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EFFECT OF SUBSTRATE WATER CONSUMPTION AND FERTILIZATION LEVELS IN THE YIELD OF STRAWBERRY (*Fragaria x ananassa* Duch.)

Alejandro **Zermeño-González**[1*], Luis Armando **Moreno-Ibarra**[1], José Alexander **Gil-Marín**[1], Armando **Hernández–Pérez**[2], Homero **Ramírez-Rodríguez**[2], Octavio **Gaspar-Ramírez**[3]

[1]Universidad Autónoma Agraria Antonio Narro. Departamento de Riego y Drenaje. Calzada Antonio Narro 1923, Buenavista, Saltillo, Coahuila, Mexico. C. P. 25315.
[2]Universidad Autónoma Agraria Antonio Narro. Departamento de Horticultura. Calzada Antonio Narro 1923, Buenavista, Saltillo, Coahuila, Mexico. C. P. 25315.
[3]Centro de Investigación y Asistencia en Tecnología y Diseño del Estado de Jalisco, Subsede Noreste. Avenida Innovación 404, Parque PIIT, Apodaca, Nuevo León, Mexico. C. P. 66628.
* Author for correspondence: azermeno@uaaan.edu.mx

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ABSTRACT

Few greenhouse studies have been carried out to evaluate the effect of substrate water consumption before the application of nutrient solutions with different electrical conductivity (EC) values. The objective of this study was to evaluate the effect of two levels of substrate water consumption for moisture replenishment and three EC values of the Steiner solution on the yield and fruit quality of a strawberry crop (*Fragaria x ananassa* Duch. cv. Albion). A randomized block split-plot design with four replicates was used. The bigger plot consisted of the water consumption assessment at levels of 350 and 700 mL, which corresponded to 11.29 and 24.19 %, respectively, of the water volume contained in the saturated substrate (after free drainage). In the smaller plot, three EC levels of the Steiner solution (0.5, 0.75, and 1 dS m^{-1}) were evaluated for a total of six treatments. The main factors analysis showed that yield (g $plant^{-1}$), fruit per plant, fruit weight, degrees Brix, and vitamin C content were higher at the 700 mL intake and the ECs of 0.5 and 0.75 dS m^{-1}. The interaction between factor levels revealed that all response variables were higher for the 700 mL consumption and the EC of 0.5 and 0.75 dS m^{-1} and lower for the EC of 1 dS m^{-1}. On the other hand, for the 350 mL consumption, a decreasing trend of the same response variables was observed as the EC increased. In addition, the combination of 700 mL water consumption and the EC of 0.75 dS m^{-1} resulted in the highest values of these variables.

Keywords: Steiner solution, electrical conductivity, water stress.

INTRODUCTION

Strawberries (*Fragaria x ananassa* Duch.) have a large demand in Mexico and in many developed countries (Romero-Romano *et al*., 2012) due to the crop's high content of micronutrients and antioxidants such as vitamin C and folic acid (Aguilar-Tlatelpa *et al*., 2019; Arriaga-López *et al*., 2023). In 2021, Mexico recorded a production of

442 150.81 Mg on a surface of 10 149.47 ha, with an average yield of 43.56 Mg ha^{-1}. The states with the largest strawberry production in the country are Michoacán, Baja California, and Guanajuato (SIAP, 2022). The countries with the biggest production are China, the United States, Mexico, Turkey, and Egypt, representing 70 % of the worldwide production. Mexico is third in the production and export of strawberries (Ramírez-Padrón *et al*., 2020; FAO, 2022).

For better phytosanitary control, nutrient application, and water use, strawberries and diverse horticultural plants are grown in greenhouses in containers with substrate (Aydi *et al*., 2023; Nakro *et al*., 2023). Substrates are materials composed of one or more combinations of different sources, such as coconut fiber, stone wool, peat, perlite, vermiculite, tezontle, and others. The physical and chemical properties of the materials used vary broadly, and their characterization is important in determining the capacity of the substrate to store and release water and nutrients (Gruda, 2019). Organic substrates such as peat have the highest cationic exchange capacity values (90 to 140 cmol kg^{-1}), while inorganic compounds such as perlite have lower values (25 to 35 cmol kg^{-1}) (Silber, 2019).

Substrates must be highly water-retentive and available for plant roots, with an adequate porosity that allows a suitable air and water supply for their growth (Bhat and Hussain, 2023). Because some substrates are inert, nutrients must be applied in the precise amounts and proportions that the plants need (Guan *et al*., 2023). Regarding this, Steiner (1961) developed a procedure to formulate a nutrient solution for crops, considering the relation of ions, pH, and electrical conductivity (EC).

Earlier studies show that the growth and yield of strawberry crops depend on the pH and EC of the Steiner solution (Preciado-Rangel *et al*., 2020; Hernández-Valencia *et al*., 2022). High EC values can reduce the rate of CO_2 intake and the transpiration rate of the plants due to the high absorption of Na^+ and Cl^-, which causes an imbalance in the availability of nutrients (Wu and Kubota, 2008). Studies carried out by González-Jiménez *et al*. (2020) on strawberry cv. Festival showed that when the EC of the Steiner solution is equal to or greater than 2.7 dS m^{-1}, the foliar concentration of P and Mg is reduced by up to 50 %, but the vitamin C content increases up to 34 %.

