Assessment of a new gravity injection system for fertigation of greenhouse tomatoes grown in volcanic rock media

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Hahn, F., M.A. Peña, P. Coras and M. Vazquez. 2009. **Assessment of a new gravity injection system for fertigation of greenhouse tomatoes grown in volcanic rock media**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **51**: 1.1–1.9. There has been continuing expansion of greenhouses in Mexico in recent years with a huge shortage of hand labor. A new fertigation system was developed using a gravity injection technique, and evaluated on tomatoes grown over volcanic rock substrate in a greenhouse. The fertigation system fills a dosing tube with the fertilizer solution, which is then mixed with the correct quantity of water and delivered to the plants in order to provide the proper electrical conductivity. This paper presents the results of a study on the effect of fertilizer dosage on biomass, fruit quantity, and flower production. Electrical conductivity (EC), which peaks during the fertigation cycle, was measured around the root zone before, during, and after fertigation. As the volcanic rock substrate stores nutrients, combined cycles of fertigation and washing (only water application) were applied to the crop. The heavier fruits were obtained with 16 combined cycles, 10 consisting of fertilizers and 6 consisting of only water. Four days of crop washing still produced tomatoes, but decreased the EC of solution around root zone by 25%. A high accuracy fertigation controller is not necessary with crops grown over volcanic rock as small yield differences are encountered under different fertigation doses owing to substrate nutrient absorption. Root microscopic images showed no damage after direct fertilizer application **Keywords:** fertigation equipment, gravity injection, fertigation frequency, tomato roots.

Il a été continue l'expansion des serres au Mexique au cours des dernières années avec une énorme insuffisance de travail de mains. Un nouveau système de fertigation a été développé en utilisant une technique d'injection de gravité et évalué sur les tomates cultivées sur le substrate du matériel pyroclastique dans une serre. Le système de fertigation remplit un tube de dosage de la solution d'engrais qui est alors mélangée avec la quantité correcte d'eau et livrée aux plantes pour fournir la conductivité électrique nécessaire. Ce papier présente les résultats d'une étude sur l'effet de dosage d'engrais sur la biomasse, la quantité de fruit et la production de fleurs. La conductivité électrique (EC), qui culmine pendant le cycle de la fertigation, a été mesurée autour de la zone de racine auparavant, pendant et après la fertigation. Comme le matériel pyroclastique du substrat conserve des nutriments, les cycles combinés de fertigation et lavant (seulement l'application d'eau) ont été appliqués à la récolte. Les plus lourds fruits ont été obtenus avec 16 cycles combinés, dix se composant des engrais et six se composant de seulement l'eau. Quatre jours de récolte lavant, de la tomate toujours produite, mais diminuée la EC de la solution autour de la racine divisent en zones de 25%.. Un contrôleur de fertigation de haute précision n'est pas nécessaire avec les produits cultivés sur le matériel pyroclastique lors que des petites différences de rendement sont rencontrés dans le cadre de différentes doses de fertigation en raison de l'absorption des éléments nutritifs sur le substrat. Les images microscopiques des racines n'ont montré aucun dommage direct, après l'application d'engrais **Mots clés:** l'équipement de fertigation, l'injection de gravité, la fréquence fertigation, les racines de tomate.

INTRODUCTION

Expansion of irrigation between 1960 and 1980 has accounted for more than 50% in global food production (Qadir and Oster 2003). Nutrient solutions are obtained by mixing highly concentrated stock solutions with "irrigation water". Application of fertilizers with "irrigation water" has several advantages over traditional methods, and several authors (Klaring 2001; Singandhupe et al. 2003) mentioned precise timing regulation and fertilizer dosage. Irrigation systems used to transmit liquid fertilizers require special injection systems (Nakayama and Bucks 1986; Yeager and Henley 1987) in order to apply nutrients uniformly to the radicular zone (Lao 1998). Over-fertilizing contaminates "ground water" (Hochmuth 1988; Bottcher and Rhue 2000) and increases crop production costs. Each cent wasted on fertilizer that does not increase crop yield can be considered a loss.

Electrical conductivity (EC) is monitored in fertigation systems, which increase tomato yield and quality. Increasing the EC of the nutrient solution reduces the rate of fruit growth and final fruit size by an osmotic effect (Johnson et al. 1992). The fruit cuticle is thicker and more resistant at high salinity, while fruit turgor pressure and firmness are reduced resulting in lower susceptibility to fruit cracking (Sonneveld and Van Der Burg 1991).

