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Comparison of aeroponics system and use of substrates in Cherry tomato cultivation (*Solanum lycopersicum* L. var. cerasiforme)

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ABSTRACT

Objective: to compare the influence of three substrates, lava rock [in Mexico called 'tezontle'] (TZ), peat+vermiculite (TV), and coconut fiber (FC) with the aeroponics technique (AE) as growing media for Cherry tomatoes (*Solanum lycopersicum* L. var. cerasiforme), under controlled nutritional conditions.

Design/Methodology/Approach: after 31 days in the seedbed, tomato seedlings were transplanted. At 28 days after transplant (DAT) in all four cultivation systems, the number of leaves was recorded. Then, at 42 and 49 DAT plant height and stem diameter (DIAM) of the main plant and lateral shoots were measured, as well as counting the number of flowers. Fruit production was assessed between days 88 and 120 DAT.

Results: AE and TV significantly improved the number of leaves. Taller plants were obtained in TV and FC, while the TV substrate improved DIAM. The number of lateral shoots was higher in AE; but their highest length and DIAM were recorded in TV. AE increased the number of flowers at 42 DAT, whereas TV did so at 49 DAT.

Limitations/ Implications of the study: the only factor of variation was the growing substrate. In addition, the nutrient solution preserved the balance between cations and anions. The aeroponics conditions of this research allowed free root growth in an *ad hoc* designed system.

Findings/Conclusions: a cluster analysis revealed that the significant differences between cultivation systems occur mainly in vegetative variables, compared to production variables. Thus, suggesting that the cultivation technique does not affect fruit production. The AE system is a promising option to study the interaction between crops and bio-stimulants, aiming to improve agricultural sustainability.

Keywords: controlled nutrition, agricultural intensification, bio-stimulants, agricultural sustainability.

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INTRODUCTION

Population growth has driven the demand for vegetables. While it demands higher yields with lower consumption of water, space, and fertilizers (Debangshi, 2021), also requires to be aligned with sustainability and the reduction of the carbon footprint (Vinci and Rapa, 2019; Kumari *et al.*, 2023). Therefore, it remains important to have alternatives for all types of current and future scenarios, in the context of a circular production system, derived from the circular economy paradigm which seeks the sustainability of any

productive activity (Schroeder *et al.*, 2019). In this context, hydroponic production systems have become relevant, and they are classified into i) those that are based on solid media (substrates and soil), and ii) those that are based on liquid media (circulating or static). Both types meet the definition of hydroponics which, according to the Greek roots (ύδρο- hydro, “water” and Πόνος- pónos, “work”), means “to work in water” or “cultivation in water” (Debangshi, 2021).

Substrates can be organic such as peat (T), coconut fiber (FC), minerals (clays, natural or processed rock), or synthetic (polymers), whose availability in the production area is key to their economic viability. Their function is to provide a means of growth and anchoring of the roots, so they are classified as inert when they only serve as support, or active if they are involved in plant growth (Mixquititla-Casbis *et al.*, 2022). Liquid media systems, on the other hand, eliminate the use of substrate, but require greater technical control and high investment (Lakhiar *et al.*, 2018). They are circulating, when there is movement of the nutrient solution and, where appropriate, recirculation [such as NFT (Nutrient Film Technique) and aeroponics], and they are static or stationary when there is no movement of the solution (floating roots), but the oxygen level is controlled (Buckseth *et al.*, 2016). These systems, used in an intensive and precise agriculture, allow adaptable and controlled production (Folta, 2019).

Tomatoes (*Solanum lycopersicum* L.) are one of the most widely grown vegetables worldwide (Kusumiyati *et al.*, 2023). In 2022, Mexico produced 4 207 889.22 Mg, which represents 1.65% of world production; so was ranked as the 8th largest producer in the world (FAOSTAT, 2024). Cherry tomatoes represent 3.5% of national production (121 476.32 Mg). Since 2020, production has increased 27%, in addition 43% is destined for exports, and 78% is grown in a protected environment, closely related to hydroponics (SIACON, 2024).

The choice of a production system depends on the socioeconomic context, and sometimes, technical feasibility is sacrificed. To evaluate differences among systems, in this research we compared substrates of different origin (coconut fiber, lava rock [‘tezontle’], peat+vermiculite) with an aeroponics system. A cluster analysis was used to determine similarities, considering agronomic and yield parameters, aiming to validate the use of the aeroponics system in subsequent research where beneficial microorganisms may be used as bio-stimulants of crops in hydroponics systems.

