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Subirrigation of Container-Grown Tomato I: Decreased Concentration of the Nutrient Solution Sustains Growth and Yield

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Abstract: Subirrigation of containerized vegetable crops is a promising strategy to increase water and fertilizer use efficiency. However, the nutrient solution may cause salts accumulation in the substrate top layer. The objective of this study was to determine the effect of nutrient solution concentration in container-grown tomato under surface drip-irrigation and subirrigation. The plants were irrigated with solutions at concentrations of −0.072, −0.058 and −0.043 MPa (100%, 80% and 60% of Steiner's nutrient solution, respectively). Except at the highest concentration, the greatest yields occurred in subirrigated (10.6 kg plant^{-1}) compared to drip-irrigated plants (9.5 kg plant^{-1}). In drip-irrigated plants, yield was higher with the highest solution concentration. The increased yield in subirrigated plants at low solution concentrations was related with increased fruit N and Ca content. The higher accumulation of N, P, K and Ca demonstrates that subirrigation allows for increased nutrient use efficiency, particularly when using nutrient solutions of low concentration. Water use efficiency was markedly increased in subirrigated tomato, as 300 to 460 g of fruit L^{-1} were produced, compared to 50 g L^{-1} in drip-irrigated plants. Our results indicate that subirrigation is a feasible system for soilless-cultivated tomato provided the nutrient solution is reduced to a 60% of the total concentration.

Keywords: greenhouse vegetable crops; nutrient use efficiency; water use efficiency; electrical conductivity of irrigation water

1. Introduction

Vegetable greenhouse production demands high fertilizer and water inputs in order to achieve high yields and good quality produce [1–4]. Common practice for greenhouse vegetable production includes surface/open irrigation systems, which are not considered to be environmentally friendly as large volumes of water and fertilizers are frequently wasted and may runoff/leach, polluting surface and groundwater systems [1,2,5].

Waste of water and nutrients result in low plant water use efficiency and high substrate leaching rates, in that, water may be delivered in greater volumes than that of the water holding capacity of the growing medium [1,2,6]. Environmental and economic concerns and government regulations [7,8] are necessitating the optimization of plant nutrient and water utilization, while minimizing nutrient leaching and runoff into the environment [9,10]. Subirrigation of vegetable crops and reuse of the nutrient solution is a promising strategy to increase water and fertilizer use efficiency, as it is a closed production system where the nutrient solution not retained by the growing medium is collected and recirculated for reuse during the next irrigation event [3,6,11,12]. Subirrigation systems for containerized plants include ebb and flow, flood floors, and though benches [1]. In recirculating systems, nutrient solution attributes such as pH, electrical conductivity (EC), and nutrient concentration may be maintained, which in turn allows for increased fertilizer use efficiency [1,13–16].

However, subirrigation systems require careful management of the nutrient solution, as highly concentrated solutions may cause an excessive accumulation of fertilizers in the top layer of the growing medium [1,12,15,17–19], increasing the EC and thus reducing growth and yield [1,20–22]. For this reason, when compared to surface irrigation systems, nutrient solutions for subirrigation should have lower nutrient concentrations [15,20,23–25].

Some studies in subirrigation, performed mainly with ornamental species, have demonstrated that the concentration of the nutrient solution may be reduced by up to 50% when compared to nutrient solutions for surface irrigation, with no detrimental effects on plant growth and quality [3,18]. However, for vegetable species, results indicate that growth and yield were reduced in subirrigated zucchini squash (*Cucurbita pepo* L.) [19] and eggplant (*Solanum melongena* L.) when the nutrient solution concentration decreased to 50% or maintained at 100%, respectively.

There is limited information regarding the optimum concentration of nutrient solutions for subirrigation systems for the cultivation of vegetable crops. Ideally, the optimum concentration should be as low as possible in order to increase nutrient use efficiency and yet provide the plants with the nutrients in adequate quantities to obtain the maximum growth, yield, and quality [22,26,27], while avoiding the buildup of EC in the growing medium. The objective of this study was to determine the effect of nutrient solution concentration in two irrigation systems, surface drip-irrigation and subirrigation, on tomato (*Solanum lycopersicum* L.) growth, fruit yield, plant water use, and plant nutrient status.

2. Materials and Methods

2.1. Cultural Conditions and Plant Material

The experiment was performed in a greenhouse at Universidad Autónoma Agraria Antonio Narro, located in Saltillo, Coah., Northeast México (25°23′42′′ N Lat., 100°59′57′′ W Long., 1743 m above sea level). Weather data were collected from a weather station located in the greenhouse. Mean maximum, minimum, and mean temperature for the study duration were 24.9 °C, 13.2 °C, and 18.1 °C, respectively, while maximum, minimum, and mean relative humidity were 87.1%, 47.8%, and 71.3%, respectively. Mean seasonal photosynthetically active radiation (PAR) was 456 µmol m^{-2} s^{-1} while mean PAR at solar noon was 683 µmol m^{-2} s^{-1}.