Several authors (Mitchell et al. 1991; Peet and Willits 1995) studied nutrient solution quantity, electrical conductivity, and frequency of irrigation given to plants in soil-less systems, and found that it varied according to the growth media, affecting yield and fruit quality. After 30 d of fertigation, peat substrate with an EC of 4.5 dS m^{-1} increased peat salinity by four times decreasing photosynthetic rate and leaf water potential (Xu et al. 1997). Sonneveld and Welles (1988) supplied nutrient solution to a tomato crop grown with rock wool substrate having an EC of 2.3 dS m^{-1} with the root environment having an EC of 3.0 dS m^{-1}.

Open irrigation systems in soil-less culture are still the most popular systems although nutrient and water loss are high. Closed irrigation systems require good knowledge of plant needs for water and nutrients (Dorais et al. 2001). Electrical conductivity controllers detect overall nutrient concentration, but are unable to sense particular ion imbalances. New ion-sensitive electrodes allow more accurate control of plant dose supply, as ion uptake varies over time due to differences in plants needs (Marschner 1995).

This work presents the development of a simple gravitational fertigation system tested with a tomato crop. As the system does not homogenize the nutrient solution, direct fertilizer solution is applied to plant roots before water injection and root damage had to be studied. Fruit yield and biomass production of a tomato fertigated crop under different fertilizer treatments were analyzed. Volcanic rock substrate behavior during nutrient dosing was analyzed by sampling EC near the tomato roots before, after, and during fertigation. Fruit weight and biomass production were evaluated under different fertigation and irrigation combined cycles.

MATERIALS and METHODS

The fertigation system was designed to work at low pressure during fertilizer dosing and at a higher pressure when it was injected to greenhouse plants. The fertigation system applies first the fertilizers and then the water, without requiring mixing (Hahn et al. 2006). The system was tested with different fertilizer dosing and plant biomass and fruit weight were monitored during 3 weeks. Volcanic rock substrate EC was also measured.

Fertigation system

The automated fertigation system injects the nutrient solution, measuring and controlling its quantity. A logic programmable controller (model Millennium, CROUZET, Basingstoke, UK) controls irrigation timing and fertilizer dosage. The prototype (Fig. 1) uses a dose tube,

