Article

Evaluation of nutrient solution recirculation methods for tomato production in short cycles

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Abstract

Tomato (*Solanum lycopersicum* L.) is the most grown vegetable in greenhouse and hydroponics. For easy handling, open hydroponic systems (without recirculation of the nutrient solution) with substrate are the most commonly used in the world. Closed systems (with recirculation) save water and fertilizers, but their technical management is difficult, because over time, the ions less consumed by the plant accumulate, which, when recirculated, cause nutritional imbalances and increases in the EC to levels that affect growth and yield, in addition to the high risk of spreading diseases, especially with cultivation cycles as long as conventionally the tomato is managed. The objective was to compare three methods of recirculation of nutrient solution against an open system, in the agronomic behavior of tomato managed in high population density with cuts to harvest only three clusters per plant. The design was randomly complete blocks with four treatments and seven repetitions, with experimental unit of 20 m^2. Morphological variables, dry weight and yield were evaluated. Except for height and diameter of stem, no variable showed statistical difference between treatments. It is concluded that, with the management of the tomatoes plants to harvest three clusters, in a cycle as short as 110 days of transplantation at the end of harvest, it is feasible to use any nutrient solution recirculation system without nutritional imbalances, so that comparing these methods with an open system does not affect the growth or yield of the plants, saving water and fertilizers.

Keywords: closed hydroponic systems, greenhouse, nutritive solution.

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Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most managed vegetables under greenhouse conditions (SIAP, 2018). Due to the intensive management in greenhouse conditions, the progressive establishment of pathogens in the soil after some growing cycles is favored (Takahashi, 1984). The compaction, salt accumulation, nutritional imbalances and weed proliferation are other factors that negatively affect yield (Liang *et al*., 2006).

An alternative to solve these problems has been hydroponics or soilless cultivation, where plants grow in a nutrient solution, with or without a substrate as support medium (Urrestarazu, 2015), allowing to develop the radical system of plants in complete soil independence. In greenhouse conditions hydroponics is gaining ground for soil production because greater efficiency and control of irrigation and mineral nutrition is achieved, as well as by the initial absence of pests, diseases and weeds and because sterilization of substrates is easier (Alarcón, 2006; Raviv and Lieth, 2008).

With the greenhouse, control of plant requirements for climate factors is achieved, while hydroponic systems are designed with the aim of rooting the most suitable environmental conditions for optimal operation. The combination of the two technologies represents the most advanced commercial agriculture currently available worldwide (Sánchez and Moreno, 2017).

In hydroponic systems based on the use of inert substrates, so that tomato plants grow without nutritional limitations, the nutrient solution must have a pH between 5.5 to 6.5, an electrical conductivity (EC) between 1.5 and 3 dS m^{-1} and mineral nutrition must be only dissociated in the appropriate proportions and concentrations according to their absorption rates and under conditions that avoid precipitates and antagonisms (Adams, 2004).

The plant modifies the consumption of nutrients based on its growth and development phases, climatic conditions, and characteristics of the nutrient solution such as CE, pH, temperature and dissolved oxygen (Sonneveld and Voogt, 2009; Velazco *et al*., 2012; Urrestarazu, 2015). An CE greater than 5 dS m^{-1} in the rhizosphere can negatively affect the absorption of water and nutrients, leading to decreases in final yield (Bustomi *et al*., 2014; Santos and Torres, 2018).

Highly soluble fertilizers are used in the preparation of hydroponic nutrient solutions that generally have a high cost (Huang, 2009), which has increased considerably in recent years. In addition, irrigation water is also an increasingly limited natural resource, so its use in hydroponic systems must be very efficient (Salazar *et al*., 2014).

This nutrient solution is normally applied by high frequency drip irrigation, allowing drainage or over-irrigation that helps to keep stable the concentration of nutrients in the rhizosphere (Sánchez *et al*., 2014). The over-irrigation of nutrient solution that drains, is usually no longer used by the plant, and can be lost in the soil or it can be recovered through a recirculation system to incorporate it back into the crop. When the drained solution is not reused and infiltration is allowed at the site or is driven out of the greenhouse, the hydroponic system is known as open; on the contrary, if collected for reuse in cultivation, after sterilization and adjustment of pH, CE and concentration of nutrition, it is called a closed system (Alarcón, 2006).

