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Arabica coffee seedling production by cuttings: hydroponic vs. conventional systems comparison

Produção de mudas de café arábica por estaquia: comparação entre sistemas hidropônico e convencional

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Highlights

Seedlings are crucial for establishing and renewing coffee crops. Innovative technologies are being integrated into the coffee seedling production process. These technologies enable the production of vigorous seedlings by cutting, leading to water savings, cost reduction, and a shorter time until field transplanting.

Abstract

Producing quality seedlings is important for coffee growing, and stem cuttings enable superior plant clones. This research aimed to evaluate the clonal seedlings' production of *Coffea arabica* in two production systems (modified hydroponics and in a greenhouse with a mist chamber) using two volumes of tubes (120 and 50 cm³). The presence of leaves, number of shoots, and survival were evaluated weekly to monitor seedling development. At 140 days after planting, the following variables were analyzed: growth (height, stem diameter, the total number of leaf pairs, leaf area, root area, shoot and root dry matter), physiological (chlorophyll content and stomatal conductance), and anatomical (stomatal density, functionality, and opening). For the statistical analysis, a completely randomized design (CRD) was used in a factorial scheme 2 x 2, with six replications of ten plants per plot. The modified hydroponic system enabled the production of *C. arabica* L. seedlings by cutting, with greater growth and better anatomical and physiological characteristics than those produced in a conventional system, and it is possible to make them in tubes of 50 and 120 cm³.

Key words: *Coffea arabica* clones. Vegetative propagation. Hydroponic agriculture.

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Resumo

A produção de mudas de qualidade é importante para a cultura do café, sendo a estaquia uma opção de propagação que tem possibilitado a clonagem de indivíduos superiores. Objetivou-se com este trabalho avaliar a produção de mudas clonais de *Coffea arabica* em dois sistemas de produção (hidropônico modificado e o tradicional em casa de vegetação com nebulização), utilizando tubetes de dois volumes (50 e 120 cm³). Para o acompanhamento do crescimento das mudas foram avaliadas semanalmente a permanência de folhas, número de brotos e sobrevivência. Aos 140 dias após o estaqueamento foram realizadas análises finais de crescimento (altura, diâmetro de caule, número total de folhas, área foliar, área, volume, diâmetro e comprimento radicular, pesos das matérias secas da parte aérea e raiz), fisiológicas (clorofila a, b e total e condutância estomática) e anatômicas (densidade, funcionalidade e abertura estomática). Para a análise estatística foi utilizado o delineamento inteiramente casualizado (DIC) no esquema fatorial 2 x 2, com seis repetições de dez plantas por parcela. O sistema hidropônico modificado permite a produção de mudas de *Coffea arabica* L. por estaquia, com maior crescimento e melhores características fisiológicas e anatômicas que as produzidas em sistema convencional, sendo viável sua produção em tubetes de 50 e 120 cm³.

Palavras-chave: Clones de café arábica. Propagação vegetativa. Agricultura hidropônica.

Introduction

Seedling quality is an essential factor to consider when it is necessary to implement or renew coffee plantations, as it allows for a greater probability of establishment and success of the crop in the field and, consequently, the obtention of high yields.

In Arabica coffee, the formation of crops occurs mainly by seedlings from seed propagation because the plants are autogamous with little variation between future individuals (D. H. Oliveira et al., 2010). On the other hand, the most used seedling production process for *Coffea canephora* is by cuttings, as the species is allogamous. However, many experiments have been carried out to develop, improve, and evaluate the production of Arabica coffee stem cuttings.

In the seedling production process, the type of container and its dimensions can also influence production quality and cost. Polyethylene bags are still the most common way to produce coffee seedlings. However, the use of seedling tubes has been increasing due to advantages such as longitudinal grooves inside, directing the roots vertically, and enabling lower cost and period of seedling production (Vallone et al., 2010).

Aiming at the development of new technologies for seedling production, a hydroponic system with modifications was developed by Chalfun and Faquin (2008), which has been studied with promising results in perennial species such as citrus (A. G. Souza et al., 2013; Gomes et al., 2019) and pear (F. F. Souza et al., 2015). However, there are no established methodologies (protocols) for seedling production by cuttings in coffee in this cultivation system. Thus, the objective of this study was to evaluate the production of Arabica coffee seedlings by cuttings in a

modified hydroponic system and to compare it with the conventional system, achieving improved results with varying volumes.