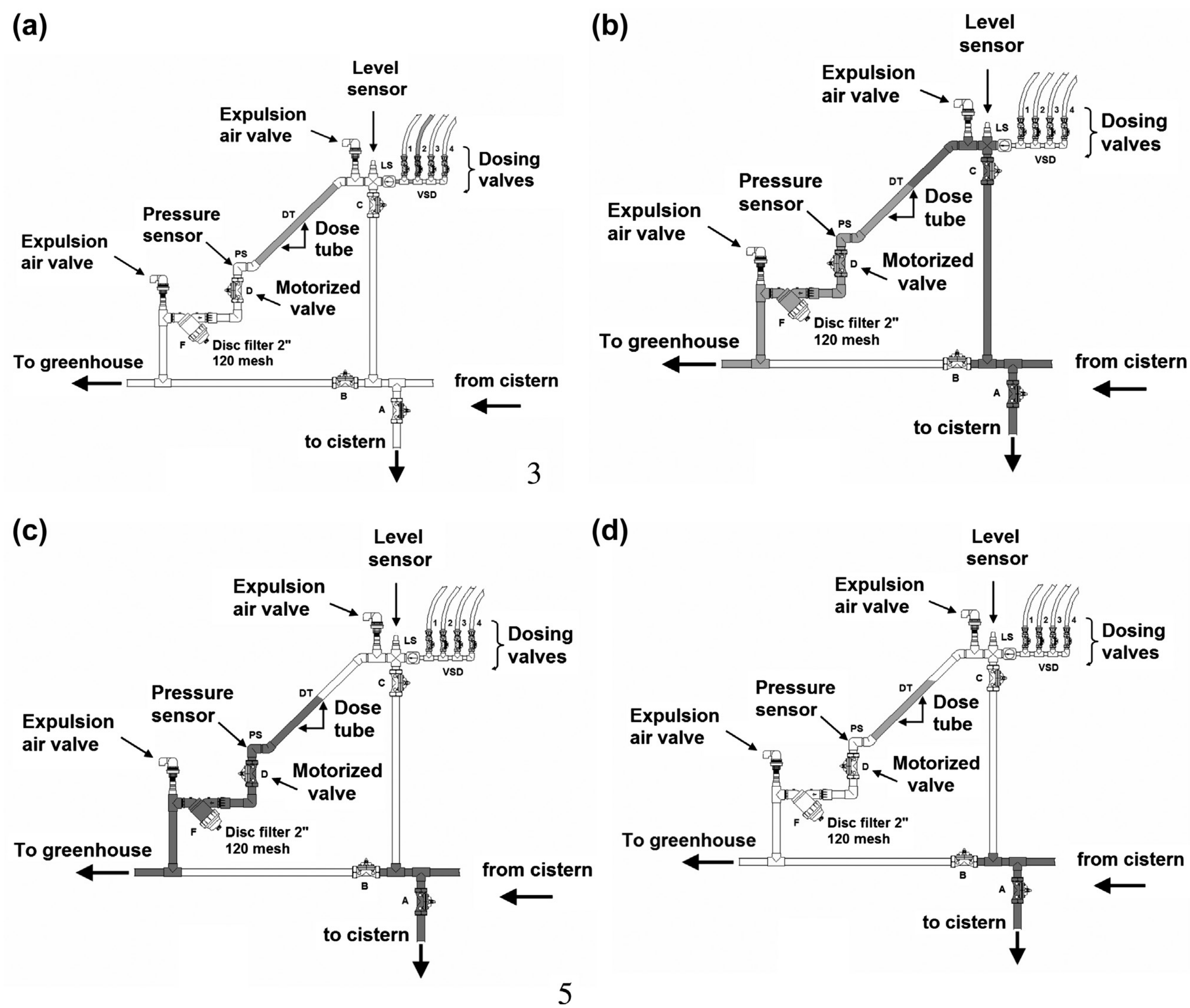

Fig. 1. Prototype (a) filling the dose tube with fertilizer; (b) dosing fertilizer to the irrigation system; (c) discharging the remaining water by gravity; and (d) recirculating water to the cistern.

which is filled with the fertilizer solution at low pressure. The fertilizers can be taken from each of the three 1100-L tanks or from all of them simultaneously filling the dose tube by gravity. The tube is isolated from the irrigation high pressure system by solenoid valves. A fourth tank handles the acid solution to control the pH.

After turning on the water pump, the pressure stabilizes and a signal is sent to the valves starting the fertigation process. Twenty seconds after turning on the pump, the dosage solenoid valves (VSD) at the bottom of each tank (1, 2, 3, and 4) are opened (Fig. 1.a) to supply the nutrient solution. The valves operate until the dose tube fills up, being detected by a level sensor (SN) that closes a limit switch. The signal from the level sensor sent to the programmable logic controller (PLC) closes solenoid valve B. Simultaneously, valves C and D are opened (Fig. 1.b.) injecting fertilizer to the greenhouse. Once valve C is disconnected the water remaining within the dosing tube descends by gravity to the greenhouse in 5 seconds, as it is 5.5 m higher than the drippers.

Valve A recirculates the water flux to the cistern (Fig. 1.c) avoiding continuous pump stopping and starting. A pressure sensor fixed at valve D base measures liquid absence inside the dosing tube and when it is empty valve D closes. The cycle is repeated as many times until the required fertilizer is injected.

Fertigation tests on plants

The fertigation system was tested on a naturally ventilated greenhouse. The greenhouse was 20 m long, 8 m wide, and 6 m high at its central ceiling. Forty tomato plants were grown in each of the six rows within the greenhouse without shade. The tomatoes planted in pots filled with volcanic rock sterile substrate (named "tezontle" in Mexico) were spaced at 0.5 m. Well irrigation water with a pH of 6.86 and an EC of 0.51 dS m^{-1} was used.

Table 1 presents some of the physical and chemical properties of the volcanic rock substrate. Pineda et al. (2008) reported that the air-filled porosity was over 20%, while its moisture retention was lower than other substrates. Electrical conductivity (EC) is very low and pH tends to be slightly acidic. Plant-available water (PAW) can be obtained by subtracting permanent wilting percentage from the field capacity. Plant-available water was 9.93% for volcanic rock substrate (Urbina et al. 2006). The same authors reported that the high degree of saturation limited the oxygen required by seedling roots. P, K, Ca and Mg values in saturation extract were obtained by Garcia et al. (2001). Volcanic rock substrate presents moderate cation exchange capacity with no organic matter, zero C:N ratio, poor quantity of total N, P, K, Ca and Mg (Villanueva et al. 1998; Garcia et al. 2001). Zamora et al. (2005) reported high correlation coefficients between substrate electrical conductivity and Ca (0.95) and K (0.93).