MATERIALS AND METHODS

The experiment was established at the facilities of the Colegio de Postgraduados [colpos.mx] Campus Montecillo (19° 27’ 39.20” N, 98° 54’ 15.07” W) at an altitude of 2246 m, in a greenhouse with a gable-glass roof (chapel roof) during May to November 2021.

Plant material

Cherry tomato plants (*Solanum lycopersicum* L. var. cerasiforme), obtained from seeds, were used. This plant is shrubby (50-80 cm), with yellow flowers, green fruits in the immature state and red fruits in the mature state; with clusters of 4 to 6 flowers (Galicia Loyola, 2020). This variety was selected because it grows spontaneously all over the world in tropical and subtropical regions. It has been collected in a wide range of habitats, at altitudes ranging from sea level up to 2400 m; mainly because it has been used in trials for the validation of technologies applied to commercial varieties of *S. lycopersicum* (Martínez-Cuenca *et al.*, 2020).

Aeroponics system

An aeroponics system (AE) was designed using 72 L capacity black plastic boxes, to prevent sunlight from reaching the roots. These boxes were adapted to allow a pipe system 1" polyvinyl chloride (PVC) to pass through for irrigation. Inside each box, three micro-sprinklers with four (20.8 L h^{-1}) outlets were installed, which provided 9.3 L per day per box, and 2.3 L of nutrient solution per plant (four plants in each box). In the lid of the containers four perforations were made with the exact diameter to introduce baskets used in floating root hydroponics. This system was replicated four times (for comparison with the substrates, only one of the boxes with four plants was taken). The four boxes and their nebulizers were fed with Steiner's nutrient solution (Steiner, 1961), adjusting this nutrition to each phenology stage of the crop (Table 1). The solution was added by a 1 HP (13 A) pump, which before entering the boxes passed through a filter system.

Substrate systems

Three substrates commonly used in tomato production were selected: coconut fiber, peat+vermiculite (1:1 v/v), and lava rock ('tezontle'). These were arranged in black and white bags, with a capacity of 15 L, this was repeated four times for each substrate. Each group of bags was supplied with Steiner's nutrient solution (nutrition that was adjusted to each phenology stage of the crop), by means of a fertigation system equipped with drippers and 8 L h^{-1} drip stakes, which were fed with a 1/2 HP pump. Two stakes were left in each pot which supplied 2.3 L of nutrient solution per day per pot.

Seedbeds

The cherry tomato seeds were disinfected with 30% sodium hypochlorite (NaClO) for 5 min, then washed with distilled water and allowed to dry. Subsequently, they were sown in polystyrene seedbeds with 50 cavities, with a volume of 60 cc per cavity. The

Table 1. Description of the nutrient solutions applied, detailing the balance between cations and anions.

Phenological stage	Salinity		Nutrients (mg L^{-1})					
	OP (MPa)	EC (dS m^{-1})	N-NO_3	P-PO_4	S-SO_4	K	Ca	Mg
20 days in seedbeds	0.018	0.5	42.0	7.7	27.3	68.6	45	12
28 days in seedbeds	0.036	1.0	84.1	15.5	55.9	136.5	90	24
Vegetative growth	0.055	1.5	126.1	23.2	83.2	205.1	135	36
Flowering	0.073	2.0	168.1	31.0	111.9	273.0	180	48
Tying of fruit and harvesting	0.109	3.0	252.2	46.5	167.8	409.5	270	72

OP: Osmotic pressure; EC: Electrical conductivity; N-NO_3: nitrogen as nitrates; P-PO_4: Phosphorus as phosphates; S-SO_4: sulfates; K: potassium; Ca: calcium; Mg: magnesium.

seedbed was installed on May 28, 2021 and was allowed for 31 days, up to 28 days after emergence (DAE). Then, plants were transplanted to the growing systems, aeroponics and substrates. During this time, irrigation with Steiner's nutrient solution at 25% was supplied for 20 days, then Steiner's nutrient solution at 50% for the remaining days until 28 DAE.