Open systems, for their ease of operation, represent the most widely used hydroponic technique in Mexico and around the world (Sandoval *et al*., 2012; Salazar *et al*., 2014), with the consequent loss of water and fertilizers that, in large installations, can adversely affect the water table by the accumulation of high amounts of salts and thus pollute rivers, lakes and seas (Alarcón, 2006). If the nutrient solution that drains is reused (closed hydroponic systems), in addition to having an economic saving of water and fertilizers, the environmental damage is much less (Nakano *et al.*, 2010).

The main problem with closed systems is the technical difficulty of their handling since, over time, an imbalance of the drained nutrient solution can occur due to the accumulation of ions less consumed by theplant (SO_4^{2-}, Ca^{2+} and Mg^{2+}) more dissolved salts present in irrigation water such as Na^+ and Cl^-, which when recirculated results in an increasing imbalance of nutrients and an increase of the CE to levels that affect growth and yield (Tunali *et al*., 2009; Van Os, 2009; Zhang *et al*., 2016).

In addition, with closed systems there is also a high risk of disease dispersal especially with growing cycles as long as the tomato is conventionally handled (Sánchez *et al*., 2014). The longer the growing cycle, the greater the possibility of root diseases and nutrient solution imbalances, which can eventually affect yield compared to systems without recirculation; therefore, lower yields are often reported in closed systems compared to those opened in crops that are managed in long cycles such as tomato or pepper chili, in which for several months vegetative growth stages coexist with reproductive (Savvas *et al*., 2009; Nakano *et al*., 2010).

So that closed hydroponic systems can be implemented with a greater probability of success and take advantage of their advantages, it is advisable to look for ways of handling that are simple for the producer, but that do not adversely affect yield or quality. One strategy that could be tested to reduce the risks of alterations in the CE, nutritional imbalances or dispersion of diseases with closed hydroponic systems, would be to produce tomato with very short growing cycles (less than four months of transplantation at the end of harvest) such as that developed at the Chapingo Autonomous University as an alternative to the conventional system and which has been validated on a commercial scale by several producers (Sánchez *et al*., 2012).

It is thought that this system could be adopted with advantages for closed hydroponic systems, but specific studies are needed for its particular management. Therefore, this study was carried out with the aim of comparing different methods of recirculation of the nutrient solution against an open system, in the agronomic behavior of a tomato culture system managed to three clusters per plant to shorten the transplant period to less than four months at the end of harvest. In particular, the yield obtained with these methods was compared and the savings in water and nutrients that can be achieved with each method of recirculation of the nutrient solution with respect to the open system (without recirculation) were determined.

Materials and methods

The experiment was conducted from July to December 2018 in a greenhouse of 1 000 m^2 of the Postgraduate of Horticulture of the Chapingo Autonomous University (UACH), in Texcoco, State of Mexico, located at 19° 29’ 35” of north latitude and 98° 52’ 19” of west longitude and a height of 2 250 m. The tomato hybrid Bullseye® from the Seminis Company was used, which is saladette type and semi-determined growth habit.

The seeds were sown in a mixture of substrate (peat, perlite and red tezontle sand at a ratio of 25, 25 and 50%, respectively) contained in polystyrene trays of 60 cavities with a volume of 250 cm^3 per cavity and a separation of 5 cm between center and center of cavities.

From 5 days after planting (dds) and up to transplantation (43 dds) two daily irrigations were applied with nutrient solution containing the following concentrations of nutriments (mg/litre): nitrogen (N)= 100, phosphorus (P)= 25, potassium (K)= 125, calcium (Ca)= 125, magnesium (Mg)= 20, sulfur (S)= 75, iron (Fe)= 2, manganese (Mn)= 1, boron (B)= 0.5, copper (Cu)= 0.2 and zinc (Zn)= 0.2, which resulted in 1.5 dS m^{-1} EC; the pH was adjusted to 6.5.

The transplant was carried out in culture beds filled with red tezontle 1-3 mm in diameter, 1 m wide by 20 m long and 0.25 m deep, with partition walls and 50 cm wide cemented corridors between beds, bottom lined with 600-gauge black polyethylene, along each bed was placed a PVC pipeline of 2” diameter, grooved at its lower base every 50 cm to allow the drained nutrient solution to be guided toward the end and to be collected.

The arrangement of the plants was three rows per bed, at a separation of 35 cm between rows and 25 cm between plants, which gave a population density of 12 plants m^{-2} useful (8 plants m^{-2} greenhouse). For the first 15 days after transplantation, the same nutrient solution was applied as in the seedbed for all treatments. From then on, the concentration of nutrients in the applied nutrient solution was double (100% nutrient solution). The treatments evaluated were the following.

