

Nutrient and inorganic solute (Na⁺ and Cl⁻) content in green onion plants under hydroponic cultivation using brackish water

Acúmulo de nutrientes e solutos inorgânicos (Na⁺ e Cl⁻) em cebolinha verde sob cultivo hidropônico com água salobra

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ABSTRACT

Cultivation using brackish waters can result in nutritional and metabolic imbalances in several plant species, consequently reducing the production of dry matter (DM) and accumulation of toxic ions (Na⁺ and/or Cl⁻) in plants. We evaluated the DM production, and nutrient and inorganic solute (Na⁺ and Cl⁻) content in green onion plants (cv. Todo Ano Evergreen - Nebuka) under different levels of nutrient solution salinity in combination with circulation frequencies of this solution. Two experiments were conducted in a hydroponic system, using a completely randomized design, in a 6 × 2 factorial scheme, with five replicates: six levels of nutrient solution salinity (1.5, 3.0, 4.5, 6.0, 7.5, and 9.0 dS m⁻¹) and two solution circulation frequencies (twice and thrice a day). In Experiment I, the evapotranspired depth was replaced using brackish water that was used to prepare each of the salinity levels (used exclusively), whereas in Experiment II, brackish water was used only to prepare each of the salinity levels and public water was used (electrical conductivity [ECw] = 0.12 dS m⁻¹) for replacement in all treatments. The increase in the nutrient solution salinity reduced the production of DM and accumulation of nutrients; the reductions were more pronounced when brackish waters were used exclusively (Experiment I). However, the circulation of solutions thrice a day resulted in the harmful effects of the salinity effect. Replacing the evapotranspired blade with water supply (Experiment II) mitigated the deleterious effects of salinity. Moreover, three circulations of the nutrient solution daily resulted in lower accumulation of inorganic Na⁺ and Cl⁻ solutes and increased accumulation of nutrients N, P, K⁺, Ca²⁺, Mg²⁺ and S in the culture.

Index terms: *Allium fistulosum* L.; nutrient solution; salinity; mineral nutrition.

RESUMO

O cultivo em águas salobras pode causar desequilíbrios nutricionais e metabólicos em várias espécies vegetais, levando a reduções na produção de matéria seca e acúmulo de íons tóxicos (N⁺ e/ou Cl⁻) nas plantas. Desse modo, o objetivo deste estudo foi avaliar a produção de matéria seca, o teor de nutrientes e solutos inorgânicos (Na⁺ e Cl⁻) em plantas de cebolinha verde (cv. Todo Ano Evergreen - Nebuka) sob diferentes níveis de salinidade da solução nutritiva em interação com a circulação frequências destas soluções. Dois experimentos foram conduzidos em sistema hidropônico, em delineamento inteiramente casualizado, em esquema fatorial 6 × 2, com cinco repetições: seis níveis de salinidade da solução nutritiva (1,5; 3,0; 4,5; 6,0; 7,5 e 9,0 dS m⁻¹) e duas frequências de circulação da solução (duas e três vezes ao dia). No Experimento I, a reposição da lâmina evapotranspirada foi realizada usando a respectiva água salobra usada para preparar cada um dos níveis de salinidade empregados (uso exclusivo), enquanto no Experimento II, a água salobra foi usada apenas para preparar cada um dos níveis de salinidade e a água de abastecimento público (CEa = 0,12 dS m⁻¹) foi utilizada para a reposição em todos os tratamentos. O aumento da salinidade da solução nutritiva reduziu a produção de massa seca e o acúmulo de nutrientes, tendo as reduções sido mais pronunciadas quando as águas salobras foram usadas exclusivamente (Experimento I); porém, quando as soluções foram circuladas três vezes ao dia o efeito da salinidade foi menos deletério. A reposição da lâmina evapotranspirada com água de abastecimento (Experimento II) mitigou os efeitos deletérios da salinidade e, quando associada a frequência com três circulações da solução nutritiva ao dia, proporcionou um menor acúmulo dos solutos inorgânicos Na⁺ e Cl⁻ e incrementou os acúmulos dos nutrientes N, P, K⁺, Ca²⁺, Mg²⁺ e S pela cultura.

Termos para indexação: *Allium fistulosum* L.; solução nutritiva; salinidade; nutrição mineral.

INTRODUCTION

Hydroponic cultivation has been rapidly increasing in Brazil, especially for the production of vegetables, such as lettuce (Aquino et al., 2017), arugula (Jardina et al., 2017), watercress (Lira et al., 2019), green onion (Araujo et al., 2016), and tomatoes (Gonçalves et al., 2018). This cultivation system can mitigate the effects of salt stress on plants because the water potential under hydroponic conditions depends on the osmotic potential, and the potential of the matrix is virtually null in the absence of soil (Soares et al., 2016).

Plants grown under salt stress exhibit several physiological and metabolic changes, whose magnitude depends on the genotype selected, mineral composition of the nutrient solution, environmental conditions, salinity level, and duration of stress (Gupta; Huang, 2014; Tedeschi et al., 2017).

High concentrations of salts, such as Na^+ and Cl^- , in the nutrient solution, can negatively affect the metabolic processes essential for plants, including absorption of nutrients. The absorption, transport, and assimilation of these nutrients under salinity conditions do not function properly due to the antagonistic and competitive effects of excess salts, resulting in nutritional imbalances and reduced plant growth and development (Silva, 2014; Sahin et al., 2018).

Hydroponic cultivation using brackish water employs several management strategies, such as circulation frequency of the nutrient solution, which further minimize the damage caused by excess salts and enhance crop production (Silva Júnior et al., 2019). In this regard, Silva et al. (2016) reported that increased frequency of nutrient solution circulation minimizes the variations in salt concentration and promotes greater oxygenation in the nutrient solution, thus mitigating the deleterious effects of salinity.

Hydroponic cultivation of economically important vegetables and crops, such as lettuce, coriander, arugula, and tomatoes, with brackish water has already been discussed in the literature (Silva et al., 2016). However, it is also important to invest in crops of regional interest with economic viability for producers.