Material and Methods

The experiment was conducted in the Department of Agriculture of Universidade Federal de Lavras (UFLA), Lavras – MG coffee and horticulture sectors.

For the obtention of cuttings, stock plants of *Coffea arabica* L. were selected. The nodal segments were obtained from orthotropic branches of cultivar Mundo Novo 379/19, which were sectioned at the base and taken to the greenhouse, where the orthotropic branches were cut in the middle region in 5 cm segments to have a pair of leaves that were cut keeping one-third of their original area. Subsequently, the cuttings were immersed in a 0.05% sodium hypochlorite solution for ten minutes and washed in running water. The base of the cuttings were then immersed in talc-containing Indolebutyric Acid (IBA) at a concentration of 4,000 mg kg-1 (Rezende et al., 2017).

The *C. arabica* cuttings were taken to two seedling production systems: a methodology considered traditional, used by Rezende et al. (2017) and modified hydroponics (Chalfun & Faquin, 2008), and each of the systems was placed to root in tubes of two sizes/volumes (50 and 120 cm^3).

After cutting preparation, they were placed in tubes containing vermiculite and sand at a 1:1 ratio, with the slow-release fertilizer Osmocote Plus®, at the following mineral concentrations: 15% N; 9% K_2O; 12% P_2O_5; 0.06% Mg; 2.3% S; 0.05% Cu; 0.45% Fe; 0.06% Mn and 0.02% Mo, at a dose of 12.5 g L^{-1} (Rezende et al., 2017), which were cultivated in a controlled environment with a nebulization system and temperature control (26 ºC) and relative humidity (90%).

Following the methodology proposed by Chalfun and Faquin (2008), the experiment used a 'pool' system with closed-loop circulation. The obtained cuttings were first placed in tubes containing vermiculite. A 1000 L reservoir contained the nutrient solution, formulated with 960g MaxSol F21, 720g calcium nitrate, and 40g EDDHA iron chelate.

Circulation was automated, with a motor pump activating for 15 minutes, four times per day, to move the solution to the pools; gravity facilitated the return of excess solution. Maintenance of the nutrient solution involved two key processes: EC was monitored for nutrient replacement (using a stock solution as recommended by the authors), and the pH was kept stable between 5.5 and 6.5. The entire solution was changed every 30 days. The average temperature and relative humidity recorded were 28.4°C and 41.5%, respectively.

Weekly evaluations were conducted to monitor seedling growth by measuring the remaining leaves, shoot number, and cutting survival per plot.

At 140 days after cutting, the following evaluations were performed: total leaf number (TLN), total shoot number (TSN), number of plagiotropic branches (NPB), seedling height, mean shoot diameter (MSD), mean shoot size (MSS), remaining leaves (RL), cutting survival (CS), shoot and root dry matter weight, total leaf area (TLA).

From the leaf area and dry matter weight data, the following parameters were estimated: leaf area ratio (LAR), in $cm^2.g^{-1}$, also known as leaf area quotient, obtained through the ratio between total leaf area (TLA) and total dry matter weight (TDMW); specific leaf area (SLA), in $cm^2.g^{-1}$, which relates the surface to the dry matter weight of the leaf itself, obtained through the ratio of TLA by dry matter leaf weight DMLW; leaf weight ratio (LWR), in g.g-¹, obtained by the ratio of DMLW by TDMW; specific leaf matter (SLM), in $mg.cm^{-2}$, which is the ratio of DMLW and TLA.

Root analyses were carried out in which the cuttings were removed from the pots, carefully washed in water, positioned on a black scale (cm) surface to generate contrast with the white roots, and photographed with a professional camera. Subsequently, to analyze root area (mm^2), volume (mm^3), length (cm), and diameter (mm) data, the images were analyzed using the SAFIRA software (Jorge & Silva, 2010).

The Falker Chlorophyll Index (FCI) was used to indirectly estimate the contents of chlorophyll a, b, and total. These values were obtained by taking readings on leaf tissue with a portable clorofiLOG - CFL1030 meter (Falker automação agrícola). This index provides values proportional to chlorophyll absorbance (Barbieri et al., 2012).We measured stomatal conductance (SC), expressed in μmol m^{-2} s^{-1}, using an SC^{-1} porometer (Decagon Devices). This instrument measures leaf vapor flow from the stomata to the atmosphere. All readings were taken between 8:00 and 10:00 a.m. on the median region of fully extended leaf blades.