Drip emitters were fixed to each pot and a tube was inserted to irrigate near the roots at a depth of 0.1 m. The greenhouse used 240 drippers, which fed the solution at a rate of 5 L h^{-1} each. Each irrigation cycle applied 24 L of water and 3.24 L of fertilizer to the greenhouse (13.5 mL of

Table 1. Physical (Pineda et al. 2008) and chemical properties (Villanueva et al. 1998) of volcanic rock substrate.

Physical properties

Particle density (Mg m^{-3})	Bulk density (Mg m^{-3})	Porosity (%)	Air-filled porosity (%)	Field capacity (%)*	Permanent wilting (%)*	Degree of saturation (%)*	pH	Electrical conductivity (dS m^{-1})
2.14	1.06	69.38	22.5	11.90	1.97	62.88	6.6	0.02

Chemical properties

Cation exchange capacity (Meq/100 g)	Organic matter (%)	C/N ratio	Total N (%)	Mg (ppm)**	Ca (ppm)**	K (ppm)**	P (ppm)**
30	0	0	0.61	30	48	580	7.6

*Data from Urbina et al. (2006).
**Data from Garcia et al. (2001).

fertilizer per plant). Each tank applied one-third of the final nutrient solution; therefore, in the case of 13.5 mL, each tank provided 4.5 mL. Solenoid valve C timing with a duty cycle of 88.11% (24/27.24) controlled the fertilizer: water ratio. Two cycles are required to apply 3.24 L of fertilizer.

Transplanted tomato plants were fertigated with a PRIMA-RAM system up to the 8th week. After the 8th week the new fertigation system used the same irrigation hoses and drippers. The nutrient solution prepared for each tank was injected by the new fertigation system to the greenhouse tomatoes.

Fertilizer was applied to each of the three tanks, mixed with water and agitated. The concentration (g L^{-1}) for the first tank was of 68.18 of calcium nitrate and 27.27 of potassium nitrate. The second tank contained 37.27 of magnesium sulfate and 21.81 of monopotassium phosphate. The third tank contained the micronutrients with 1.69 of ferrous sulfate, 0.56 of manganese sulfate, 0.21 of zinc sulfate, 0.85 of sodium tetra borate and 0.19 of copper sulfate.

Electrical conductivity and pH of the solutions were measured with a laboratory conductivity bridge (model 31, YSI, Yellow Springs, Ohio, USA) and with a potentiometer electrode (model 540, Corning, New York, USA). The electrical conductivities for each concentration were 77.99, 27.22 and 16.04 dS m^{-1}. The pH registered in each solution was of 2.01, 2.92 and 1.46, being acidic due to nitric acid addition. The fertigation system presented real-time electrical conductivity measurements carried out with electrodes (model HI7634-00, HANNA, Woonsocket, USA) at the output of each tank. The signal coming out from each electrode was processed and read by the PLC before timing the dose rate. Periodical maintenance avoided salt accumulation on the electrodes.

Fertigation dosing and fruit production

A comparison was made between hand- and system-irrigated plants 8 weeks after transplanting. Four different fertigation doses were applied to the tomato root zone (9 weeks after transplanting) 0.10 m below the surface. The demand of the first row was of 540 mL of fertilizer (40 plants @ 13.5 mL fertilizer) and 4 L of water. One-third of the injected fertilizer was obtained from each tank. The second, third, and fourth rows injected 480 mL:4 L, 360 mL:4 L and 300 mL:4 L of fertilizer-water ratios, respectively.

The last three plants were hand irrigated, applying first the fertilizer dose and finally water. Manual injection per plant was of 13.5 mL of fertilizer solution and 100 mL of water, on the first row. Nutrient solution manually injected on the second, third, and fourth rows was of 12, 9 and 7.5 mL of fertilizer per plant, respectively; afterwards 100 mL of water was added to each plant. The doses were applied six times a day during 3 weeks beginning at 0830. One plant per row was unfertilized applying only 100 mL of water six times a day.

Plant yield evaluation was based on biomass and fruit production. At the beginning of the experiment all the tomato fruits were cut from each plant. Each plant of the experiment had plant growth and fruit size measured every 2 days with a ruler and a vernier caliper, respectively. Branch number and flowers were counted calculating the percentage of flowers that produced tomatoes. The biomass produced by each plant was estimated by a non-destructive technique proposed by Hahn (2005) using branch length, thickness and leaf color.

