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Effects of a reel hydroponic system (RHS) on the production and biochemical quality of tomato

Efecto de un sistema hidropónico en carrete (RHS) en la producción y calidad bioquímica de tomate

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ABSTRACT

Los Hydroponic production systems are a viable technique that allows better use of resources, to increase their functionality through the adaptation of existing systems to make management more efficient to increase the production and quality of crops. The objective of this work was to evaluate the effects of a reel hydroponic system on the production (RHS) and biochemical quality of tomato fruits compared with those of a conventional substrate hydroponic system (SHS). Statistical differences in biochemical variables, such as vitamin C content, antioxidant capacity, and total protein content, as well as characteristics of commercial interest, such as total soluble solids and titratable acidity, were detected among the treatments. There were no differences in glutathione, phenolic compound, flavonoid, lycopene, or beta-carotene content, and the production of the RHS and the plants that experienced less water stress in their flowering and harvest stages was 15 % greater than that of the SHS. The RHS influences the content of biocomposites in tomato fruits of biochemical and commercial interest; similarly, it increases the total plant yield, which represents a productive and economic advantage, for which the RHS is an important production system.

PALABRAS CLAVE: Yield, biocomposites, water, adventitious roots, stems.

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RESUMEN

Los sistemas de producción hidropónicos son una técnica viable que permite un mejor uso de los recursos, actualmente se busca incrementar su funcionalidad, por medio de la adaptación de sistemas existentes, para hacer más eficiente el manejo, incrementar producción y calidad de los cultivos. El objetivo de este trabajo es evaluar el efecto de un sistema hidropónico en carrete en la producción (RHS) y calidad bioquímica de frutos de tomate, comparado con un sistema hidropónico convencional en sustrato (SHS). Se encontraron diferencias estadísticas entre tratamientos para variables bioquímicas como vitamina C, capacidad antioxidante y proteínas totales, así como en características de interés comercial como solidos solubles totales y acidez titulable; no hubo diferencias para glutatión, compuestos fenólicos, flavonoides, licopeno y beta-caroteno; la producción se incrementó en un 15 % en el RHS y las plantas tuvieron menor estrés hídrico en sus etapas de floración y cosecha en comparación con el SHS. El RHS influye en el contenido de biocompuestos, en frutos de tomate, de interés bioquímico y comercial; así mismo incrementó el rendimiento total por planta, lo cual representa una ventaja productiva y económica, por lo que el RHS es una propuesta importante como sistema de producción.

PALABRAS CLAVE: Rendimiento, biocompuestos, agua, raíces adventicias, tallos.

Introduction

Greenhouse production has important implications for food production, especially when hydroponic systems are implemented, due to its ability to optimize the use of resources and increase productivity. (Khan *et al*., 2017). In this context, the cultivation of tomato varieties with indeterminate growth, characterized by their ability to prolong fruit production for a longer period (Mngoma *et al*., 2022), has become an important production alternative to meet the commercial demand for this product (Ampim *et al*., 2022).

Tomato is the most consumed horticultural product worldwide and is the main vegetable produced in protected environments because of its economic importance (Orona-Castillo *et al*., 2022). Its production in Mexico represented, by 2022, an economic value of 2.6 million dollars and a production volume of 4.2 million tons (FAO - FAOSTAT, 2023). Production in protected environments, such as greenhouses, offers advantages related to the management of environmental conditions and crop health, which favor productivity and profitability (Flores & Edwards, 2019). According to SIAP data for the agricultural year 2022, tomato production under greenhouse systems was 1.4 million tons, with Puebla being the main production state, with 154 tons per hectare. Tomato

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has important nutraceutical value since it contains different pigments, vitamins, and antioxidants of interest for human consumption (Fortis-Hernández *et al*., 2018), and the contents of these compounds vary according to multiple factors related to the production system, cultivars used, and general management (Fernández *et al.*, 2021).

For tomato production, different varieties are used according to the production system, in protected environments and, in the case of greenhouses with hydroponic systems, varieties with indeterminate growth are used (Vicente *et al*., 2015). These varieties develop long stems over time, which implies that the plants must transport water and nutrients from the basal part to the apical part, which can affect their productivity as the production cycle progresses (Cuellar-Murcia & Suárez-Salazar, 2018).

Hydroponic production is a technique in which the roots of a crop are in contact with water and fertilizer in the form of a nutrient solution, using another support medium different from the soil, which can be replaced by an inert medium or by structures that do not use a substrate *(Swain et al., 2021)*. Hydroponic systems can be modified according to the needs of the crop and the management of the nutrient solution, one of the systems that follows this principle is the nutrient film technique (NFT) (Sharma *et al*., 2019). The NFT system consists of establishing the plants in gutters or tubes, with a inclination percentage, so that a thin layer of nutrient solution passes through the roots, using a pump to carry the solution from a container to the gutters (Domingues *et al*., 2012).