For anatomical evaluation, leaf samples from coffee cuttings were prepared for scanning electron microscopy (SEM). The protocol began with fixing the samples in Karnovsky solution for 24 hours. Subsequently, they were washed three times (10 minutes each) in 0.05M cacodylate buffer. Dehydration was performed in a progressive acetone gradient (25, 50, 75, and 90% for 10 minutes each), followed by three 10-minute washes in 100% acetone. Samples were then dried using a Bal-Tec critical point apparatus and metalized with gold in a Bal-Tec 050 evaporator. Finally, observations were conducted on a Carl Zeiss LEO Evo40 XVP scanning electron microscope at the Electron Microscopy and Ultrastructural Analysis Laboratory (UFLA).

The Imagetool software was used to determine stomatal density (number of stomata per mm^2), counting the number of stomata per area in samples consisting of four replications of the plant leaf tissue of each treatment and; in each of them, the leaf surface was observed in five fields of view, totaling 20 micrographs per treatment, at 500x magnification. The same samples were used to measure stomatal opening (μm) and functionality (polar diameter divided by equatorial diameter), and ten micrographs magnified at 4000x per treatment were observed.

Energy dispersive x-ray microanalysis (EDX) was also performed, in which samples of leaves and roots of coffee cuttings were collected and carefully sectioned crosswise with the aid of a scalpel, mounted in aluminum stubs, dried in an oven at 60 °C for 24 hours and metalized with carbon coating. Readings of the chemical elements present in the

samples were then taken in percentage and mapping, indicating the location of these nutrients in the plant tissue, using the Bruker x-ray energy dispersive detector coupled to a scanning electron microscope (Carl Zeiss LEO Evo40 XVP) from the Electron Microscopy and Ultrastructural Analysis Laboratory at UFLA.

The experiment was carried out in a completely randomized design (CRD), in a 2 x 2 factorial scheme, with 2 cutting production systems (modified hydroponics and traditional methodology) and two tube sizes (50 and 120 acm³), making up four different treatments, with six replications and ten plants per plot. The data were submitted to normality and homogeneity tests; for analysis of variance, the statistical analysis software SISVAR® (Ferreira, 2019) was used, and for the grouping of means, the Scott-Knott test at 5% of significance was used.

Results

The results of the growth assessment of Arabica coffee seedlings, which were produced by cuttings and maintained in a polyethylene greenhouse or the hydroponic production system (MHS), are presented in Table 1. During the seedling production process, it was found that cuttings began to deteriorate around 30 days after being cut (DAC). By 70 DAC, survival rates decreased across all treatments with varying intensities. At the end of the experiment, it became evident that seedlings produced in the modified hydroponic system (MHS) using 120 cm³ tubes showed no significant difference in cutting survival compared to those in the greenhouse system with fogging. However, using 50 cm³ tubes, it was clear that seedlings grown in a fogging-equipped greenhouse outperformed those produced in the MHS by 67.87%. Additionally, the remaining leaves remained consistently higher in the greenhouse system starting from 21 DAC onwards, with minimal leaf loss over time, regardless of tube size.

Shoot formation initiation occurs at the cellular and microscopic levels before becoming visually observable. Visual confirmation of shoot formation varied across all treatments. Shoot formation in treatments within a conventional greenhouse exhibited an earlier onset at 21 DAC than in the hydroponic system, which began at 42 DAC. From 70 DAC onwards, there was a tendency for the number of shoots to stabilize across all treatments, with a greater abundance of shoots in the traditional greenhouse environment. However, by 140 DAC (the experiment's conclusion), the total number of shoots appeared similar in seedlings produced within the two tested production systems, regardless of tube volume. The height of seedlings produced in 120 cm³ tubettes within the modified hydroponic system measured 9.78 cm, surpassing the values obtained in seedlings from other treatments by a substantial margin, with a difference of at least 64%.