Solanum lycopersicum L. cv. Clermon transplants with two fully expanded leaves were planted on 28 Apr. 2015 into 13 L black polyethylene containers (one plant per container) filled with a mixture of sphagnum moss, coconut fiber, and perlite (40%, 40%, 20% *v/v*) to a height of 27 cm. Initial medium pH and EC were 5.9 and 0.9 dS m^{-1}, respectively. Plant containers were placed 40 cm apart within the row and rows were kept 120 cm apart.

2.2. Nutrient Solutions and Irrigation Methods

Nutrient concentration in the solutions were expressed as osmotic potential (MPa) and corresponded to 100% (-0.072 MPa) 80% (−0.058 MPa) and 60% (−0.043 MPa) of Steiner's formulation [28] (meq L^{-1}: 12 NO_3^-, 1 $H_2PO_4^-$, 7 K, 4 Mg, 7 SO_4^{2-}; in mg L^{-1}: 8.0 Fe, 0.6 Zn, 3.9 Mn, 0.3 Cu, 0.7 B and 0.2 Mo).

Nutrient solutions were applied through two irrigation systems: subirrigation and drip surface irrigation. The subirrigation system consisted of rigid plastic trays/troughs (69 × 39 × 16 cm; length, width, and height) with a 2% slope on which two 13 L containers were placed. Distance between pots within the tray/trough was 35 cm and tray/trough lines were separated 1 m. The subirrigation solutions were distributed with a $\frac{1}{2}$ HP pump at the higher end of the tray/trough through e PVC pipe system. Subirrigation started when the growing medium registered a moisture tension of 10 KPa, with an initial flooding depth and duration of 15 cm and 30 min on which the containers remained standing in the nutrient solution; the unabsorbed solution was drained through a discharge pipe system and conducted back into a 200 L storage tank for reuse in the following irrigation event. The subirrigation solutions were renewed every 15 d. The drip surface irrigation system consisted of four emitters dispensing a total of 4 $L \cdot h^{-1}$ of nutrient solution per container. Subirrigation started when the growing medium registered a moisture tension of 10 KPa, with an initial flooding depth and duration of 15 cm and 30 min on which the containers remained standing in the nutrient solution; the unabsorbed solution was drained back into a 200 L storage tank for reuse in the following irrigation event and renewed every 15 d. In the drip irrigation system, irrigation was conducted at the same moisture tension with enough solution to achieve a 25% to 30% leaching fraction.

The nutrient solutions in subirrigated and drip-irrigated plants were checked and adjusted as required for pH and EC prior to each irrigation event. The nutrient solution pH was adjusted to 6.0 ± 0.1 with H_2SO_4 (0.1 N) and EC was maintained at 2.0, 1.6 and 1.2 dS m^{-1} for the −0.072, −0.058 MPa and −0.043 MPa solutions, respectively.

2.3. Plant Growth and Mineral Composition

Fruits from 15 trusses were harvested, initiating 81 d after transplanting and finishing 268 d after transplanting; fruit yield was calculated on a monthly and a total yield basis. The fruit was considered ready for harvest when 80% of the pericarp was red. At experiment termination, whole plants were harvested and washed twice in distilled water, separated into roots, stems + leaves (the shoot), and fruits, and dried in an oven at 70 °C for 72 h prior to measuring dry weight.

Dry plant tissues (root, shoot and fruit) were ground to pass a 20 mesh sieve (Thomas Wiley Mill, model ED-5, Swedesboro, NJ, USA). Dry ground tissues were analyzed for total nitrogen (N) concentration, utilizing the Kjeldhal's procedure [29]. Phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) concentrations were determined in previously digested ground tissues (2:1 mixture of H_2SO_4:$HClO_4$ and 2 mL of 30% H_2O_2) with Inductively Coupled Plasma Emission Spectrometer (ICP-AES, model Liberty, VARIAN, Santa Clara, CA) [30]. Macronutrients accumulated in the entire plant were calculated considering their concentration in the root, shoot and fruits and the dry weight of each plant part.

Water consumption by plants was measured indirectly for both irrigation systems. In subirrigation, the volume of water retained by the growing medium was calculated by measuring the nutrient solution depleted from the tray/trough at flooding termination (30 min), while in drip-irrigated plants it was calculated by measuring the solution dispensed through the emitters when the leaching fraction was achieved. Water consumed throughout the study was used to calculate the water use efficiency in terms of vegetative biomass (WUE_b) and fruit yield (WUE_y).