Currently, agricultural production focuses its efforts on innovating technologies, methodologies, and practices that increase productivity, reduce costs, and optimize time and resources (Velázquez-González *et al*., 2022). In greenhouse production systems, particularly in hydroponic tomato cultivation, improving or modifying existing processes is essential to maximize the productivity and quality of the crop (Szekely & Jijakli, 2022). The reel-type NFT system is a variant of the already-known system, where instead of using gutters, a reel-shaped structure is implemented (Ayala-Contreras *et al*., 2022). This modification represents an operational and design advantage in terms of stem management and space optimization, which makes the reel hydroponic system (RHS) a promising option for intensive tomato production. This system aims not only to increase the number of fruits per plant but also to improve the biochemical quality of the product, which directly affects its commercial value and consumption preferences (Rusu *et al*., 2023).

On the other hand, the generation of new technologies may present limitations related to initially high implementation costs since it could imply the manufacture of prototypes, training, and introduction into the market; however, the innovations have a wide scope that allows profitability and sustainability to be generated (Fuentes-Peñailillo *et al*., 2024).

Taking into account the opportunities offered by the NFT system, the purpose of this work was to evaluate the production and biochemical quality of tomato fruits of indeterminate growth produced in an RHS, contributing to a greater understanding of the technologies applied in production in protected environments and their potential to increase the productive efficiency and quality of commercial products.

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Materials and Methods

This experiment was established during the February–December 2022 cycle at Antonio Narro Autonomous Agrarian University, Saltillo, Coahuila, Mexico, inside a tunnel-type greenhouse with fiberglass and semiautomated heating and cooling systems located in the area. Horticulture (coordinates 25° 21'21.7" N and 101° 02'06.7" W). The plant material used was from Harris Moran, a tomato of indeterminate growth, variety EL CID F1. The seedlings for the study were produced in polystyrene trays using peat as a substrate.

Treatments

Two production systems were evaluated: a substrate hydroponic system (SHS) and a reel hydroponic system (RHS). A completely randomized experimental design was used with 10 repetitions for each treatment, and the repetitions consisted of a bag and a reel with two tomato plants each.

Production systems

For the SHS, the transplanting was carried out in black polyethylene bags of 20 L capacity, 2 plants were placed per bag, and the plants were guided to a stem per plant with raffia thread; the sowing density was six plants/m^2. Steiner's nutrient solution (NS) was applied to cover the nutritional requirements of the crop via drip irrigation. In the vegetative stage, 3.5 meq L^{-1} (milliequivalents per liter) sulfate (SO_4^-) and potassium (K^+) were applied; 1.5 meq L^{-1} magnesium (Mg^{++}) and phosphates ($H_2PO_4^-$), 7 meq L^{-1} nitrate (NO_3^-), 0.5 meq L^{-1} ammonium (NH_4^+) and 6 meq L^{-1} calcium (Ca^{++}) were applied; and in the fruiting stage, the concentrations used in the vegetative stage were doubled, except for $H_2PO_4^-$ and NH_4^+, which remained the same.

For the RHS, plastic reels were used according to the procedure established by (Ayala-Contreras *et al*., 2022); 2 plants per reel, three reels $m^{-2,}$ and a recirculating drip irrigation system that works for 24 hours were used for the application of SN (Figure 1). One hundred days after transplantation (DAT), when the stems reached a length of more than 2 m, the main root was cut, and the stems were wound on the reel, without leaves or fruits, keeping the area of the rolled stem exposed to SN to generate adventitious roots (AR) (Figure 2). This activity continued throughout the production cycle as the bunch harvest progressed, cutting stem sections, always seeking to maintain productive plants 2 m in length (Figure 2).

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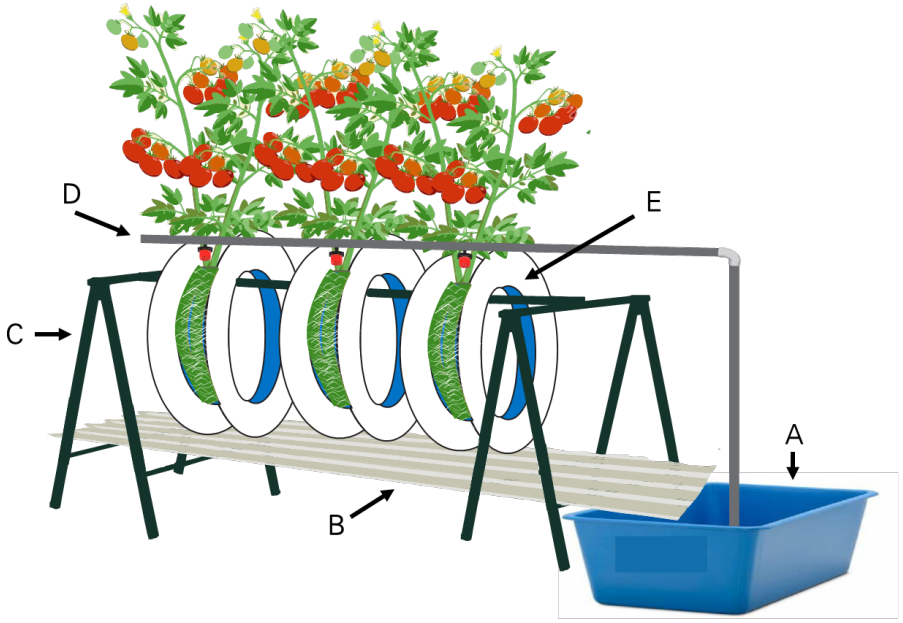

