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Nutrient solution concentration and growing season affect growth and quality of potted petunia in a recirculating subirrigation and drip-irrigation system

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Abstract

Petunias (*Petunia* × *hybrida* Hort. Vilm.-Andr. 'Giove') were grown in closed soilless systems to evaluate the effects of irrigation system (drip and subirrigation) and nutrient solution concentration (half and full) during two consecutive growing seasons (spring and winter) in terms of substrate electrical conductivity (EC_s), growth, quality, crop evapotranspiration (ET_c), growth index water use efficiency (WUE_{GI}) and nutrient uptake. At the end of the cultural cycle the highest EC_s in the upper and lower layers were recorded in the spring season on plants grown in subirrigation using a full nutrient solution concentration. The higher EC_s recorded with subirrigation under full strength nutrient solution in the spring season, had no negative effect on plant growth parameters and quality index indicating that petunia can be considered tolerant to salinity. The highest shoot biomass, leaf area, and plant growth index were recorded in the winter season on plants grown in both drip-irrigation and subirrigation using full nutrient solution concentration, whereas the lowest values were observed in the winter season on plants grown using the half nutrient solution concentration. Higher total evapotranspiration was recorded in the winter compared to spring season (4.3 vs. 3.5 L m^{-2}), because the plants grown during the winter season required more days (20) to reach the commercial maturity in comparison to those grown during the spring season. The WUE_{GI} recorded on plants grown during the spring season was significantly higher by 24% than those recorded during the winter season. The highest N, P, K, Ca and Mg uptake values were measured during winter season using full strength nutrient solution. The variation of the EC in the nutrient solution during the spring growing cycle was less pronounced in the subirrigation than with a drip-irrigation system which represents an important aspect for the simplification of the closed loop management of the nutrient solution.

Key words: Closed soilless system, drip-irrigation, growing season, nutrient uptake, *Petunia* × *hybrida*, subirrigation.

Introduction

The public is becoming more concerned with water quality and water conservation, and it is likely that there will be more regulations concerning water management [1]. It is of increasing importance to recognize the need to modify greenhouse production practices due to environmental concerns, cost efficiency, and increased governmental regulations [1, 2]. Strategies for optimum plant nutrition with minimum fertilizer, water usage and environmental contamination are needed. The only possibility, both to optimize fertilization and keep environmental contamination under control, is to adopt cultivation systems which collect and reuse the extra irrigation water (closed-soilless systems). Hence, closed-soilless systems have been declared "environmentally friendly" because they drastically improve the use efficiency of water and fertilizer as compared with systems allowing drainage water runoff [3-7].

Various types of irrigation closed-soilless systems have been developed for containerized crops. The most widely used are the surface system (drip-irrigation) and subirrigation systems (ebb-and-flow benches, capillary mats, trough benches and flooded floors) [8]. In drip-irrigated culture, water is generally distributed in excess. Therefore, the salts not taken by the crop are removed from the substrate by the drainage water and tend to be accumulated in the recirculating nutrient solution, which has to be flushed out more or less frequently with consequent waste of water and fertilizers [9, 10]. Recirculating subirrigation culture has lower nutrient and water requirements, delivers nutrients in a uniform manner, avoids foliar wetting (disease prevention), offers greater flexibility in pot sizing and spacing, and reduce the discharge of nutrients to surrounding ecosystems [11-13]. These benefits lead to savings in labor, material input and product losses [14, 15]. Besides, the subirrigation system can simplify the closed-loop management of the nutrient solution. In fact, in subirrigation systems, elements that are not absorbed by the plant accumulate in the upper part of the substrate where roots are less present, rather than accumulating in the nutrient solution as it would do in a drip-irrigation system [16, 17]. However, salt accumulation at the substrate surface is a major drawback of this cultural technique [16, 18-20]. This problem can be exacerbated by high fertilizer application rates. Commercial greenhouse growers typically use high nutrient concentrations in an attempt to maximize crop performance. This practice does not present an economically optimized production strategy, as excessive nutrients do not necessarily translate into higher growth and yields. Several papers have documented the advantages of using low nutrient solution concentration for greenhouse cultivation of pot ornamentals. For instance, Rouphael *et al.* [17] showed that macronutrient concentrations, commonly used by commercial greenhouse geranium growers, can be reduced by 50% during the winter cropping cycle without having any adverse effect on shoot dry weight, growth and quality index. Similarly, for potted gerbera production, Zheng *et al.* [21] demonstrated that current nutrient application rates could be reduced by at least 50% without any detrimental effect on plant growth and quality.

An optimal fertilizer and water supply of bedding plants in closed fertigation systems also depends on the environmental conditions. Unfortunately, most recommendations for the fertilization of bedding plants do not take into account environmental conditions. The evapotranspiration (ET) rate of plants generally increases with increasing temperature and solar radiation, decreasing the water use efficiency (WUE). Therefore, different temperatures and solar radiation conditions may be good treatments variable to look at possible interactive effects of environmental conditions and nutrient solution concentration on plant growth.