Green onion (*Allium fistulosum* L.) is a leafy vegetable used as a condiment in a variety of foods. It is commonly used throughout Brazil, majorly in the Northeast region, and is marketed along with coriander or parsley in the form of sauces, and is a part of the seasoning known as “green smell” (Cardoso; Berni, 2012; Araujo et al., 2016). Little information is available on the cultivation of

green onion in a hydroponic system with brackish waters. Moreover, no information on the mineral nutrition of the crop under such conditions is available, thus evidencing the necessity and importance of studies related to mineral nutrition of this crop under salinity conditions.

According to Portela, Peil and Rombaldi (2012), the nutritional quality of foods is affected by the composition of the nutrient solution, by variations in the electrical conductivity (EC_w) of this solution, and by the type of management adopted. However, hydroponics has emerged as an auxiliary technique to understand these effects on crops.

Here, we evaluated the dry matter (DM) production, and nutrient and inorganic solute (Na^+ and Cl^-) content in green onion plants (cv. Todo Ano Evergreen - Nebuka) under different levels of nutrient solution salinity in combination with circulation frequencies of these solutions.

MATERIAL AND METHODS

Two experiments were conducted in an uncontrolled, protected environment (greenhouse), from December to March (during spring and summer, Experiment I) and from March to May (summer and autumn, Experiment II), 2018. The study was conducted in the experimental area of the Agricultural Engineering Department (DEAGRI) of the Federal Rural University of Pernambuco (UFRPE), Recife-PE, Brazil (08° 01' 07" S, 34° 56' 53" W and an average altitude of 6.5 m).

During the experiments, the maximum average temperature of 37.4 °C and a minimum of 32.2 °C were recorded inside the greenhouse, with the maximum average relative humidity of 61.4% and a minimum of 44.5%.

In both experiments, the experimental design was completely randomized, in a 6×2 factorial scheme, with five replicates. The treatments consisted of using six levels of nutrient solution salinity (1.5, 3.0, 4.5; 6.0, 7.5, and 9.0 dS m^{-1}) and two circulation frequencies of the solutions (twice a day at 8 and 16 h; and thrice a day at 8, 12, and 16 h).

The experimental structure used consisted of a low-cost hydroponic module (Santos Júnior et al., 2013). It was composed of a wooden support, with dimensions of 6×1.4 m and was designed to support 12 PVC tubes, each with a length of 6 m, leveled, and 100 mm in diameter. Holes of 60 mm in diameter were drilled in these tubes, equidistantly spaced every 0.15 m, considering the central axis of each hole.

Elbows with the same diameter were connected to these PVC tubes and subsequently to a tap for water outlet, in a spillway-type system to induce a constant 4-cm deep film of a nutrient solution along the tube, thus making the solution equally available to all plants. At the outlet of the elbows, a perforated cap was placed to enable gas exchange, when the water fell from one tube to another.

Nutrient solution was prepared using public supply water (electrical conductivity [EC_w]: 0.12 dS m⁻¹) according to the quantity of fertilizers recommended by Furlani et al. (1999) for leafy vegetables, using reservoirs with a capacity of 90 L. The level of EC_w of the nutrient solution was 1.5 dS m⁻¹ in control (without NaCl), whereas other EC_ns levels (3.0, 4.5, 6.0, 7.5, and 9.0 dS m⁻¹) were obtained by adding NaCl to the containers until the desired EC_{sn} was achieved using a conductivity meter.

In both experiments, the EC_ns levels were the same; however, the strategy to replace evapotranspiration depth was alternated using fresh and brackish waters. In Experiment I, the evapotranspired depth was replaced with the brackish water used to prepare each of the salinity levels (used exclusively). In Experiment II, the brackish water was used only to prepare each of the salinity levels, and public water was used (EC_w = 0.12 dS m⁻¹) for replacement in all treatments.

The nutrient solution was managed via the recycling of water and nutrients (closed system). The evapotranspired solution was replaced weekly according to each treatment. The frequency of circulation was performed according to treatments; however, twice the volume, established by the tap inside the tube, was applied in each circulation event to homogenize and aerate the solution.

Electrical conductivity and pH of the nutrient solution were measured daily, with no requirement to make the necessary corrections.

Seeds of green onion (cv. Todo Ano Evergreen - Nebuka) were sown in 180 mL of disposable plastic cups using treated coconut powder as the substrate. In Experiment I, the seeds were sown on December 27, 2017. In Experiment II, the seeds were sown on March 7, 2018. Eight seeds were sown in each cup to guarantee germination, and subsequently, at 24 days after sowing (DAS), thinning was performed, leaving only one seedling. During the germination period until thinning, the plants received water from the public supply (EC_w = 0.12 dS m⁻¹).

Cups were inserted into the definitive culture tubes at 16 DAS. Only the nutrient solution without the addition of NaCl was applied to them. In total, each tube had 40 cups (spaced at 0.15 m) that were divided into five equal

parts to represent five repetitions of each treatment. The nutrient solution was applied at 25 DAS, when the plants had an average height of 0.10 m.

Harvest was performed 65 days after the application of treatments (90 DAS). The aerial parts were collected from four plants per plot. The plants were dried in an oven with forced air circulation (65 °C) until a constant dry weight was obtained. Subsequently, they were weighed to quantify the DM. The average of the four plants was obtained, and the DM was expressed in g plant⁻¹.

Next, the samples were grounded in a Wiley-type mill with a 2-mm-mesh sieve. The samples were subsequently extracted for macronutrients including nitrogen (N), phosphorus (P), potassium (K⁺), calcium (Ca²⁺), magnesium (Mg²⁺), and sulfur (S), as well as the micronutrients chlorine (Cl⁻) and the element sodium (Na⁺).

Total N concentration was determined using the Kjeldahl method; K⁺ and Na⁺ using the flame photometry method; P using the molybdate–vanadate colorimetric method; S using the turbidimetric method of barium sulfate; Ca²⁺ and Mg²⁺ by atomic absorption spectrophotometry, and Cl⁻ by Mohr's volumetric method following methodological procedures recommended by Bezerra Neto and Barreto (2011). The accumulation of nutrients N, P, K⁺, Ca²⁺, Mg²⁺, S, and Na⁺ is expressed in g kg⁻¹, and Cl⁻ is expressed in mg kg⁻¹.