2.4. Statistical Design

The experimental design was a completely randomized block, with six treatments (three nutrient solution concentrations × two irrigation systems) and four replicates of the experimental unit. The experimental unit consisted of two containers (i.e., two plants); the two containers were placed on a single tray/trough. Data were analyzed with ANOVA and Tukey's multiple mean comparison test ($p \leq 0.05$) using SAS v. 9.2 (SAS Institute, Inc., Cary, NC, USA).

3. Results

3.1. Growth, Yield and Water Use Efficiency

In drip-irrigated plants, root and shoot dry weight increased with decreasing osmotic potential (-0.043 to -0.072 MPa) of the nutrient solution (Figure 1A,B). In subirrigated plants, root and shoot dry weight were highest at an osmotic potential of -0.058 MPa (Figure 1A,B).

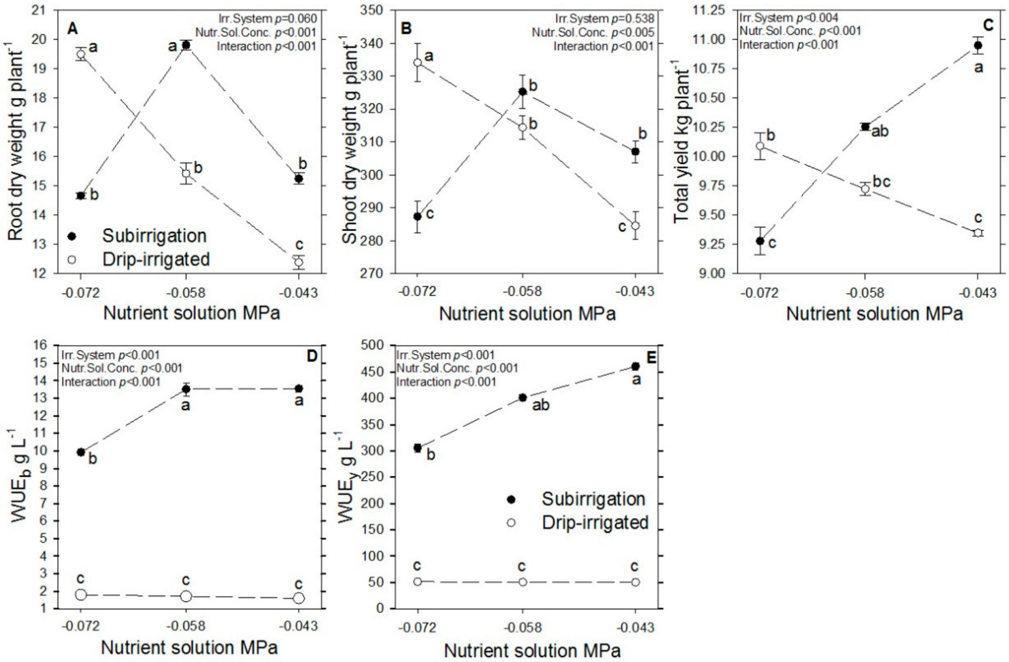

Figure 1. (**A**–**E**) Growth, yield, and water use efficiency in terms of biomass (WUE_b) and fruit yield (WUE_y) in subirrigated and drip-irrigated tomato (*Solanum lycopersicum* L.) plants with solutions of varying nutrient concentration. ANOVA significance for both factors, irrigation system (Irr. System) and nutrient solution concentration (Nutr. Sol. Conc.), and the interaction is shown. Means with the same lower-case letter indicate non-significant differences according to Tukey's multiple comparison test. Bars represent the standard error of the mean ($n = 4$).

Averaged across nutrient solution concentration, fruit production was higher in subirrigated plants; however, there was a contrasting response as yield in subirrigated plants linearly increased with decreasing nutrient concentrations, whereas it linearly decreased in drip-irrigated plants (Figure 1C). Compared with drip-irrigated plants, WUE was higher in subirrigated plants, and it was even higher at lower solution concentrations (Figure 1D,E).

