Evaluation of electrical conductivity and pH in a nutrient solution with recirculating system in rose crop

Evaluación de la conductividad eléctrica y el pH de una solución nutritiva con sistema de recirculación en el cultivo de rosa

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ABSTRACT

Soilless culture systems with drainage recycling require continuous monitoring of electrical conductivity (EC) and pH, which are basic indicators of the chemical state of the solution that determine the extent to which recycling of nutrients is possible. These indicators are influenced by the physical, chemical, and microbiological properties of the substrates, as well as evapotranspiration, substrate temperature, and the stage of plant development. A rose crop cv. 'Charlotte' was established in three different substrates composed of mixtures of coconut fiber (CF) and burned rice husk (BRH). An automatic drainage recycling system was implemented with three percentages of nutrient recycling (0, 50, and 100%) to record the changes in EC and pH over 8 weeks of cultivation. This bifactorial experiment was carried out under a split-plot design in randomized complete blocks, where the main plot corresponded to the recycling percentage factor and the subplot to the substrate factor. The EC was significantly higher when recycling the nutrient solution in the following substrates: 35% BRH and 65% CF (35BRH) and 65% BRH and 35% CF (65BRH) at 1, 2, and 3 weeks after pruning (WAP). It was also higher for 100% BRH (100BRH) and 65BRH at 7 and 8 WAP. At 6 WAP, recycling at 50% and 100% had a significant effect on the EC values independent of the substrate. This could be caused by the release of ions and higher water retention, typical of CF, and the high adsorption of ions by the BRH. For pH, the trend was acidification, which was significant for the 100BRH treatment without recycling between 0 and 4 WAP. This could be related to changes in the absorption of ions such as NO_3^- and the activity of nitrifying microorganisms facilitated by the properties of the CF.

Key words: horticulture, cut flowers, recirculation drainage, soilless culture, substrate.

RESUMEN

Los sistemas de cultivo sin suelo con reciclaje de drenajes requieren del seguimiento continuo de variables determinantes como la conductividad eléctrica (CE) y el pH, indicadores básicos del estado químico de la solución que determinan hasta dónde son posibles los eventos de reciclaje. Estas variables son influenciadas por las propiedades físicas, químicas y microbiológicas de los sustratos, la evapotranspiración del cultivo, la temperatura de los sustratos, y el estadio de desarrollo de las plantas sembradas. Un cultivo de rosa cv. 'Charlotte' se estableció en sustratos compuestos por tres diferentes mezclas de fibra de coco (FC) y cascarilla de arroz quemada (CAQ), donde se implementó un sistema automático de reciclaje de drenajes con tres porcentajes de reciclaje de nutrientes (0, 50 y 100%), con el objetivo de conocer los cambios en CE y pH a lo largo de 8 semanas de cultivo. Este experimento bifactorial se llevó a cabo bajo un diseño de parcelas divididas en bloques completamente al azar, donde la parcela principal correspondió al factor porcentaje de reciclaje y la subparcela al factor sustrato. A las 1, 2 y 3 semanas después de la poda (SDP) la CE fue significativamente mayor al reciclar la solución en los sustratos: 35% CAQ con 65% FC (35CAQ) y 65% CAQ con 35% FC (65CAQ) y a las 7 y 8 SDP lo fue para 100% CAQ (100CAQ) y 65CAQ. A las 6 SDP hubo un efecto significativo de 50% y 100% de reciclaje independiente del sustrato. Lo anterior pudo ser causado por liberación de iones y alta retención de agua, propias de la FC y la alta adsorción de iones por la CAQ. Para el pH, la tendencia fue la acidificación, siendo significativa para el tratamiento 100CAQ sin reciclaje entre 0 y 4 SDP, lo que posiblemente se relaciona con los cambios en la absorción de iones como el NO_3^- y la actividad de microorganismos nitrificantes, facilitada por las propiedades de la FC.

Palabras clave: horticultura, flores de corte, recirculación de drenaje, cultivo sin suelo, sustrato.

Introduction

Colombia is the second largest exporter of flowers in the world, after the Netherlands, with a 20% market share. Roses dominate this export, making up 19.1%, with the USA as the primary destination, comprising 79.7% of the total export value (ICA, 2024).