Treatment 1

Recirculation without chemical analysis of the draining solution. In a 5 000-liter water tank, the nutrient solution was prepared at 100% concentration. It was applied in drip irrigation, providing 20% drainage at each irrigation. Each time the vat was emptied, 4 000 L were prepared with a new nutrient solution at 100% concentration plus 1 000 L of the drained, collected and disinfected solution, without making corrections of pH, CE or any of its nutrients.

Treatment 2

With chemical analysis of the drained solution. In a vat of 5 000 liters capacity, starting from a nutritive solution at 100% concentration, it was applied in drip irrigation providing 20% drainage in each irrigation. Each time the vat was emptied, 4 000 L were prepared with a nutrient solution selectively adjusted by nutritional element (N, P, K, Ca, Mg and S) basedon a chemical analysis of the drainage that was done every 15 days, the remaining 1 000 L were contributed with the drained nutrient solution, collected and disinfected.

Treatment 3

With solution adjustment according to theoretical absorption. In a 5 000 L water tank, starting with a nutrient solution at 100% concentration, it was applied in drip irrigation, providing 20% drainage in each irrigation. Each time the vat was emptied, 4 000 L were prepared with a selectively adjusted nutrient solution considering an estimate of the absorption rates of tomato plants for each nutritional element (90% for N, P and K and 50% for Ca, Mg and S), compared to the initial nutrient solution (Adams, 2004; Velazco *et al*., 2012; Urrestarazu, 2015), the missing 1 000 L were supplemented with the drained, collected and disinfected solution.

Treatment 4

Witness, with open system. In a vat of 5 000 L capacity, the nutrient solution was prepared at 100% concentration and applied in drip irrigation, seeking 20% drainage and each time the tank was emptied, 100% of the initial volume (5 000 L) was prepared again with the complete nutrient solution.

The frequency of irrigation and the amount of nutrient solution to be applied daily seeking 20% drainage of nutrient solution in each treatment, it was achieved by applying between 3 and 6 irrigations daily depending on the climatic conditions and phenological stage of the crop.

The drainage of each treatment was collected and temporarily stored in 1 000 L vats before recirculating it, returning it every fifth to seventh day to the 5 000 L vat that corresponded to it according to the treatment. Oxygen water (50% hydrogen peroxide) was applied prior to recirculation to disinfect the drained solution at the rate of 50 ml of commercial product per 1 000 L vat (60 ppm H_2O_2 in solution).

For the chemical analysis of the drained solution required to define the concentration of salts in the preparation of the nutrient solution in treatment 2, a sample of 500 ml was taken from the 1 000 L tank collected from this treatment, placing it in amber bottles for laboratory analysis. To determine nitrogen the micro-kjeldahl method was used, for phosphorus the vanadato-molibdate method was used, reading in a GENESYS 10 UV spectrophotometer with an absorbance of 420 nm and potassium was determined by means of a JENWAY flame photometer (Chapman and Pratt, 1973).

To measure calcium and magnesium, a Phillips Pye Unicam SP 9 atomic absorption spectrophotometer was used and finally sulfur was determined by the turbidimetric method with barium chloride (Chesnin and Yien, 1951). The plants were blunted (removal of the terminal bud from the main stem) at 81 dds, leaving two leaves above the third formed inflorescence. All the lateral shoots were eliminated as they appeared, leading the crop to a single stem per plant, from where the fruits of the three clusters were harvested.

A random complete block design was used with four treatments and seven repetitions. The experimental unit was 20 m^2 (240 plants). The data obtained were subjected to variance analysis and average comparisons with the Tukey test (p= 0.05), using the SAS statistical program (2002) version 9.0. Morphological variables (plant height, stem diameter and foliar area), dry weight (total plant and fruit), and yield and its components (average weight and number of fruits) were evaluated.

The plant height (cm) was measured from the base of the stem to the height where the apex pruning was made. The stem diameter (mm) was measured with an electronic vernier ‘digimatic caliper’ (Mitutoyo, model CD-6 CS) at the height of between the first and second inflorescence. The foliar area per plant (cm^2) was determined with the support of a foliar area integrator brand LI- 3000A, Lincoln, Nebraska and with this data the foliar area index (m^2 leaf m^{-2} of covered area) was estimated.

The total dry weight per plant (g) was measured with the support of a balance and stove for drying at 60 °C to constant weight. The dry weight of fruit (g) was measured with a balance drying it at the same time as the rest of the plant, with this data and with the total dry weight per plant, the harvest index (dry weight of fruit/total dry weight of plant) was estimated. The number of fruits (fruits m^{-2}) was obtained from the sum of the commercial quality fruits obtained in each cut.