Data obtained were subjected to analysis of variance by F test (p<0.05). After a significant effect was verified, polynomial regression analysis was performed at 5% probability level for quantitative factors. Tukey's test was applied at 5% probability level for qualitative factors. The analyses were performed using the statistical software Sisvar (Ferreira, 2019).

RESULTS AND DISCUSSION

The analysis of variance indicated a significant effect of the interaction between nutrient solution salinity levels and circulation frequency on the DM production in Experiment I (p<0.01 (Figure 1A)) and Experiment II (p<0.05 (Figure 1B)).

DM production at frequencies with two and three circulations decreased linearly for both types of evapotranspired blade replacement evaluated (Experiments I and II) due to the increased salinity levels. According to Sá et al. (2013), high salt concentrations interact negatively with the physiology of plants and promote harmful ionic, osmotic, and nutritional interactions. However, the effect occurs at varying levels of intensity, depending on species tolerance, with a reflection on biomass production of the vegetable.

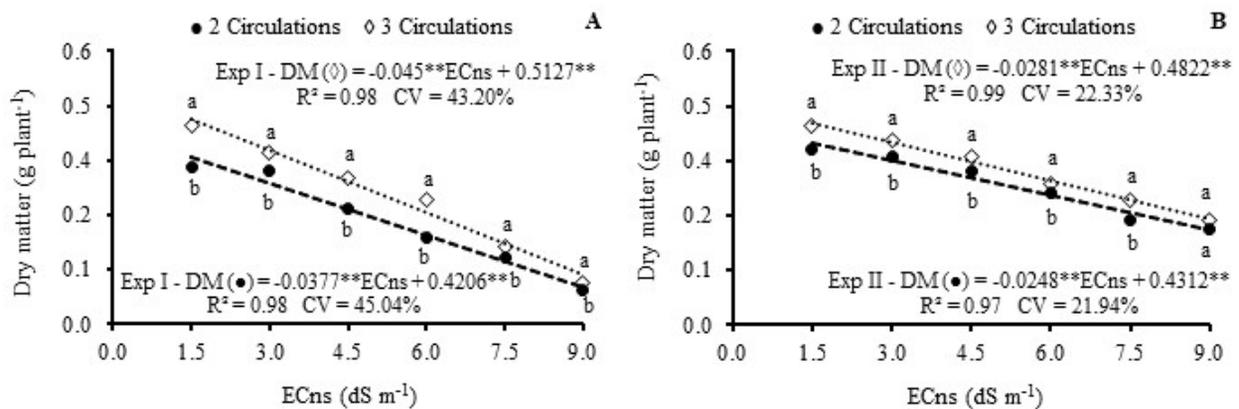


Figure 1: Follow-up analyses of the interaction between nutrient solution salinity and circulation frequencies of the solutions for dry matter (DM) production of green onion in Experiment I (A) and Experiment II (B). For each salinity level, different letters indicate significant differences between circulation frequencies using Tukey's test ($p < 0.05$).

In Experiment I (Figure 1A), frequencies with two and three circulations of the solution resulted in unit decreases of 0.38 and 0.045 g plant⁻¹, respectively, in DM, with the maximum DM yields of 0.36 and 0.45 g plant⁻¹ at the saline level of 1.5 dS m⁻¹. Compared to Experiment II (Figure 1B), frequencies with two and three circulations of the solution resulted in unit decreases of 0.025 and 0.028 g plant⁻¹, with the maximum DM yields 0.40 and 0.44 g plant⁻¹ at the saline level of 1.5 dS m⁻¹.

Araujo et al. (2016) studied the growth of the onion crop under different concentrations of NPK in the nutrient solution. They obtained a DM production of 0.37, 0.38, and 0.35 g plant⁻¹ at ideal concentrations of NPK. Furthermore, Schmitt et al. (2016) evaluated the production of chives intercropped with parsley under fertigation and reported average production of DM of 0.53 g plant⁻¹ of chives in an EC_w of the nutrient solution of 0.8 dS m⁻¹ in the single cultivation system.

As shown in Figure 1A, a frequency of three-times circulation of the nutrient solution, when evaluated within the salinity levels, resulted in DM production higher than 20% as compared with the frequency using two circulations. In this regard, Silva et al. (2016) evaluated the circulation frequencies of the nutrient solution in the hydroponic cultivation of coriander using brackish water. The group found that a high number of recirculations of the nutrient solution minimized the effect of salinity on plants.

Based on the results, it can be inferred that the highest accumulation of DM by the plants was obtained in Experiment II, where the replacement of the evapotranspired blade was performed with public water supply. These results could be attributed to a lower

accumulation of salts in the nutrient solution of this experiment because of the practically constant maintenance of EC of the nutrient solution. Consequently, greater absorption of nutrients by plants was observed in this experiment in relation to experiment I, where the salinity of the solution increased due to the progressive accumulation of salts because of replacement with brackish water.

With respect to the circulation of nutrient solution in the hydroponic system, we verified that the circulation thrice a day mitigated the effects of salinity in both experiments, favoring the increase in DM production.

Silva Júnior et al. (2019) studied the production of green onion in brackish waters under frequencies of nutrient solution circulation. The group reported that more frequent circulation of the nutrient solution during the day resulted in a reduced concentration of salts in the solution that was retained in the hydroponic profile. This could possibly be associated with the frequent homogenization between the profile solution and the supplying tank, consequently increasing the oxygenation of the system.

The enhanced oxygenation of the system increases the supply of dissolved oxygen to the roots, thus favoring the absorption of water and nutrients, and ensuring the growth of the aerial parts of the plants. In their study on coriander culture under intervals of nutrient solution recirculation, Silva et al. (2020) reported higher growth and production with 0.25 h recirculation intervals. However, the dissolved oxygen reduced due to the increased volume of roots produced, although without reducing the crop yield.

With respect to the accumulation of macronutrients, sodium, and chloride in Experiment I, we observed a

significant interaction between the factors for phosphorus ($p < 0.01$), potassium ($p < 0.01$), magnesium ($p < 0.01$), sulfur ($p < 0.01$), sodium ($p < 0.01$), and chloride ($p < 0.05$). An isolated effect between the factors for nitrogen ($p < 0.01$) and calcium ($p < 0.01$) was found. In experiment II, we observed a significant interaction between the factors for phosphorus ($p < 0.01$), magnesium ($p < 0.01$), sulfur ($p < 0.01$), and sodium ($p < 0.01$), and an isolated effect between factors for nitrogen ($p < 0.01$), potassium ($p < 0.01$), calcium ($p < 0.05$), and chloride ($p < 0.01$).

