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Modified hydroponics and phenolic foam as technological innovations in the production of coffee seedlings from cuttings

Hidroponia modificada e espuma fenólica como inovações tecnológicas na produção de mudas de cafeeiro oriundas de estacas

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Highlights

The use of hydroponics in the production of coffee seedlings is innovative.
The production of seedlings through hydroponics provides high quality seedlings.
Importance in the comparison between conventional and hydroponic seedling production.

Abstract

Brazilian coffee production represents an important activity in the country's agricultural sector and, for this reason, it requires innovative technologies for the production of seedlings, which is one of the most important inputs in crop implantation. Thus, plant cloning by cutting, mineral nutrition via modified hydroponics and the use of alternative substrates appear as technological innovations for seedling production. This study evaluated the production of clonal coffee seedlings in a modified hydroponic system in comparison to the conventional climate-controlled greenhouse system, using vermiculite and phenolic foam as alternative substrates. At the end of the experiment, the seedlings were analyzed for growth (height, stem diameter, number of total leaves, leaf area, root area, shoot and root dry matter) and physiological (chlorophyll content and stomatal conductance) characteristics. For the statistical analysis, a completely randomized design was used in a factorial scheme 2 (types of substrate) x 2 (cultivation systems) with six replications and ten plants per plot. The innovative modified hydroponic system leads to a greater growth of coffee seedlings produced by cuttings in tubes with vermiculite compared to those produced in conventional systems. The substrate phenolic foam can be used alternatively in the air-conditioned greenhouse system. However, in the modified

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hydroponic system, it is not indicated, as it causes total seedling mortality.
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Resumo

A cafeicultura brasileira representa uma importante atividade no setor agrícola do país e por isto necessita de tecnologias inovadoras para a produção de mudas, que é um dos insumos de maior importância na implantação das lavouras. Sendo assim a clonagem de plantas por estaquia, a nutrição mineral via hidroponia modificada e o uso de substratos alternativos surgem como inovações tecnológicas para a produção de mudas. Objetivou-se com o presente trabalho avaliar a produção de mudas clonais de cafeeiro em sistema hidropônico modificado em comparação ao sistema convencional de casa de vegetação climatizada, utilizando a vermiculita e espuma fenólica como substratos alternativos. Ao final do experimento as mudas foram analisadas quanto as características de crescimento (altura, diâmetro de caule, número total de folhas, área foliar, área radicular, matéria seca da parte aérea e raiz) e fisiológicas (teores de clorofila e condutância estomática). Para a análise estatística foi utilizado o delineamento inteiramente casualizado no esquema fatorial 2 (tipos de substrato) x 2 (sistemas de cultivo) com seis repetições e dez plantas por parcela. Concluiu-se, portanto que o sistema inovador de hidroponia modificada promove maior crescimento das mudas de cafeeiro produzidas por estaquia em tubetes com vermiculita em relação àquelas produzidas em sistema convencional. O substrato espuma fenólica pode ser utilizado alternativamente no sistema de casa de vegetação climatizada, porém no sistema de hidroponia modificada não é indicado pois promove mortalidade total das mudas.
Palavras-chave*:* Clonagem. Casa de Vegetação. Vermiculita. Coffea*.*

Introduction

The production of quality seedlings is of paramount importance for coffee crop formation and renewal, since the use of low-quality seedlings can cause losses in crop development. In *Coffea arabica,* seed propagation is the method currently used, as it is an autogamous species, with 5 to 10% cross-fertilization (Oliveira, Baliza, Rezende, Carvalho, & Guimarães, 2010). One of the technologies that can be used to increase seedling quality is plant cloning by cutting. This method is a technology that has been useful in coffee genetic breeding, since it allows the selection and multiplication of superior plants at any development stage of a breeding program, thus reducing the time for the obtention of a new cultivar with greater productive potential (Rezende et al., 2017). Research centers in Brazil are developing hybrid-type cultivars with higher yields than pure-line cultivars, in addition to multiple resistance to pests and diseases (Andreazi et al., 2015). In order to facilitate the propagation of these hybrids, cloning techniques are necessary, among which cutting can be one of the alternatives (Jesus, Carvalho, Castro, & Gomes, 2013).

The use of cuttings is also of great interest, since it provides a reduction in seedling production time, with the advantages of the possibility of anticipating planting, consequently taking advantage of the rainy season and increasing field setting (Baliza, Oliveira, Dias, Guimarães, & Barbosa, 2013). However, it requires precautions and several factors can influence growth and development.