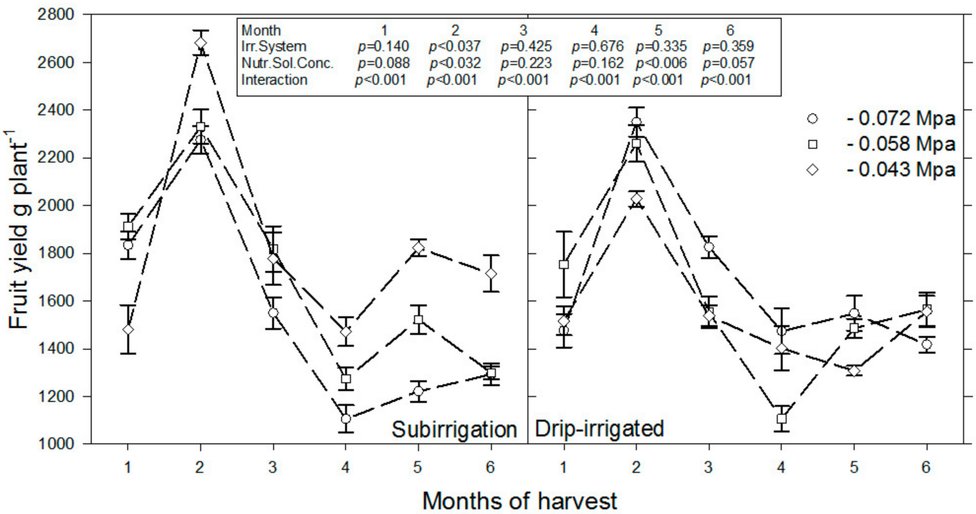

Figure 2. Fruit yield on a monthly basis in subirrigated and drip-irrigated tomato (*Solanum lycopersicum* L.) plants with solutions of varying nutrient concentration. ANOVA significance for both factors, irrigation system (Irr. System) and nutrient solution concentration (Nutr. Sol. Conc.), and the interaction is shown. Means with the same lower-case letter indicate non-significant differences according to Tukey´s multiple comparison test. Bars represent the standard error of the mean ($n = 4$).

During the first month of harvest, yield of subirrigated plants irrigated with solutions of higher concentrations (−0.058 and −0.072 MPa) was greater than that of those fed with solutions at the lowest concentration (−0.043 MPa) (Figure 2); however, from the second month onwards, the highest yields were obtained by plants fed with solutions with the lowest nutrient concentration. In general, in drip-irrigated plants the yield was greater in plants irrigated with the highest nutrient concentration (Figure 2).

3.2. Total Nutrient Accumulation

In drip-irrigated plants, mineral nutrient accumulation was higher than that of subirrigated plants only when the concentration of the irrigation solution was -0.072 MPa (Figure 3A–E). Total Mg accumulation in the plants was not affected by the concentration of the nutrient solution in drip-irrigated plants (Figure 3E); however, in subirrigated plants, the accumulation of Mg was highest when plants were fed with −0.058 and −0.043 MPa solutions.

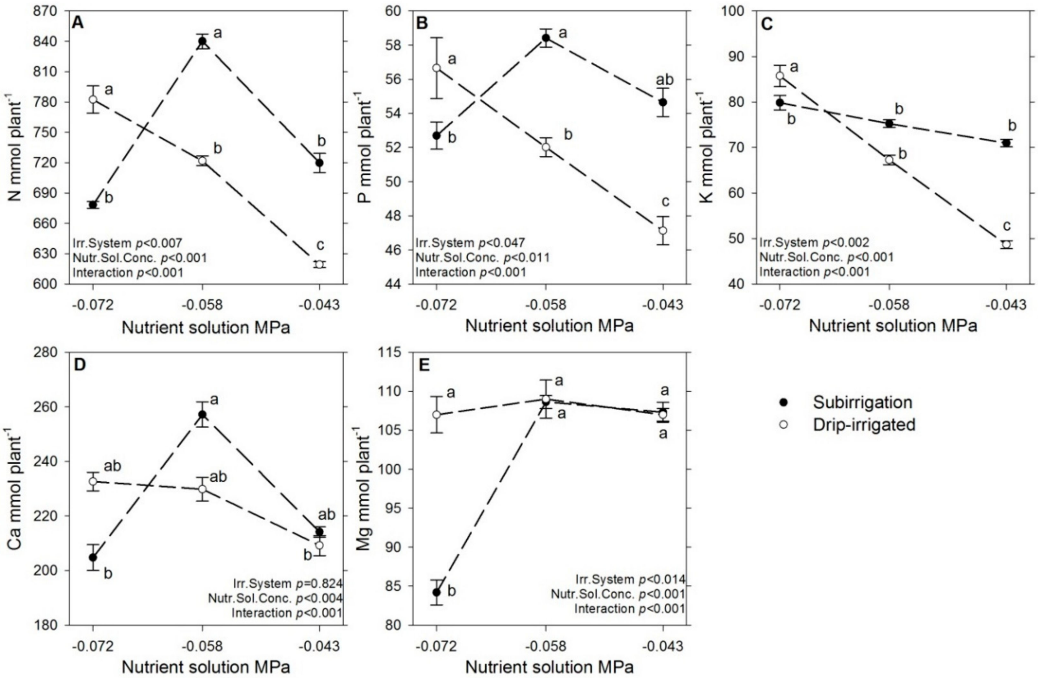

Figure 3. (**A**–**E**) Effect of the irrigation system and the concentration of the nutrient solution on total tomato (*Solanum lycopersicum* L.) plants content of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg). ANOVA significance for both factors, irrigation system (Irr. System) and nutrient solution concentration (Nutr. Sol. Conc.), and the interaction is shown. Means with the same lower-case letter indicate non-significant differences according to Tukey's multiple comparison test. Bars represent the standard error of the mean (n = 4).