As shown in Figures 2A and 2B, the accumulation of N reduced linearly with the increase in salinity levels. Moreover, the frequency of three circulations of the nutrient solution attenuated the deleterious effects of salinity and, consequently, resulted in the highest accumulation of the nutrient in relation to the circulation frequency.

In Experiment I (Figure 2A), there was a unit decrease of 1.12 g kg⁻¹ in the accumulation of N and the maximum accumulation of 43.20 g kg⁻¹ at the saline level of 1.5 dS m⁻¹. In Experiment II (Figure 2B), the corresponding unit decrease was 0.71 g kg⁻¹, and the maximum accumulation, at the saline level of 1.5 dS m⁻¹, was 36.38 g kg⁻¹. The reduction by the unit increment of salinity was more pronounced in Experiment I because of the progressive accumulation of salts due to the use of brackish water to replace the evapotranspirated blade.

These findings corroborate with those obtained by Paulus et al. (2012), who assessed the concentration of nutrients in lettuce grown in hydroponics with brackish waters. Similar to the results of our study, the group obtained a linear reduction in the accumulation of N due to increased salinity with a total reduction of 81.54% between the level of 0.42 and 7.43 dS m⁻¹. Further, the results of our study were similar to those obtained by Araujo et al. (2016), who evaluated the culture of chives grown in a hydroponic system under different concentrations of N and reported a maximum accumulation of 39.83 g plant⁻¹ in the appropriate dose of this nutrient.

With regard to the two evapotranspirated blade replacement strategies evaluated (Experiments I and II), the accumulation of P (Figures 2C and 2D) by plants at frequencies with two and three circulations decreased linearly as a function of the increase in salinity levels.

The frequencies with two and three circulations of the nutrient solution in Experiment I (Figure 2C) resulted in a unit decrease of 0.39 and 0.20 g kg⁻¹, respectively, in the accumulation of P, respectively, and the maximum accumulation of 7.27 and 7.45 g kg⁻¹ of the nutrient at a saline level of 1.5 dS m⁻¹. In Experiment II (Figure 2D), the frequencies with two and three circulations of the solution

resulted in a unit decrease of 0.28 and 0.18 g kg⁻¹ and a maximum nutrient accumulation of 5.67 and 4.76 g kg⁻¹ at a saline level of 1.5 dS m⁻¹.

These results show that the harmful effects associated with increased EC_w of the nutrient solution, which became more severe after using brackish water to replace the evapotranspirated blade by the culture, were mitigated after using a frequency of three circulations of the nutrient solution. These results are indicative of reduced harmful effects of the salinity on plants and, consequently, greater accumulation of P by them with respect to the use of two circulations of the solution. In contrast, the greatest accumulation of P was achieved with the use of two circulations of the nutrient solution when replacing the evapotranspirated blade with water supply (Figure 2D).

According to Soares et al. (2016), reduced accumulation of P can result in decreased salinity levels of the nutrient solution that caused the precipitation of this nutrient, or even due to its antagonism with other anionic elements, such as chloride.

Araujo et al. (2016), who studied the cultivation of chives under hydroponic conditions with different concentrations of NPK, reported a maximum P accumulation of 5.12 g plant⁻¹ under the adequate concentration of this nutrient, which is a lower value than that obtained in Experiment I of this study. This was possibly associated with the use of brackish water. In this regard, Paulus, Dourado Neto, and Paulos (2012) reported that salt stress could increase the requirement for and absorption of P by certain cultures to mitigate the deleterious effects of salinity.

Figures 2E and 2F show that for both evapotranspirated blade replacement strategies evaluated (Experiments I and II), the accumulation of K⁺ linearly reduced with the increased salinity levels of the nutrient solution. In Experiment I (Figure 2E), the highest K⁺ accumulation was achieved with the use of three replacement frequencies of the evapotranspirated blade. In contrast, in Experiment II (Figure 2F), the highest K⁺ accumulation, regardless of the assessed salinity, was achieved with the use of two circulations of the nutrient solution.

We observed that frequencies with two and three circulations of the nutrient solution in Experiment I (Figure 2E) resulted in a unit decrease of 0.62 and 1.14 g kg⁻¹ in K⁺ accumulation, respectively, and the maximum nutrient accumulation of 14.58 and 18.52 g kg⁻¹ at a saline level of 1.5 dS m⁻¹. In Experiment II (Figure 2F), a unit decrease of 0.88 g kg⁻¹ and a maximum accumulation of 16.66 g kg⁻¹ at a saline level of 1.5 dS m⁻¹.