Potted petunias (*Petunia* × *hybrida* Hort. Vilm.-Andr.) are significant part of the Italian bedding plant industry. Several studies have focused on the influence of fertilizer concentration[22], potassium and phosphorus concentrations [23, 24], irrigation systems (subirrigation versus hand-watered system) [25] and interactions between temperature and fertilizer concentration [26] on subirrigated petunia growth, whereas there is a lack of information on the influence of the growing season, irrigation system and nutrient solution concentration interactions on growth, quality, water use efficiency and nutrient uptake of petunia production.

The objective of the current study was to determine the effects of nutrient solution concentration (full or half strength) and irrigation method (closed drip-irrigation or subirrigation) during two consecutive growing seasons (spring and winter) on substrate electrical conductivity (ECs), plant growth and quality, water use efficiency and nutrient uptake of potted petunias.

Materials and Methods

Location, plant material and growth conditions: Two experiments were conducted in two consecutive growing seasons: spring season (Experiment 1) and winter season (Experiment 2) in a polyethylene 200 m^2 greenhouse situated on the Experimental Farm of Tuscia University, Central Italy (lat. 42°25’N, long. 12°08’E). Inside the greenhouse, ventilation was provided automatically when the air temperature exceeded 26°C, light was provided only by natural solar radiation. The following climate data inside the greenhouse was determined: dry and wet bulb air temperature by means of wire resistance thermometers in aspirated boxes and solar radiation by means of a pyranometer (CM11 Kipp and Zonen, Netherlands). All measurements were collected on a data logger system (CR10X, Campbell Scientific, Inc., UK), the sensors were scanned every minute and the 30 min average values were recorded.

Rooted cuttings of petunia (*Petunia* × *hybrida* Hort. Vilm.-Andr. ‘Giove’) were obtained from a commercial grower (Albani and Ruggieri, Civitavecchia, Italy) and transplanted on 17 Apr. 2008 (Experiment 1) and 5 Nov. 2008 (Experiment 2) into pots (d 14 cm, h 12 cm) containing 1.5 L of a mixture peat:perlite (perlite have a particle size of 2-5 mm in diameter) in a 2:1 volume ratio. The pots were placed on 16 cm wide and 5 m-long troughs, with 30 cm between pots and 30 cm between troughs, giving a plant density of 11 plants m^{-2}.

In both growing seasons (Experiments 1 and 2), treatments were arranged in a randomized complete-block design with three replicates. The treatments were defined by a factorial combination of two nutrient solution concentrations (50% or 100% of a full strength nutrient solution) and two irrigation systems (drip and subirrigation). Each experimental unit consisted of one bench containing 15 plants.

Nutrient solution management: The full strength nutrient solution used in both experiments consisted of the following macro- and micronutrients: 14.4 mM N-NO$_3$, 2.0 mM S, 1.2 mM P, 6.0 mM K, 4.5 mM Ca, 2.3 mM Mg, 20 mM Fe, 9 mM Mn, 1.5 mM Cu, 3 mM Zn, 20 mM B and 0.3 mM Mo. The half strength nutrient solution had 50% of the macronutrients and the same micronutrient concentrations of the full strength nutrient solution. All nutrient solutions were prepared using de-mineralized water.

In all tanks, electrical conductivity (EC) was kept at 2.0 ± 0.5 dS m^{-1} and 1.0±0.25 dS m^{-1} for the full and half strength nutrient solutions, respectively. Moreover, when the EC values exceeded the threshold of 2.5 and 1.25 dS m^{-1} for the full and half strength nutrient solutions, respectively, water was added to the nutrient solutions in order to restore the EC to the original target values. In all treatments, the pH of the solution was maintained between 5.8 and 6.2 by adding an acid mixture with the same anionic ratio of the nutrient solution using concentrated nitric, phosphoric and sulfuric acid.

In both growing seasons (Experiments 1 and 2), nutrient solution was pumped from independent tanks (one tank of 30 L per experimental unit) through a drip and subirrigation systems. In the subirrigation system the nutrient solution was pumped at the elevated end of the benches and allowed to run slowly down the trough past the pots, and the excess was drained back to the tank for later recirculation. In the drip-irrigation system, the nutrient solution was pumped from independent tanks and administrated through one emitter per plant (flow rate of 2 L h^{-1}) and the excess was drained back to the tank for later recirculation. In all treatments (drip-irrigation and subirrigation), irrigation scheduling was performed using electronic low-tension tensiometers (LT Irrometer) that control irrigation based on substrate matric potential [27]. Tensiometers have been placed at about the midpoint of the pots (≈ 6 cm depth). In each treatment, three tensiometers were installed, and they were located in different pots to provide a representative reading of the moisture tension. Tensiometers were connected to an electronic programmer that controlled the beginning (-5 kPa) and the end of irrigation (-1 kPa), which correspond to high and low tension set points for the major part of media [28]. The timing varied from 3-7 fertigations per day lasting 20-30 min for the subirrigation and from 3-9 fertigations per day of 1-3 min for the drip-irrigation. Nutrient solution supply with the drip-irrigation system ended when leachate was equal to 30% of nutrient solution applied; the 30% excess of the solution applied was collected for recycling. Typically, leaching fractions of 20-30% are needed to maintain the EC in the substrate at recommended level [29]. In subirrigated pots at the end of each irrigation event, the substrate surface appeared to be wetted.