The total yield was calculated per unit of surface area (kg m^{-2}), adding the weight of the fruits in each of the cuts harvested in each m^2. The average fruit weight (g) was calculated by dividing the yield per unit surface (g m^{-2}) by the number of total fruits harvested. Morphological variables were measured at 102 dds and dry weight variables were measured at 143 dds. In addition, water and macronutrients expenditure were calculated and plant tissue analysis of the plants managed was performed in each of the tested treatments.

The water consumption (L m^{-2}) was determined by adding up the number of liters of nutrient solution applied during the transplant period at the end of the harvest, and the expenditure of macronutrients (g m^{-2}) was calculated based on the concentration (mg L^{-1}) of the nutrients with which the nutrient solution was prepared in each treatment and the amount (liters) applied throughout the crop cycle from transplant to end of harvest.

Since these determinations were made once the crop cycle had ended, comparisons between the different treatments were made only on the basis of the absolute values calculated, without statistical tests being applied. The analysis of plant tissue was also performed at 143 dds, for which three plants were taken per experimental unit in each of the repetitions. With the three plants a composite sample was made, which was dried in a stove at 70 °C.

With a WILEY mill model 4 of 110 VAC, the samples were ground and then stored in transparent glass flasks for later digestion. In a Kjeldahl flask was placed 0.5 g of ground sample, to which 4 ml of a mixture of sulphuric acid and perchloric acid was added in proportion 4:1 plus 1 ml of 30% oxygenated water, giving a black extract. The flask was then placed on a hot plate until the extract boiled and changed to light color.

Then it was allowed to cool for one hour, then it was made up to 50 ml with distilled water. From the solution obtained with this procedure, the determinations of nitrogen, phosphorus, potassium, calcium and magnesium were made (Alcántar and Sandoval, 1999). For sulfur, similar alternating digestion was carried out, but in this case nitric acid was used in the mixture instead of sulfuric acid in 2:1 ratio (Alcántar and Sandoval, 1999). The determination of each of the macronutrients was done with the same methodologies used for the drained nutrient solution mentioned above.

Results and discussion

Morphological variables

The variance analysis of this group of variables (data not shown) indicated that there was a highly significant difference for plant height and significant for stem diameter, but not for foliar area index. Mean comparisons (Table 1) show that the plant height in the treatment with 20% recirculation without chemical analysis of the drained solution (T1) was higher with respect to the other two recirculation treatments (T2 and T3) and of the witness (T4).

Table 1. Comparisons of means of morphological variables at 102 days after planting in tomato *cv* Bullseye with different methods of recirculation of the nutrient solution.

Recirculation treatment	Plant height (cm)	Stem diameter (mm)	Foliar area index (m^2 leaf m^{-2} covered area)
T1 (no analysis)	114.9 a	12.2 ab	5.15 a
T2 (with analysis)	104.1 b	13.8 a	5.33 a
T3 (according to theoretical absorption)	106 b	12.9 ab	4.99 a
T4 (witness, without recirculation)	98.3 b	11.4 b	4.56 a
DMS	8.2	2.3	1.23

Means with the same letter in each column are statistically equal (Tukey, p= 0.05). DMS= minimum significant difference.

There is no special explanation for the increased height growth of plants from simple drainage recirculation treatment (T1), possibly it is explained by the influence of differences in microclimatic factors that were presented in plants from the seedbed and that differentially affected their growth in height. For stem diameter, the recirculation treatment with prior analysis of the drains (T2) overcamed the witness without recirculation, with no differences between the other treatments. In foliar area index (IAF), all treatments were statistically equal, with an oscillation between 4.5 and 5.3.

These values are possibly high for optimal net photosynthesis, since according to Sánchez and Moreno (2017), the optimal IAF values for a greater accumulation of daily dry matter in tomato handled in greenhouse and high population density should be between 3 and 4. Values greater than 5 cause excessive shading between plants, which could be noticed in the crop, which affects the rate of net photosynthesis per plant and consequently the final yield (Taiz *et al*., 2014).

Dry weight variables, harvest and yield index and their components

Both the variance analysis (data not shown) and the mean comparison analysis (Table 2) indicate that, for the total dry plant weight variables, harvest index, number of fruits per plant, average fruit weight and yield, there were no significant differences between treatments.

Table 2. Comparisons of means of yield variables in tomato cv. Bullseye with different methods of recirculation of the nutrient solution.