After the three experimental weeks, roots from hand-irrigated (13.5:100 fertilizer: water dose) plants and from only watered plants were extracted from the soil and washed twice with distilled water. Root images magnified 40 × were taken with a digital camera (model WAT-250D, Watec, New York, USA) coupled to a stereoscopic microscope (model ZM160, ZEIGEN, D.F., Mexico). An external light was used to illuminate the crystals over the root surface. The vision algorithm that determined the minerals over the root surface used a gamma correction of -64, a contrast enhancement of 54, before being thresholded to obtain a black and white image.

Electrical conductivity and fruit production on combined fertigation cycles

In the second experiment, the six greenhouse rows were fertigated with different treatments to discover the effect of fertigation frequency on fruit weight and biomass. Six, 10, 12 and 16 fertigation frequency cycles were applied on the first four rows. The fifth and sixth rows presented 12 and 16 frequency cycles of mixed fertigation and irrigation per day. The first 30 plants presented the corresponding fertigation treatment and the last 10 were only watered in rows one to four. The first 20 plants of the fifth row received eight fertigation and four irrigation cycles, while the last 20 plants received 10 fertigation and 2 irrigation cycles. The first 20 plants of the sixth row were fertigated for eight cycles and only watered for eight cycles, while the other 20 plants received 10 fertigation and 6 irrigation cycles. On both the fifth and sixth rows, fertigation cycles were applied first, and irrigation cycles last. All the rows were fertigated with a 13.5:100 mL fertilizer: water ratio per plant. Tomato clusters were cut before starting the experiment; biomass production and tomato weight of the first cluster were measured on each plant 15 days later.

An EC stainless probe (model HI98331, HANNA, Woonsocket, USA) was inserted in the volcanic rock substrate at a depth of 0.10 m in order to measure the electrical conductivity near the root environment. The sensor was calibrated before being inserted and measured soil EC on a daily basis with a 0.01 dS m^{-1} resolution. Electrical conductivity samples were obtained every 15 minutes starting at 0830 for 10 hours during 4 consecutive days of one fertigated plant chosen randomly. The experiment was repeated three times on different plants of the first row (six cycles/day) and in only water irrigated (without fertilizer) plants. Daily EC monitoring of only watered plants lasted 10 hours during 3 days, beginning at 0800, and finishing at 1700. Electrical conductivity was measured during fertigation during 4 days on two plants per treatment selected randomly.

Table 2. Fertilized, new flowers, and tomatoes produced during the three experimental weeks for both hand-irrigated (HI) and system-irrigated (SI) treatments.

System or hand irrigated	Plant line	Fertilizer: water	Number of flowers	Fruit number	Fruit weight (g)	Grown fruit (%)	New flowers
SI	1	13.5:100	17	12	127	71	10
SI	2	12:100	17	12	124	71	10
SI	3	9:100	17	12	122	71	10
SI	4	6:100	17	11	121	65	7
HI	1	13.5:100	18	14	128	83	9
HI	2	12:100	18	14	126	78	9
HI	3	9:100	17	13	122	76	9
HI	4	6:100	17	12	119	71	6
SI	water fertilizer	0:100	18	8	123	42	5

RESULTS and DISCUSSION

Fertigation operation

System accuracy depends on precise fill-up of the 2.5 L dosage tube. If 12 L of fertilizers are dosified, four pulses of 2.5 L are required together with one of 2.0 L. The closed motorized valve (Valve D, Fig. 1) maintains water, and if the dose tube is filled-up it will not receive 2.5 L of fertilizer. A motorized valve was selected as a pressurized system is required by diaphragm solenoids. The valve was left open until the dose tube became empty discharging the liquid slowly. It used a 24 V_{CD} motor, which rotated both ways to open and close the valve; two microswitches avoided hermetical closure with excessive motor stress. When the dose tube is empty a new pulse is generated until the entire fertigation cycle finishes. When the total fertilizer required is not an exact multiple of the dose tube volume it is necessary to supply the remaining fertilizer via solenoid time control (Hahn et al. 2006).

The small greenhouse required a minor dose tube of 100 mL; its diameter remained at 50 mm to avoid friction losses and its length decreased to 51 mm. The minimum dose of 300 mL for each row of 40 plants required to fill up the dose tube three times, taking 1 minute to fertigate; for maximum dose 1 minute and 40 seconds was required. Previous timings do not consider emitters, and each plant would take 2.54 minutes to finish the injection with 5 L h^{-1} emitters. Emitters of 1 L h^{-1} were used to increase the dose time to 6.36 min. The nutrient solution supplied by the system presented identical electrical conductivity values throughout the entire row.

