brix		Dry matter (%)	
	T0	T1	T0	T1	T0	T1	T0	T1
Sweet pepper	—	—	—	—	2.56	2.59NS	8.17	7.97NS
Grafted tomato	4.45	4.28NS	4.55	4.60NS	4.55	4.53NS	9.11	8.62NS
Ungrafted tomato	3.97	4.00NS	5.84	5.49*	5.98	5.95NS	7.01	7.30*

T0 = control treatment, T1 = quadrupled delivery time of fertigation to the cultivation unit.

*, **, and NS mean significant differences at $P \leq 0.05$ and $P \leq 0.01$ and differences that are not significant, respectively.

15% and improved the distribution in the cultivation unit.

The increased duration of fertigation positively affected the water absorption by 7% in the pepper and ungrafted tomato crops.

When the time of fertigation application was increased, the nitrate uptake improved by 7% and 20% for the pepper and ungrafted tomato crops, respectively. A consequent reduction in polluting emissions by 16% and 5% was observed for these crops.

With the slower application of the fertigation volume, the number of fruits in the pepper crop increased by 11%, while in the tomato crop, the commercial production improved by 13%.

The distribution of sizes was unaffected in the grafted tomato crop, while in the ungrafted crop, the longer duration of the treatment compared with the control increased the size of 43% of the fruits, with a consequent positive impact on business profitability.

The most of quality parameters of production were not significantly affected by the treatments in any of the crops.

In the grafted tomato crop, the measured parameters were unaffected by treatment, most likely because the vigor of the grafting technique prevented the benefits of improving the availability of fertigation from manifesting.

Literature Cited

Cáceres, R., J. Casadesús, and O. Marfà. 2007. Adaptation of an automatic irrigation-control tray system for outdoor nurseries. *Biosystems Eng.* 96:419–425.

Cornillon, P. and A. Fellahi. 1993. Influence of root temperature on potassium nutrition of tomato plant, p. 213–217. In: M.A.C. Frago and M.L. van Beusichem (eds.). *Optimization of plant nutrition*. Kluwer Academic, New York.

De Rijk, G. and E. Schrevens. 1998. Distribution of nutrients and water in rockwool slabs. *Sci. Hort.* 72:277–285.

DO. 2000. Reglamento (CE) No 790/2000 de la Comisión de 14 de abril de 2000 por el que se establecen las normas de comercialización de los tomates [Regulation (CE) No 790/2000 of the Commission of 14 Apr. 2000 through which marketing standards for tomatoes are established]. *La Comisión de las Comunidades Europeas*. 8 Oct. 2013. <<http://www.boe.es/doue/2000/095/L00024-00029.pdf>>.

Fernández-García, N., V. Martínez, A. Cerda, and M. Carvajal. 2002. Water and nutrient uptake of grafted tomato plants grown under saline conditions. *J. Plant Physiol.* 159:899–905.

Gallardo, M., R.B. Thompson, J.S. Rodríguez, F. Rodríguez, M.D. Fernández, J.A. Sánchez, and J.J. Magán. 2009. Simulation of transpiration, drainage, N uptake, nitrate leaching, and N uptake concentration in tomato grown in open substrate. *Agr. Water Mgt.* 96:1773–1784.

Gorbe, E. and A. Calatayud. 2010. Optimization of nutrition in soilless systems: A review. *Adv. Bot. Res.* 53:193–245.

Hayward, H.E. and E.M. Long. 1943. Some effects of sodium salts on the growth of the tomato. *Plant Physiol.* 184:556–569.

Ityel, E., A. Ben-Gal, M. Silberbush, and N. Lazarovitch. 2014. Increased root zone oxygen by a capillary barrier is beneficial to bell pepper irrigated with brackish water in an arid region. *Agr. Water Mgt.* 131:108–114.

Lee, J.M. 1994. Cultivation of grafted vegetables. I: Current status, grafting methods, and benefits. *HortScience* 29:235–239.

Lee, J.M. and M. Oda. 2003. Grafting of herbaceous vegetable and ornamental crops. *Hort. Rev.* 28:61–124.

Little, T.M. and F.J. Hill. 1978. *Agricultural experimentation: Design and analysis*. Wiley, New York.

Massa, D., L. Incrocci, R. Maggini, G. Carmassi, C.A. Campiotti, and A. Pardossi. 2010. Strategies to decrease water drainage and nitrate emission from soilless cultures of greenhouse tomato. *Agr. Water Mgt.* 97:971–980.

Min, J., H. Zhangb, and W. Shia. 2012. Optimizing nitrogen input to reduce nitrate leaching loss in greenhouse vegetable production. *Agr. Water Mgt.* 111:53–59.