Application of nutrient solution

Plants were fertigated (irrigated with fertilizer) in the substrates, and nebulized in the aeroponics system with Steiner's nutrient solution, at different concentrations according to the phenology stage, preserving the balance between cations and anions (Table 1). The nutrient solutions were prepared from a mixture of commercial fertilizers such as $Ca(NO_3)_2 \bullet 4H_2O$, KNO_3, KH_2PO_4, $MgSO_4 \bullet 7H_2O$, K_2SO_4, and a commercial micronutrient blend (Tradecorp® AZ) at a rate of 42.85 mg L^{-1}, with sulphuric acid (H_2SO_4) for pH adjustment (5.5-6.5) and as sulphates supply.

Variables evaluated

Data on vegetative growth were collected including plant height (FH-8M Tape measure Truper®, Mexico), number of leaves, and stem diameter (LEIDSANY® Vernier caliper, Britt Technology Inc., American Samoa). For all plants, the number of lateral shoots was counted, as well as their length and diameter (LEIDSANY® Vernier caliper, Britt Technology Inc., American Samoa). For the flowering stage, the flower buds and the number of flowers were counted, as well as the number of fruits, at set and at maturation. From harvested fruits, we recorded number and weight (digital scale, Diyife® China) as yield variables. In the end, plants were harvested to determine the total weight of fresh and dry biomass (digital scale, Diyife®, China). Yield was estimated with the average weight of the fruits and the number of flowers that the plants had at the time of harvesting. These variables were measured each week throughout the experiment, anytime their measurement were required.

Design and statistical analysis

The established experiment included four treatments with four replicates, in a complete randomized design. The experimental unit was a plant of *S. lycopersicum* L. var. cerasiforme. To determine the similarity or difference of the substrates according to the physiological and production responses of the plants, a cluster analysis was performed on three data sets of recorded variables, 1) the complete set of 55 variables, 2) the 25 physiological variables, and 3) the 30 production variables.

Ward's minimum variance method was used, in order to minimize the sum of squares within each group, to create naturally close-related groups (Strauss and von Maltitz, 2017). Data were standardized into a normal distribution with mean 0 and variance 1 to prevent the scale of the data from influencing clustering.

Data were also analyzed using analysis of variance ($p \leq 0.05$) and a multiple means comparison test (Tukey, $p \leq 0.05$) (SAS Institute Inc., 2013) to determine differences among treatments. For the analysis of production, data were previously managed with the area under the curve method, since the data were recorded on different dates; then, these areas were compared with an analysis of variance (SAS Institute Inc., 2013).

RESULTS AND DISCUSSION

Cluster analysis

The cluster analysis performed with all the evaluated variables and vegetative variables indicated that there are two groups clearly defined by the Ward method (data not graphed). For the variables overall, in the first group only the FC substrate was found, and in the second group AE, TZ and TV were associated. In the case of vegetative variables, grouped as measured on different sampling dates, the first group included FC and TZ, and the second group, AE and TV (data not graphed). For the production variables, also grouped as measured on different sampling dates, the cluster analysis did not show groups clearly defined by the Ward method; it is possible that distance was not sufficient to differentiate groups.

Other experiments, comparing the nutritional content of varieties of *S. lycopersicum* grown on different substrates in protected environments, highlighted that the differences found in nutrition are due to the environmental conditions of growth. Or else, to the intrinsic characteristics of the varieties, which are not associated by the effect of the substrate when it is chemically inert (Ozyigit *et al.*, 2024). So, assuming that plant growth and production are consequences of plant nutrient balances (Lara-Herrera *et al.*, 2023), then the results of evaluations on specific dates would show significant differences.

Plant height showed significant differences after 49 DAT, when TV and FC treatments were better (95 and 94 cm, respectively) compared to AE (76.75 cm) (Figure 1A). DIAM showed significant differences after 49 DAT, TV treatment (8.15 mm) outperformed the rest of the treatments. It is important to note that AE treatment was not statistically different from FC and TZ for this variable (Figure 1B). The number of leaves after 28 DAT showed significant differences, with AE and TV treatments (15 leaves) presenting on average 1.5 leaves more than TZ and FC (Figure 1C).

The number of lateral shoots had significant differences on dates 42 and 49 DAT, when AE treatment showed the highest number of sprouts on both dates (9 y 12.5, respectively, Figure 2A). Each shoot length showed significant differences on both dates, only the TV treatment was outstanding at the end (27.5 and 48.25 cm, respectively); there was no statistical difference among the rest of treatments (Figure 2B). The DIAM of the shoots was also measured at the same dates, when the TV treatment (6.35 and 6.82 mm, respectively) was outstanding compared to the other treatments; those were statistically equal at 42 DAT. At 49 DAT, the AE treatment showed the significantly smallest DIAM 5.37 mm, compared to the rest of the treatments (Figure 2C).