Fruit and biomass production under different fertigation doses

Table 2 shows the average number of flowers, fruits and the ratio of fruits:flowers obtained during the 3 fertigation weeks. All system-irrigated plants flowered in the same way (17 flowers), while hand-irrigated plants produced one more flower on the 13.5:100 and 12:100 fertilizer:-water treatments. Plants with no fertilizer applied produced 18 flowers, as the initial phosphorus remains still or moves at most 5 mm (Simonne and Hochmuth 2005).

Flower production standard deviations were of 0.45, 0.33, 0.45, and 0.18 for system treatments of 13.5:100, 12:100, 9:100, and 6:100, respectively. Fewer plants were hand irrigated showing a maximum standard deviation of 0.56. Fruit production standard deviations were evaluated for each dose on both system- and hand-irrigated plants and the maximum value achieved was of 0.26.

All the treatments presented similar yields and were a little higher on hand-irrigated plants. The best tomato fruit yield was obtained with the 13.5:100 fertilizer:water

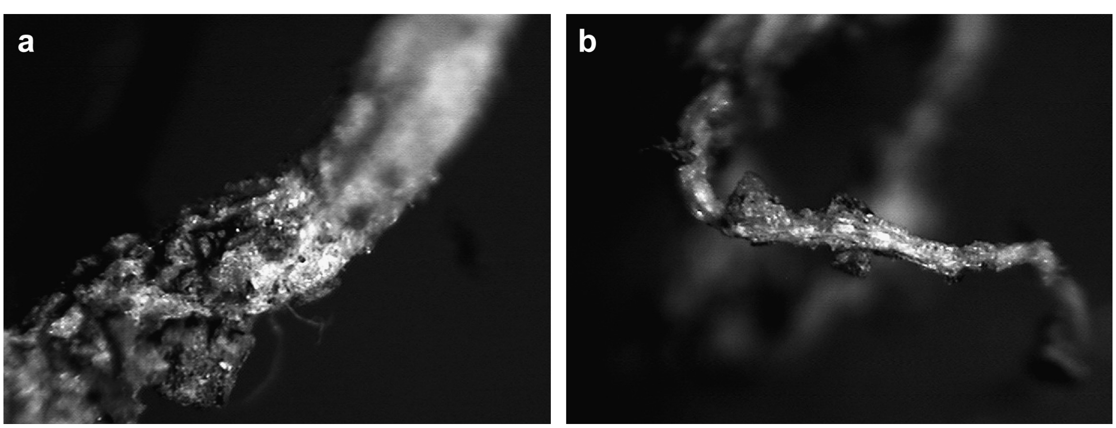

Fig. 2. Microscopic image of hand-irrigated root with (a) water only; (b) 13.5:100 fertilizer: water dose.

Table 3. Biomass and average branch produced during the experiment for each treatment.

System or hand irrigated	Plant line	Fertilizer: water	Average branch number	Average new biomass (g)
SI	1	13.5:100	18	68
SI	2	12:100	17	56
SI	3	9:100	16	43
SI	4	6:100	16	44
HI	1	13.5:100	18	73
HI	2	12:100	18	66
HI	3	9:100	16	42
HI	4	6:100	16	43
SI	Withoutfertilizer	0:100	12	37

treatment on hand-irrigated plants. A fruit weight difference of 9 g was found between the heavier and the lighter tomato, with a standard deviation of 2.63. The highest standard deviation (3.82) was found on the 9:100 system treatment. Watered plants without fertilizer produced eight tomatoes during the 3 weeks as the fertilizer remained stored within the volcanic rock substrate. The number of fertilized flowers was lower and at the end of the period fewer flowers were produced.

It is believed that manual irrigation injected more oxygen. Oxygen changes the electrical charges in the water and nutrients, and allows the roots to extract water and nutrients with much less energy. Lynch (1995) reported that root systems alter their structure to acquire oxygen, water and nutrients in the most efficient way. Dissolved oxygen (model DO-BTA, VERNIER,Beaverton, USA) measured 5.1 mg L^{-1} in the 13.5:100 mL water: fertilizer treatment of hand-irrigated plants. The solution of system-irrigated plants presented a dissolved oxygen range within 4.3–4.8 mg L^{-1}. Nakano (2007) found that tomato shoot and root dry weights per plant were higher on plants having dissolved oxygen values ranging between 2.6 and 5.8. Poor aeration also increases the intensity of root-related diseases (Allmaras et al. 2003).