3.3. Nutrient Concentration

3.3.1. Nitrogen

In drip-irrigated plants, shoot N (Figure 4A) exhibited similar trends as N accumulation in the entire plant (Figure 3A), as it increased as the solution concentration increased. In contrast to drip-irrigated plants, in subirrigated plants, the highest total concentration was achieved with solutions of -0.058 MPa (Figure 4A). Regardless of the irrigation system, root (Figure 4B) and fruit (Figure 4C) N was higher when the solution concentration was low.

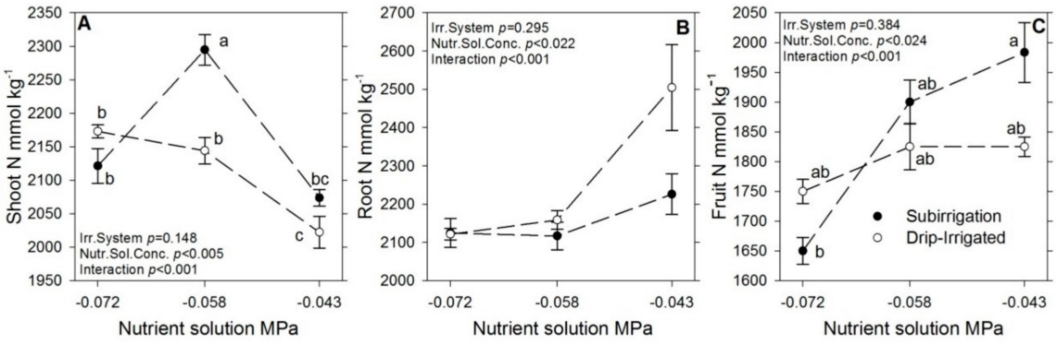

Figure 4. (**A**–**C**) Effect of the irrigation system and the concentration of the nutrient solution on nitrogen concentration in tomato (*Solanum lycopersicum* L.) plants. ANOVA significance for both factors, irrigation system (Irr. System) and nutrient solution concentration (Nutr. Sol. Conc.), and the interaction is shown. Means with the same lower-case letter indicate non-significant differences according to Tukey's multiple comparison test. Bars represent the standard error of the mean (n = 4).

3.3.2. Phosphorus

Shoot P was higher in subirrigated plants when compared to drip-irrigated plants (Figure 5A), while in the roots (Figure 5B) and fruits (Figure 5C), P was higher in drip-irrigated plants. When compared to the fruits, P in the shoot and roots exhibited a contrasting response, in that, in the vegetative plant parts there was a higher concentration in both subirrigated and drip-irrigated plants irrigated with solutions of higher concentration, while P in the fruits increased in plants irrigated with solutions of reduced nutrient concentration.

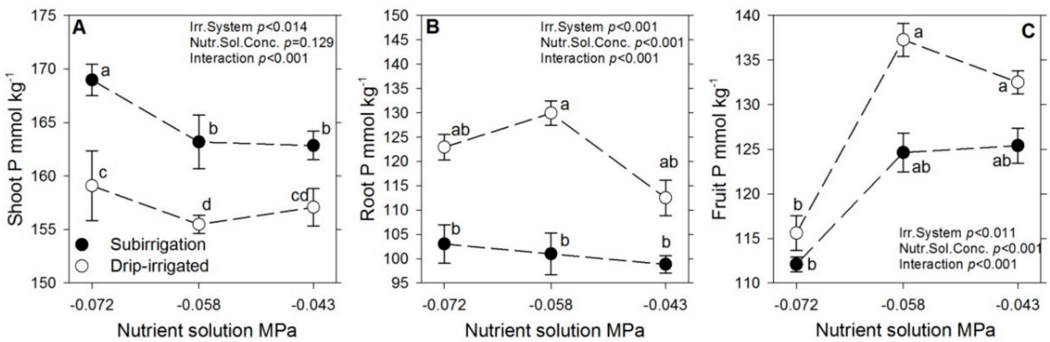

Figure 5. (**A**–**C**) Effect of the irrigation system and the concentration of the nutrient solution on phosphorus concentration in tomato (*Solanum lycopersicum* L.) plants. ANOVA significance for both factors, irrigation system (Irr. System) and nutrient solution concentration (Nutr. Sol. Conc.), and the interaction is shown. Means with the same lower-case letter indicate non-significant differences according to Tukey's multiple comparison test. Bars represent the standard error of the mean (n = 4).