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A modern cultivation technique in roses uses suspended container beds. To prevent salinization of the growth media, drainage must account for 30 to 50% of the applied fertilizer solution. This increases water consumption and negatively impacts the environment, with fertilizers being lost when drained into the ground. This could be minimized with their recycling (Blok, 2023). Key variables in soilless culture systems are the temperature and aeration of the rhizosphere, the pH of the nutrient solution, the NH_4^+:NO_3^- concentrations and ratio, the size of the container or root volume, the medium of growth, and the electrical conductivity (EC) of the solution (Kafkafi, 2001).

Maas *et al*. (1986) modeled plant tolerance to salts by defining: 1) salinity threshold value (STV), which is the maximum salinity value at which there is no significant decrease in growth or yield, and 2) the decrease in yield due to salinity (DYS), which indicates the percentage decrease in yield for each unit increase in EC above the STV. Sonneveld *et al.* (1999) concluded that the absorption of sodium and chloride by the plants increased as their concentrations in the root environment increased, potentially benefitting salinity management, depending on the species. For carnation (*Dianthus caryophyllus* L.), STV was 4.3 dS m^{-1}, with a DYS of 3.9% per dS m^{-1}, whereas for rose (*Rosa* sp.), STV was 2.1 dS m^{-1} and DYS 5.3% per dS m^{-1}. Other authors mention EC values in soil extract no higher than 1.5 dS m^{-1} for rose (Cabrera *et al*., 2017).

EC values above the STV decrease yield mainly due to osmotic effects, which are influenced by the composition of the nutrient solution (Stamatakis *et al*., 2003). Salinity affects the quality of cut flowers, decreasing stem diameter and length as well as firmness and vase life (De Kreij & Van Den Berg, 1990). Under saline conditions, gerbera (*Gerbera* sp.) and rose react by reducing the number of flowers, while carnation and bouvardia (*Bouvardia* sp.) adjust flower weight instead (Sonneveld *et al*., 1999).

In addition to EC and pH, the preparation of the initial fertilizer solution must consider nutrient concentration relationships and water quality. The pH in the root zone for most hydroponic cultures is between 5.5 and 6.0; pH values between 5.0-5.5 and 6.5-7.0 would not cause problems in most cultures (Signore *et al*., 2016). However, pH values greater than 7.0 could cause problems in the absorption of P, Fe, and Mn, as well as possible symptoms of Cu and Zn deficiency (Meselmani, 2022).

The pH in a substrate system varies during the growing season due to the reduced container volume, especially when the substrate has a low buffering capacity as in the case of low reaction substrates, while in organic substrates pH is more stable. The buffering capacity of the nutrient solution is typically very low and almost only determined by phosphate concentrations (Sonneveld & Voogt, 2009). In periods of high growth rate and sufficient light intensity, anion absorption normally exceeds cation absorption, due to a high absorption of NO_3^- used in plant metabolism. This difference in ion absorption rate is mitigated by the release of HCO_3^- and OH^- to the rhizosphere by the roots (Neumann & Ludewig, 2023), increasing the pH of the root zone. However, under conditions of low light intensity, this situation is reversed, with decreases in NO_3^- absorption and increases in the cation:anion absorption ratio; the rapid uptake of cations is compensated by the release of H^+ by the roots (Nietfeld & Prenzel, 2015).

Excess nitrate in the recycled nutrient solution increases dry mass allocation to leaves at the expense of buds and inflorescences. The pH values of the nutrient solution between 3.0 and 4.0 increase the absorption of P and its concentration in leaves, reducing the sucrose biosynthesis and negatively affecting the yield in flower production. Bar-Yosef *et al*. (2009) and Masood *et al*. (2023) found that appropriate mixtures of NO_3^-, NH_4^+, and urea reduce the harmful effects produced by changes in pH, including ionic imbalances and competition for absorption of Ca, P, and Mn, among other elements.

The pH in the solution can be controlled by modifying the NH_4^+:NO_3^- ratio in the recycled solution, applying the required nitrogen in nitric form and applying an acid. The salt load in the system is reduced by eliminating the need for additional acid; however, NH_4^+ could inhibit the absorption of Ca^{2+}, Mg^{2+} and K^+ by the roots and negatively affect root development (Bar-Yosef, 2008; Coleto *et al*., 2023).