One of these factors is the mineral nutrition of these seedlings, which must be carefully performed, since the root system is poorly developed at the beginning of the production process, making it necessary to use methods that can optimize nutrient absorption. As an alternative to a sufficient, balanced nutrition with greater control of nutrient supply, the hydroponic system has been used in several agricultural crops. However, in the case of coffee, there are still few studies. This system has several advantages such as lower water use (considering a "closed" supply system) and inert substrate (reducing the incidence of pests and diseases), being able to supply the nutrients that the plant needs in a more available way through a nutrient solution (Savvas & Gruda, 2018). There is also the need to reduce costs of the substrate used in seedling production by cutting, despite the many options in the market. Therefore, the use of phenolic foam appears as a technological option with the potential for the production of coffee seedlings, as it has low cost and favorable characteristics (Silva, Costa, Santos, Silva, & Martins, 2013), with a great potential use. In this context, the use of a modified hydroponic system, combined with the use of phenolic foam in the production of coffee seedlings by cuttings, appear as options with great potential.

Therefore, the objective of this study was to evaluate the integration of innovative technologies in the production process of coffee seedlings, which enable vigorous seedlings obtained by cutting, saving water, reducing costs and the time until transplanting in the field. Specifically, the production of clonal *Coffea arabica* L. seedlings in different cultivation systems and substrates was evaluated.

Material and Methods

The experiment was carried out in the nursery of the Coffee Sector, and in the Horticulture Sector, located in the Department of Agriculture of Universidade Federal de Lavras (UFLA), Lavras - MG, Brazil.

For the obtention of the cuttings, healthy stock plants of *Coffea arabica* L. ('Mundo Novo IAC 379-19') were selected from an experimental field of UFLA. It was carried out in the cultivation system for the production of seedlings in modified hydroponics, proposed by Faquin and Chalfun (2008). The changes in relation to the conventional hydroponic system are related to the fact that it is a closed system for the supply of the nutrient solution, which eliminates the need for aeration. In this system, the seedlings absorb nutrients from a nutrient solution proposed by the above-mentioned authors, which is another modification, since most solutions are adapted for plant species. An inert substrate is used to support the root system, and only the bottom of the container with the substrate is in contact with the solution in the pools. Therefore, it is possible to maintain the hydroponic characteristics and, at the same time, obtain a consistent root system supported by a substrate in order to preserve the structure of the rhizosphere, avoiding defects as impacting on the coffee crop as the curving of the pivoting root. This system was found inside a greenhouse also with a metallic structure with a transparent plastic cover and a 50% shade layer under the cover, but it did not have a spray irrigation system or temperature control with fans.

The tubes containing vermiculite were placed in crates and the cubes of phenolic foam, in their own polystyrene plates, previously adjusted on the edges of boxes of synthetic material, with dimensions of 3.20m x 0.60m x 0.30m, called pools, and leveled on masonry benches, inside a greenhouse covered with double-sided polyethylene film. The "pools" were covered with white polyethylene film, with an opening for positioning the tubes and foam, thus avoiding the entry of light and the consequent growth of algae in the nutrient solution.

The pools had a closed system for circulating the nutrient solution, where the tank received the solution proposed by Faquin and Chalfun (2008), coming from a 1000-L reservoir. The solution circulated in the pools through the engine-pump assembly by activating the timer with an interval of 15 minutes of circulation and 45 minutes off. The excess of the nutrient solution in the pool returned to the reservoir by gravity, through its own pipe. The nutrient solution was exchanged every 30 days.

In the experiment, the evaluation of two different substrates (vermiculite in polyethylene tubes - as a control treatment and phenolic foam cut into cubes - as an innovative substrate), in two cultivation systems (air-conditioned greenhouse with spray irrigation - as a control treatment and a modified hydroponic system - as an innovative system), making up a 2 x 2 factorial scheme with 6 replications, 10 plants per plot, totaling 240 plants. Therefore, the experiment had four treatments: hydroponics + vermiculite, hydroponics + phenolic foam, greenhouse + vermiculite and greenhouse + phenolic foam.

Nutrients were supplied differently in the two cultivation systems. 12.5 g L^{-1} of Osmocote Plus® slow-release fertilizer substrate were applied to the seedlings in the air-conditioned greenhouse with 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, according to the methodology of Rezende et al. (2017). In the hydroponic system, the supply occurred via nutrient solution, previously described.

The evaluations of seedling survival percentage after cutting and those of shoot number were carried out twice a week. At the end of the experiment, when the seedlings had three pairs of true leaves, totaling 150 days, the following evaluations were carried out: seedling height (cm), average stem diameter (mm), bud height (cm), number of total leaves (TLN), number of remaining leaves, shoot dry matter (SDM) and root dry matter (RDM). From the data on leaf area and dry matter weight, the following characteristics were estimated: leaf area ratio (LAR), in $cm^2.g^{-1}$, obtained by the ratio between the total leaf area (TLA) and the RDM weight of the plant; specific leaf area (SLA), in $cm^2.g^{-1}$, which relates the surface to the dry matter weight of the leaf itself, obtained by the ratio between TLA and SDM and the weight of specific leaf matter (SLM), in $mg.cm^{-2}$; this was the ratio between SDM and TLA.