Recirculation treatment	Total dry weight (g plant^{-1})	Number of fruits m^{-2}	Average weight fruit (g)	Yield (kg m^{-2})	Harvest index (fruit ps/ total ps)
T1 (no analysis)	140.4 a	100.5 a	110.4 a	11.13 a	0.47 a
T2 (with analysis)	132 a	107.9 a	118.1 a	12.71 a	0.45 a
T3 (according to theoretical absorption)	118.4 a	104.6 a	110.7 a	11.6 a	0.48 a
T4 (witness, without recirculation)	131 a	109.3 a	108.6 a	11.79 a	0.44 a
DMS	45.7	13.3	10.41	1.58	0.1

Means with the same letter in each column are statistically equal (Tukey, p= 0.05). DMS= minimum significant difference. Ps= dry weight.

The dry weight and harvest index results obtained suggest that, in tomato handled in a short cycle such as that established in this study, with any of the recirculation systems tested does not affect the growth of the plants or the distribution of the dry matter that is directed towards the fruits, compared to an open system, results that coincide with Sánchez *et al*. (2014), who, in evaluating different recirculation systems of the nutrient solution in tomato, also managed in a short cycle, found no difference between treatments for this variables.

Instead, Tunali *et al*. (2009); Massa *et al*. (2010) reported decreases in the growth of tomato plants when using a nutrient solution recirculation system, possibly because they drove the crop with conventional long-cycle management (Sánchez *et al*., 2012), where over time, there are significant imbalances in the drained nutrient solution (Tunali *et al*., 2009; Van Os, 2009).

The yield oscillated between 11.13 and 12.71 kg m^{-2} of greenhouse, over a period of 110 days of transplantation at the end of harvest, which gives the opportunity to obtain three growing cycles per year. Taking as an example the average yield of the three systems with recirculation (11.81 kg m^{2}), there would be an annual yield potential of at least 350 t ha^{-1}, which is similar or even slightly higher than that reported in companies with high technical performance under the long cycle system (Castellanos and Bourbon, 2009).

Surely the short period with which the harvest was finalized (less than four months from transplantation) allowed to escape the nutritional imbalances in the recirculating nutrient solution that occur over time (Tunali *et al*., 2009; Van Os, 2009; Sánchez *et al*., 2014), so there were no differences in yield between the closed systems and the open system studied. In other work on recirculation of the nutrient solution with tomato, where the growing cycle is much longer, significant decreases in yield have been reported with respect to open systems (Tunali *et al*., 2009; Van Os, 2009).

In addition, with the management of the crop with long cycles, recirculation promotes the appearance of diseases that gradually spread throughout the crop affecting yield and quality (Sánchez *et al*., 2014). In similar research with the high population density system and cut to the third cluster, yields of around 15 kg m^{-2} have been achieved in four months transplant cycle to harvest (Sánchez *et al*., 2012; Sánchez *et al*., 2014).

However, the yield obtained in this studio was relatively low, possibly due to the high index of foliar area formed (about 5), which caused shading between the plants and a higher rate of maintenance breathing, affecting the daily net photosynthesis and with it the yield (Sánchez and Moreno, 2017).

In any case, with the results obtained it can be noted that, any of the recirculation treatments of the nutrient solution evaluated, is able to be implemented in the tomato production system in short cycles, without affecting the yield, with advantages in saving water and fertilizers with respect to the witness treatment without recirculation as shown below, and that contamination of the water table would also be avoided as mentioned by Nakano *et al*. (2010).

Expenditure of water and fertilizers

Table 3 shows the amounts of water and nutrition provided per m^2 of greenhouse during the end-of-harvest transplant period. It is observed that the water expenditure was 437.6 L m^{-2} of greenhouse for each of the treatments with recirculation of nutrient solution, while for witness treatment without recirculation (T4), the expenditure was 547.2 L.

Table 3. Water expenditure (L) and quantity (g) of macronutrients applied per m^2 of greenhouse in tomato *cv* Bullseye during 110 days of transplantation at the end of harvest with different methods of recirculation of the nutrient solution.

Recirculation treatment	Water	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium	Sulfur
T1 (no analysis)	437.6	91.3	22.4	116	120.8	20.8	68
T2 (with analysis)	437.6	97.6	26.4	132.8	116	16	66.4
T3 (according to theoretical absorption)	437.6	100	24.8	127.2	88	16	48
T4 (witness, no recirculation)	547.6	108.8	27.2	138.4	145.8	25.6	81.6

This difference of 109 l m^{-2} was due to the fact that, in the first three treatments, the drained nutrient solution was recirculated, corresponding to approximately 20% of the total applied. Extrapolating these data to a greenhouse hectare and establishing three growing cycles per year, which is possible with the system of three clusters per managed plant, a water saving of approximately 3 300 m^3 per year would be obtained by recirculating the drained nutrient solution, which represents a considerable decrease in the use of this resource.