Measurements and analysis: Each day at the same hour, during both growing cycles, the solution of each tank was brought to its initial volume to replace the water lost by evapotranspiration, and the volume of the refill fresh solution was determined with a flowmeter (Electronic Digital Meter). The nitrate concentration of the solution obtained from the 12 treatment tanks in both growing seasons was analyzed at two-week intervals to establish the percentage of nitrate variation using the Cataldo's method [30].

In both experiments, plant height and plant diameter were measured weekly, starting at transplanting on 10 plants per plot. Height (H) was determined as the distance from the surface of the medium to the top of the plant, width (diameter, W) as the average of two measurements (one perpendicular to the other). Plant growth index (GI) was calculated as:

$$GI = \pi\left(\frac{W}{2}\right)^2 H \qquad (1)$$

The growth index water use efficiency (WUE_{GI}) was calculated as the GI divided by the crop ET and expressed in cm^3 L^{-1} [17].

To characterize the time evolution of the growth index a sigmoidal model was used [31]:

$$Y = \frac{a}{\left(1 + e^{-\frac{1}{b}(x - x_0)}\right)} \qquad (2)$$

where a is the maximal value of y, x is the time expressed in days after transplanting, x_0 represents the time period (days after transplanting) to reach 50% of the final maximal value a and b is the fitting parameter of the model.

Thirty-four and 45 days after transplanting for Experiment 1 and 2, respectively, the net assimilation of CO_2 (ACO_2, μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$) was determined with a portable photosynthesis system (LI-6200; LI-COR Inc., Lincoln, NE, USA). This measurement was made on the most recent fully-expanded leaves, using six replicate leaves per treatment. The LI-6200 was equipped with a well-stirred 2.5×10^{-5} m^3 leaf chamber with constant-area inserts (1.2×10^{-3} m^2) and fitted with a variable intensity red source (Model QB1205LI-670, Quantum Devices Inc. Barneveld, WI, USA) [32]. Leaf temperature within the chamber was 30±2ºC, vapor pressure difference between the leaf and air was 2.6±0.3ºC and CO_2 concentration 365±10 ml·L^{-1}. The net assimilation of CO_2 measurement was made between 11.00 and 13.00 HR.

In Experiments 1 and 2, petunias were harvested on 29 May 2008 (43 d after transplanting) and 7 Jan. 2009 (63 d after transplanting), respectively, at the same physiological age, expressed as the standard accumulation of growing-degree (base-temperature of 8°C; ceiling temperature of 28°C) days after transplanting, which was in the range of 572-597 degree-days. Ten plants per plot were separated into stems, leaves and roots, and their tissues were dried in a forced-air oven at 80°C for 72 h for biomass determination. Shoot biomass was equal to the sum of aerial vegetative plant parts (leaves + stems). Root to shoot ratio was calculated by dividing root dry weight by the sum of leaf and stem dry weights. Leaf area (LA) was measured with an electronic area meter (Delta-T Devices Ltd., Cambridge, UK). The number of flowers per plant was recorded including any buds developed to the point of showing flower color. Quality rating was scored using the 1 to 5 scale (1 = poorest and 5 = best salable quality).

In both experiments, dried plant tissues (leaf, stem and root) were ground separately in a Wiley mill to pass through a 20 mesh screen, then 0.5 g of the dried plant tissues was analyzed for the following macronutrients: N, P, K, Ca and Mg. Nitrogen concentration in the plant tissues was determined after mineralization with sulfuric acid by regular Kjeldahl method [33], P, K, Ca, and Mg concentrations were determined by dry ashing at 400°C for 24 h, dissolving the ash in 1:25 HCl, and assaying the solution obtained using an inductively coupled plasma emission spectrophotometer (ICP Iris, Thermo Optek, Milano, Italy) [34]. The uptake of macronutrients was calculated by multiplying the biomass (g $plant^{-1}$) of each plant organ (leaves, stems and roots) by its nutrient concentration (mg g^{-1} of dry weight). All nutrient amounts of plant organs were then summed to get the nutrient uptake of the whole plant (mg $plant^{-1}$).

In both experiments, at the middle cycle and after the plants were harvested, the growth medium was sampled for EC measurement. The substrate from four pots from each experimental unit was divided into two equal layers from the surface to the bottom of the pots to determine the EC at the upper (0-5 cm) and lower (5-10 cm) layers. The EC of the water extract was obtained using the 1:2 (growth medium:deionized water, v/v) method by adding 80 cc of deionized water to a sample of 40 cc. Growth medium and water were well mixed for 30 min and then the mixture was filtered and the solids discarded. The EC of filtered extracts was then measured using a conductivity meter (EC 214, Hanna Instruments).