Regarding yield variables at 42 DAT, the number of flowers in AE treatment showed significant differences compared to TZ and TV, these in turn were different from FC, which did not show flowering on that date. At 49 DAT, the TV treatment showed significant differences compared to the other treatments (Figure 3A). At 120 DAT, no significant differences were found in the number of flowers, indicating that flower production had stabilized for all treatments (Figure 3B).

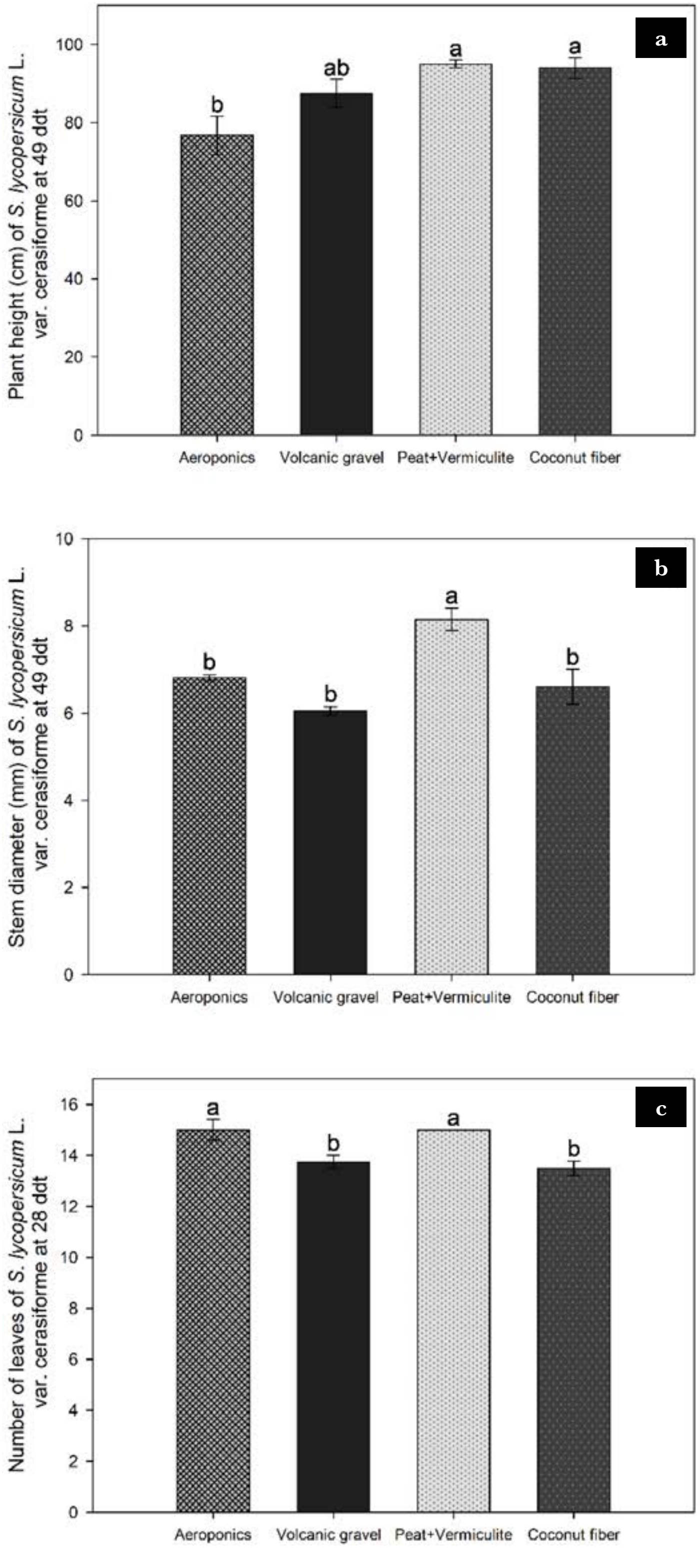

Figure 1. A: plant height, B: stem diameter and C: number of leaves of Cherry tomato (*Solanum lycopersicum* L. var. cerasiforme) grown in four cultivation systems: lava rock ('tezontle'), peat+vermiculite, coconut fiber, and aeroponics, evaluated at 28 and 49 DAT. Means ± standard error. Different letters in each graph indicate significant differences (Tukey, $p \leq 0.05$; n=4). DAT: days after transplant.