Table 1
Growth characteristics (seedling height, total leaf number - TLN, longest root length - LRL, total shoot number - TSN, mean shoot size - MSS, mean shoot diameter - MSD, number of plagiotropic branches - NPB, remaining leaves - RL and cutting survival - CS), evaluated in *Coffea arabica* Mundo Novo 379/19 seedlings, produced by cuttings in modified hydroponic production system (MHS) and greenhouse (CV), and two tube sizes at the end of the experiment

System	Height (cm)		TLN		LRL (cm)	
	50 cm³	120 cm³	50 cm³	120 cm³	50 cm³	120 cm³
MHS	5.960 Ab	9.778 Aa	7.310 Aa	8.741 Aa	13.625 Ab	26.283 Aa
CV	5.628 Aa	5.621 Ba	4.571 Ba	5.377 Ba	10.817 Aa	11.937 Ba
System	**TSN**		**MSS (mm)**		**MSD (mm)**	
	50 cm³	120 cm³	50 cm³	120 cm³	50 cm³	120 cm³
MHS	1.818 Aa	1.688 Aa	25.323 Ab	60.507 Aa	2.928 Aa	2.883 Aa
CV	1.715 Aa	1.883 Aa	24.191 Aa	27.955 Ba	2.368 Ba	2.408 Ba
System	**NPB**		**RL**		**SS (%)**	
	50 cm³	120 cm³	50 cm³	120 cm³	50 cm³	120 cm³
MHS	0.50 Aa	1.61 Aa	0.000 Bb	0.583 Ba	46.66 Ba	58.33 Aa
CV	0.50 Aa	1.25 Aa	1.497 Aa	1.588 Aa	78.33 Aa	66.66 Aa

*Means followed by the same uppercase letter in the column and lowercase letter in the row do not differ by the Scott Knott test at 5% probability.

When assessing the total number of leaves (TLN), it was evident that, regardless of the tubette size, the values obtained for seedlings produced in the modified hydroponic system were significantly higher, showing an increase of up to 91.24% when compared to the conventional system (8.74 for seedlings in the modified hydroponic system with 120 cm³ tubettes and 4.57 for seedlings in the traditional system with 50 cm³ tubettes).

Regarding the length of the longest root, higher values were recorded in seedlings produced within the modified hydroponic system, particularly in 120 cm³ tubettes, demonstrating a difference of at least 92.95% compared to values observed in the other treatments (26.28 cm for seedlings in the modified hydroponic system with 120 cm³ tubes and 13.62 cm for seedlings produced in the same system, but in 50 cm³ tubes).

The production systems and the tube sizes assessed in this trial did not yield significant differences in coffee seedlings regarding shoot number. However, seedling size exhibited notable disparities, with those cultivated in larger tubes (120 cm³) within the modified hydroponic system showcasing a remarkable superiority of at least 116.42% compared to the other treatments (measuring 60.51 cm for seedlings in the modified hydroponic system in 120 cm³ tubes and 27.96 cm for seedlings produced in a conventional system using 120 cm³ tubes). Notably, when assessing shoot diameter, higher values were consistently observed

when the modified hydroponic system was employed, irrespective of tube size, with differences reaching up to 23.63 cm.

The data for Leaf dry matter weight (LDMW), stem dry matter weight (SDMW), root dry matter weight (RDMW), total dry matter weight (TDMW), total leaf area (TLA), leaf area ratio (LAR), specific leaf area (SLA), and leaf weight ratio (LWR) of Coffea arabica seedlings, which were produced using cuttings in a modified hydroponic production system (MHS) and a greenhouse (CV), and were grown in two different tubette sizes (50 and 120 cm³), are summarized in Table 2.

Table 2
Leaf dry matter weight (LDMW), stem dry matter weight (SDMW), root dry matter weight (RDMW), total dry matter weight (TDMW), total leaf area (TLA), leaf area ratio (LAR), specific leaf area (SLA) and leaf weight ratio (LWR) of *Coffea arabica* Mundo Novo 379/19 seedlings, produced by cuttings in modified hydroponic production system (MHS) and greenhouse (CV), and two tube sizes (50 and 120 cm³)