Benoit and Ceustermans (1995) cited by Gul (2011) mention that, for soilless crops, with 15 to 25% over-irrigation of nutrient solution, approximately 2 900 m^3 ha^{-1} $year^{-1}$ are lost, similar to what is observed in this study. Sánchez *et al*. (2014) reported savings of 32.6% in water by comparing a system with recirculation of nutrient solution compared to one without recirculation in the cultivation of tomato grown in beds filled with tezontle substrate.

It should be noted that the saving of water with the recirculation of the nutrient solution is of great agronomic importance, in particular for its implementation in areas where water is an increasingly scarce resource for crop production. Table 3 also it is noted that, based on the absolute values calculated, in the three methods of recirculation of the nutrient solution, the supply of nutrition was lower than the witness.

With the recirculation treatment of the nutrient solution without analysis (T1) less nitrogen, phosphorus and potassium were applied (17.5, 4.8 and 22.4 g m^{-2} greenhouse less than the witness, this is approximately 16% for each nutrient), while with the recirculation treatment according to the established theoretical absorption (T3), less calcium, magnesium and sulfur were provided (57, 9.6 and 33.6 g m^{-2} of greenhouse less than the witness, corresponding to 39, 37 and 41% for each nutriment, respectively). In T1 treatment, savings of up to 20%of all nutrients would be expected from the witness; however, the savings were only in the order of 16% because this treatment continued to apply the complete nutrient solution until one month after transplantation.

In the preparation of the nutritive solution in the T3 treatment for Ca, Mg and S, only 50% of what was applied in the complete solution was supplied; however, the savings were not of that magnitude because the recirculation of the nutritive solution in this treatment was also initiated one month after transplantation. In this regard Sánchez *et al*. (2014) in an experiment with recirculation of nutritive solution in tezontle beds in tomato crop, they exhibited macronutrient contributions of 59.3, 31, 135 and 93.3 g m^{-2} for nitrogen, phosphorus, potassium and calcium, respectively.

When extrapolating the data obtained to one ha of greenhouse and three growing cycles per year, the savings with the T1 treatment compared to the witness would be in the order of 525 kg of nitrogen, 144 kg of phosphorus and 672 kg of potassium, while with the T3 treatment the savings from the witness would be 1 734 kg of calcium, 288 kg of magnesium and 1 008 kg of sulfur, which from an economic point of view is very important for the producer.

Nutritional analysis

Analysis of variance (data not shown) and mean comparisons (Table 4) shows that between treatments there were no significant differences for any of the nutrients determined in plant tissue, suggesting that plants absorb nutrients in similar proportions regardless of the concentration to which the nutrient solution has been prepared. With these results it can also be noted that with the management of tomato in short cycles can achieve considerable savings in fertilizers with any of the proven recirculation methods, compared to the witness, without affecting the rate of nutrient absorption by plants (Adams, 2004).

In general, it is also observed (Table 4) that plants absorbed a greater amount of potassium, followed by nitrogen and calcium, and in a lower proportion phosphorus, magnesium and sulfur, results consistent with Quesada and Bertsch (2013); Vargas-Canales (2014) in similar studies with tomato. It should be noted that the percentages of macronutrients absorbed by the plants were within the sufficiency ranges reported by Sánchez (2004) for the cultivation of tomato, indicating that, with any of the management systems evaluated, the plants had available the elements necessary for their normal growth and development (Sánchez, 2004; Alcántar *et al*., 2016).

Table 4. Comparisons of means of the macronutrient content expressed in g and (%) in tomato plants cv. Bullseye at 101 days after transplantation, with different nutrient solution recirculation methods.

Recirculation treatment	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium	Sulfur
T1 (no analysis)	3.47 a (2.45)	0.93 a (0.66)	6.38 a (4.6)	3.2 a (2.27)	1.14 a (0.8)	0.94 a (0.65)
T2 (with analysis)	3.09 a (2.32)	0.87 a (0.66)	5.94 a (4.5)	2.91 a (2.2)	0.66 a (0.5)	0.68 a (0.51)
T3 (theoretical absorption)	2.74 a (2.3)	0.7 a (0.59)	5.13 a (4.17)	2.29 a (1.95)	0.61 a (0.52)	0.64 a (0.54)
T4 (witness, open system)	2.77 a (2.12)	0.92 a (0.71)	5.58 a (4.3)	3 a (2.27)	0.65 a (0.5)	0.46 a (0.35)
DMS	1.74	0.3	1.6	1.43	0.58	0.54

Means with the same letter in each column are statistically equal (Tukey, p= 0.05). DMS= minimum significant difference.