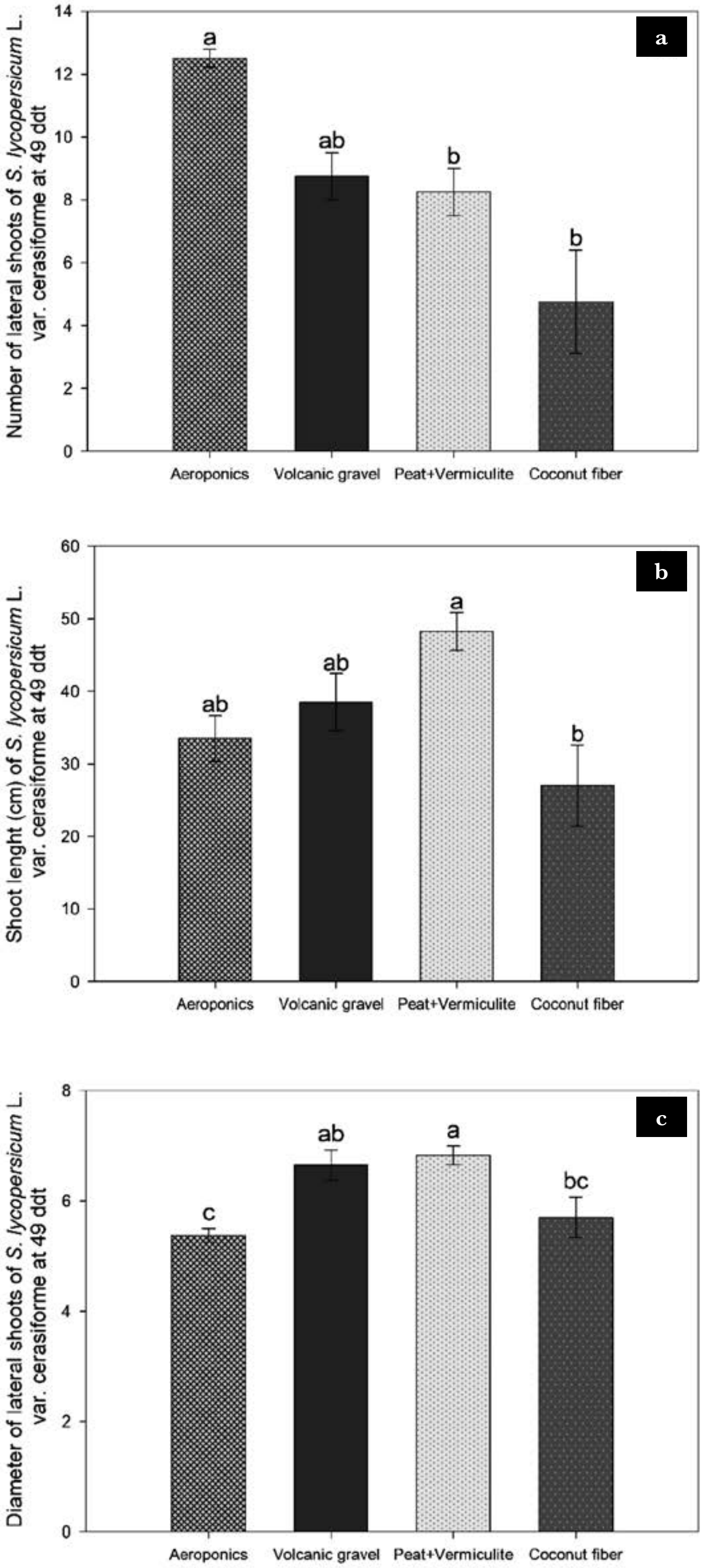

Figure 2. A: lateral shoots, B: length of lateral shoots, and C: diameter of lateral shoots of Cherry tomato plants (*Solanum lycopersicum* L. var. cerasiforme) grown in four cultivation systems: lava rock ('tezontle'), peat+vermiculite, coconut fiber, and aeroponics, at 49 DAT. Means±standard error. Different letters in each graph indicate significant differences (Tukey, p≤0.05; n=4). DAT: days after transplant.