System	LDMW (g)		SDMW (g)	
	50 cm³	120 cm³	50 cm³	120 cm³
MHS	5.960 Ab	9.778 Aa	7.310 Aa	8.741 Aa
CV	5.628 Aa	5.621 Ba	4.571 Ba	5.377 Ba
System	**RDMW (g)**		**TDMW (g)**	
	50 cm³	120 cm³	50 cm³	120 cm³
MHS	1.818 Aa	1.688 Aa	25.323 Ab	60.507 Aa
CV	1.715 Aa	1.883 Aa	24.191 Aa	27.955 Ba
System	**TLA (cm²)**		**LAR (cm².g⁻¹)**	
	50 cm³	120 cm³	50 cm³	120 cm³
MHS	0.50 Aa	1.61 Aa	0.000 Bb	0.583 Ba
CV	0.50 Aa	1.25 Aa	1.497 Aa	1.588 Aa
System	**SLA (cm².g⁻¹)**		**LWR (g.g⁻¹)**	
	50 cm³	120 cm³	50 cm³	120 cm³
MHS	1993.401 Ba	1755.506 Ba	0.776 Ba	0.804 Aa
CV	4240.963 Aa	3901.092 Aa	0.843 Aa	0.857 Aa

*Means followed by the same uppercase letter in the column and lowercase letter in the row do not differ by the Scott Knott test at 5% probability.

Higher leaf (LDMW), stem (SDMW), root (RDMW), and total (TDMW) dry matter weights were observed in seedlings produced in the modified hydroponic system, considering the 120-cm³ tube with superiority of up to 336.45%, 553.57%, 348.38%, and 366.50%, respectively, than the other treatments.

The seedlings' total leaf area (TLA) did not vary between systems or tube sizes. The seedlings produced in a greenhouse

showed higher values for leaf area ratio (LAR) and specific leaf area (SLA) in both tube sizes and higher values for leaf weight ratio (LWR) using a 50-cm³ tube. However, there was a lower accumulation of dry matter weight in seedlings produced in a greenhouse with a 120 cm³ tube.

Table 3 presents the concentrations of chlorophyll a, b, and total in coffee seedlings produced by cuttings in the modified hydroponic production system (MHS) and greenhouse (CV) across two different tube sizes. This means that sharing the same uppercase letter within columns and lowercase letters within rows are not statistically different based on the Scott-Knott test at a 5% significance level.

Significant differences were observed for physiological characteristics. In seedlings cultivated in MHS, higher levels of chlorophyll a, b, and total were observed when using a 50 cm³ tube, with superiority of up to 15.58%, 53.00%, and 25.85%, respectively. In this study, SLA was higher in seedlings cultivated in a greenhouse, indicating that, in this system, the leaves were thinner and had lower chlorophyll values when using a smaller container (Tables 2 and 3).

Table 3
Chlorophyll a, b, and total were evaluated in Coffea arabica Mundo Novo 379/19 seedlings produced by cuttings in the modified hydroponic production system (MHS) and greenhouse (CV) and two tube sizes

System	Chlorophyll a (ICF)		Chlorophyll b (ICF)		Total chlorophyll (ICF)	
	50 cm³	120 cm³	50 cm³	120 cm³	50 cm³	120 cm³
MHS	442.7 Aa	427.8 Aa	221.7 Aa	166.5 Ab	664.4 Aa	594.3 Ab
CV	383.0 Bb	411.3 Aa	144.9 Ba	171.5 Aa	527.9 Ba	582.8 Aa

* Means followed by the same uppercase letter in the column and lowercase letter in the row do not differ by the Scott Knott test at 5% probability.

Table 4 presents a comprehensive analysis of key characteristics of Coffea arabica seedlings produced from cuttings, considering two different cultivation environments: Modified Hydroponic Production System (MHS) and Greenhouse (CV). Furthermore, it evaluates two tube sizes, providing a more complete insight into the factors influencing the development of these seedlings. Complementing this information, Figure 1 includes electron micrographs of Coffea arabica seedlings' leaf surface, showcasing the density and stomatal opening observed in the different tested systems.

Table 4
Conductance (SC), density (DEN), functionality (FUN), and stomatal opening (SO) of *Coffea arabica* Mundo Novo 379/19 seedlings produced by cuttings in modified hydroponic production system (MHS) and greenhouse (CV) and two tubes sizes

System	SC (μmol m^{-2} s^{-1})		DEN (nº estômatos. mm^{-2})	
	50 cm^3	120 cm^3	50 cm^3	120 cm^3
MHS	149.606 Aa	185.392 Aa	203.493 Aa	180.219 Ab
CV	41.375 Ba	54.815 Ba	130.210 Ba	133.356 Ba
System	**FUN**		**SO (μm)**	
	50 cm^3	120 cm^3	50 cm^3	120 cm^3
MHS	1.706 Aa	1.804 Ba	3.411 Aa	2.576 Ab
CV	1.946 Aa	2.067 Aa	2.515 Ba	2.743 Aa

* Means followed by the same uppercase letter in the column and lowercase letter in the row do not differ by the Scott Knott test at 5% probability.