For optimal growth and yield, it is necessary to supply the required amount of water at the right time so plants can maintain a high transpiration rate that dissipates the solar radiation they absorb (Ramos-Tamayo *et al*., 2023, Márquez-Zambrano *et al*., 2023). When the water availability of the substrate decreases, so does the transpiration rate. If water stress becomes severe, the opening of the stomata decreases, affecting the entry of CO_2 to the leaves and reducing the rate of photosynthesis (Fischer *et al*., 2022; Maldonado-Peralta *et al*., 2022). On the other hand, when a very high humidity rate is maintained, oxygen availability for plants can be affected, thus also affecting growth and yield. Based on the sensitivity of the crop to water and oxygen deficits in the root zone, an adequate range of substrate humidity fluctuations must be maintained for the optimum development of the plants.

Few studies at a greenhouse level have evaluated the combined effect of different water consumption levels of the substrate before irrigating with different EC values of the nutrient solution. Therefore, under the hypothesis that the combined effect of the water consumption level of the substrate and the electrical conductivity of the Steiner solution affects the yield and quality of fruits in a strawberry crop, this study aimed to evaluate the effect of two water consumption levels for the replacement of humidity and three EC levels of the Steiner solution on fruit yield and quality.

MATERIALS AND METHODS

The study was carried out in the 2022 summer-fall cycle in a chapel-style greenhouse (16 m wide, 24 m deep, and 9 m high) covered with a diffused, high-density polyethylene (0.94 g cm^{-3}, 80 % diffusivity) with one zenithal and several lateral windows. The greenhouse is located in the facilities of the Antonio Narro Autonomous Agrarian University, in Buenavista, Saltillo, Mexico (25° 23′ 42″ N and 100° 59′ 57″ W, at an altitude of 1745 m).

In this study, strawberry plants (*Fragaria x ananassa* Duch.) cv. Albion were used. This cultivar grows on short and long photoperiod days, producing fruits with good quality and size. Fruits are easy to gather and have an extended shelf life. They are resistant to adverse weather conditions and diseases such as anthracnose, *Vercillium*, and *Phytophthora*, and pests such as the spider mite (*Tetranychus* sp.) (Eurosemillas, 2019).

A total of 24 polyvinyl chloride (PVC) containers (NMX-E-199/1), 19.4 cm inside diameter and 20 cm tall, were used for the plant establishment and growth. At one end of each container, a double layer of plastic mesh with a diameter of 1 mm was placed, on which filter paper (80 g m^{-2}) was fixed. The containers were used as weighing lysimeters; therefore, all of them were adjusted to the same weight (950 g) with small metallic discs.

Each container was filled with 800 g (dry weight) of a composite substrate (based on volume) consisting of 70 % *Sphagnum* peat (Premier brand, Pro-Mix, Inc., Quebec, Canada) and 30 % perlite with a bulk density of 0.09 g cm^{-3} (Termolita, S.A.P.I. de C.V., Monterrey, Mexico), which reached a height of a 17 cm container, equivalent to a substrate volume of 5.025 L. The average dry weight of the container and the substrate was 1750 g. The highest level of water retention of the substrate in the container (saturated substrate, after free drainage) was 3100 mL, equivalent to 616.9 mL of water per liter of the substrate.

Treatments and statistical evaluation

A randomized block design arranged in divided plots with four replicates was used to evaluate the effect of the substrate's water consumption before irrigation and the EC of the nutrient solution (Steiner). The largest plot was used for the substrate water consumption evaluation with levels of 350 and 700 mL, which corresponded to 11.29

and 24.19 % of the volume of water contained in the saturated substrate. The smallest plot consisted of three EC levels of the Steiner solution (0.5, 0.75, and 1 dS m^{-1}), for a total of six treatments. The experimental unit was one plant per repetition of each treatment. Multiple treatment means were compared using Tukey's test ($p \leq 0.05$).

Transplanting, irrigation, and fertilization

The strawberry seedlings were transplanted on June 9, 2022, in PVC containers with peat and perlite substrate (70 and 30 % v/v). Irrigation was applied by sub-irrigation (capillary rise), placing the containers inside plastic boxes. The nutrient solution was added to the boxes up to a height of 20 cm so that the solution entered the container from the bottom and reached the surface through the capillary rise. This way, the water (with the nutrient solution) fills the porous space of the substrate. Once the substrate becomes saturated, the nutrient solution contained in the box and the excesses drained out of the containers were recovered in bottles using valves connected to the bottom of the boxes for reuse and to avoid wasting water and nutrients and polluting the environment.

Steiner nutrient solutions with ECs of 0.5, 0.75, and 1 dS m^{-1} and pH levels of 6 to 6.5 were used, with 98 % sulfuric acid added for adjustment. To eliminate the concentration of salts in the substrate and avoid modifications to the nutrient solution, every time the EC of the corresponding treatment increased by 0.2 dS m^{-1}, the substrate was washed using distilled water. The weight for irrigation to be applied was determined by the difference between the weight of the container and saturated substrate (4850 g) and the consumption of water of the corresponding treatment (350 and 700 mL), using a digital scale with a capacity of 10 kg and a precision of 1 g.

Response variables

Harvests were carried out on different dates based on the degree of maturity of the fruit. The first cut was on August 15, 2002, and finished on September 17, 2022. In each cut, the number of fruits per plant was obtained. At the end of the harvest, the total number of fruits per plant was determined, along with their corresponding weight (of all cuts performed). The fruits harvested in each cut were weighed using a digital precision scale. Soluble solids were measured using a refractometer (Spectrum Technologies, 2801, USA). The vitamin C content of the fruits from the different treatments was determined using the methodology described by Padayatt *et al*. (2001).