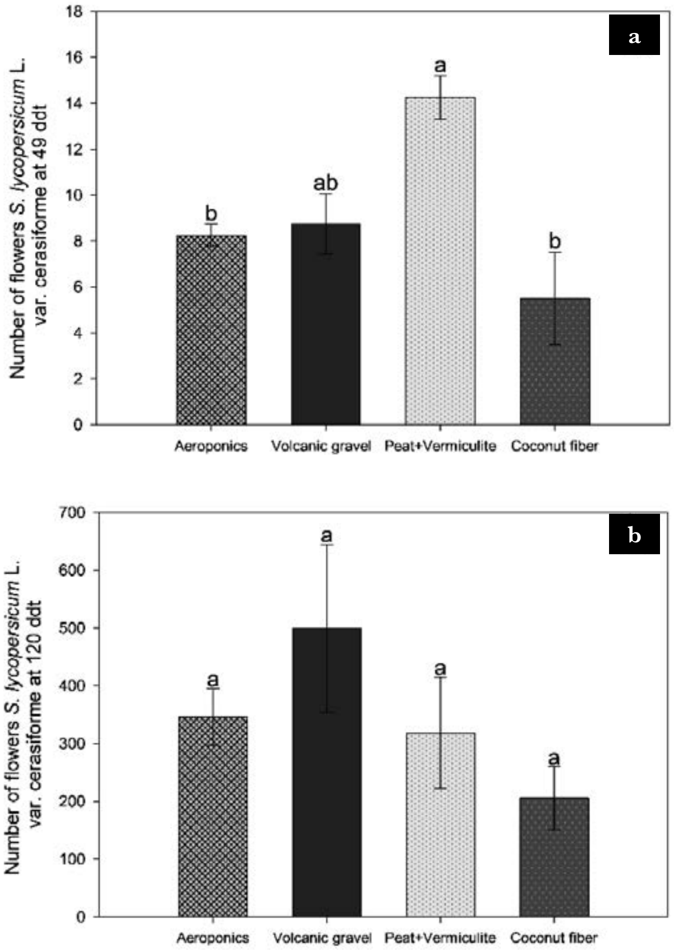

Figure 3. Number of flowers at A: 49 DAT and B: 120 DAT of Cherry tomato plants (*Solanum lycopersicum* L. var. cerasiforme) grown in four cultivation systems: lava rock ('tezontle'), peat+vermiculite, coconut fiber, and aeroponics. Means±standard error. Different letters in each graph indicate significant differences (Tukey, $p \leq 0.05$; n=4). DAT: days after transplant.

The first count of fruits was done at 49 DAT; no significant differences were found due to the high coefficient of variation (80%), because in those plants where no fruits were counted, absence was recorded as "zero" value. However, on that date, AE and TV treatments presented an average of 7 and 5 fruits, respectively, while TZ and FC treatments presented on average 2.5 and 0.25 fruits at the beginning of fruit setting. Therefore, production was analyzed as a cumulative effect and not as a one-off event with the area under the curve method, the progress of the harvest in this case.

Fruits were harvested at 88, 91, 95, 99, 103, 108, 114 and 120 DAT. In this analysis, no significant differences were found either in the area under the curve of the number of fruits or in the fresh weight of fruits. These results do not allow us to reject the null hypothesis, which indicates that there is no effect of the growing substrate on cherry tomato production (Figure 4A). The average weight of the fruits, the total weight of the harvested fruits, and the estimated yield were also analyzed, in which no effect of the growing substrate was recorded (Figures 4B, 4C, 4D).