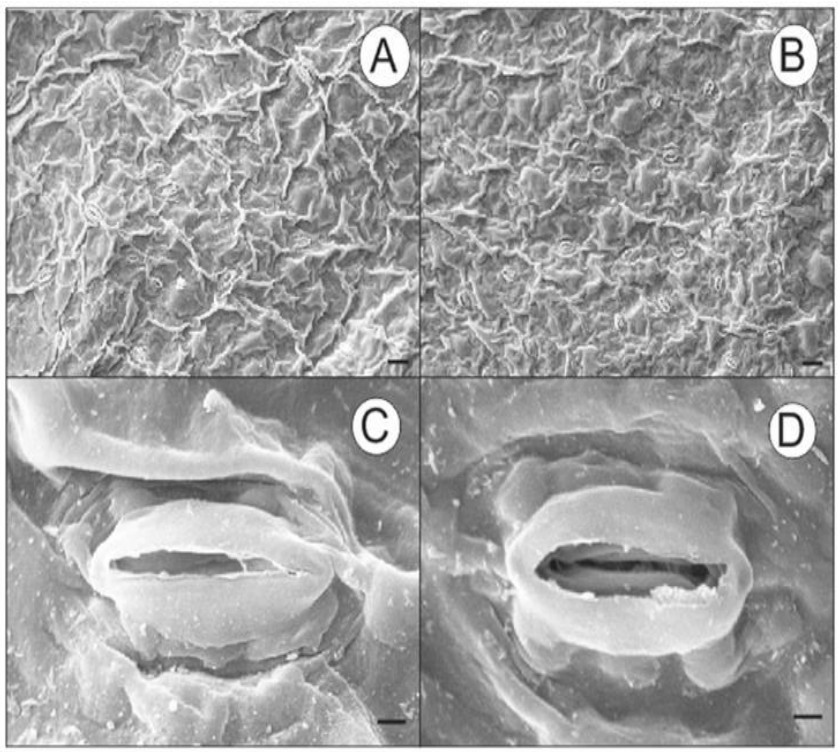

Figure 1. Electron micrographs of *Coffea arabica* Mundo Novo 379/19 seedlings' leaf surface show the density and stomatal opening in seedlings produced in different systems.
A: Seedlings produced in a greenhouse with a fogging system. B: Seedlings produced in a modified hydroponic system. Detail of stomatal opening. C: Seedlings produced in a modified hydroponic system. D: Seedlings produced in a greenhouse with a fogging system. A and B: Scale bar = 20 μm, C and D: 2 μm.

Stomatal conductance and density were up to 338.07% and 56.28% higher in seedlings under MHS for the two tube sizes, and stomatal functionality was 14.58% higher under CV for seedlings produced in 120 - cm³ tubes (Table 4). Lower stomatal density was observed in seedlings produced in CV compared to MHS (Table 4, Figure 1A). It was observed that stomatal functionality was higher in seedlings produced in a greenhouse, considering the 120-cm³ container. Although the seedlings produced in this system have a lower stomatal density, the greater functionality may be related to the good seedling development in this system and may have contributed to meeting physiological needs.

There were no significant differences between systems and tube sizes in quantifying volume, surface area, and root diameter. The data obtained through the Safira software are complementary to RDMW data, as the software's results indicate how these roots are distributed, whether they are roots of greater or lesser caliber. Consequently, it is possible to have information about the surface area of contact and absorption.

Figure 2 displays scanning electron micrographs with X-ray microanalysis of chemical elements located in the leaves of the Coffea arabica seedlings obtained from cuttings and maintained in the two tested systems, a greenhouse with fogging and modified hydroponics.