Conclusions

With the management of tomato plants in high population density and cut to harvest only three clusters, in a production cycle as short as 110 days from transplanting to the end-of-harvest, it becomes feasible to recirculate 20% of the nutritive solution with or without an analysis of the same or considering an analysis of the same or considering an absorption rates of the plants of 90% for N, P and K and 50% for Ca, Mg and S, with respect to the initial nutrient solution, without nutritional imbalances, nor proliferation of root diseases, so that when comparing these methods with an open system, the growth or yield of the plants is not affected, saving water and fertilizers and making the production process more sustainable.

Cited literature

Adams, P. 2004. Aspectos de la nutrición mineral en cultivos sin suelo en relación al suelo. *In*: tratado de cultivo sin suelo. (Ed.). Urrestarazu, G. M. Ediciones Mundi-Prensa. Madrid, España. 81-111 pp.

Alarcón, V. A. 2006. Proyectos en cultivo sin suelo ¿Cómo empezar? *In*: cultivos sin suelo. Alarcón, V. A. (Ed.). Compendios de horticultura 17. Ediciones de Horticultura, SL. Reus. España. 11-21 pp.

Alcántar, G. G. y Sandoval, V. M. 1999. Manual de análisis químico de tejido vegetal guía de muestreo, preparación, análisis e interpretación. Sociedad Mexicana de la Ciencia del Suelo, AC. Chapingo, Estado de México. Publicación Especial 10. 156 p.

Alcántar, G. G.; Trejo-Téllez, L. I.; Fernández, P. L. y Rodríguez, M. M. N. 2016. Elementos esenciales. *In*: nutrición de cultivos. Alcántar, G. G.; Trejo-Téllez, L. I. y Gómez, M. F. C. (Ed). Editorial BBA. Texcoco, Estado de México. 21-55 pp.

Bustomi, R. R. A.; Masateru, S.; Diding, S. and Ahmad, T. 2014. The effect of EC levels of nutrient solution on the growth, yield, and quality of tomatoes (*Solanum lycopersicum*) under the hydroponic system. J. Agric. Eng. and Biotech. 2(1):7-12.

Chapman, H. D. y Pratt, P. E. 1973. Métodos de análisis de suelos, plantas y agua. Traducido al español por Contin, A. (Ed.). Trillas. México, DF. 195 p.

Chesnin, L. and Yien, C. H. 1951. Turbidimetric determination of available sulphur. Proceedings of Soil Science Society of America. 149-151 pp.

Gul, A.; Tuzel, Y.; Tuzel, I. H.; Irget, M. E.; Kidoglu, F. and Tepecik, M. 2011. Effects of nutrition and irrigation on sweet pepper production in volcanic tuff. Span. J. Agric. Res. 9(1):221-229.

Huang, W. Y. 2009. Factors contributing to the recent increase in U.S. fertilizer prices, 2002-08. Agricultural resources situation and outlook number AR-33. U.S. Department of Agriculture, Economic Research Service, Washington, DC. 21 p.

Liang, W.; Jiang, Y. and Zhang, Y. 2006. Accumulation of soil soluble salt in vegetable greenhouses under heavy application of fertilizers. Agric. J. 1(3):123-127.

Massa, D.; Incrocci, L.; Maggini, R.; Carmassi, G.; Campiotti, C. A. and Pardossi, A. 2010. Strategies to decrease water drainage and nitrate emission from solilless culture of greenhouse tomato. Agric. Water Manag. 97(7):971-980.

Nakano, Y.; Sasaki, H.; Nakano, A.; Suzuki, K. and Takaichi, M. 2010. Growth and yield of tomato plants as influenced by nutrient application rates with quantitative control in closed rockwool cultivation. J. Japan. Soc. Hort. Sc. 79(1):47-55.

Quesada-Roldán, G. y Bertsch-Hernández, F. 2013. Obtención de la curva de extracción nutrimental del híbrido de tomate FB-17. Terra Latinoam. 31(1)1-7.

Raviv, M. and Lieth, H. 2008. Significance of soilless culture in agriculture. *In*: soilless culture. Theory and practice. Raviv, M. and Lieth, H. (Eds.). Elsevier. Amsterdam, the Netherlands. 1-11 pp.