3.3.3. Potassium

Regardless of the irrigation system, shoot (Figure 6A) and root K (Figure 6B) exhibited an increasing trend in plants irrigated with solutions of increasing nutrient concentration. Fruit K was highest when drip-irrigated plants were irrigated with solutions of −0.058 and −0.072 MPa, while in subirrigated plants solutions of −0.043 and −0.058 MPa resulted in the highest fruit K (Figure 6C).

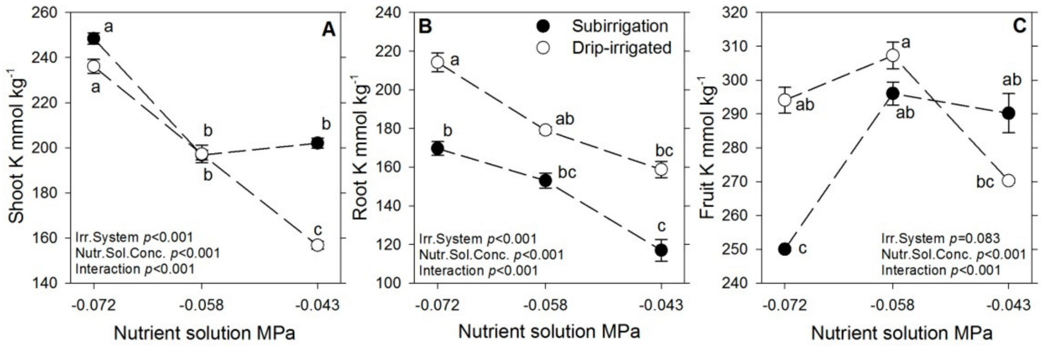

Figure 6. (**A**–**C**) Effect of the irrigation system and the concentration of the nutrient solution on potassium concentration in tomato (*Solanum lycopersicum* L.) plants. ANOVA significance for both factors, irrigation system (Irr. System) and nutrient solution concentration (Nutr. Sol. Conc.), and the interaction is shown. Means with the same lower-case letter indicate non-significant differences according to Tukey's multiple comparison test. Bars represent the standard error of the mean (n = 4).

3.3.4. Calcium

Increased shoot Ca occurred in plants irrigated with nutrient solutions of -0.058 MPa in subirrigated plants, while in drip-irrigated plants shoot Ca decreased with increasing nutrient solution concentration (Figure 7A). Root Ca concentration was not affected by nutrient solution concentration in subirrigated plants, while in drip-irrigated plants root Ca increased with increasing nutrient solution concentration. Root Ca was higher in drip-irrigated plants when compared to subirrigated plants, except at the lowest nutrient solution concentration (−0.043 MPa) (Figure 7B). In both irrigation systems, fruit Ca decreased with increasing nutrient solution concentration. Fruit Ca concentration was higher in drip-irrigated plants when compared to subirrigated plants, except at the lowest nutrient solution concentration.

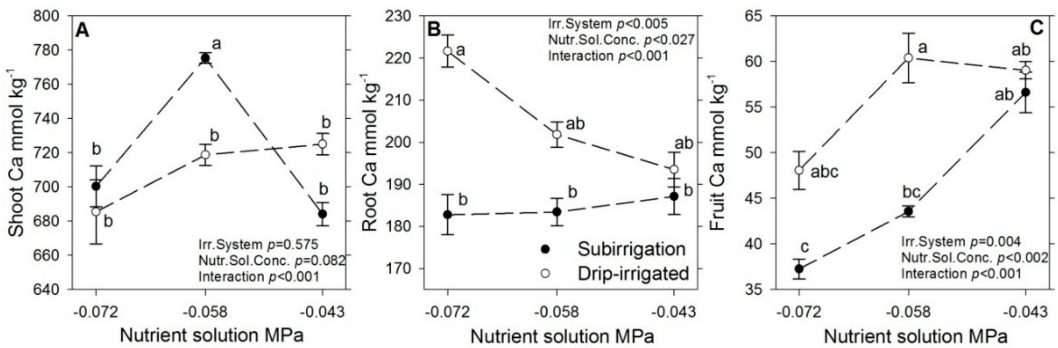

Figure 7. (**A**–**C**) Effect of the irrigation system and the concentration of the nutrient solution on calcium concentration in tomato (*Solanum lycopersicum* L.) plants. ANOVA significance for both factors, irrigation system (Irr. System) and nutrient solution concentration (Nutr. Sol. Conc.), and the interaction is shown. Means with the same lower-case letter indicate non-significant differences according to Tukey's multiple comparison test. Bars represent the standard error of the mean (n = 4).