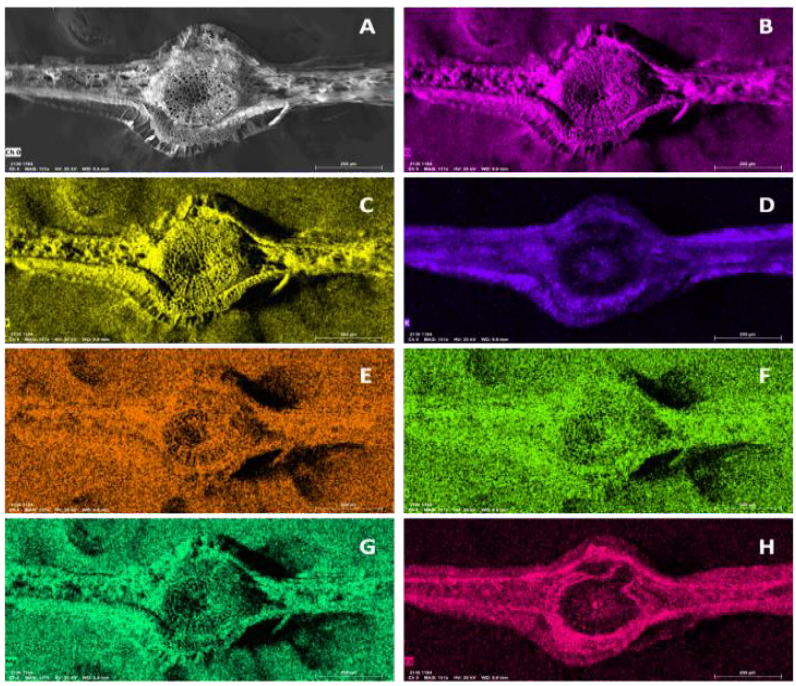

Figure 2. Scanning electron micrographs with x-ray microanalysis of chemical elements located in *Coffea arabica* Mundo Novo 379/19 leaves from cuttings produced in a greenhouse system with fogging and modified hydroponics.
A: The coffee blade's cross-section shows the mesophile and vascular bundle (analyzed region). Mapping indicating the location of chemical elements B: Oxygen, C: Fluor, D: Potassium, E: Phosphorus, F: Sulfur, G: Magnesium, H: Calcium.

X-ray dispersive spectroscopy detected the following chemical elements in the leaves: oxygen, potassium, calcium, fluorine, magnesium, aluminum, phosphorus, sulfur, silicon, chlorine, and sodium.

It was observed in the leaves, for all treatments, that most chemical elements are deposited homogeneously in this plant tissue, except calcium and potassium, located in lesser intensity in the vascularized region (Figure 2). The percentage of chemical elements did not differ regarding container size or production system used, showing that both cultivation environments and containers provided adequate mineral nutrition for seedling development and growth.

Except for sodium, the same chemical elements verified in the leaf analysis were detected in the roots. The location of the chemical components found in the roots did not vary between treatments, and the main nutrients are shown in Figure 3. As in the leaves, calcium and potassium are less abundant in the vascularized region of the xylem. It was found that calcium was deposited with greater intensity in the outer area of the roots near the phloem.