This research aimed to determine the effects of drainage recycling at 0%, 50%, and 100% in three organic substrate mixtures: 100% burned rice husk (100BRH), 65% burned rice husk and 35% coconut fiber (65BRH), and 35% burned rice husk and 65% coconut fiber (35BRH). The focus was on assessing pH and electrical conductivity (EC) values of the nutrient solution from 0 to 8 weeks after pruning (WAP) in rose plants cv. 'Charlotte' grown in a commercial plastic-covered system.

Materials and methods

Plant material and growth conditions

The research was carried out at the Center for Agricultural Biotechnology of SENA located in the municipality of

Mosquera (Cundinamarca, Colombia) (4°41' N, 74°13' W, 2516 m a.s.l.), with an annual average temperature of 12.6°C and precipitation of 670 mm. The site corresponds to lower montane dry forest (bs-MB) life zone (Guzmán González, 1996).

A traditional wooden plastic cover was used (AgroClear® plastic, Productos Químicos Andinos, Colombia) with five spans of 65 x 6.8 m each. The rose cv. 'Charlotte' was grafted onto the rootstock 'Natal Briar' and grown in 33 raised beds of 15 x 0.8 m. 8 L pots were placed for a planting density of 7 plants m^{-2}.

The fertilizer formula, in mg L^{-1}, was as follows: 170 total N (15% NH_4^+); 35 P; 150 K; 110 Ca; 60 Mg; 82 S; 1 Mn; 0.5 Zn; 0.5 Cu; 3 Fe; 0.5 B; and 0.1 Mo. This formula was prepared according to the commercial formulas used in the region and adjusted according to the characteristics of the water. The phytosanitary management was carried out according to standard practice for this crop. Organic substrates consisted of a mixture of burned rice husk (BRH), with a burning degree between 70 and 100%, and washed coconut fiber (CF) in different proportions (Tab. 1): 100% burned rice husk (100BRH), 65% burned rice husk and 35% coconut fiber (65BRH), 35% burned rice husk and 65% coconut fiber (35BRH).

An automatic drainage recycling system (ADRS) was implemented to recycle drainages at three levels: 0%, 50%, and 100%. The ADRS is detailed in Cuervo *et al.* (2012) and Cuervo-Bejarano *et al.* (2011).

Data analysis

The experiment consisted of nine treatments, achieved by combining the three levels of recycling percentages with the three types of substrates, each repeated three times (Tab. 2). Each experimental unit corresponded to a raised bed. A bifactorial experiment was carried out under a split-plot design with randomized complete blocks. The main plot was based on the recycling percentage factor, and the subplot was determined by the substrate factor.

The statistical model used for the analysis was:

$$Y_{ijk} = \mu + \alpha_i + \delta_k + \eta_{ik} + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \quad (1)$$

with: $i = 1, 2, 3; j = 1, 2, 3; k = 1, 2, 3$

where:

μ = effect of the overall mean;

α_i = effect of the *i-th* level of the recycling percentage factor;

δ_k = effect of the *k-th* block;

η_{ik} = effect of random error on the main plot (recycling percentage per block);

β_j = effect of the *j-th* level of the substrate factor;

$(\alpha\beta)_{ij}$ = effect of the *ij-th* interaction between the two factors (recycling percentage per substrate;

ε_{ijk} = effect of random error in the subplot;

Y_{ijk} = observation in the *k-th* block of the *i-th* level of the percentage recycling factor and the *j-th* level of the substrate factor.

TABLE 2. Treatments evaluated in rose cv. 'Charlotte' grown in substrates with automatic drainage recycling.

Treatment	Substrate	Percentage of drainage recycling
100BRH-0R*	100BRH	
65BRH-0R*	65BRH	0
35BRH-0R*	35BRH	
100BRH-50R	100BRH	
65BRH-50R	65BRH	50
35BRH-50R	35BRH	
100BRH-100R	100BRH	
65BRH-100R	65BRH	100
35BRH-100R	35BRH	

100BRH = 100% burned rice husk; 65BRH = 65% burned rice husk and 35% coconut fiber; 35BRH = 35% burned rice husk and 65% coconut fiber; R – percentage of drainage recycling.
*Treatments that did not enter the automatic drainage recycling system.

TABLE 1. Chemical properties of the substrates used in the experiment.