3.3.5. Magnesium

Shoot Mg (Figure 8A) was higher in drip-irrigated plants when compared to subirrigated plants. Decreasing concentrations of the nutrient solution were associated with increased shoot Mg. A marginal effect of solution concentration on root Mg was observed in subirrigated plants, while in drip-irrigated plants Mg was highest when irrigated with solutions of -0.058 MPa (Figure 8B). Fruit Mg increased with decreasing nutrient solution concentration (Figure 8C). Fruit Mg was higher in drip-irrigated plants, regardless of nutrient solution concentration.

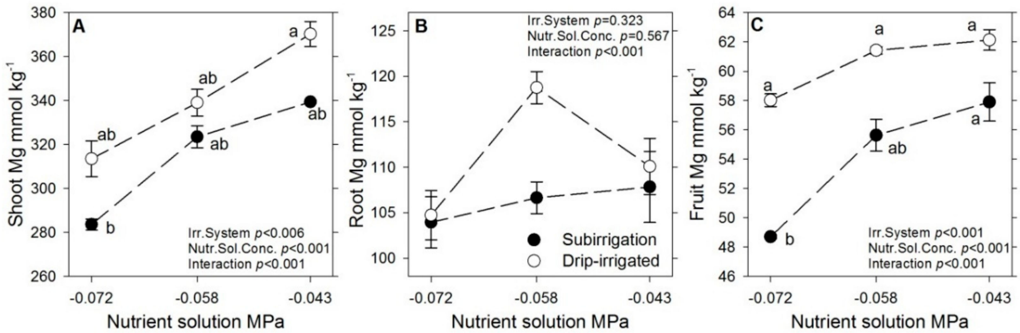

Figure 8. (**A**–**C**) Effect of the irrigation system and the concentration of the nutrient solution on magnesium concentration in tomato (*Solanum lycopersicum* L.) plants. ANOVA significance for both factors, irrigation system (Irr. System) and nutrient solution concentration (Nutr. Sol. Conc.), and the interaction is shown. Means with the same lower-case letter indicate non-significant differences according to Tukey's multiple comparison test. Bars represent the standard error of the mean (n = 4).

4. Discussion

4.1. Vegetative Growth

Compared to drip-irrigated plants, subirrigated tomatoes increased plant biomass when nutrient solution concentrations were moderately reduced (−0.058 MPa). These responses have been ascribed to a more uniform watering [31], lower water stress, and to an improved nutrition status due to a higher nutrient retention in the growing medium [32] in subirrigated when compared to drip-irrigated plants. The optimum growth of subirrigated plants irrigated with solutions of −0.058 MPa was associated with high total N, P, Ca, and Mg plant accumulation. Decreased growth observed in plants subirrigated with the lowest nutrient concentration solutions may be due to both the reduced supply of nutrients and reduced nutrient accumulation in the growing medium, which resulted in the nutrient demands of the tomato plants not being met. These results are in agreement with reports by van Iersel [22] in poinsettia (*Euphorbia pulcherrima* Willd. ex Klotz).

Studies performed with subirrigation of vegetable species show contrasting reports. For example, García-Santiago et al. [33] reported favorable results as subirrigated bell pepper (*Capsicum annuum* L.) exhibited higher dry weight of vegetative parts when compared to drip-irrigated plants. However, Rouphael and Colla [12,19] in zucchini squash, Bouchaaba et al. [21] in green beans (*Phaseolus vulgaris* L.), Martinetti et al. [15] in eggplant, and Montesano et al. [34] in cherry tomato, reported decreased biomass in subirrigated plants when compared to drip-irrigated plants. Dry weight of subirrigated zucchini squash was reported to decrease when the concentration decreased by 50%, suggesting that the plant nutrient demand was not met under low nutrient concentrations [19]. The contrasting responses to subirrigation may be due to the tolerance of each species to the high EC under subirrigation systems and specific nutrient demands [35].

4.2. Fruit Yield

Fruit yield increased with decreasing nutrient solution concentration in subirrigated plants. In contrast, in drip-irrigated plants, fruit yield increased with increasing nutrient concentration (Figure 1). Except at the highest nutrient solution concentration, greatest yields occurred in subirrigated plants.