RESULTS AND DISCUSSION

For the different EC levels of the Steiner solution, yield (g $plant^{-1}$) was 29.54 % higher in plants with a consumption of 700 mL of water for the application of irrigation from the saturated substrate compared to a consumption of 350 mL (Tukey, $p \leq 0.05$) (Figure 1A), which indicates that maintaining an elevated water level in the substrate affects root function and reduces yield. For any level of water consumption in the substrate,

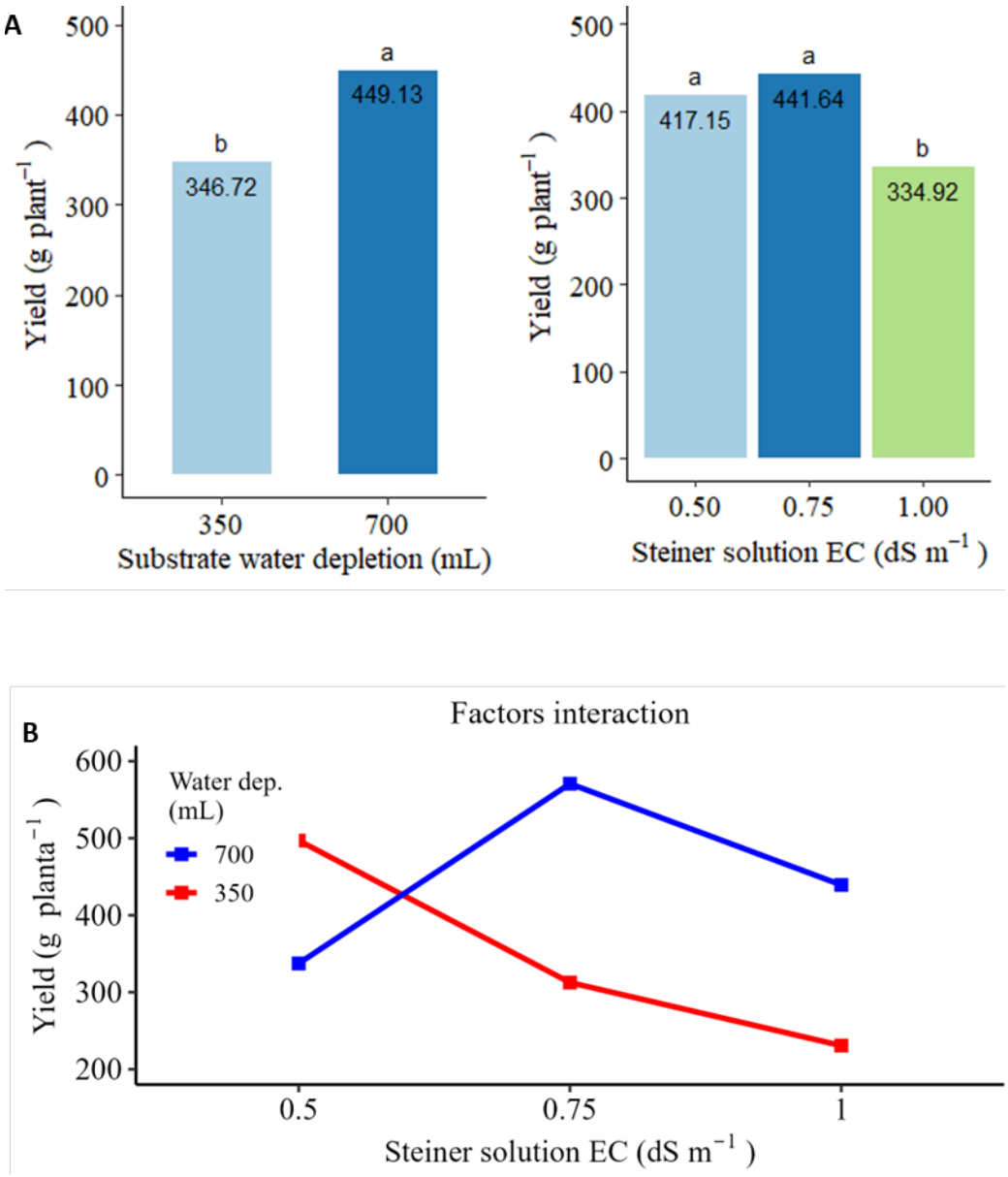

Figure 1. Effect of substrate water consumption for irrigation and electrical conductivity (EC, dS m^{-1}) of the Steiner solution on yield (g plant^{-1}) of the strawberry crop (*Fragaria x ananassa* Duch. cv. Albion). Means with the same letter are statistically equal (Tukey, $p \leq 0.05$). A: Effect of the main factors; B: effect of the interaction of the factor's levels.

yield was equivalent in EC levels of 0.75 and 0.5 dS m^{-1}, and these, in turn, were higher than that observed at 1 dS m^{-1} (Tukey, $p \leq 0.05$) (Figure 1A). The yield was 31.84 % higher at an EC of 0.75 dS m^{-1} than that obtained at 1 dS m^{-1}, indicating that plant yield decreases at high EC levels of the Steiner solution.

The interaction between the water consumption of the substrate and the EC of the Steiner solution showed that, for the consumption of 700 mL of water by the substrate, the highest yield appeared at 0.75 dS m^{-1} and decreased towards 0.5 and 1 dS m^{-1} (Figure 1B). For the consumption of 350 mL, yield decreased with the increase in the value of EC in the solution. The highest yield (570.72 g $plant^{-1}$) corresponded to the combination of 700 mL and 0.75 dS m^{-1}, and it was 1.47 times higher than the combination of 350 mL and 1 dS m^{-1} (Tukey, $p \leq 0.05$). This result shows that the substrate's high humidity and the Steiner solution's EC affect the plant yield.