Figure 1. Diagram of the RHS. A: SN collection tray; B: SN circulation channel; C: trestle-type support; D: recirculating irrigation system with a submersible pump; E: reel.

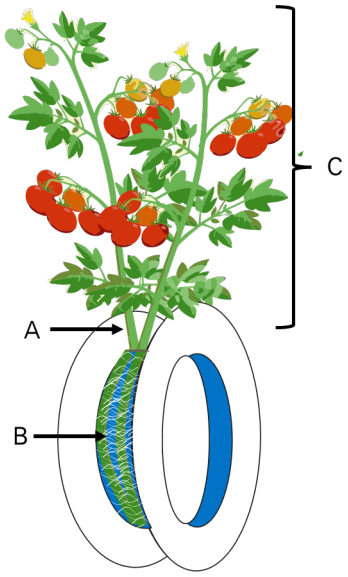

Figure 2. Diagram of tomato plants established in RHS. A: Tomato stem coiled on the reel; B: AR production on the winding stem; C: 2 m productive stem with flowers and fruits (productive section).

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Variables evaluated

The biochemical variables were determined in six tomato fruits per plant, which were collected at random when they presented color and firm texture. The samples were frozen and stored in a deep freeze (Thermo-Scientific TSX vertical). To perform the analysis, the samples were lyophilized in a lyophilizer (Labconco Legacy 6 L) for 8 days and then macerated with a ceramic mortar. The dry samples were stored in plant bags in an environment in a dark cardboard box to avoid contact with light.

To carry out the extraction and evaluate the antioxidant capacity, glutathione, and total proteins, 100 mg dry samples were placed in 2 mL tubes, and 10 mg polyvinylpyrrolidone (PVP) was added. Later, 2 mL 0.1 M phosphate buffer was added, and the mixture was homogenized, homogenized for 5 min, and centrifuged at 12,500 rpm at 4 $^{\circ}C$ for 10 minutes. Once the process was finished, the supernatant was collected, and quantification was carried out.

Hydrophilic antioxidant capacity (ABTS)

The procedure used for the quantification of this variable was carried out as proposed by Re *et al.* (1999) and involved decolorization of the radical cation ABTS (2,2'-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid)). To give rise to the radical, the reaction was carried out with potassium persulfate at 2.45 mM and ABTS at 7 mM (1: 1 v/v) for 16 hours in the dark, and the radical had an absorbance of 0.7 at 754 nm. Subsequently, 0.980 mL of each sample was placed in 2 mL tubes, shaken, and left in darkness for 7 min. Once the resting time had elapsed, the measurement was carried out at 754 nm in a UV–Vis spectrophotometer (Genesis 10 s, Thermo Scientific, USA), and the data are reported in milligrams of ascorbic acid equivalents in 100 g of dry weight (mg AAE 100 g^{-1} DW).

Glutathione

This compound was determined by spectrophotometry, a methodology proposed by Xue *et al*. (2001), using DTNB (5,5'-dithio-bis- [2-nitrobenzoic acid]). For the staining reaction, 0.48 mL of the sample, 2.2 mL of disodium phosphate, and 0.33 mL of DTNB at 1 mM were used. Subsequently, the mixture was left to rest for 15 min, and the reading was performed on a UV–Vis spectrophotometer. (Genesis 10 s, Thermo Scientific, USA) at 412 nm, the result is expressed in mg 100 g^{-1} PS.

Total proteins

Quantification was carried out via the spectrophotometry of Bradford, (1976). One milliliter of Bradford reagent and 0.1 mL of sample were added, the mixture was allowed to stand for 5 minutes, and the absorbance at 595 nm was read with a UV–Vis spectrophotometer (Genesis 10 s, Thermo Scientific, USA). The results are presented in mg 100 g^{-1} DW.