***Statistical analysis*:** All data were statistically analyzed by ANOVA using the SPSS software package (SPSS 10 for Windows, 2001). Combined analysis of variance was performed using season as a fixed variable [35]. Duncan's multiple range test was performed at $P \leq 0.05$ on each of the significant variables measured.

Results

***Climatic data*:** Daily solar radiation (R_s), mean air temperature (T_a) and mean vapour pressure deficit (VPD) inside the greenhouse in the spring and the winter seasons are presented in Fig. 1. During the spring season, the daily R_s, T_a and VPD ranged from 6.9 to 24.4 MJ m^{-2}, 17.2 to 27.1ºC and 0.5 to 2.1 kPa, respectively, while in the winter season the daily R_s, T_a and VPD ranged from 1.0 to 9.7 MJ m^{-2}, 14.9 to 19.6°C and 0.5 to 1.2 kPa, respectively. Moreover, there was a positive simple linear correlation between R_s and T_a ($r = 0.89$, $P < 0.001$) and between R_s and VPD ($r = 0.85$, $P < 0.001$) and between T_a and VPD ($r = 0.88$, $P < 0.001$). These relationships between the climate parameters inside the greenhouse can be expected because under protected conditions it is very difficult, if not impossible, to change one environmental factor without simultaneously affecting many others [36].

Electrical conductivity of the growing medium: The electrical conductivity of the growing medium (EC_s) in the upper and lower layers at the mid and at the end of the cultural cycle are shown in Table 1. The EC_s in the upper and lower layers at the mid and at the end of the cultural cycle was significantly affected by S × I and S × C interactions. When averaged over all irrigation treatments (S × C interaction), the highest EC_s in both layers was recorded in the spring season using a full nutrient solution concentration, whereas the lowest value was observed in the winter season using the half strength nutrient solution concentration. Moreover, when averaged over all nutrient solution concentration treatments (S × I interaction), the percentage of EC_s at the mid and at the end of the cultural cycle increase in the lower layer caused by high temperature and radiation (spring season) was significantly higher (by 113 and 140% at the mid and at the end of the cultural cycle, respectively) in subirrigation than in drip-irrigation (by 56 and 81% at the mid and at the end of the cultural cycle, respectively).

***Plant quality and growth parameters*:** The sigmoidal equation (Eq. (2)) was well adapted to the experimental data relative to the evolution of the growth index (GI) during the two growing seasons (Fig. 2). The coefficient of determination (R^2) for the GI was always higher than 0.99 and the P values were always significant ($P< 0.001$), which indicated a good fit. Initial GI at transplanting ranged from 91 to 98 cm^3 $plant^{-1}$. The maximum GI (a) was recorded in the winter season with both irrigation systems using full nutrient solution concentration, followed by the spring season treatment, whereas the lowest value was recorded in the winter season using half strength nutrient solution (Fig. 2). Moreover, the GI observed in the spring period, especially with subirrigation using the full nutrient solution concentration, required less time ($P < 0.001$) to reach the 50% of the maximum value than those recorded during the winter period (Fig. 2). The shoot biomass dry weight, the root-to-shoot ratio (R/S), the plant growth index at the end of the growing cycle, and the quality index were significantly affected by S × C interaction, while the root biomass dry weight and flower number were significantly influenced by the growing season (Table 2). Irrespective of the irrigation treatment (S × C interaction), the highest shoot biomass was recorded in the winter season using full nutrient solution concentration. The highest values of the plant growth index were observed in both growing season using a full nutrient solution concentration. Moreover, the highest root-to-shoot ratio was measured in the winter season using the half strength nutrient solution, whereas the highest quality index was recorded in the spring season using both half and full nutrient solution concentration. Finally, the root biomass dry weight was significantly lower by 31% in the spring in comparison to the winter season, whereas an opposite results were observed on flower number, with the highest values recorded in the spring in comparison to the winter season.

***Leaf area, crop evapotranspiration and water use efficiency*:** The total leaf area, net assimilation CO_2 (A_{CO2}) and crop evapotranspiration (ET_c) were significantly affected by S × C interaction, while the growth index water use efficiency (WUE_{GI}) was significantly affected by the growing season (Table 3). When averaged over all irrigation system treatments (S × C interaction), the highest LA, and ET_c values were recorded on plants grown during the winter season using the full nutrient solution concentration, whereas the highest values of A_{CO2} were observed in both spring and winter growing season treatments using the full strength nutrient solution. Moreover, the WUE_{GI} was highly influenced by the cropping season, since the WUE_{GI} recorded on plants grown during the spring season was significantly higher by 24% than those recorded during the winter season.

Plant mineral uptake: The effects of irrigation system and nutrient solution concentration on total uptake of macronutrients of petunia plants grown in the winter and spring seasons are displayed in Table 4. The total nutrient uptake of N, P, K, Ca and Mg was significantly influenced by S × C interaction, with the highest values recorded in the winter season on plants grown at 2 dS m^{-1}.