Root images presented bonded volcanic rock structures (Fig. 2), which were quantified. Black and white images quantified crystal coverage by counting the white pixels. Only two dimensions were analyzed, although the entire surface presented a similar pattern. Manual irrigated plants with a 13.5:100 fertilizer: water dose presented a crystal surface coverage of 69%, while plants only watered presented crystal coverage of 35%.

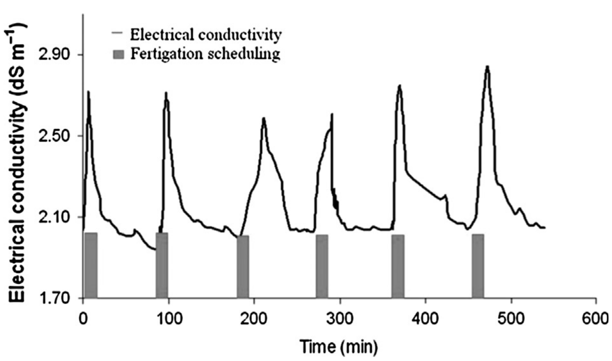

Fig. 3. Volcanic rock substrate EC measured during six fertigation cycles.

In hand-irrigated plants, nutrient electric charges displace the neutral volcanic rock from the roots and nutrient uptake takes place. Three roots from system-irrigated plants were extracted showing average crystal coverage of 63% as ions and cations recombine during irrigation.

Table 3 shows the biomass produced by each treatment during the 3 experimental weeks. Biomass growth was proportional to fertilizer dosage and was higher in hand-irrigated treatments. Biomass standard deviation on the different system-irrigated treatments ranged between 3.48 and 4.75, being the worst in the 6:100 fertilizer: water treatment. Hand-irrigated plants presented biomass standard deviations lower than 3.89. Direct application of fertilizer to plants did not reduce biomass production, and leaf coloration was more intense in plants where fertilizer was applied first (hand-irrigated plants) than when it was mixed with water (system-irrigated plants).

Plants irrigated with only water produced a biomass similar to those dosed with the lowest fertilizer treatment (6:100 fertilizer: water). Irrigated plants without fertilizer produced 50.68% less biomass than maximum dosed hand-irrigated plants (13.5:100 fertilizer: water). Hand-irrigated plants with the higher fertilizer dosage produced 7.35% more biomass than system-irrigated plants under the same dosage. The plastic tube inserted into the substrate to inject the solution to the plant presented localized moisture spots at the tube end. This phenomenon taps the tube with crusts formed from hardened substrate sediments avoiding proper nutrient solution dissemination.

Electrical conductivity substrate measurements

Fertilizers contacted the root surface before water, and mineral crystals attached to it. Fresh inert volcanic rock substrate presents an EC of 0.02 dS m^{-1}, increasing to 0.09 dS m^{-1} once irrigated with pure water. Figure 3 shows the EC collected during an entire day on system-irrigated plants with a 13.5:100 mL fertilizer:water treatment. The red marks show the six fertigation cycles with average EC increments of 16%, due to nutrient ions and cations; a higher EC was noted on the cycle starting at 1130. Thirty minutes after ending the fertigation cycles the electrical conductivity value comes back to 2.10 dS m^{-1}.

Table 4. Average fruit weight, EC after the first four days of application, and biomass production after 10 days.

Frequency	Fertilizer/water	Fruit weight (g)		EC after 4 days (dS m^{-1})	Biomass production (g)	
cycles	cycles	Average	Std. dev devdev	days	Average	Std. dev
6	6/0	128	2.44	2.1	15	1.91
10	10/0	137	3.83	2.1	19	1.81
12	12/0	122	3.26	4.1	22	1.62
12	8/4	130	2.48	2.1	23	2.42
12	10/2	139	3.38	2.3	22	1.97
16	16/0	114	3.05	6.1	26	1.51
16	8/8	130	2.78	2	26	2.71
16	10/6	141	3.96	2.2	29	3.13

It was noted that 12 high-frequency cycles per day (every 45 minutes) increased EC up to 4.1 dS m^{-1} after 4 d, reducing fruit size. Ten fertigation cycles per day spaced by 1 hour did not increase the substrate EC and presented an average tomato weight of 137 g (Table 4). As the number of cycles increased, more biomass was produced as nutrient uptake was higher. Higher water absorption was obtained at low EC values, while the nutrient uptake was found to be the highest at high EC values as found by Ehret and Ho (1986). Fruit weight had a minimum average value of 114 g when plants were fertigated 16 times a day, caused by an EC increase as reported by Dorais et al. (2001).