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Phenolic compounds

To measure this variable, the methodology was proposed by Ainsworth & Gillespie (2007). For the extraction, 2 mL of acetone with water (1:1 v/v) with 100 mg of dry sample was used, and the mixture was stirred for 20 s via a vortex. The mixture was subsequently homogenized for 5 min and centrifuged for 10 min at 12,000 rpm at 4 °C. For the quantification, 50 µL of extraction supernatant was placed in test tubes, 0.5 mL of 20 % sodium carbonate, 0.2 mL of Folin-Ciocalteu reagent, and 5 mL of distilled water were added; the mixture was allowed to rest at 45 °C for 30 min in a drying oven (CONAQUIN ICB 18 L), after which the reading was performed in a UV–Vis spectrophotometer (Genesis 10 s, Thermo Scientific, USA) at 750 nm, and the data were reported in mg gallic acid equivalents per 100 g of dry matter (mg GAE 100 g^{-1} DW).

Flavonoids

The determination of this compound was performed according to Zhishen *et al.* (1999). Two milliliters of 80 % methanol and 100 mg of vortexed sample were used, and the mixture was heated for 5 min and then centrifuged at 4,000 rpm for 10 min at 4 °C. The quantification was carried out by keeping the sample at rest for 5 min with 75 µL of 5 % $NaNO_2$, after which 1.5 mL of 10 % $AlCl_3$, 2 mL of distilled water, and 0.5 mL of 1 M NaOH were added. A UV–Vis spectrophotometer (Genesis 10 s, Thermo Scientific, USA) was used at 510 nm, and the results are expressed in mg catechin equivalents per 100 grams of dry weight (mg CE 100 g^{-1} DW).

Lycopene and β-carotene

These variables were evaluated according to Fish *et al.* (2002). First, 0.1 g of dry material was mixed with 2 mL of hexane and acetone at a ratio of 3:2. A UV–Vis spectrophotometer (Genesis 10 s, Thermo Scientific, USA) was used for measurement at 453, 505, 645, and 663 nm. The results are expressed in mg kg^{-1} DW.

Compounds are calculated via the following equations (Fish *et al.*, 2002):

$$Licopene\,(=-\,0.0458\,x\,A663\,+\,0.204xA645\,+\,0.372\,x\,A505\,-\,0.0806\,x\,A453$$

(Equation 1)

$$Beta-carotene=0.216\,x\,A663\,-\,1.22\,x\,A645\,-\,0.304\,x\,A505\,+\,0.452\,x\,A453$$

(Equation 2)

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Vitamin C

This variable was quantified by titration, and 20 g of juice diluted in 20 mL of distilled water was used. Thielmann reagent and 2 % HCl were used for titration. The vitamin C content was quantified (Igbokwe & Anagonye, 2013) as follows:

$$Vitamine\,C = VRT * 0.088 * VT * 100\ \frac{100}{Pv} * G$$

(Equation 3)

VRT is the expenditure in mL of Thielmann, VT is the total volume in mL captured of vitamin C in HCl, Pv is the volume in mL of the proportional, and G is the number of grams of the sample. The results are expressed in mg of ascorbic acid in 100 g of fresh sample (mg AA 100 g $^{-1}$ FW).

Total soluble solids (TSS)

TSS were determined with a Civeq portable refractometer and are reported in ° Brix.

Titratable acidity (TA)

The determination of this compound was carried out via titration with 0.1 N NaOH and phenolphthalein. A volume of juice equivalent to 7 g of fruit was placed in a beaker with 100 mL of distilled water for dilution. To determine the content, the following equation was used (Anthon & Barrett, 2012):

$$AT = \frac{(V * N * 0.064 * 100)}{VM}$$

(Equation (4))

V: mL of NaOH, N: Normality of NaOH, VM: sample volume. The results are expressed as a percentage of mg citric acid 100 mL $^{-1}$.

Crop yield

The fruits were harvested over 100 days, and as the maturation progressed in each cluster, 6 fruits were selected per cluster to obtain average data per fruit. The following variables were evaluated: the diameter of the fruit (polar and equatorial) via a digital caliper (Sunnimix), the quantity and weight of the fruits per plant via a digital scale (Ohaus-precision 0.01 g), and the production was reported in kg m ^{2}.

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Hydric potential in leaves

Leaves were cut within the productive area at two points during phenological development: during flowering and harvest. A Scholander pressure pump (PMS Instrument Company, Albany, OR, USA) was used to determine the water potential in the stems of the leaves, and the results are reported in megapascals (MPa).

Statistical analysis

Given the nature of the experiment, for the statistical analysis of the data obtained, the Welch t-test was used ($p \leq 0.05$) in RStudio version 1.3.1093.