In this study, the average yield observed was 397 g $plant^{-1}$. In an investigation on drip irrigation with treatments based on moisture replacement at tensions of 15 and 30 kPa in strawberry plants cv. Monterrey and Seascape, Cormier *et al*. (2020) reported yields ranging between 360 and 441 g $plant^{-1}$. For cv. Albion under deficit irrigation with reductions of 15 and 30 % below the reference evapotranspiration, average yields of 260.66 g $plant^{-1}$ were reported (Adak, 2019), which are lower than those obtained in this study.

Ahmed and Gad (2022), in strawberry cv. Festival planted in a perlite and vermicompost substrate with an irrigation level of 100 % of the reference evapotranspiration, obtained a yield of 789.67 g $plant^{-1}$, higher than that obtained in this study. Results indicate that when EC is higher than 0.75 dS m^{-1}, the yield of strawberry cv. Albion decreases. Similar results were reported by Denaxa *et al*. (2022) in cv. Camarosa and Rociera when increasing the EC of the nutrient solution from 0.4 to 4 dS m^{-1}, leading to a yield reduction in each variety of 29.1 and 22.7 %, respectively.

For the different levels of EC of the Steiner solution, yield (fruits per plant) was also higher (21.25 %) for the consumption of 700 mL than the one observed in 350 mL (Tukey, $p \leq 0.05$) (Figure 2A). For both humidity consumption levels by the substrate, the highest yield (fruits per plant) was obtained in the EC of 0.75 dS m^{-1}; its value decreased to 0.5 dS m^{-1}, and it was lower than 1 dS m^{-1} (Tukey, $p \leq 0.05$) (Figure 2A). Yield decreased by 30.14 % when EC increased from 0.75 to 1 dS m^{-1} (Tukey, $p \leq 0.05$) (Figure 2A).

The interaction between humidity consumption by the substrate and the EC of the Steiner solution displayed a very similar relation to that observed for yield. The highest value (41 fruits per plant) was observed in the consumption of 700 mL and an EC of 0.75 dS m^{-1}, and decreased in the EC of 0.5 and 1 dS m^{-1} (Figure 2B). On the other hand, for the consumption of 350 mL, yield (fruits per plant) decreased with the increase in EC of the Steiner solution. The higher yield (fruits per plant) was obtained in plants with the treatment with 700 mL and an EC of 0.75 dS m^{-1}, and the lowest one, in plants with the treatment with 350 and an EC of 1 dS m^{-1} (Tukey, $p \leq 0.05$).