Electrical conductivity in the nutrient solution: In the winter season, the electrical conductivity (EC) of the half and full strength nutrient solution did not exceed the preset maximum limit (2.5 and 1.25 dS m^{-1}, for full and half strength nutrient solutions, respectively) in both subirrigation and drip-irrigation systems (Fig. 3). Moreover, during the warm season, the EC value of the nutrient solution was always within the range for plants grown in subirrigation, whereas with drip-irrigation in both full and half strength nutrient solution, the EC exceeded the maximum limit and therefore water was added in order to restore the EC to the original target values (Fig. 3).

Table 1. Effects of irrigation system and nutrient solution concentration on electrical conductivity (EC_s) of the substrate aqueous extract in the middle and at the end of the cultural cycle at two layers (upper and lower) in the spring and winter growing seasons. Values are the means of three replicate samples.

Growing Season	Irrigation System	Nutrient concentration (dS m^{-1})	EC_s (dS m^{-1})			
			Mid-cycle		End-cycle	
			Upper	Lower	Upper	Lower
Spring	Drip-irrigation	1.0	0.80	0.65	1.08	0.86
		2.0	1.45	1.06	2.67	1.67
	Subirrigation	1.0	0.97	0.75	1.46	1.00
		2.0	2.77	1.47	3.89	2.10
Winter	Drip-irrigation	1.0	0.39	0.36	0.44	0.41
		2.0	0.74	0.74	1.02	0.98
	Subirrigation	1.0	0.45	0.38	0.53	0.42
		2.0	0.86	0.66	1.08	0.87
Significance[a]						
Season (S)			***	***	***	***
Irrigation system (I)			*	NS	*	NS
Nutrient concentration (C)			**	**	***	***
S × I			*	*	*	*
I × C			NS	NS	NS	NS
S × C			*	*	**	*
S × I × C			NS	NS	NS	NS

NS, *, **, *** Nonsignificant or significant at P< 0.05, 0.01 and 0.001, respectively.

Table 2. Effects of irrigation system and nutrient solution concentration on shoot and root biomass dry weight, root-to-shoot ratio (R/S), growth index (GI), flower number, and quality index of petunia plants grown in the spring and winter growing seasons. Values are the means of three replicate samples.

Growing Season	Irrigation System	Nutrient conc. (dS m^{-1})	Shoot dry wt. (g plt^{-1})	Root dry wt. (g plt^{-1})	R/S	GI (cm^3 plt^{-1})	Flower (no. plt^{-1})	Quality index (0-5)
Spring	Drip-irrigation	1.0	8.05	1.06	0.13	9556.4	36.9	4.7
		2.0	8.82	1.07	0.12	10420.5	33.7	4.5
	Subirrigation	1.0	8.31	1.18	0.14	9623.1	34.0	4.7
		2.0	8.49	1.21	0.15	10075.8	30.3	4.8
Winter	Drip-irrigation	1.0	8.83	1.75	0.20	8012.3	7.3	2.5
		2.0	13.25	1.50	0.11	10864.3	3.8	3.8
	Subirrigation	1.0	9.02	1.74	0.18	8879.2	9.8	2.3
		2.0	12.43	1.55	0.13	11646.9	4.6	3.1
Significance[a]								
Season (S)			***	***	*	NS	***	***
Irrigation system (I)			NS	NS	NS	NS	NS	NS
Nutrient concentration (C)			**	NS	**	**	*	*
S × I			NS	NS	NS	NS	NS	NS
I × C			NS	NS	NS	NS	NS	NS
S × C			**	NS	**	*	NS	NS
S × I × C			NS	NS	NS	NS	NS	NS

NS, *, **, *** Nonsignificant or significant at P< 0.05, 0.01 and 0.001, respectively.

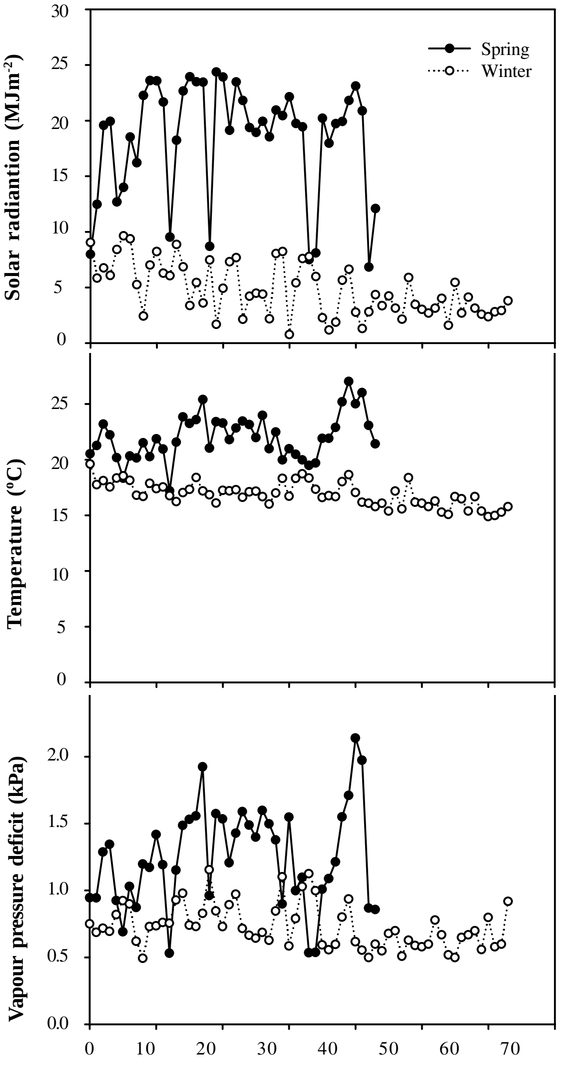

Figure 1. Daily mean values of solar radiation, air temperature and vapour pressure deficit recorded inside the greenhouse during the spring and the winter seasons.