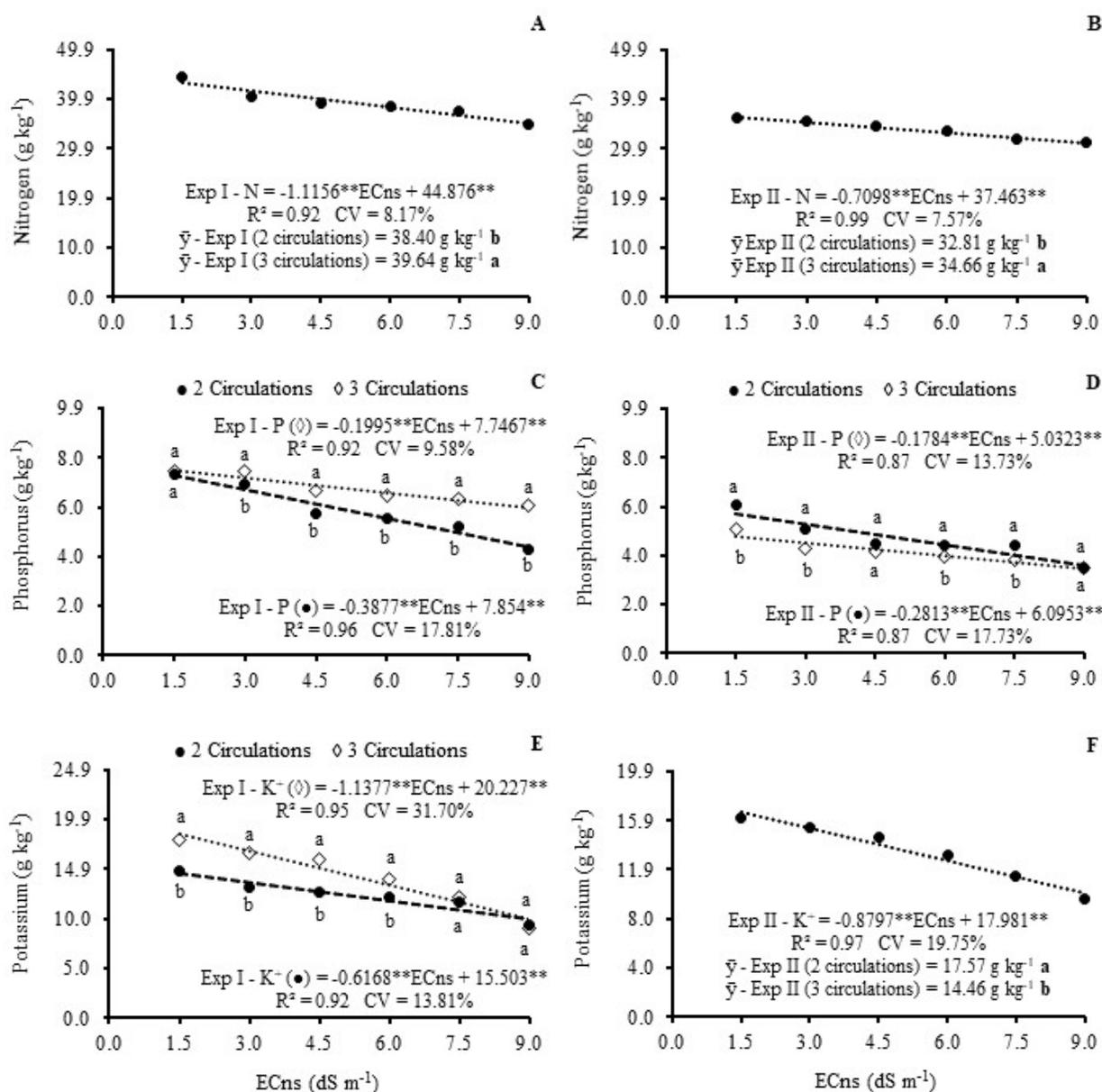


Figure 2: Follow-up analyses of the interaction between nutrient solution salinity and circulation frequencies of the solutions for nutrient concentrations in green onion: Phosphorus in Experiment I (C) and Experiment II (D) and potassium in Experiment I (E); single effect of factors on nitrogen in Experiment I (A) and Experiment II (B) and on potassium in Experiment II (F). For each salinity level, different letters indicate significant differences between circulation frequencies using Tukey's test ($p < 0.05$).

In their study, Araujo et al. (2016) reported a maximum accumulation of 18.06 g plant⁻¹ K⁺, corroborating with the results found in this study in the frequency with three circulations of the nutrient solution. This could be associated with the mitigating effects of salinity with increased frequency of circulation of nutritive solution.

Sousa et al. (2010) reported that increased sodium concentration in the rhizosphere could inhibit K⁺ absorption due to the competitive relationship between these monovalent cations. According to Tuteja et al. (2012), increased salinity resulted in increased concentration of Na⁺ ions in the nutrient solution, leading

to reduced K⁺ absorption because Na⁺ competes for the same absorption site as K⁺.

Paulus et al. (2012) studied the accumulation of nutrients in lettuce grown in a hydroponic system with saline water. They found reduced K⁺ absorption when Na⁺ was added to the nutrient solution and attributed this effect to the antagonism existing between these cations, thereby confirming the reduced K⁺ accumulation reported in the present study.

The increased salinity in the nutrient solution linearly reduced the Ca²⁺ accumulation in both Experiments (Figure 3A and 3B). We observed a unit reduction of 1.64 and 2.33 g kg⁻¹ and maximum accumulation 25.79 and 34.68 g kg⁻¹ of the nutrient in the salinity corresponding to 1.5 dS m⁻¹ for Experiments I and II, respectively. The low accumulation of Ca²⁺ at the highest salinity levels induced deficiency of this nutrient in the plants, which is detrimental to the accumulation of salts. It is worth pointing out that Ca²⁺ ion is a fundamental nutrient for maintaining the integrity of the plasma membrane of plant cells. Moreover, its deficiency affects the absorption of other nutrients, especially K⁺ (Lima et al., 2016).

The accumulation of Ca²⁺ ions was favored by replacing the evapotranspired blade with water supply (Experiments I and II) because the EC of the nutrient solution remained constant in this experiment. Santos et al. (2005), who studied the accumulation of nutrients in chives grown under doses of KCl in a nutrient solution, reported 15.20 g kg⁻¹ of Ca²⁺ as the ideal dose considered, corroborating the results of Experiment I in the study.

In Experiment I, the accumulation of Ca²⁺ was favored when there were only two circulations of the nutrient solution, whereas in Experiment II, the frequency with three circulations of the nutrient solution reduced the deleterious effects of salinity. Similar to K⁺, Ca²⁺ is important for plant growth and development, as well as for maintaining osmotic adjustment and cell turgor. These are essential for maintaining the selectivity and integrity of membranes, which directly affect the response of the plant under saline conditions (Paulus; Dourado Neto; Paulus, 2012; Osakabe et al., 2014).

However, at high salinity levels such as those evaluated in this study (6.0, 7.5, and 9.0 dS m⁻¹), the absorption of Ca²⁺ was inhibited by the excess of salts present in the nutrient solution, resulting in several nutrient deficiencies and associated symptoms, compromising the development and production of the crop.

The accumulation of Mg²⁺ in Experiment I (Figure 3A) decreased by 0.16 and 0.12 g kg⁻¹ with each

unit increase in saline levels, at frequencies with two and three circulations of the nutrient solution, respectively. The maximum accumulation of this nutrient was 2.50 and 2.16 g kg⁻¹ in both frequencies, respectively, at a salinity corresponding to 1.5 dS m⁻¹.