Substrate	pH	EC	OC	N	P	Ca	K	Mg	Na	Cu	Fe	Mn	Zn	B	S
		(dS m^{-1})				(%)						(mg kg^{-1})			
100BRH	5.53	6.82	27.2	0.51	0.06	0.11	0.01	0.04	0.03	4.4	225	136	54	28	481
65BRH	5.31	6.52	23.6	0.39	0.08	0.4	0.01	0.06	0.08	13.4	433	87	50	34	470
35BRH	5.18	5.18	6.04	26.6	0.5	0.06	0.16	0.01	0.17	19.1	704	66	47	-	548

EC – electrical conductivity, OC – organic carbon.

Drainage from each experimental unit was collected in a 20 L container and the EC (dS m^{-1}) and pH were recorded daily between weeks 0 and 8 after pruning (WAP) using a portable Oakton AN 23 (Cole-Parmer, USA). The statistical software R (R Core Team, 2020) was used for performing the analysis of variance (ANOVA) and the subsequent Tukey's comparison test ($P<0.05$) for multiple comparisons (de Mendiburu, 2023). Scientific visualizations were made using the ggplot2 package v3.4.2 (Wickham, 2016).

Results and discussion

The chemical characteristics of the recycled nutrient solution varied, possibly due to the interactions with the physical and chemical characteristics of the organic substrate, the microbiological dynamics, the roots exudates, and the climatic conditions, among others. Emphasis was placed on the concentration of ions and their potential environmental impact, in addition to their influence on EC, a critical factor determining the useful life of the solution to be recycled.

Electrical conductivity (EC)

An increasing trend of the EC was observed over time. Initially, the substrates with higher percentages of CF increased the EC of the drainages, especially when recycling occurred. However, over time, these effects on EC diminished and no significant differences were observed (Tab. 3). At 1, 2, and 3 WAP, the EC was significantly higher ($P<0.05$) in the drainages from the treatments that contained CF (35BRH and 65BRH). At 6 WAP, a significant effect of the substrate was not determined; however, a significant effect of the recycling (50% and 100%) was observed.

At 7 WAP and 8 WAP, the trend reversed. The substrates with CF had no effect on EC, and at higher BRH contents the EC significantly increased in the drained solutions (Tab. 3). This behavior may be associated with the release of ions from the CF, such as Na^+, K^+, NH_4^+, NO_3^-, Fe^{3+}, and S (Tab. 1). However, it is also possible that over time the CF has become saturated with ions (Okafor *et al.*, 2012; Song *et al.*, 2014), resulting in minimal adsorption and increased leaching. The low EC values may be explained by high plant demand for mineral elements that contribute significantly to the EC and that are being absorbed during the vegetative growth phases; therefore, the content of these ions in the solution was reduced (Bugbee, 2004; Van Der Sar *et al.*, 2014). While EC values during the evaluated period did not exceed those reported for DYS, they did exceed those for STV (Sonneveld *et al.*, 1999).

When BRH undergoes the carbonization process, its surface area and mineral fixation capacity increase, which makes it an appropriate material for the adsorption of heavy metals, Ca^{2+}, $Fe^{3+,}$ Cu^{2+}, and Zn^{2+} (Kuan *et al.*, 2011; Phonphuak & Chindaprasirt, 2015) and as an acidity corrector in soils (Islabão *et al.*, 2014; Kath *et al.*, 2018). In this study, significant evidence was found that higher BRH content in the substrate and higher percentage of drainage recycling leads to increases in the EC in the drainages over time (Tab. 3), possibly due to the degradation of the material or the increase in the adsorption of cations that saturate the exchange sites, decreasing the cation exchange capacity. It is possible that BRH adsorbs Ca^{2+} and Mg^{2+} from the nutrient solution, which agrees with what was found by Vélez-Carvajal *et al.* (2014) in a carnation crop planted in the same mixtures of BRH and CF.

Results showed that the Ca^{2+} contents in plant tissue were below the values recommended by Cabrera and Perdomo (2003), which range between 1.0 and 2.0%. The substrate

TABLE 3. Tukey's multiple comparison test for electrical conductivity (EC). Mean EC values (dS m^{-1}) ± standard deviation are presented for the treatments evaluated each week after pruning (WAP) in the automatic drainage system. Different letters indicate a significant difference at $P<0.05$.