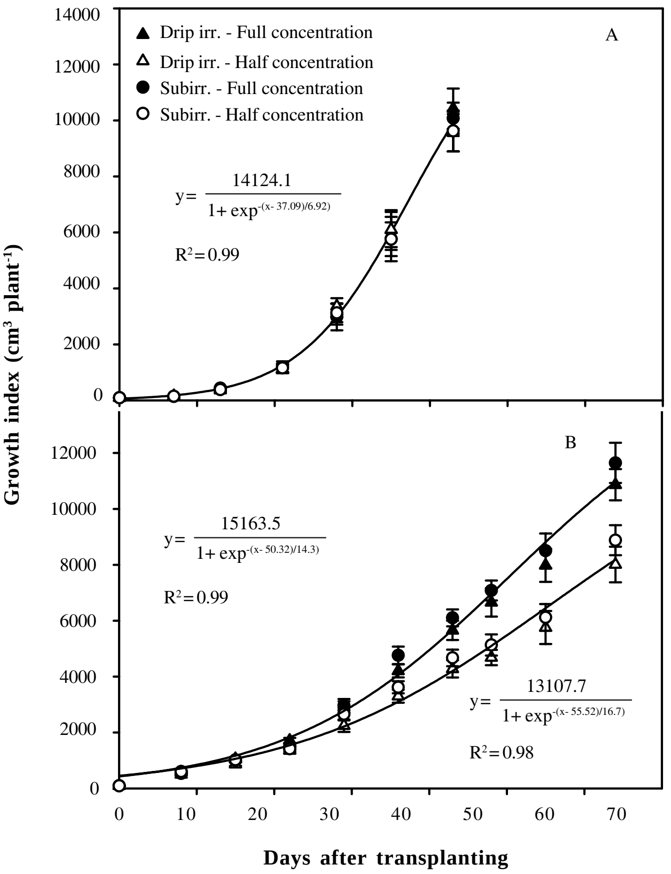

Figure 2. Growth index evolution of greenhouse petunia plants drip irrigated or subirrigated with full or half strength nutrient solution during the growing cycle in the spring (A) and the winter (B) seasons. Data are means of three replicates. Vertical bars indicate ± S.E. of means, their absence indicates the size was less than the symbol.

Table 3. Effects of irrigation system and nutrient solution concentration on final leaf area (LA), net assimilation CO_2 (A_{CO2}), total crop evapotranspiration (ET_c), and growth index water use efficiency (WUE_{GI}) of petunia plants grown in the spring and winter growing seasons. Values are the means of three replicate samples.

Growing Season	Irrigation System	Nutrient conc. (dS m^{-1})	LA (cm^2 plt^{-1})	A_{CO2} (mmol CO_2 m^{-2} s^{-1})	ET_c (L plt^{-1})	WUE_{GI} (cm^3 L^{-1})
Spring	Drip-irrigation	1.0	410.5	17.7	3.50	2730.0
		2.0	428.1	18.1	3.50	2975.9
	Subirrigation	1.0	402.2	17.8	3.47	2771.3
		2.0	417.2	18.6	3.48	2891.4
Winter	Drip-irrigation	1.0	528.0	16.3	3.74	2144.3
		2.0	780.3	18.9	4.73	2297.9
	Subirrigation	1.0	638.2	15.9	4.00	2220.8
		2.0	842.1	18.5	4.67	2490.8
Significance[a]						
Season (S)			***	NS	***	**
Irrigation system (I)			NS	NS	NS	NS
Nutrient concentration (C)			*	NS	***	NS
S × I			NS	NS	NS	NS
I × C			NS	NS	NS	NS
S × C			*	*	**	NS
S × I × C			NS	NS	NS	NS

NS, *, **, *** Nonsignificant or significant at P<0.05, 0.01 and 0.001, respectively.

Table 4. Effects of irrigation system and nutrient solution concentration on total uptake of macronutrients of petunia plants grown in the spring and winter growing seasons. Values are the means of three replicate samples.