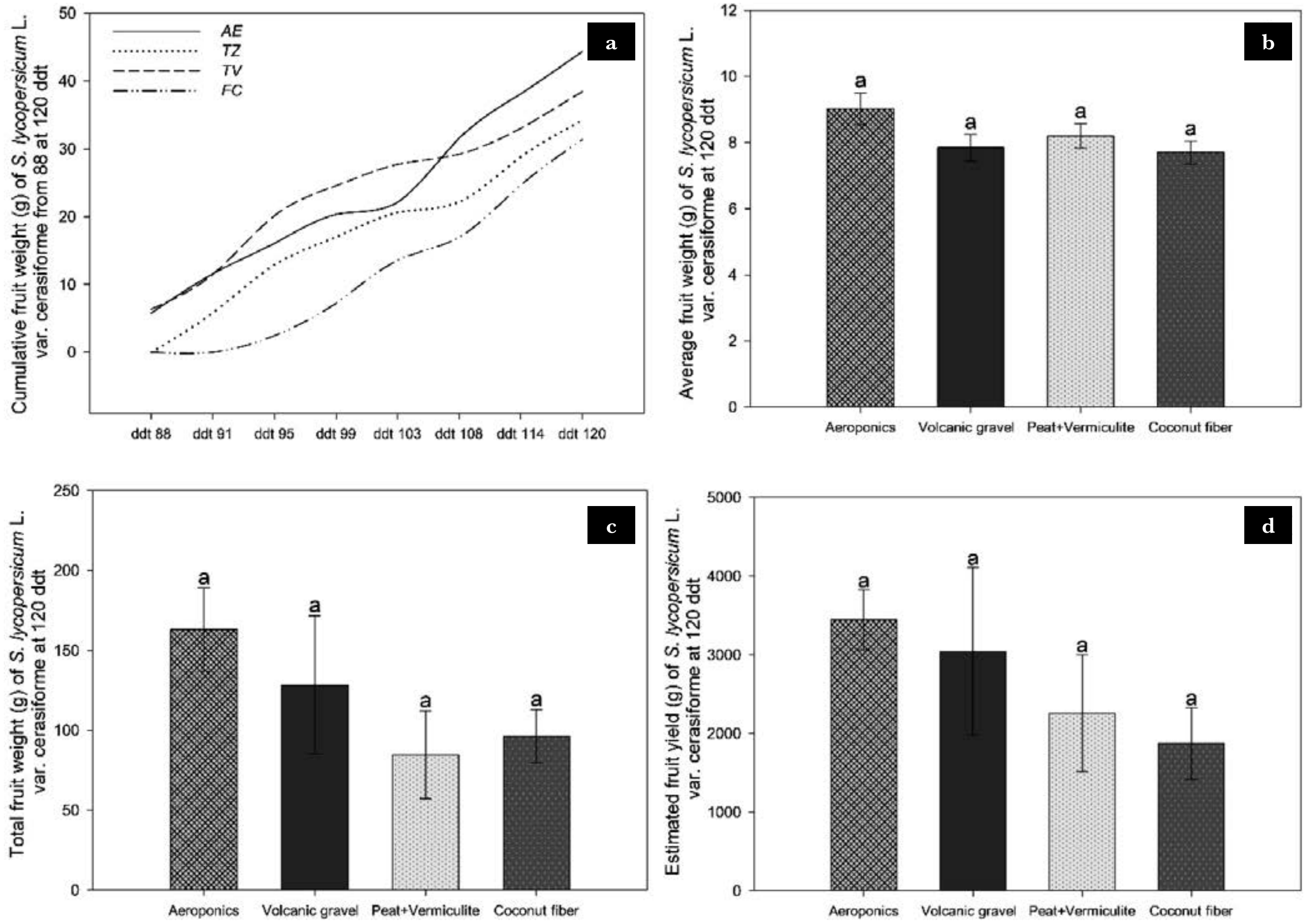

Figure 4. A: cumulative weight of fruits harvested from 88 to 120 DAT, B: average weight of harvested fruits at 120 DAT, C: total weight of harvested fruits at 120 DAT, and D: estimated yield of Cherry tomato plants (*Solanum lycopersicum* L. var. cerasiforme) grown in four cultivation systems: lava rock ('tezontle'), peat+vermiculite, coconut fiber, and aeroponics. Means±standard error. Different letters in each graph indicate significant differences (Tukey, $p \leq 0.05$; $n=4$). DAT: days after transplant.

These results are similar to those reported by Ramírez Gómez (2015) when comparing different mixtures of pumice, perlite, vermiculite or coconut fiber to produce tomato SUN7705. Those authors found significant differences in vegetative variables such as stem diameter, but not in yield per plant, since all treatments were statistically the same for yield and fruit quality. Similar results have been reported by Ojodeagua-Arredondo *et al.* (2008) for the commercial yield of *L. esculentum* Mill. cv. 'Gironde' grown on two substrates (tezontle and soil of the Mexican Bajío area) whose commercial yield was not statistically different, under similar management and nutritional conditions.