Morales, I. and M. Urrestarazu. 2013. Thermography study of moderate electrical conductivity and nutrient solution distribution system effects on grafted tomato soilless culture. *HortScience* 48:1508–1512.

Parry, M.A.J., J. Flexas, and H. Medrano. 2005. Prospects for crop production under drought: Research priorities and future directions. *Ann. Appl. Biol.* 147:211–226.

Patanè, C., S. Tringali, and H. Sortino. 2011. Effects of deficit irrigation on biomass, yield, water productivity, and fruit quality of processing tomato under semi-arid Mediterranean climate conditions. *Sci. Hort.* 129:590–596.

Petersen, R.G. 1994. *Agricultural field experiments*. Marcel Dekker, New York.

Pulupol, L.U., H.M. Behboudian, and K.J. Fisher. 1996. Growth, yield, and postharvest attributes of glasshouse tomatoes produced under deficit irrigation. *HortScience* 31:926–928.

Robinson, D. 1994. The responses of plants to non-uniform supplies of nutrients. *New Phytol.* 127:635–674.

Rodríguez, D., J. Reca, J. Martínez, L. Lopez-Luque, and M. Urrestarazu. 2015. Development of a new control algorithm for automatic irrigation scheduling in soilless culture. *Appl. Math. Info. Sci.* 9:1–10.

Schwarz, D., Y. Roupahel, G. Colla, and J.H. Venema. 2010. Grafting as a tool to improve tolerance of vegetables to abiotic stresses: Thermal stress, water stress, and organic pollutants. *Sci. Hort.* 127:162–171.

Sonneveld, C. and N. Straver. 1994. Voedingsoptimalisatie voor groenten en bloemen geteeld in water of substraten [Nutrient solutions for vegetables and flowers grown in water or substrates]. 10th ed. Proefstation voor Tuinbouw onder Glas, Naaldwijk.

Sonneveld, C. and W. Voogt. 1990. Response of tomatoes *Lycopersicon esculentum* to an unequal distribution of nutrients in the root environment. *Plant Soil* 124:251–256.

Steidle, A.J., S. Zolnier, and D. De Carvalho. 2014. Development and evaluation of an automated system for fertigation control in soilless tomato production. *Comput. Electron. Agr.* 103:17–25.

Thompson, R.B., M. Gallardo, J.S. Rodríguez, J. A. Sánchez, and J.J. Magán. 2013. Effect of N uptake concentration on nitrate leaching from tomato grown in free-draining soilless culture under Mediterranean conditions. *Sci. Hort.* 150:387–398.

Topcu, S., C. Kırdar, Y. Dasgan, H. Kaman, M. Cetin, A. Yazici, and M.A. Bacon. 2007. Yield response and N-fertiliser recovery of tomato grown under deficit irrigation. *Eur. J. Agron.* 26:64–70.

Urrestarazu, M. 2004. *Tratado de cultivo sin suelo [Treated soilless culture]* 3rd ed. Mundi-Prensa, Madrid, Spain.

Urrestarazu, M. 2013. State of the art and new trends of soilless culture in Spain and in emerging countries. *Acta Hort.* 1013:305–312.

- Urrestarazu, M., C. Guillén, P.C. Mazuela, and G. Carrasco. 2008a. Wetting agent effect on physical properties of new and reused rockwool and coconut coir waste. *Sci. Hort.* 116:104–108.
- Urrestarazu, M., G.A. Martínez, and M.C. Salas. 2005. Almond shell waste: Possible local rockwool substitute in soilless crop culture. *Sci. Hort.* 103:453–460.
- Urrestarazu, M. and P.C. Mazuela. 2005. Effect of slow-release oxygen supply by fertigation on horticultural crops under soilless culture. *Sci. Hort.* 106:484–490.
- Urrestarazu, M., M.C. Salas, D. Valera, A. Gómez, and P.C. Mazuela. 2008b. Effects of heating nutrient solution on water and mineral uptake and early yield of two cucurbits under soilless culture. *J. Plant Nutr.* 31:527–538.
- Van Noordwijk, M. and P.A.C. Raats. 1980. Drip and drainage systems for rockwool cultures in relation to accumulation and leaching of salts. *Proceedings of the Fifth International Congress on Soilless Culture*. Wageningen, 1980, p. 279-287. International Society for Soilless Culture.
- Wamser, A.F., I. Morales, J.E. Álvaro, and M. Urrestarazu. 2014. The effect of drip flow rate with multiple manifolds on the homogeneity of the delivered volume. *J. Irr. Drain. Eng.* 141(2):04014048.