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

Miguel Urrestarazu
Departamento de Agronomía, Universidad de Almería, Spain; and Universidad de Tarapacá, Chile

Isidro Morales, Tommaso La Malfa, and Ruben Checa
Experimental Centre of Bital, University of Almería, Almería E 4120, Spain

Anderson F. Wamser
Agricultural Research and Rural Extension Office, Rodovia Admar Gonzaga, 1347 Bairro Itaocurubi, Caixa Postal 502, Florianópolis 88034-901, Santa Catarina, Brazil

Juan E. Alvaro
Pontificia Universidad Católica de Valparaíso, Escuela de Agronomía, Quillota, Chile

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 treated tomato and pepper crops. The fruit quality parameters were unaffected.

Additional index words. grafted tomato, sweet pepper, nitrate emission, electrical conductivity, water uptake, irrigation time, irrigation flow rate

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 (Pathak 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 nutrient solutions 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., Ciceres 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 et al., 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, mL·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, mL·m⁻²) is equal to A + LF.

AV = A + LF.

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

The time tᵢ must be less than tᵢ 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.
Materials and Methods

Three independent experiments were conducted.

Experiment 1. The pepper cultivation was performed at the facilities of the University of Almería (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 L·h⁻¹ (0.66 gal·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.
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.

| Expt. | Crop                                      | Plant/m² | Date                      |
|-------|-------------------------------------------|----------|---------------------------|
| 1     | Sweet pepper cv. *Padua* F1               | 2        | 14 Oct. 2013              |
| 2     | Tomato cv. *Zynac* F1 rootstock with graft Maxifort | 1        | 18 Feb. 2014              |
| 3     | Tomato cv. *Caniles* F1                   | 1.8      | 20 Aug. 2013              |

†Also 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.](image-url)
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.
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., Corrillon 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 Schrevens, 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 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 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 benefited 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

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**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.**

| Exp. | Drainage (%) | pH | Electrical conductivity (dS·m⁻¹) | Water (L·m⁻²) | Uptake | Emission |
|------|--------------|----|-------------------------------|---------------|--------|----------|
|      | T0 | T1 | T0 | T1 | T0 | T1 | T0 | T1 | 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 |

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

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**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 | 245.46s |
| 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).
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 | 3.02        | 9.83        | 9.54$^*$     |
| G (67–82 mm)   | 2.31 | 2.10$^*$    | 13.29       | 12.21$^*$    |
| M (57–67 mm)   | 1.01 | 1.01$^*$    | 8.58        | 8.54$^*$     |
| MM (47–57 mm)  | 0.52 | 0.50$^*$    | 7.08        | 6.83$^*$     |
| MMM (40–47 mm)| 0.02 | 0.05$^**$   | 0.54        | 1.33$^*$     |
| Total          | 6.78 | 6.68$^*$    | 39.33       | 38.46$^*$    |
| Ungrafted tomato |    |             |             |             |
| M (57–67 mm)   | 0.42 | 0.74$^*$    | 4.28        | 7.43$^*$     |
| MM (47–57 mm)  | 1.82 | 2.33$^*$    | 22.52       | 28.72$^*$    |
| MMM (40–47 mm)| 2.31 | 2.08$^*$    | 41.78       | 36.15$^*$    |
| Total          | 5.55 | 5.15$^*$    | 55.85       | 72.20$^*$    |

$^*$, $^**$, 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             |
| Sweet pepper   |      |                                      |       |                |
|                | —    | —                                    | —     | 2.56           |
| Grafted tomato | 4.45 | 4.28$^*NS$                           | 4.55  | 4.60$^*NS$     |
| Ungrafted tomato |    | 3.97 $^*NS$                         | 5.84  | 5.49$^*$       |

$^*$, $^*NS$, 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 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 pollution 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.

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