On the other hand, Martínez-Rodríguez *et al.* (2017) evaluated and compared 'tezontle' and a mixture of 'tezontle' with compost, and found specific differences per cluster of fruits in quality variables, but not in the global average between treatments. Even when comparing two hydroponic systems, one open and one closed, no significant differences were found in tomato yield or in the classification by fruit quality, all evaluations under the same nutrition and irrigation conditions, without variation in environmental conditions (Rosa-Rodríguez *et al.*, 2020). In turn, when comparing organic tomato production systems between soil and substrate, no significant differences were found in yield or fruit quality, although there were significant differences in nutrition variables and in the efficiency of the cultivation system (Carballo-Méndez *et al.*, 2018).

In this research, the only factor of variation was the growing substrate, where the variety, environmental conditions, nutrition and amount of irrigation were the same. Therefore, the existence of significant differences at specific times could be explained, but when analyzing the overall set of variables evaluated, most of them did not present significant differences. This response was proved by the cluster analysis, in which all the variables showed that two of the three chosen substrates did not differ in their results compared to AE.

On the contrary, there are also studies in which one substrate is outstanding in tomatoes yield in regard to the soil and other substrates. Ortega Martínez *et al.* (2016) reported that 'tezontle' generated statistically different fruit yields compared to coconut fiber, soil, and a mixture of sawdust and compost. All those substrates were maintained with nutrient solution throughout the plant phenology, but with variations in nutrient levels, which introduced a variation factor that was not considered. On the other hand, Valqui *et al.* (2021) compared substrates of organic origin (rice husks in different combinations with sand and sawdust) to produce tomatoes. Those authors found significant effects on plant height and stem diameter; also, unlike our study, they found differences in yield, but did not specify the nutritional balance with which they made their evaluations.

Other experiments similar to our research were conducted by Komosa *et al.* (2014), who compared the yield of tomato cv. Alboney F1 grown in a greenhouse with a processed mineral substrate (rock wool), and contrasting an open irrigation system with a closed one, and to aeroponics cultivation. Their results indicated higher total and marketable yields in the closed system compared to that obtained in the open system, and in aeroponics, respectively. The initial design of that aeroponics system consisted of a U-shaped gutter (11 cm×15 cm×14 m) with plants placed every 50 cm and nebulizers at 25 cm from the roots, which limited the space for root development and affected yield. In subsequent studies, when comparing substrates (rock wool, polyurethane foam) and agricultural production techniques (NFT and aeroponics), aeroponics excelled in fruit yield. This was achieved by adjusting the system to allow the roots to hang freely, while the gutter was used for the NFT technique (Komosa *et al.*, 2020). Unlike the aforementioned study, the aeroponics conditions in our research allowed free root growth, which provides greater physiological and production benefits.

When analyzing similar studies, some aspects that could have influenced this study include water use, fertilizer consumption, and yield per area unit, where aeroponics offers advantages compared to substrates and soil (Komosa *et al.*, 2020; Pomoni *et al.*, 2023). Hydroponic systems that use substrates or other growing media for plants are a reality, although they are still limiting both technologically and economically. These systems optimize the use of resources in growth and production. Aeroponics represents a significant advance within hydroponic systems in terms of technical knowledge and handling. Although its results do not differ from those obtained with traditional hydroponic systems that use substrates, aeroponics is considerably more efficient in the use of water resources.

When yield was evaluated using alternative methods to analysis of variance and comparison of means, such as cluster analysis and the area under the curve, no statistical differences were found between substrates and aeroponics, under the same environmental and management conditions. This suggests that aeroponics is more efficient, which allows us to affirm that, in the specific case of cherry tomato, larger plants do not necessarily signify a greater production volume.

CONCLUSIONS

The comparative analysis among substrates of different physical composition and an aeroponics system allowed us to obtain a comprehensive view of the similarity and differences in yield and vegetative development of a Cherry tomato crop in a controlled context. Cluster analysis showed that the vegetative variables present greater differences among cultivation systems, compared to the production variables. This suggests that, despite some substrates share similar characteristics in terms of yield, differences in vegetative development could influence the choice of a cultivation system for more specific research.

The intermediate position of the aeroponics treatment in the generated groups indicates that this system can perform in a similar way to the use of substrates, especially when grouped with the peat+vermiculite treatment in the response of the vegetative variables. This validates aeroponics potential as a feasible system for future research, including studies on the use of beneficial microorganisms as bio-stimulants in hydroponic systems. Therefore, the aeroponics system can be considered a useful option to explore the interaction between crops and bio-stimulants, with a view to optimizing sustainable agricultural production.

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