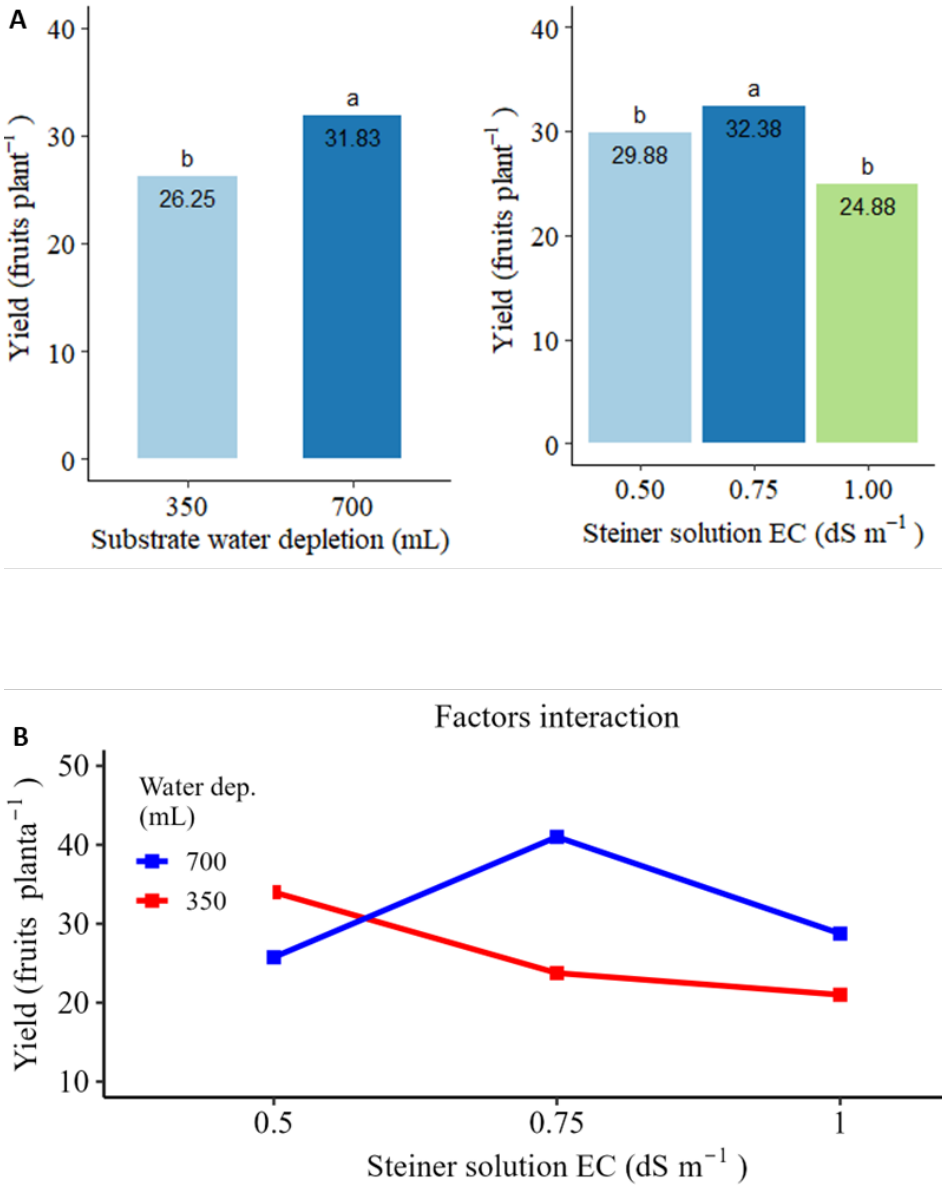

Figure 2. Effect of the substrate water consumption for irrigation and electrical conductivity (EC, dS m^{-1}) of the Steiner solution on yield (fruits plant^{-1}) of the strawberry crop (*Fragaria x ananassa* Duch. cv. Albion). Means with the same letter are statistically equal (Tukey, $p \leq 0.05$). A: Effect of the main factors; B: effect of the interaction of the factor's levels.

These results suggest that high substrate humidity values and the Steiner solution's EC reduce the yield in plants (fruits per plant). However, Ahmed and Gad (2022) showed that the application of irrigation at 100 % of the reference evapotranspiration in strawberry cv. Festival plants had the highest yield (31 fruits per plant), whereas, with irrigation applied at 60 %, lower yields were obtained (17 fruits per plant). This difference is probably due to the level of water stress corresponding to 60 %, being much higher than the one induced with the 700 mL of water consumption by the substrate in this study. The adverse effect of the increase of EC on the number of fruits per plant was also reported by Ferreira *et al*. (2019) on cv. Albion, since the increase in EC from 0.7 to 2.5 dS m^{-1} reduced the number of fruits per plant by 24.7 %.

For the three levels of EC of the Steiner solution, average fruit weight was also greater (14.41 %) for 700 mL than 350 mL (Tukey, $p \leq 0.05$) (Figure 3A). For both levels of substrate water consumption, the fruit weight was greater in the EC of 0.5 dS m^{-1}, decreased to 0.75 dS m^{-1}, and was lower than 1 dS m^{-1} (Figure 3A). Fruit weight decreased by 12.31 % when the EC of the solution increased from 0.5 to 1 dS m^{-1} (Tukey, $p \leq 0.05$) (Figure 3A).

Regarding the interaction between substrate water consumption and the EC of the Steiner solution, for 700 mL of consumption, the same change pattern as observed in the variables-response described earlier was found. Fruit weight was greater with an EC of 0.75 dS m^{-1} and lower at 0.5 and 1 dS m^{-1}. For the consumption of 350 mL, fruit weight decreased with the increase of EC (Figure 3B). For the combined effect of water consumption of the substrate and EC of the solution, the highest fruit weight was obtained in plants where the consumption was 700 mL and EC was 0.75 dS m^{-1}, and the lowest, with 350 mL and 1 dS m^{-1} (Tukey, $p \leq 0.05$).

As opposed to the results in this study, earlier work on strawberry plants from different cultivars indicates that the fruit weight is greater at higher irrigation levels (Ameri *et al*., 2012; Perin *et al*., 2019; Ahmed and Gad, 2022), which may be due to the fact that, with the consumption of 700 mL of the humidity by the substrate, no greater stress was produced, whereas with 350 mL, an oxygen deficit could have been induced in the roots area due to the high frequency of irrigation. On the other hand, despite irrigation at 100 % of the reference evapotranspiration in other studies, the irrigation frequency was not very high.

In this study, the average fruit weight decreased as the EC of the solution increased (for 350 mL of substrate water consumption). The greatest weight was obtained with the combined effect of 700 mL and an EC of 0.75 dS m^{-1}, whereas the lowest was obtained with the combination of 350 mL and 1 dS m^{-1} (Figure 3C). Garriga *et al*. (2017) also reported reductions in fruit weight of the cv. Camarosa due to the increase in saline stress.

For the three EC levels of the Steiner solution, the degrees Brix of the juice of the fruits were 8.73 % higher in the consumption of 700 mL compared to those observed with 350 mL (Tukey, $p \leq 0.05$) (Figure 4A). For both levels of substrate water consumption, the degrees Brix were greater for the EC of 0.75 dS m^{-1}, being 11.55 % higher than those with 0.5 dS m^{-1} (Tukey, $p \leq 0.05$) (Figure 4A).