Growing Season	Irrigation System	Nutrient conc. (dS m^{-1})	Macronutrients (mg $plant^{-1}$)				
			N	P	K	Ca	Mg
Spring	Drip-irrigation	1.0	245.0	44.3	284.7	121.7	63.4
		2.0	298.7	54.9	367.9	125.6	63.7
	Subirrigation	1.0	306.0	56.7	365.5	140.1	68.1
		2.0	324.7	60.6	396.8	162.6	84.9
Winter	Drip-irrigation	1.0	298.7	57.3	373.5	165.6	80.2
		2.0	518.0	108.3	669.0	259.2	132.6
	Subirrigation	1.0	306.3	56.8	368.1	174.1	82.8
		2.0	489.0	109.3	652.2	248.5	127.4
Significance[a]							
Season (S)			***	***	***	***	***
Irrigation system (I)			NS	NS	NS	NS	NS
Nutrient concentration (C)			***	***	***	***	***
S × I			NS	NS	NS	NS	NS
I × C			NS	NS	NS	NS	NS
S × C			***	***	***	***	**
S × I × C			NS	NS	NS	NS	NS

[a] NS, *** Nonsignificant or significant at P< 0.001, respectively.

Discussion

Accumulation of salts in the growing medium depends on the concentration of salts applied with the nutrient solution, the irrigation system, and the evaporative demand of the environment [17, 26]. The subirrigation resulted in higher EC_s increasing in the upper and lower layers than with drip irrigation. The most remarkable effect was observed during the spring season. The highest EC_s with subirrigation at the end of the growing cycle can be expected because the unidirectional flow of nutrient solution inside the subirrigated substrate is due to capillarity force and bulk flow [6, 16, 20]. The water movement is created by evaporation from substrate surface and it is favored by plant transpiration. Therefore, a progressive accumulation of the mineral elements not used by the plant occurs in the upper portion of the substrate[8]. A similar pattern of salt accumulation with subirrigation systems has been reported in numerous other studies on ornamental plants [22, 23, 26, 37]. The salts build up into the substrate may be more of a problem during the hot dry conditions (spring season) and with increasing the EC of the fertilizer solution especially in subirrigation, where in the upper layer the EC_s observed during the spring season at the end of the growing cycle was three-fold than the one observed in the winter season due to the high evaporative demand (higher solar radiation and higher air temperature), and was almost double in full than in half strength nutrient solution (Table 1). Consequently, plants should be grown with more dilute fertilizer solutions at higher temperatures and radiation especially with subirrigation, in order to keep the EC_s within the optimal range.

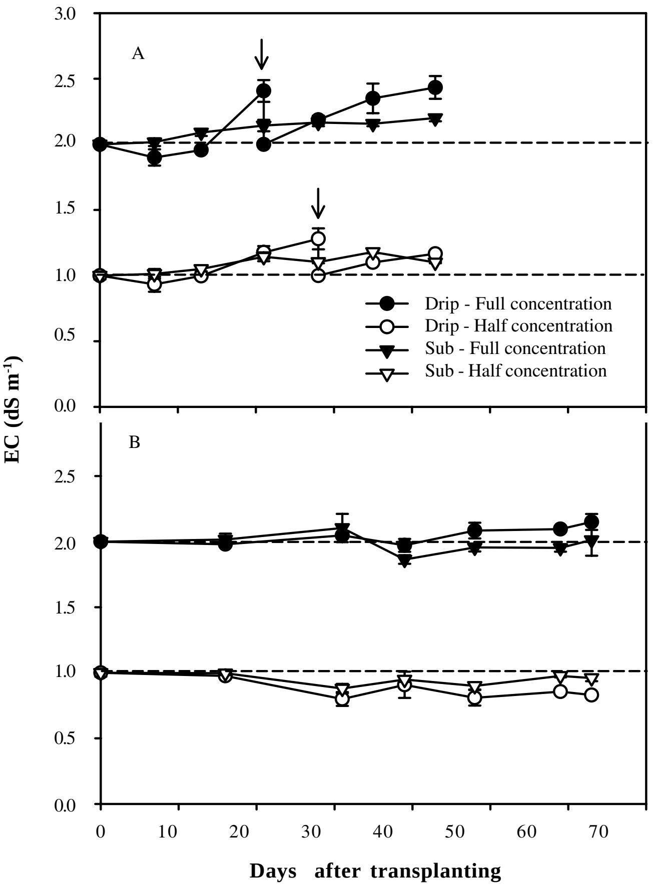

Figure 3. Changes in the electrical conductivity (EC) of the recirculating nutrient solution as affected by the irrigation system (drip-irrigation vs subirrigation) and nutrient solution concentration (half vs full strength) of greenhouse petunia plants grown in spring (A) and winter (B) growing seasons. The arrows indicate when the EC exceeded the threshold values of 2.5 and 1.25 dS m^{-1} for the full and half strength nutrient solutions, respectively. The EC of the solutions was restored to the target value by adding water. The values are means of three replicates.