Results and Discussion

The bioactive compounds present in the tomato fruits are presented in Figure 3. The variables glutathione, carotenoids, phenolic compounds, and flavonoids did not significantly differ between the hydroponic systems (Welch's t-test $\alpha \leq 0.05$), whereas vitamin C (Figure 3: A), total protein and antioxidant capacity (Figure 4: A and B) did significantly differ between the treatments. The vitamin C content increased by 32 % in RHS, with an average value of 34.88 mg ascorbic acid in 100 g of fresh weight. The total protein content in the RHS was 33 % greater than that in the SHS, which was 58 mg greater. Similarly, the fruits established in the RHS presented antioxidant capacity values 7 % greater than those in the SHS, which had an average value of 79.09 mg AAE per 100 g of dry matter.

In vegetables, l-ascorbic acid (AA or vitamin C) is the most abundant antioxidant that is solubilized in water and is of great commercial interest because of its nutritional value (Yactayo-Chang *et al*., 2017). The fruits produced in RHS have a higher content of vitamin C than do those produced in SHS, Sronsri *et al.* (2022) indicating that tomato fruits established in a soilless crop presented a higher vitamin C content than did those cultivated in soil, which attributed to the increased use of recirculating SN and the stable contribution of the elements that the plant needs for the synthesis of this compound. The SHS, although it is a soilless production system, does not use recirculating SN, which is why the higher vitamin C content in the RHS is attributed to the fact that the system allows the recirculation of the solution at all times. Crops produced in hydroponic systems can increase the content of biocomposites with antioxidant capacity, such as vitamin C, due to the availability of nutrients in the NS (Delgadillo-Díaz *et al*., 2019); Kaur *et al.* (2018) mentioned that hydroponic systems without substrate allow a better supply of nutrients and more directly in the different stages of plant growth, which improves the quality parameters. The RHS provides the necessary nutrients in a way that guarantees that the plant has what is necessary to synthesize the compounds efficiently. The adequate nutritional supply during fertilization directly influences the antioxidant content of tomato (Fanasca *et al.,* 2006); the RHS contributes to SN at all times and in a way close to the productive part through the AR, which favors the adsorption of

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nutrients. On the other hand, the total protein content in the fruits indicates a high nutritional and functional value for the different metabolic processes that are carried out in the fruit; (Almeselmani *et al*., 2009) I carry out a study where I conclude that the relationship between nutrients and the precise supply, according to the needs of the crop, favors an increase in total proteins and other bioactive compounds.

Carotenoids (lycopene and beta-carotene) are pigments synthesized during fruit ripening (Perveen *et al*., 2015), and their accumulation is influenced by the air temperature. At 22–25 °C, they are considered ideal for the biosynthesis of these compounds; below 10 °C and above 30 °C, their biosynthesis is compromised (Chen *et al*., 2014). During this experiment, the monthly average minimum air temperature varied between 7 °C and 10 °C, and the maximum temperature varied between 23 °C and 38 °C. The content of these compounds in the tomato fruit is not influenced by the hydroponic system but rather by the effects of the environmental conditions where they were developed, mainly temperature and light, which are fundamental factors for the synthesis of these pigments (Verdoliva *et al*., 2021). Concerning glutathione, phenolic compounds, and flavonoids (Figure 3: B, E, and F), the production system did not influence the content of these secondary metabolites; the content of these compounds can be modified to a greater extent when plants are subjected to some type of stress or stimuli that affect the metabolic routes for the synthesis of these compounds (Toscano *et al*., 2019). Although in the RHS, the plants suffer periods of stress during the cutting of their stems, this does not affect their metabolic performance in the production of biocomposites, since the RHS overcomes the lack of main roots generating a stimulus in the stems and producing roots. The plant takes advantage of the irrigation and fertilization that the system provides at all times.

Few studies have investigated the effects of culture medium on quality parameters (Olle *et al*., 2012); Gruda (2009) has suggested that there are significant changes in the quality parameters of many vegetables in response to the growing medium used. Factors such as the type of variety, nutrition, environmental conditions, management practices, and growing media can influence the content of bioactive compounds, with the state of maturation being the main factor (Fernandes *et al.,* 2021; Nour *et al.,* 2015).

The results corresponding to total soluble solids (TSS) and titratable acidity (TA) in fresh tomato fruits are shown in Table 1. In terms of both variables, there were significant differences between the hydroponic systems (Welch's t-test $\alpha \leq 0.05$). These variables are highly influenced by the state of maturation of the tomato fruit; inversely, the higher the maturation stage is, the higher the TSS content, the lower the TA content, the lower the ripening stage, the lower the TSS content, and the higher the TSS content. TA (Agius *et al*., 2018; Casierra-Posada & Aguilar-Avendaño, 2008). The harvest of the fruits in both systems was carried out following the same methodology, varying in color, and the results indicate that the fruits in the RHS presented a relatively high state of maturity. This is attributed to the fact that the RHS is elevated concerning the ground (Figure 1) and, therefore, closer to the roof of the greenhouse, has a high temperature, which causes the fruits to ripen more quickly.