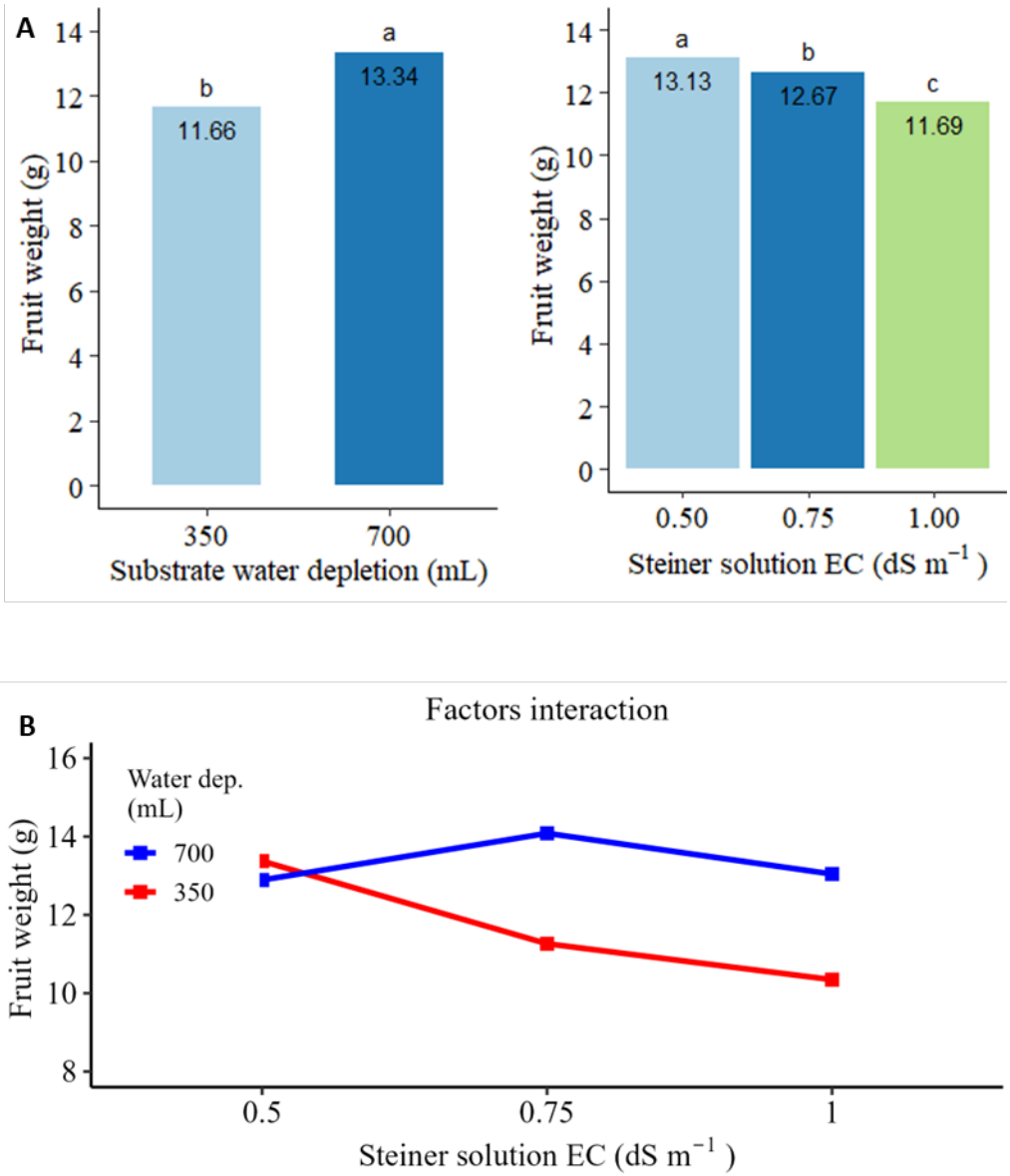

Figure 3. Effect of the substrate water consumption for irrigation and electrical conductivity (EC, dS m^{-1}) of the Steiner solution on the average fruit weight (g) of the strawberry crop (*Fragaria x ananassa* Duch. cv. Albion). Means with the same letter are statistically equal (Tukey, $p \leq 0.05$). A: Effect of the main factors; B: effect of the interaction of the factor's levels.