Dole and Wilkins [38] reported that an ECs between 1.25-2.25 dS m^{-1} obtained with the dilution method (1:2 v/v) is considered acceptable for most floricultural crops. In our case, the EC_s in the upper layer at the end of the growing cycle was clearly supraoptimal for soilless petunia culture (>2.25 dS m^{-1}), especially with subirrigation under full strength nutrient solution in the spring season. Moreover, except for subirrigation in the spring season, the EC_s of the bottom layers at the end of the growing cycle were all below the threshold value. Maintaining favorable EC_s in the lower layers of substrate is very important for optimal crop performance due to the presence of the greatest proportion of the petunia root system at this depth. Similarly, Kent and Reed [39] and Rouphael *et al.* [17] found that the growth of New Guinea impatiens (*Impatiens* × *hawkeri*), spathiphyllum (*Spathiphyllum schott*) and geranium was not affected by the high EC_s in the top layer, and they concluded that salt accumulation in the top layer did not necessarily have detrimental effects on plant growth.

In the present study no significant differences on shoot biomass, plant growth index, total leaf area, number of flowers and quality index were recorded between drip and subirrigation, and between full and half strength solution during the spring season (Tables 2 and 3). The higher EC_s recorded with subirrigation under full strength nutrient solution in the spring season, had no negative effect of plant growth parameters and quality index indicating that petunia can be considered tolerant to salinity [40]. Our results are in line with those of James and van Iersel [22] who found that petunia grows well when the growing medium EC was between 2.1 and 5.4 dS m^{-1}. James and van Iersel [22] determined EC with the pour-through method, which generally gives higher values than the dilution method (1:2 v/v) [41]. Taking into the account the difference between the pour-through and the 1:2 dilution methods ($EC_{(1:2)} = EC_{PT} \times 0.39 + 0.03$; Huang *et al.* [41]), the range of the EC_s during the spring season at the end of the trial was similar to those reported previously by James and van Iersel [22], since we found that an EC_s had no effect on growth and quality of petunia within a range between 0.86 and 2.10 dS m^{-1}. Moreover, in the winter season, the lower medium EC recorded at the end of the trial with half strength nutrient solution reduced shoot biomass, plant growth index, leaf area and quality index compared to the plants grown with full nutrient solution concentration (Tables 2 and 3), presumably because of mild nutrient deficiencies. In fact the EC_s recorded with half strength solution in both layers at the end of the trial ranged between 0.4 and 0.5 dS m^{-1} indicating low nutrient levels which may not be sufficient to sustain growth [38].

When averaged among all treatments, the crop evapotranspiration (ET_c) increase was less pronounced in the winter season (0.068 L $plant^{-1}$ day^{-1}) compared to spring season (0.081 L $plant^{-1}$ day^{-1}) due to the reduced evaporative demand of the atmosphere (lower R_s, T_a and VPD). However, the higher total evapotranspiration was recorded in the winter compared to spring season (4.3 vs. 3.5 L m^{-2}), because the plants grown during the winter season required more days (20) to reach the commercial maturity in comparison to those grown during the spring season. The longer winter cropping cycle increase the crop water requirement especially with subirrigation, where more evaporation occurred when nutrient solution flows in the trough due to higher water surface exposed and to longer irrigation events [20]. Consequently, the lower growth index water use efficiency (WUE_{GI}) recorded in the winter season in comparison to the spring season was mainly associated to the higher ET_c values.

The highest macronutrient uptake of petunia plants in winter vs. spring and in full vs. half strength nutrient solution treatments was mainly related to the total plant biomass. The total plant uptake of N, P, K, Ca and Mg in greenhouses is usually enhanced by stronger natural radiation or supplemental light [42, 43]. This was not the case in the current experiment, since the highest biomass production was recorded during the winter season using a full strength nutrient solution and consequently the total uptake of macronutrients was higher. One of the main concerns over using low concentration nutrient solutions is the potential for N deficiency. Results indicate that, except the plants grown during the winter season using half strength nutrient solution, the N concentration recorded in all treatments was closed to the target value. Moreover, based on the total uptake of macronutrients, current nutrient application rates can be reduced by at least 50% in the spring season without any detrimental effect on plant growth and quality.

Finally, the variation of the EC in the nutrient solution during the spring growing cycle was less pronounced in the subirrigation than with drip-irrigation systems which represent an important aspect for the simplification of the closed loop management of the nutrient solution.

Conclusions

The results demonstrate that growing season, irrigation system, and nutrient solution concentration have an interactive effect on potted petunia production. During the spring season the growing medium EC increases much more rapidly with subirrigation than with drip-irrigation systems especially at 2 dS m^{-1}. The higher EC_s recorded with subirrigation under full strength nutrient solution in the spring season, had no negative effect on plant growth parameters and quality index indicating that petunia can be considered tolerant to salinity. In addition, our study showed, that during the spring season the nutrient solution concentration in both recirculating irrigation systems, can be reduced at 50% without any detrimental effect on plant growth and quality, but subirrigation should be preferred under our conditions during this cropping season due to the similar plant growth, and quality of drip-irrigation, and less variation of EC in the solution during the growing cycle leading to a simplification of the closed loop management of the nutrient solution. The results also indicated that the effect of the nutrient solution concentration was more pronounced in the winter season since half strength nutrient solution reduced shoot biomass, plant growth index, leaf area and quality index compared to the plants grown with full nutrient solution concentration presumably because of mild nutrient deficiencies. These results may be applied in management decisions of the grower for improving crop performance.

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