In Experiment II, the unit reduction in the accumulation of Mg²⁺ was 0.09 and 0.015 g kg⁻¹, with a maximum accumulation of 2.25 and 2.45 g kg⁻¹ for frequencies with two and three circulations of the nutrient solution, respectively. Araujo et al. (2016) reported an accumulation of 2.79 g plant⁻¹ of Mg²⁺ in green onion plants grown hydroponically under NPK concentrations, under the recommended dose for the crop, corroborating the values found in the present study.

The frequency with two circulations of the nutrient solution mitigated the harmful effects of excess salts in the nutrient solution. However, a severe reduction in the accumulation of Mg²⁺ was observed in both experiments, resulting in various deficiencies rather than the imbalanced nutritional value due to increased salinity in the nutrient solution. In this regard, Sahin et al. (2018) analyzed the effects of water and salt stress on the physiological, nutritional, and biochemical properties of cabbage. Moreover, the concentration of nutrients K⁺, Ca²⁺, and Mg²⁺ gradually decreased with the increase in the salinity levels.

A study of the coriander crop under the effects of brackish water and nutrient solution recirculation by Silva et al. (2018) concluded that a total of 12 recirculations of the nutrient solution per day could be adopted without losses in coriander production. Therefore, the obtained data revealed that an increased number of circulations of the nutrient solution attenuated the effects of salinity on the absorption of nutrients by the green onion crop.

The unitary reductions in the accumulation of S (Figure 3E and 3F) were observed to be 0.04 and 0.06 g kg⁻¹ with a maximum accumulation of 0.51 and 1.33 g kg⁻¹ at frequencies with two and three circulations of the solution used in Experiments I and II, respectively. Santos et al. (2005) reported an accumulation of 4.3 g plant⁻¹ of S accumulation in green onion at the standard dose of KCl, corroborating with the results found in the present study.

In both experiments, the frequency with three circulations of the nutrient solution mitigated the deleterious effects of salinity on the accumulation of S, thus proving the potential of this technique to help and enable the cultivation of green onions in nutrient solutions with brackish waters.

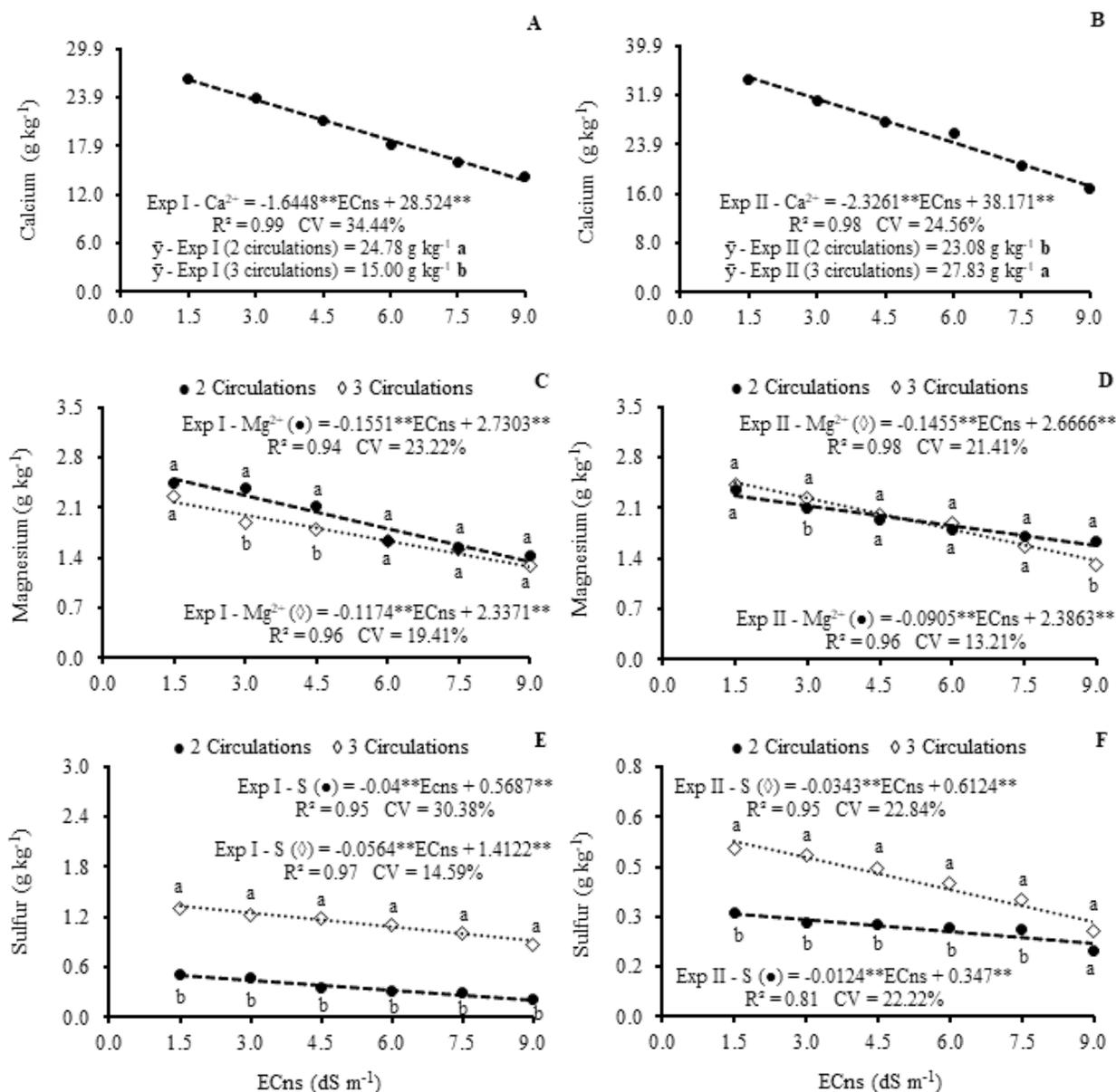


Figure 3: Follow-up analyses of the interaction between nutrient solution salinity and circulation frequencies of the solutions for the concentration of nutrients in green onion: magnesium in Experiment I (C) and Experiment II (D), and sulfur in Experiment I (E) and Experiment II (F). Single effect of factors for calcium in Experiment I (A) and Experiment II (B). At each salinity level, different letters indicate significant differences between circulation frequencies using Tukey's test ($p < 0.05$).