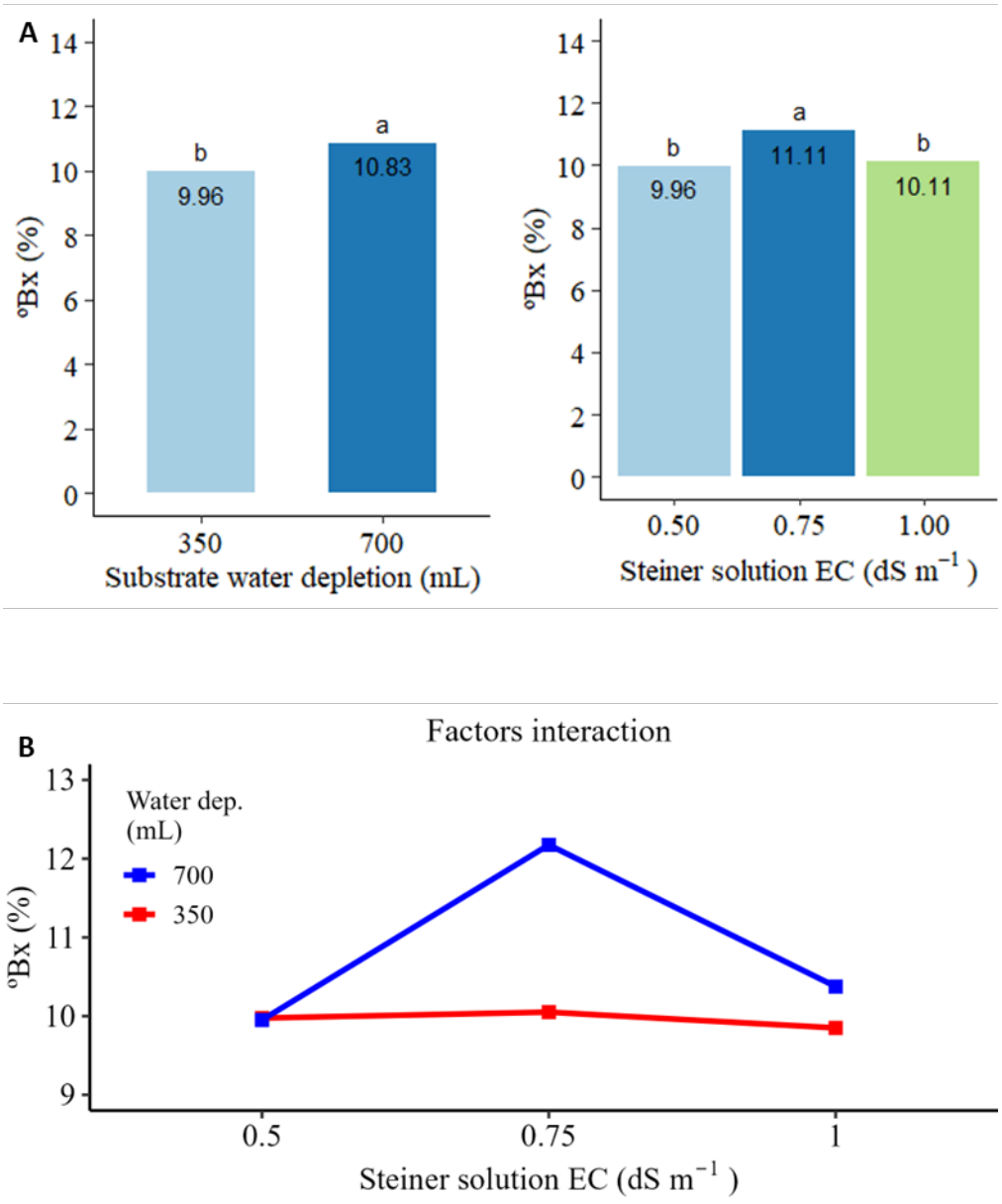

Figure 4. Effect of the substrate water consumption for irrigation and electrical conductivity (EC, dS m^{-1}) of the Steiner solution on the degrees Brix of the juice of fruits (%) of the strawberry crop (*Fragaria x ananassa* Duch. cv. Albion). Means with the same letter are statistically equal (Tukey, $p \leq 0.05$). A: Effect of the main factors; B: effect of the interaction of the factor's levels.

The interaction between substrate water consumption and the EC of the solution indicates that the highest value of degrees Brix takes place in the consumption of 700 mL while being noticeably lower at 0.5 and 1 dS m^{-1}. For the consumption of 350 mL, the values of degrees Brix were very similar in all EC levels of the nutrient solution (Figure 4B). This indicates that maintaining moderate EC and substrate moisture levels favors the increase in degrees Brix, whereas higher values for humidity of the substrate and EC of the solution reduce degrees Brix. For the combined effect of the substrate water consumption and the EC of the nutrient solution, the highest value for degrees Brix was obtained in plants with a consumption of 700 mL and an EC of 0.75 dS m^{-1}, whereas the lowest was obtained for 350 mL and an EC of 1 dS m^{-1} (Tukey, $p \leq 0.05$).

Other studies indicate that salinity has a positive effect on the concentrations of total soluble solids (degrees Brix), organic acids, and sugars, which are compounds that contribute to improving the aroma and flavor of many fruits (Kader, 2008; Rouphael *et al.*, 2018). The optimum value for degrees Brix for red fruits ranges between 6 and 9 %. The average of degrees Brix observed in this study was 10.4 %, a slightly higher value than the optimum (Hancock, 1999). For strawberry cv. Festival, the highest values of degrees Brix were obtained with higher irrigation levels (Ahmed and Gad, 2022). Ferreira *et al*. (2019) found no significant effects of different EC levels on degrees Brix in cv. Albion. The increase in the concentration of sodium chloride in the nutrient solution increased the degrees Brix and total acids in strawberry plants cv. Elsanta, Korona, and Camarosa (Saied *et al*., 2005; Keutgen and Pawelzik, 2007; Galli *et al*., 2016). However, other studies report that degrees Brix and total acids do not change with the increase in salinity of irrigation water (Keutgen and Pawelzik, 2007; Khayyat *et al*., 2007; Jamalian *et al*., 2008).

For the three EC levels of the Steiner solution, the vitamin C content in fruits was also greater (22.56 %) in the substrate water consumption of 700 mL compared to 350 mL (Tukey, $p \leq 0.05$) (Figure 5A). For both levels of substrate water consumption, the vitamin C content was higher and equal for EC of 0.5 and 0.75 dS m^{-1} and lower at 1 dS m^{-1} (Tukey, $p \leq 0.05$) (Figure 5A). This result indicates that plants under slight water stress, when irrigated at 700 mL of substrate moisture consumption, increase the vitamin C content of the fruits in combination with a moderate EC value of the Steiner solution.

The highest vitamin C content in the fruits was obtained with the consumption of 700 mL and an EC of 0.75 dS m^{-1}, and its concentration decreased (for the same substrate water content) with an EC of 0.5 and 1 dS m^{-1}. For the consumption of 350 mL, vitamin C content decreased with the increase of the EC of the nutrient solution (Figure 5B). For the combined effect of water consumption and EC, the highest vitamin C content was obtained in plants with a consumption of 700 mL and an EC of 0.75 dS m^{-1} and with a consumption of 700 mL and an EC of 0.5 dS m^{-1}, making these greater than the rest of the treatments (Tukey, $p \leq 0.05$).