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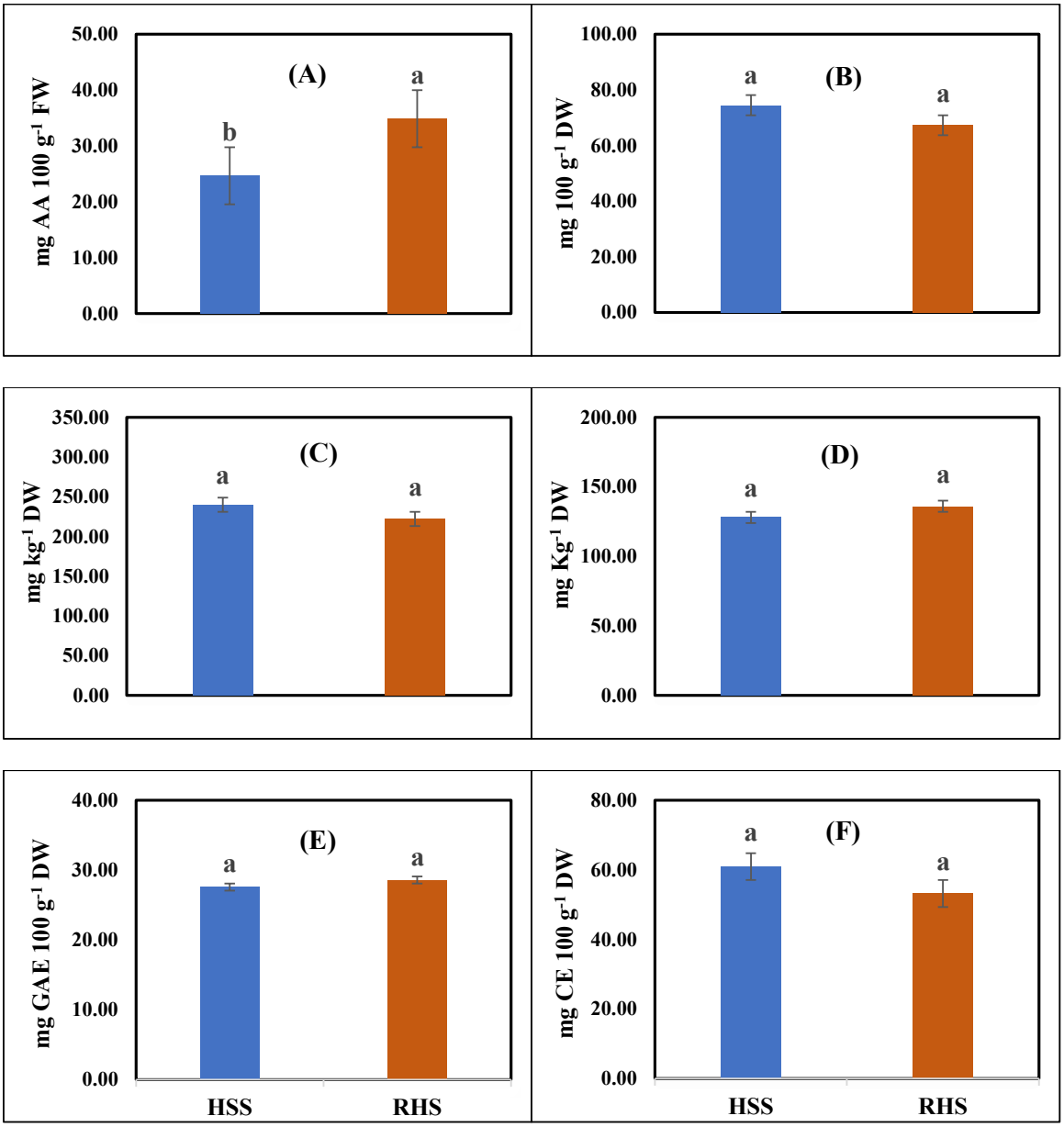

Figure 3. Contents of nonenzymatic antioxidant compounds in tomato fruits grown in different hydroponic systems. SHS: hydroponic system in a substrate; RHS: reel hydroponic system. A: vitamin C; B: glutathione; C: lycopene; D: β-carotene; E: phenolic compounds; F: flavonoids. The same letters within each column indicate no statistically significant differences between the treatments (Welch's t-test, $\alpha \leq 0.05$).