WAP	Treatment								
	100BRH-0R	100BRH-50R	100BRH-100R	35BRH-0R	35BRH-50R	35BRH-100R	65BRH-0R	65BRH-50R	65BRH-100R
0	1.92±0.27a	2.17±0.29a	2.06±0.36a	2.14±0.2a	2.49±0.38a	2.42±0.35a	2.42±1.3a	2.44±0.54a	2.56±0.22a
1	2.45±0.27c	2.62±0.43bc	2.62±0.35bc	2.61±0.23bc	2.92±0.29abc	3.01±0.44ab	2.58±0.28bc	3.13±0.41a	3.16±0.45a
2	2.22±0.17e	2.89±0.23bc	2.83±0.46bcd	2.4±0.19cde	2.95±0.2b	3.49±0.97a	2.35±0.22of	3.3±0.31ab	3.08±0.16ab
3	2.57±0.19c	2.82±0.25abc	2.89±0.29abc	2.74±0.12bc	2.99±0.21ab	3.15±0.24a	2.7±0.35bc	2.99±0.22ab	3.11±0.17ab
4	2.05±0.4a	2.68±0.59a	2.59±0.35a	2.23±0.41a	1.96±0.44a	2.65±0.5a	2.48±0.37a	3.0±1.1a	2.6±0.6a
5	2.51±0.3a	2.75±0.3a	3.05±0.62a	3.02±1.01a	2.83±1.05a	3.18±0.99a	2.67±0.29a	3.13±0.76a	2.94±0.4a
6	2.4±0.49d	3.43±0.89abc	3.96±0.98a	2.65±0.54bcd	3.17±0.57	3.33±0.8abcd	2.49±0.32cd	3.67±0.68a	3.61±0.72ab
7	2.25±0.38d	4.19±0.7abc	4.83±1.03a	2.43±0.41d	3.76±0.59c	4.06±0.51bc	2.36±0.27d	4.24±0.86abc	4.51±0.43ab
8	2.28±0.25d	4.62±0.79ab	5±0.92a	2.67±0.57d	3.77±0.65c	4.16±0.71bc	2.23±0.27d	4.24±0.48bc	4.46±0.82ab

100BRH = 100% burned rice husk; 65BRH = 65% burned rice husk and 35% coconut fiber; 35BRH = 35% burned rice husk and 65% coconut fiber; R – percentage of drainage recycling.

contents in initial conditions were 0.06, 0.4 and 0.11% for 35BRH, 65BRH and 100BRH, respectively. At 8 WAP, these values were higher for the 35BRH and 65BRH substrates, reaching 3.0 to 3.8%, while the Ca^{+2} concentrations in the nutrient solution were 110 mg L^{-1}.

pH

The pH trend of the drainages showed acidification (Tab 4). The ANOVA and the Tukey´s mean comparison test indicated that between 0 and 4 WAP, the pH values were significantly lower (P<0.05) for 100BRH-0R compared to the other treatments. The trend indicates that the drainage becomes more alkaline as the CF fraction and the percentage of drains increase. Assuming that the exchange sites in the CF are being saturated by Ca^{2+}, an accumulation of H^+ could occur in the drained solution. There were significant effects for the percentage of recycling and the type of substrates on pH (P<0.05). The lower the percentage of recycling, the greater the tendency to acidify the drainages (0R > 50R > 100R). In the same way, the lower the CF content in the substrates, the greater acidity of the drainages (100BRH > 65BRH > 35BRH) (Tab. 4).

These results are consistent with those of Mesa *et al.* (2011), Vélez *et al.* (2014), and Vélez-Carvajal *et al.* (2014), who reported increases in EC and a decreasing trend in pH during the transition between vegetative and reproductive stages for a carnation crop grown on BRH and CF-based substrates with drainage recycling.

Decreases in pH may be related to the reduction in the active absorption of NO_3^- and the increase in the absorption of NH_4^+ by the plants (Bugbee, 2004; Chapagain & Hoekstra, 2003; Sonneveld & Voogt, 2009), as well as to the nitrification by microorganisms, whose metabolic activity decreases the pH of the medium (Arp *et al.*, 2007; Avrahami & Conrad, 2003). Nitrification requires a medium with greater aeration, as is the case of substrate mixtures with lower CF contents (Londra *et al.*, 2018; Udayana *et al.*, 2017) and lower recycling percentages. In addition, the mixtures of organic materials used as substrates for crops not only improve physical and chemical properties (Awang *et al.*, 2009) but also promote metabolic activity such as urea hydrolysis, nitrite, and ammonia oxidation, and increasing respiration rate (Grunert *et al.*, 2016).