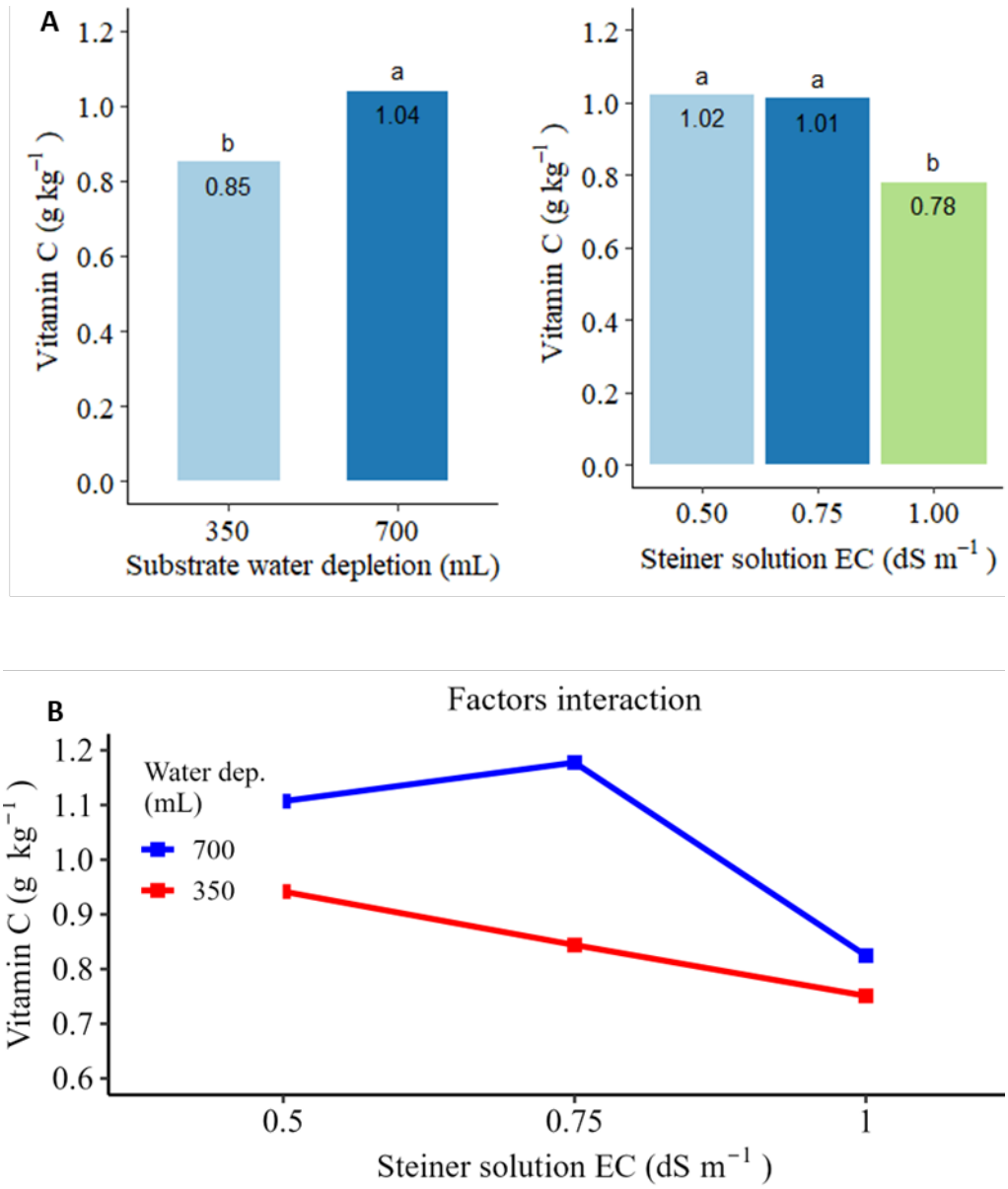

Figure 5. Effect of the substrate water consumption for irrigation and electrical conductivity (EC, dS m^{-1}) of the Steiner solution on the content of vitamin C of the juice of fruits (g kg^{-1}) of the strawberry crop (*Fragaria x ananassa* Duch. cv. Albion). Means with the same letter are statistically equal (Tukey, $p \leq 0.05$). A: Effect of the main factors; B: effect of the interaction of the factor's levels.

Water deficit may interrupt metabolic processes in strawberries, including the biosynthesis of vitamin C. Ascorbic acid is synthesized in plants using enzyme reactions that require adequate water availability (Fenech *et al*., 2019). A study by Medyouni *et al*. (2021) shows that water deficit increases the total content of carotenoids and vitamin C in tomato fruits (*Solanum lycopersicum* L.), but reduces the levels of soluble sugar and organic acids. However, Ahmed and Gad (2022) found a maximum and minimum value for vitamin C contents in strawberries of 0.782 and 0.708 g kg^{-1} with the highest and lowest levels of irrigation, respectively. These values are lower than the average observed for this study (0.941 g kg^{-1}). When the EC of the nutrient solution increases from 0.75 to 1 dS m^{-1}, the vitamin C content decreases. Similar results were observed by Hernández-Valencia *et al*. (2022) in strawberry cv. Camino Real when the vitamin C content decreased from 0.615 to 0.562 g kg^{-1} when increasing the EC of the nutrient solution from 1.4 to 1.7 dS m^{-1}.

CONCLUSIONS

For the three levels of electrical conductivity (EC) of the Steiner solution evaluated (0.5, 0.75, and 1 dS m^{-1}), yield (g $plant^{-1}$ and fruits $plant^{-1}$), fruit weight, degrees Brix, and vitamin C content were higher with a substrate water consumption of 700 mL (24.19 % of the saturated substrate volume consumption) than with 350 mL (11.29 % of the saturated substrate volume consumption). For both water consumption levels, the highest values for the variables were obtained with EC values of 0.5 and 0.75 dS m^{-1}. The interaction between substrate water consumption and the EC of the Steiner solution showed that the highest values for the same response variables were obtained with a consumption of 700 mL of substrate water and an EC of 0.75. With a consumption of 350 mL of substrate water, the variables mentioned were lower and generally decreased as the EC value of the solution increased.

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