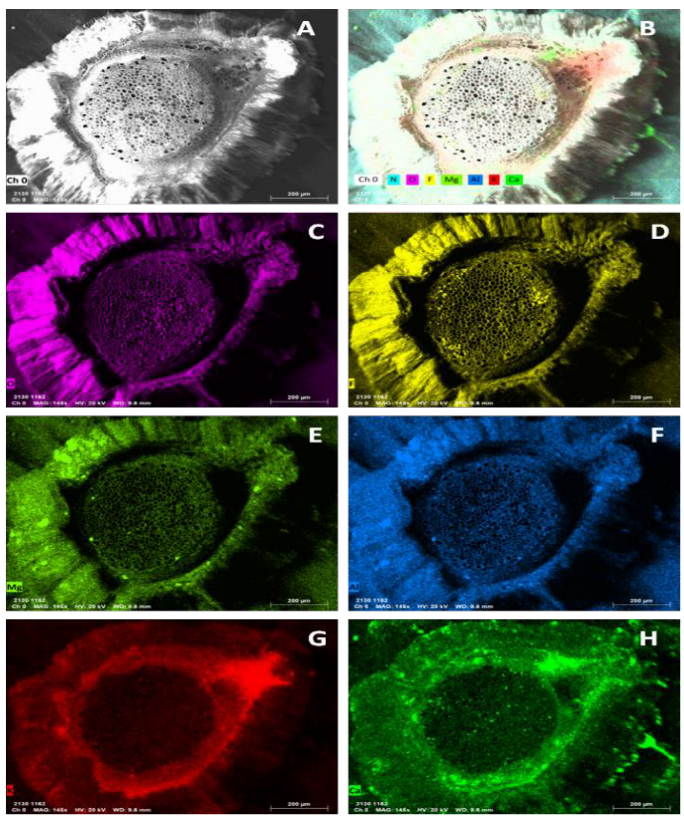

Figure 3. Scanning electron micrographs with x-ray microanalysis of chemical elements in *Coffea arabica* Mundo Novo 379/19 roots from cuttings produced in a greenhouse with fogging and modified hydroponics.
A: Cross section of coffee seedling roots (analyzed region). Mapping indicating the location of chemical elements B: Overlapping of the location of the chemical aspects observed, C: Oxygen, D: Fluor, E: Magnesium, F: Aluminum, G: Potassium, H: Calcium.

Discussion

Early shoot formation was observed in seedlings produced in a conventional greenhouse environment compared to those in the hydroponic system. This indicates that the greenhouse environment can expedite the shoot initiation process. However, this precocity may not be desirable since it may result in a prioritized allocation of metabolites toward shoot formation at the expense of root development. This allocation strategy can potentially hinder the subsequent development of seedlings, given the crucial role of roots in supplying carbohydrates and nitrogen reserves (Lima et al., 2006). Therefore, it is essential to consider the balance between shoots and roots when assessing seedling quality.

Relative air humidity plays a significant role in the survival and development of seedlings. The greenhouse system with mist chamber provided an environment with high relative air humidity, which may have contributed to the increased survival and leaf retention in seedlings. Air humidity directly affects plant water loss through transpiration and can influence the allocation of resources to leaf and root growth (Taiz et al., 2017). The same consideration was made by Jesus et al. (2013) regarding the production of clonal Arabica coffee seedlings maintained in greenhouses. Another important element for better coffee plant development is the absence of water restriction (Assis et al., 2014).

The height of seedlings produced in larger tubes (120 cm^3) in the modified hydroponic system was significantly greater than in other treatments. This can be attributed to the larger volume of substrate available for root development, which, in turn, promoted increased seedling growth. The number of leaves was also higher in seedlings from the modified hydroponic system, indicating greater vigor and maturity (Ministério da Agricultura, Pecuária e Abastecimento [MAPA], 2012). Partelli et al. (2014) found higher levels of chlorophyll b and total in coffee plants grown in less shaded environments, which may be related to greater leaf thickness; they also observed that leaf area increased with shading. In the present study, SLA was higher in seedlings cultivated in a greenhouse, indicating that, in this system, the leaves were thinner and had lower chlorophyll values when using a smaller container.

Differences between production systems were observed regarding physiological characteristics such as chlorophyll levels. Changes in chlorophyll levels are directly related to the efficiency of the photosynthetic apparatus. Seedlings produced in the modified hydroponic system exhibited higher chlorophyll a, b, and total levels, especially when using 50 cm^3 tubes. This difference may be related to light and nutrient availability in the cultivation environment. A constant supply of nutrients through the nutrient solution may have contributed to the increased chlorophyll content in MHS seedlings (Ramírez-Olvera et al., 2019).

Stomatal conductance and stomatal density were also affected by the production systems. Seedlings in the MHS showed higher stomatal conductance and density, indicating a higher rate of gas exchange, including CO_2 absorption and H_2O release.

These factors are closely related to photosynthesis and plant water relations (E. C. Oliveira & Miglioranza, 2014; Craparo et al., 2017).

It's important to note that the differences observed in physiological and growth characteristics between production systems may have significant implications for the quality and performance of coffee seedlings. The modified hydroponic system showed potential in seedling growth and development, particularly regarding increased root length, height, and chlorophyll content. However, it's crucial to consider seedling survival and resource allocation when choosing the most suitable production system.

In summary, the results of this study suggest that the modified hydroponic system may offer significant advantages in coffee seedling production in terms of growth and physiological characteristics. However, it's essential to consider the specific requirements of each production system and environmental conditions to ensure the success of high-quality seedling production.

Conclusions

The modified hydroponic system allows *Coffea arabica* L. seedlings to be produced by cutting, with better biometric growth and good physiological and anatomical characteristics than the conventional method. Furthermore, their production in 50 and 120 cm³ tubes is viable, with superiority in larger containers.

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