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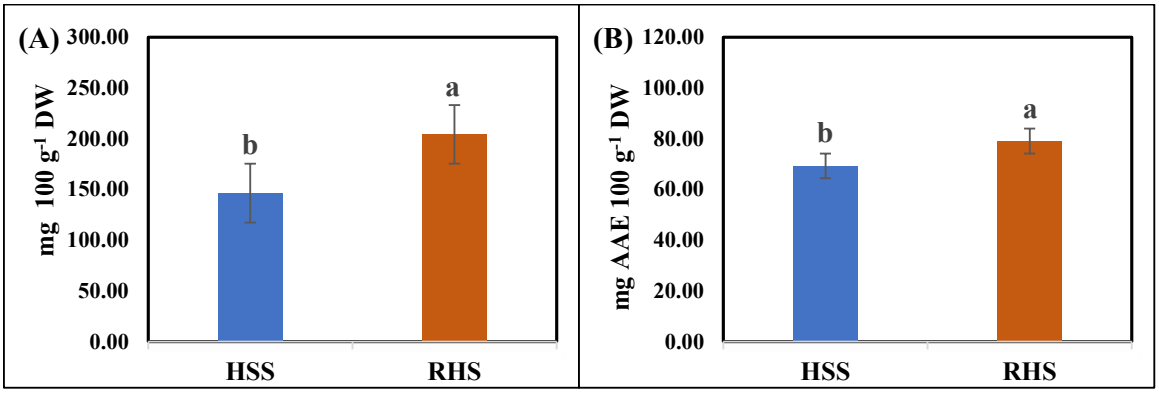

Figure 4. Total protein content (A) and antioxidant capacity (B) in tomato fruits grown in a hydroponic substrate system (SHS) and in a reel hydroponic system (RHS). Different letters within each column indicate significant differences (Welch's t-test, $\alpha \leq 0.05$).

The production system can influence the content of these compounds, mainly in terms of its relationship with the electrical conductivity (EC) of the solutions where the plants are developed (Beckles, 2012). In hydroponic systems, the relationship in the EC of the NS can vary significantly between substrates, given the climatic conditions and the accumulation of nutrients Dorai *et al.* (2001). This relationship indicates that in substrates such as peat and recirculating hydroponic systems, the EC may affect the content of nutraceutical compounds in greenhouse tomato fruits. Khanbabaloo *et al.* (2018) reported that an increase in the EC (3 dS m^{-1}) improves tomato quality and flavor without affecting yield. Mitsanis *et al,* (2021) carried out a study in which the nutraceutical characteristics of tomato fruits were related to different hydroponic substrates, management systems, and harvest times, where harvest time was the most important factor, followed by the type of substrate, which was related mainly to flavor traits and antioxidant content. TSS content is an important quality attribute during the maturation phase (Siddiqui *et al*., 2015); commercially, high-quality tomato fruits must have °Brix values greater than 3 (Schwarz *et al*., 2013), and the TSS values reported in this experiment were higher than the previously suggested values.

The variables related to tomato fruit production (Table 2) significantly differed between treatments (Welch's t-test $\alpha \leq 0.05$) in terms of fruit weight and production per m^2, except for fruit diameter. The production per m^2 increased by 15 % in the RHS, representing 0.68 kg per plant compared with the SHS.

Fayezizadeh *et al.* (2021) reported that production in recirculating hydroponic systems increases crop productivity and makes the use of water and fertilizers more efficient; Haghighi & Teixeira Da Silva, (2013) these findings indicate that yield can be positively affected depending on the type of crop and system used. The data in this study suggest that the higher yield was because in the RHS, with recirculating SN, the nutrients were available directly and close to the productive area of the plant (Figure 2) through the AR produced by the stem, as reported (Ayala-Contreras

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et al., 2022) in a preliminary study with the reel-shaped NFT system; other authors, such as (Olagunju *et al*., 2023), indicate that the tomato yield is greater when the plants are kept vertically with short stems, as opposed to long stems placed horizontally; Asaduzzaman, (2015) mention that performance can be increased by 2-5 times in hydroponic systems. The agricultural trends in protected environments focus their efforts on the search for efficient production alternatives through the modification or innovation of production systems, management techniques, and environmental control (Urrestarazu, 2013). On the other hand, having SN at adequate nutritional concentrations and balanced with the EC improves the development and production of fruits and their biochemical characteristics. (Lu *et al*., 2022), as provided by the RHS.

Table 1. Different hydroponic systems produce total soluble solids (TSS) and titratable acidity (TA) in tomato fruits.

	TSS (° Brix)	**TA** mg 100 mL^{-1}
RHS	0.49 ± 0.06 **a**	3.15 ± 0.02 **b**
SHS	0.36 ± 0.09 **b**	3.85 ± 0.03 **a**
CV *	4.14	2.18
α	0.001	0.0004

* CV: coefficient of variation. Different letters within each column indicate a statistically significant difference (Welch's t-test, α ≤ 0.05).

Table 2. Yield of tomato crops established in a reel-type hydroponic system (RHS) and in hydroponic substrate (SHS).