The higher yields in subirrigated plants irrigated with solutions of reduced concentration may be associated with the low EC of the growing medium. In the present study, the top layer of the root ball reached EC as high as 19.5 dS m^{-1} when subirrigated with high nutrient solution concentration (data not shown), which may have resulted in plant osmotic stress. However, root ball EC was 8.0 to 9.0 dS m^{-1} when nutrient solution concentration was reduced (data not shown). Fruit yield reduction with solutions of high nutrient concentration may be because of salts buildup in the growing medium, mainly in the top layer, which causes alterations in plants physiology [12,20,22,36–38], although other authors have indicated that the higher salts concentration in the top layer of the growing medium in subirrigated plants did not affect plant growth as roots tend to develop in the bottom layer of the rootball [16,20,34,36–38].

Our results are in contrast to those reported by Rouphael and Colla [19] which indicated that yield of subirrigated zucchini squash showed 58% decrease when the concentration of the nutrient solution decreased by 50%, suggesting that plant nutrient demands were not met. Other reports with zucchini squash [12,27], tomato [16], eggplant [15] and green beans [21] showed deleterious effects on yield in subirrigated plants when compared to drip-irrigated plants.

Yield fluctuated throughout the study but exhibited similar trends between irrigation systems. During the first month of harvest, yield was higher in plants subirrigated with nutrient solutions at the highest concentration. However, as the study progressed, yields were higher in plants irrigated with nutrient solutions at the lowest concentration. In drip-irrigated plants, yield was usually higher in plants irrigated with higher nutrient concentrations during the entire study. These results indicate that in order to avoid yield reduction over time in subirrigated tomato plants, the concentration of the nutrient solution must be lower than that of drip-irrigated plants.

4.3. Nutrient Status

Higher yield of subirrigated plants at low nutrient solution concentrations was related with increased fruit N and Ca. The fact that increased yields occurred even with low shoot N and Ca concentrations suggests that there was an augmented allocation of N and Ca towards the fruit despite the reduced total plant content. Increased P and K allocations to the fruit were also observed. These results are in contradiction to reports in subirrigated bell pepper plants where no variations in the allocation of N and Ca among the plant parts were detected, although there was an increased allocation of P and K to the fruit when flooding depth and duration was modified [33]. The reduced uptake of N and Ca at increased solution concentrations may be due to the growth limitation caused by salinity stress resulting from salts build up in the growing medium.

In drip-irrigated plants, shoot dry weight and yield were directly associated with N and K, but fruit yield was higher when fruit N, P, Ca, and Mg were low, probably due to a dilution effect as suggested by the increased total plant content of these nutrients in plants irrigated with solutions of the highest nutrient concentration. In contrast, shoot dry weight in drip-irrigated plants was indirectly associated with Mg, which may be due to a dilution effect associated with growth promotion, as suggested by the unaffected total nutrient content regardless of nutrient solution concentration.

The higher accumulation of N, P, K and Ca in subirrigated plants demonstrates that subirrigation allows for increased nutrient use efficiency, particularly when using nutrient solutions at low concentrations. Similar results have been reported in vinca (*Catharanthus roseus* L.) as subirrigated plants exhibited increased N, P, K and Mg content [13], and in bell pepper with increased N, P, Mg and S [33].

In contrast to our results, Rouphael and Colla [12] demonstrated that, in zucchini squash, subirrigation was associated with reduced N, P, K, Ca, and Mg content when compared to surface-irrigated plants. In our study, we detected that subirrigation may be associated with reduced N, P, K, Ca and Mg accumulation only when tomato plants were irrigated with a nutrient solution at the highest concentration, probably due to the increased EC associated with salts buildup in the growing medium. This is in agreement with reports indicating that increased salinity is associated with reduced nutrient uptake [39], which may be caused by the reduced water uptake under high salinity, as reported in tomato plants [40].

4.4. Water Use Efficiency

In the present study, subirrigation with optimum nutrient solution concentration at -0.043 MPa markedly increased water use efficiency, as demonstrated by the fact that 300 to 460 g of fruit per liter of water were produced by subirrigated plants, compared to ~50 g L^{-1} in drip-irrigated plants. Water use efficiency is reportedly higher in subirrigated plants as this system allows for the full recovery of the solution not retained by the growing medium [34,41–43]. In drip irrigation, apart from restoring the evapotranspirated water by saturating the growing medium, a 20 to 35% leaching fraction has to be provided in order to avoid salt accumulation [44–46].

5. Conclusions

Our results indicate that subirrigation is a feasible system for soilless-cultivated tomato provided the nutrient solution concentration is reduced to 60% of the original concentration (-0.043 MPa), with no negative effects on fruit yield. Subirrigation of tomato resulted in increased water use efficiency and increased mineral nutrient accumulation in plant tissues. Thus, subirrigation systems optimize water and nutrient use.

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