However, plants exposed to high levels of salinity (7.5 and 9.0 dS m⁻¹) exhibited clear symptoms of nutritional deficiency, irrespective of the number of times the solution was circulated. According to Marschner (2012), high Cl⁻ concentrations in the

nutrient solution could reduce the absorption of S due to the antagonistic interactions between them.

The accumulation of Na⁺ increased linearly with increased salinity levels in both evapotranspirated blade replacement strategies evaluated (Experiments I and II)

(Figures 4A and 4B) and in frequencies with two and three circulations.

The frequencies with two and three circulations of the nutrient solution in Experiment I (Figure 4A) resulted in a unitary increase of 0.55 and 0.73 g kg⁻¹ in the Na⁺ accumulations and maximum accumulation of 8.20 and 9.85 g kg⁻¹ at a saline level of 9.0 dS m⁻¹. In Experiment II (Figure 4B), the frequencies with two and three circulations of the nutrient solution resulted in a unitary increase of 0.38 and 0.55 g kg⁻¹ and maximum accumulation of 5.0 and 6.71 g kg⁻¹ at a saline level of 9.0 dS m⁻¹.

The higher accumulation of Na⁺, in both strategies of replacement of the evapotranspirated blade (Experiments I and II) (Figures 4A and 4B) and frequency with three circulations, could be associated with higher growth of plants. Consequently, higher accumulation of DM (Figures 1A and 1B) resulted in a greater accumulation of this ion.

Severe symptoms of nutritional deficiency as well as damage to the development of plants, including yellowing, stunting, and reduction in the number of tillers, were observed at the highest levels of salinity (7.5 and 9.0 dS m⁻¹) (Figure 5).

Based on these results, it can be inferred that plants could reach critical levels of salt stress with an increased salt concentration in the nutrient solution, to the point that it interfered in the mechanisms of absorption and translocation of water and nutrients. These were evident from the symptoms of nutritional deficiency and toxicity and, consequently, premature senescence of the plants and reduced growth. Modesto et al. (2019) reported that excess Na⁺ resulted in symptoms that hampered the plant metabolism, such as oxidative stress of proteins, nucleic acids, and lipids and, when combined with toxicity by Cl⁻, resulted in reduced nutrient assimilation, plant growth, and development, leading to premature senescence.

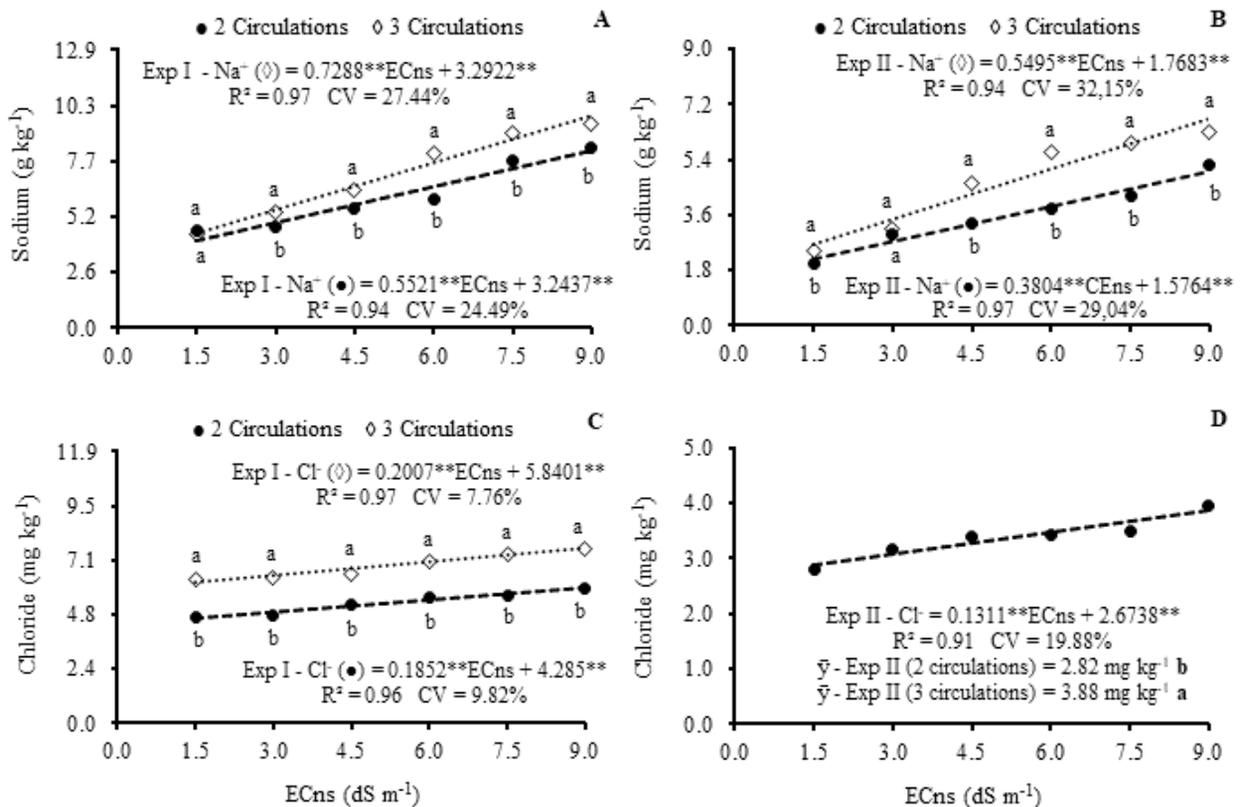


Figure 4: Follow-up analyses of the interaction between nutrient solution salinity and circulation frequencies of the solutions for the concentration of nutrients in green onion: sodium in Experiment I (A) and Experiment II (B) and chloride in Experiment I (C); single effect of factors for chloride in Experiment II (D). For each salinity level, different letters indicate significant differences between circulation frequencies using Tukey's test ($p < 0.05$).