Salazar, M. R.; Rojano, A. A. y López, C. I. L. 2014. La eficiencia en el uso del agua en la agricultura controlada. Tecnología y Ciencias del Agua. 5(2):177-183.

Sánchez, C. F. y Moreno, P. E. C. 2017. Diseño agronómico y manejo de invernaderos. Universidad Autónoma Chapingo (UACH). Chapingo, Texcoco, Estado de México. 405 p.

Sánchez, C. F.; Moreno, P. E. C.; Pineda, P. J.; Osuna, J. M.; Rodríguez, P. J. E. y Osuna, E. T. 2014. Producción hidropónica de jitomate (*Solanum lycopersicum* L.) con y sin recirculación de la solución nutritiva. Agrociencia. 48(2):185-197.

Sánchez, P. A. 2004. Análisis y diagnóstico nutricional en los cultivos sin suelo. *In*: tratado de cultivo sin suelo. Urrestarazu, G. M. (Ed). 3ª. Ediciones Mundi-Prensa, Madrid, España. 49-79 pp.

Sánchez-Del, C. F.; Moreno, P. E. C. and Contreras, M. E. 2012. Development of alternative comercial soilless production systems I. Tomato. Acta Hortic. 947:179-187.

Sandoval, V. M., Sánchez, G. P. y Alcántar, G. G. 2012. Principios de la hidroponía y del fertirriego. *In*: nutrición de cultivos. Alcántar, G. G. y Trejo-Téllez, L. I. (Ed.). Colegio de Postgraduados. Campus Montecillo, Texcoco, Estado de México. 373-438 pp.

Santos, B. M. and Torres-Quezada, E. A. 2018. Irrigation and fertilization. *In*: tomatoes. 2nd Edition, (Ed.). Heuvelink, E. CAB International, Wallingford, UK. 180-206 pp.

SAS. Institute. 2002. Statistical Analysis System. SAS/STAT 9.1 user´s guide. Cary, N. C. USA.

Savvas, D.; Sigrimis, N.; Chatzieustratiou, E. and Paschalidis, C. 2009. Impact of a progressive Na and Cl accumulation in the root zone on pepper grown in a closed-cycle hydroponic system. Acta Hort. 807:451-456.

SIAP. 2018. Servicio de Información Agroalimentaria y Pesquera. Atlas Agroalimentario. SAGARPA. Ciudad de México, México.

Sonneveled, C. and Voogt, W. 2009. Substrates: chemical characteristics and preparation. *In*: plant nutrition of greenhouse crops. Sonneveld, C. and Vogt, W. (Eds.). Springer. 227-252 pp.

Taiz, L.; Zeiger, E.; Ian, M. and Morphy, A. 2014. Plant physiology and development. 6 (Ed.). Sinauer associates, Inc. Publisher. Suderland, Massachusetts, USA. 761 p.

Takahashi, K. 1984. Injury by continuous cropping in vegetables: various problems in the cultivation using grafted plants. Yasaishikenjo Kenkyu Shiryo. 18:87-89.

Tunali, U.; Tüzel, I. H.; Tüzel, Y. and Öztekin, G. B. 2009. Effects of salinity on tomato in a closed system. Acta Hort. 807:457-462.

Urrestarazu, G. M. 2015. Manual práctico del cultivo sin suelo e hidroponía. (Ed.). Mundi-Prensa. Madrid, España. 267 p.

Van-Os, E. 2009. Comparison of some chemical and non-chemical treatments to disinfect a recirculating nutrient solution. Acta Hort. 843:229-234.

Vargas-Canales, J. M.; Castillo-González, A. M.; Pineda-Pineda, J.; Ramírez-Arias, J. A. y Avitia-García, E. 2014. Extracción nutrimental de jitomate (*Solanum lycopersicum* L.) en mezclas de tezontle con aserrín nuevo y reciclado. Rev. Chapingo Ser. Hortic. 20(1):71-88.

Velasco, H. E.; Nieto, Á. R. y Navarro, L. E. R. 2012. Cultivo del tomate en hidroponía e invernadero. Tercera edición, Primera reimpresión. Universidad Autónoma Chapingo (UACH). Chapingo, Estado de México. 126 p.

Zhang, P.; Senge, M. and Dai, Y. 2016. Effects of salinity stress on growth, yield, fruit quality and water use efficiency of tomato under hydroponics system. Reviews in Agricultural Science. 4:46-55.