Combined cycles of fertigation and irrigation (only water) provided better yields. Twelve irrigation cycles (10 of fertigation and two of only water) presented an average tomato weight of 139 g while maintaining an EC of 2.3 dS m^{-1} after 4 days. The highest tomato weight standard deviation of 3.96 was obtained on the treatment that fertigated 10 times and irrigated six times. The highest average fruit weight of 141 g was obtained with 16 irrigation cycles (10 of fertigation and six of water) producing also the highest biomass with an average value of 29 g. All the treatments without irrigation showed standard deviations lower than two and as the number of irrigation cycles increased the biomass varied more between plants, increasing the standard deviation.

The EC values measured when the substrate was washed (water application only) decreased by 25% after 4 days (Fig. 4). Substrate EC lost 0.15 dS m^{-1} (1.15 to 1 dS m^{-1}) during the first day, while on the second day EC did not decrease. Third day EC decreased by 0.04 dS m^{-1}, meanwhile during the fourth day EC varied from 0.96 to 0.88 dS m^{-1}.

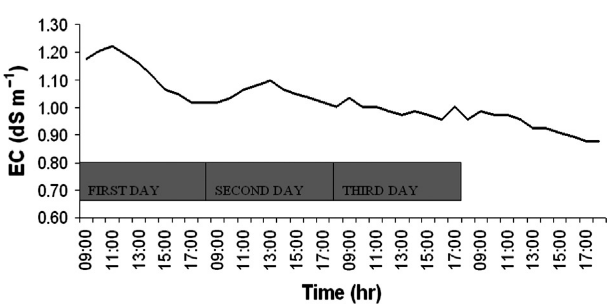

Fig. 4. Electrical conductivity measured near the root from 8:00 AM to 5:00 PM for three days with water dosage only.

The electrical charge of the minerals present within the volcanic rock material is not available; therefore, nutrient plant absorption discussed by different researchers (Silberbush et al. 1993; Bar-Josef 1999; Gastal and Lemaire 2002) was not considered. Water needs to flow through the mineral stored at the volcanic rock substrate in order to transport ions and cations towards the root. Dorais et al. (2001) reported 30–50% water and nutrient losses from the root environment during high light periods in order to avoid salt accumulation on open irrigation systems.

CONCLUSIONS

This work concludes that fertilizer manual injection presented higher yields, probably due to an increase in the dissolved oxygen of the solution, allowing the roots to extract water and nutrients with much less energy. Daily dosing rate applications did not cause differences on tomato fruit weight, flower production, and branch number. Biomass growth was proportional to fertilizer dosage and leaf coloration was more intense in plants where fertilizer was applied first (hand-irrigated plants) than when it was mixed with water (system-irrigated plants). Precise fertilizer dosage is unnecessary on plants grown on volcanic rock substrate as nutrients are stored in the substrate. Therefore, a high accuracy fertigation controller is not required.

A gravimetric system was developed to dose fertilizers in greenhouses and its accuracy was dependent on precise fill-up of the dosage tube. The small greenhouse required a minor dose tube of 100 mL, having a diameter of 50 mm and a length of 51 mm. Greenhouse tests with the automatic system showed that with a higher number of fertigation cycles more biomass was produced, increasing nutrient uptake by the tomato plant. Electrical conductivity peaked during fertigation and decreased 30 minutes later to a constant value of 2.1 dS m^{-1}. Electrical conductivity increased at the root zone if no washing cycles were provided. As a result of combining fertigation and irrigation (only water) cycles, better yields were obtained. The heaviest average fruit, of 141 g, and biomass was obtained with 16 cycles of mixed fertigation and irrigation (10 of fertigation and six of water).

Microscopic images of plant roots dosed with fertilizers presented crystals adhered in 69% of its surface, while plants only watered presented crystal coverage of 35%. Roots did not suffer damage from direct fertilizer application as no burning was noted in the images. Plants only watered (without fertilizer) took nutrients from the volcanic rock to produce tomatoes, decreasing substrate EC by 25% after 4 days.

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