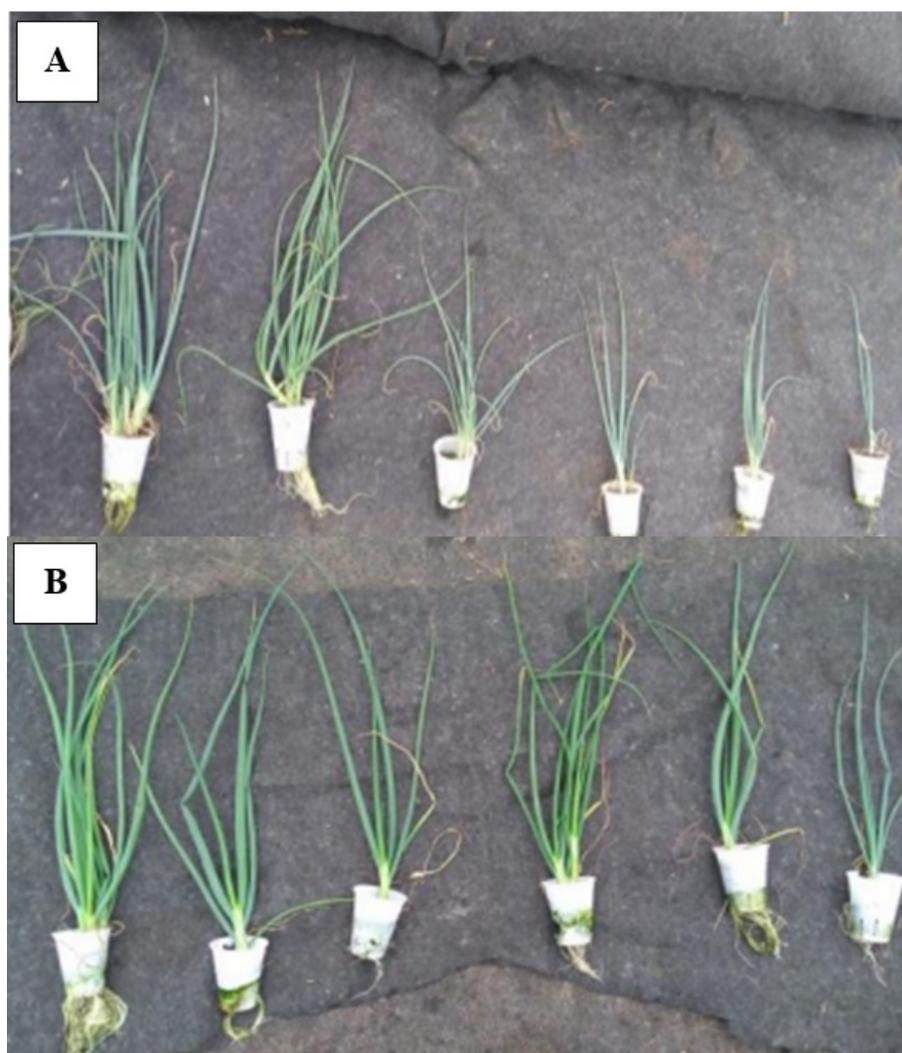


Figure 5: Onion green plants (cv. Todo Ano Nebuka) under the effect of nutritive circulation with the replacement of brackish water. Left to right: Plants representing salinity levels in the ascending order 1.5, 3.0, 4.5, 6.0, 7.5, and 9.0 dS m^{-1} using two frequencies of nutrient solution circulation (A) and three circulation frequencies (B) per day.

Soares et al. (2016) evaluated the effect of six water salinity levels used for the preparation of the nutrient solution (0.2, 1.2, 2.2, 3.2, 4.2, and 5.2 dS m^{-1}) and two strategies for replacing the evapotranspirated blade (brackish water from the respective treatment in experiment I) and (supply water [0.2 dS m^{-1}] in experiment II). The group found that the increased salinity of the water used in the preparation of the nutrient solution, irrespective of the evapotranspirated blade replacement strategy employed, resulted in increased sodium levels in the culture. Similarly, Santos et al. (2017) evaluated the accumulation of Na^+ in cherry tomatoes and observed

increased ion accumulation by the crop as a function of increased nutrient solution salinity.

Figures 4C and 4D show that for both evapotranspirated blade replacement strategies evaluated (Experiment I and II), the accumulation of Cl^- linearly increased with the increase in the salinity levels of the nutrient solution. In Experiment I (Figure 4C), the greatest accumulation of Cl^- was obtained with the use of three replacement frequencies of the evapotranspirated blade. Similarly, in Experiment II (Figure 4D), the highest ion accumulation, irrespective of the assessed salinity, was achieved with the use of three circulations of the nutrient solution.

It can be seen from Figure 4C that frequencies with two and three circulations of the nutrient solution in Experiment I resulted in a unitary increase of 0.19 and 0.20 mg kg⁻¹ in the Cl⁻ accumulation and maximum accumulation of the nutrient at a saline level of 9.0 dS m⁻¹. In Experiment II (Figure 4D), there was a unit increase of 0.13 mg kg⁻¹ and a maximum accumulation of 3.85 mg kg⁻¹ at a saline level of 9.0 dS m⁻¹.

Corroborating with the results of the present study, Soares et al. (2016) found in their experiments that increase in the salinity levels of the nutrient solution up to 5.2 dS m⁻¹ resulted in enhanced accumulation of Cl⁻ by the plants, with higher ion accumulation reported in the plants of the experiment where brackish water replaced the evapotranspirated blade. Santos et al. (2017) evaluated the nutrient concentrations in cherry tomato under the application management of the nutrient solution with brackish water and demonstrated that the increase in the salinity of the nutrient solution resulted in enhanced accumulation of Cl⁻ by plants.

CONCLUSIONS

The salinity of the nutrient solution, in both experiments evaluated, reduced the DM accumulation by plants and nutrients. However, the frequency with three circulations of the nutrient solution per day, in both experiments, mitigated the effects of salinity levels. Replacing the evapotranspirated blade with water supply (Experiment II) mitigated the deleterious effects of salinity and, when associated with the frequency with three circulations of the nutrient solution daily, resulted in the lower accumulation of inorganic Na⁺ and Cl⁻ solutes and increased accumulation of nutrients N, P, K⁺, Ca²⁺, Mg²⁺, and S by the culture. At the two highest levels of nutrient solution salinity (7.5 and 9.0 dS m⁻¹), plants exhibited severe symptoms of nutritional deficiency and could not be commercialized.

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