Finally, Yepes and Flórez (2013), in a manual recycling system for a one-harvest-cycle crop of roses, did not find EC and pH values exceeding those that are considered to have a negative impact on production; however, an increasing trend in the EC and pH values was observed. Treatments with 100BRH and 0% drainage recycling had the lowest pH values.

Conclusions

A trend of increasing EC was observed. At 1, 2 and 3 WAP, the EC was significantly higher when recycling the solution in 35BRH and 65BRH, and at 7 and 8 WAP, it was higher for 100BRH and 65BRH. At 6 WAP there was a significant effect of recycling at 50% and 100% on EC independent of the substrate. This behavior can be caused by the release of ions and high-water retention, characteristic of the CF and the high adsorption of ions by the BRH. Between 0 and 4 WAP, the pH was significantly lower for the 100BRH treatment without recycling, which is possibly related to changes in the absorption of ions, such as NO_3^-, by the plants and to the activity of nitrifying microorganisms facilitated by the properties of CF.

TABLE 4. Tukey's multiple comparison test for pH. Mean pH values ± standard deviation are presented for the treatments evaluated each week after pruning (WAP) in the automatic drainage system. Different letters indicate a significant difference at P<0.05.

WAP	Treatment								
	100BRH-0R	**100BRH-50R**	**100 BRH-100R**	**35BRH-0R**	**35BRH-50R**	**35BRH-100R**	**65BRH-0R**	**65BRH-50R**	**65BRH-100R**
0	7.3±0.2e	7.71±0.19bc	7.89±0.16ab	7.56±0.22cd	7.71±0.22bc	8±0.18a	7.37±0.28de	7.73±0.23bc	7.84±0.16ab
1	7.19±0.1d	7.47±0.13abc	7.68±0.19a	7.38±0.15bcd	7.53±0.19ab	7.69±0.23a	7.23±0.15cd	7.53±0.17ab	7.65±0.12a
2	7.21±0.14c	7.44±0.12abc	7.55±0.23ab	7.48±0.25abc	7.49±0.15abc	7.69±0.18a	7.33±0.17bc	7.56±0.18ab	7.54±0.11abc
3	7.19±0.18bc	7.26±0.15bc	7.38±0.29ab	7.21±0.11bc	7.38±0.18ab	7.57±0.19a	7.11±0.17c	7.33±0.26abc	7.45±0.1ab
4	7.07±0.51c	7.36±0.2abc	7.49±0.35ab	7.35±0.34abc	7.43±0.42abc	7.68±0.23a	7.19±0.21bc	7.54±0.11ab	7.46±0.23ab
5	6.91±0.33a	7.24±0.18a	7.13±1a	7.19±0.95a	7.04±1.05a	7.31±0.95a	7.08±0.16a	7.45±0.14a	7.36±0.17a
6	6.84±0.19a	7.04±0.22a	7.14±0.46a	7.12±0.3a	6.83±0.2a	7.13±0.27a	6.93±0.18a	7.15±0.18a	7.08±0.23a
7	7.04±0.24a	6.77±0.14a	6.9±0.34a	7.17±0.24a	6.72±0.14a	7.01±0.13a	7.04±0.14a	7.1±0.21a	6.94±0.19a
8	6.9±0.15a	6.68±30.2a	6.84±0.27a	7.09±0.25a	6.73±0.16a	6.93±0.26a	7.09±0.16a	7.04±0.26a	6.9±0.2a

100BRH = 100% burned rice husk; 65BRH = 65% burned rice husk and 35% coconut fiber; 35BRH = 35% burned rice husk and 65% coconut fiber; R – percentage of drainage recycling.

The observed increase in EC and decrease in pH can be attributed to the physical and chemical properties of the substrates, including factors such as cation exchange capacity and mineralization rate. Additionally, microbiological activity involved in the degradation of the growth media, particularly in substrates with higher CF content, could play a significant role. While it is essential to consider the mineral nutrition of the plants and the appropriate percentage of recirculation, it is equally important to account for the substrate composition when formulating the fertigation solution, as this can influence both EC and pH levels.

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Conflict of interest statement

The authors declare that there is no conflict of interests regarding the publication of this article.

Author's contributions

WJCB and VJFR: conceptualization, funding acquisition research, writing – original draft, visualization, writing, and editing. SEMM: formal analysis, visualization, writing, and supervision editing. All authors have read and approved the final version of the manuscript.

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