	RHS	**SHS**	CV	α
Production (kg m^2)	29.96 ± 2.49 **a**	25.92 ± 2.79 **b**	9.13	0.0198
Fruit weight (g)	114.7 ± 9.31 **a**	105.84 ± 8.84 **b**	10.39	0.0174
Polar diameter (mm)	67.53 ± 1.71 a	62.65 ± 3.73 a	11.22	0.428
Equatorial diameter (mm)	59.78 ± 2.08 a	52.61 ± 1.19 a	14.04	0.703

* CV: coefficient of variation. Different letters within each column indicate a statistically significant difference (Welch's t-test, α ≤ 0.05).

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The water potential of the tomato leaves (Figure 5) in both phenological stages significantly differed among the treatments (Welch's t-test $\alpha \leq 0.05$), being greater in the RHS, which presented less negative values than did the SHS. During the flowering period, the plants established in RHS had an average value of -0.24 MPa, which represents more than half of that presented by the SHS, which was -0.45 MPa. At the harvest stage, the value of the water potential was 41 % and 66 % greater for flowering in the RHS and SHS, respectively.

Lipan *et al*, (2021) reported that there were no significant differences in the water potential of leaves under deficit irrigation, but they did find a correlation between the yield and content of compounds such as TSS and the antioxidant capacity of the fruits since when water stress is generated in plants with more negative values, these variables can be affected. The water potential in leaves is a measure that allows us to evaluate the water status of a plant and how it is being managed under stress conditions (Putti *et al*., 2023), and values close to -1 MPa have an important effect on the productive development of tomato plants (Karaca *et al*., 2023). The highest water stress is observed in the harvest stage at the SHS, where the nutritional requirements are high and the movement of water should be greater in plants with long stems, unlike the RHS where irrigation is constant, which is reflected with values close to 0 in both phenological stages. These results allow us to complement the results presented in production, since the plants in the RHS did not present water stress, given the aforementioned characteristics in the system with AR, absorbing the necessary nutrients closely to the leaves and fruit production area.

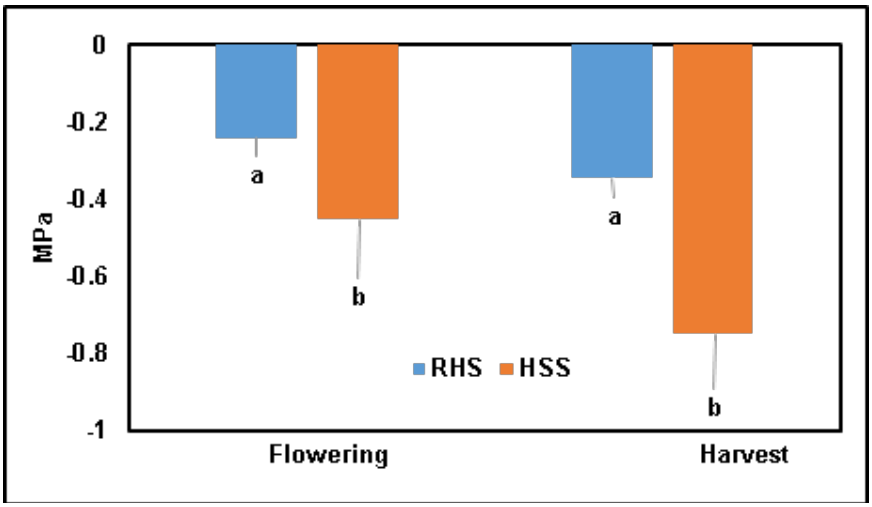

Figure 5. The water potential of leaves in tomato plants is determined in a reel hydroponic system (RHS) and a hydroponic substrate system (SHS).

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Conclusions

This study revealed that the hydroponic system in reel (RHS) offers significant advantages in terms of yield and quality of tomato fruits of indeterminate growth compared with the conventional hydroponic system in substrate (SHS). The results of this study indicate a 15 % increase in production, with greater fruit weights and a reduction in the water stress of the plants in the critical stages of development. Likewise, in the RHS, a significant increase in the content of biochemical compounds of commercial interest and for human consumption, such as vitamin C and antioxidant capacity, is promoted.

This system proposes an innovative and viable alternative to improve the production efficiency and quality of tomatoes in hydroponic systems, contributing to the continuous improvement of processes and the optimization of resources. It is important to propose new areas of study around this type of system based on the benefit-cost relationship.

Authors' contributions

Conceptualization of work (CAAC, JAGF); development of the methodology (CAAC, JAGF, OSA); software management (CAAC, OSA); experimental validation (CAAC, JAGF, ABM); results analysis (CAAC, ABM, OSA); data management (CAAC, OSA); writing and preparation of the manuscript (CAAC, ABM, PPR); writing, proofreading and editing (ABM, PPR, JAGF); project manager (CAAC, JAGF); acquisition of funds (JAGF, ABM, PPR).

All the authors of this manuscript have read and accepted the published version of it. CAAC, JAGF, OSA, ABM, PPR.

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Conflicts of interest

The authors declare that they have no conflicts of interest.

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