The roots were analyzed by the SAFIRA software, 'Fiber and Root Analysis System', developed by Embrapa Instrumentação, where the roots were removed from the containers, carefully washed in water, positioned next to the scale (cm) on a black surface for creating contrast, and photographed with the aid of a professional camera. Subsequently, data on root volume (mm^3), area (mm^2), length (cm) and diameter (mm) were analyzed. Contents of chlorophyll a, b and total were indirectly measured, obtained through readings taken on a leaf tissue using a portable meter clorofiLOG - CFL1030 (Falker automação agrícola), which provides values called Falker chlorophyll indices (FCI), proportional to chlorophyll absorbance (Barbieri, Rossielo, Silva, Ribeiro, & Morenz, 2012).

Stomatal conductance (SC) (μmol m^{-2} s^{-1}) was obtained from the leaf vapor flow through the stomata to the external environment using a porometer (SC^{-1} Decagon Devices); readings were performed in the median region of the limbus completely extended, between 8 a.m. and 10 a.m.

The collected data were tabulated, submitted to normality and homogeneity tests and analyzed by SISVAR® (Ferreira, 2011). To compare the means, the Scott-Knott test was used at 5% significance.

Results and Discussion

The formation of clonal *Coffea arabica* seedlings by cuttings was significantly affected by the type of substrate, and by the system used for their formation. Seedlings cut in phenolic foam in a modified hydroponic system did not survive (Table 1). There was possibly an increase in osmotic pressure with the increase in salinity; consequently, despite the available water in the nutrient solution, the environment becomes inadequate for the plant to absorb sufficient water and replace the loss through transpiration (Couto, Moreira, & Araújo, 2015).

However, the seedlings cut in tubes with vermiculite in the modified hydroponic system had a greater height (increase of 103.90%) and number of leaves (increase of 94.17%) than those produced in a conventional system (air-conditioned greenhouse), despite having lower survival (20% lower) and, consequently, lower number of remaining leaves (35.99% lower) (Table 1).

At the end of this study, we had, in absolute values, 9.39 fully expanded leaves in seedlings produced in tubes in modified hydroponics (4.695 pairs of leaves) and 4.836 fully expanded leaves in seedlings produced in tubes in the conventional system (2.418 pairs of leaves). Thus, it is possible to infer that the seedlings produced in tubes and modified hydroponics grew 2.28 pairs of fully expanded leaves more than the conventional system, in the same time of production, considering an average time of 23 days for the emission of new pairs of leaves. These can anticipate planting in the field by about 52 days, compared to the traditional system. This anticipation can be decisive in the success of plantation, as it allows the planting of seedlings at the beginning of the rainy season. With the use of the air-conditioned greenhouse system, the seedlings had similar survival rates, both in seedlings produced in tubes with vermiculite (78.33%) and in those produced in phenolic foam (73.33%)

Table 1
Survival, total height, number of leaves and remaining leaves of clonal coffee seedlings, grown in phenolic foam and vermiculite, under modified hydroponics and conventional cultivation

	Survival (%)	
	Vermiculite	Foam
Modified Hydroponics	58.333 Ba	0.000 Bb
Conventional System	78.333 Aa	73.333 Aa
	Total height (cm)	
	Vermiculite	Foam
Modified Hydroponics	10.970 Aa	0.000 Bb
Conventional System	5.380 Ba	5.438 Aa
	Number of leaves	
	Vermiculite	Foam
Modified Hydroponics	9.390 Aa	0.000 Bb
Conventional System	4.836 Ba	4.751 Aa
	Remaining leaves	
	Vermiculite	Foam
Modified Hydroponics	0.583 Ba	0.000 Bb
Conventional System	1.620 Aa	1.433 Aa

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

The higher moisture in the cutting seedling production environment is a factor of great importance, as it acts in water status regulation, since the cutting has no means of absorbing water and nutrients. Therefore, the moisture of the substrate and the environment play an important role, as it prevents the plant material from drying. This explains the reason for the better performance in terms of survival in the greenhouse which, during the experiment, had an average relative moisture of 84.9%; while in the hydroponic system, this moisture was 41.5%. However, the use of phenolic foam as an alternative substrate is not ruled out since, in the air-conditioned greenhouse environment (conventional environment), the results of survival, height, number of leaves and remaining leaves were the same as those obtained with the conventional substrate (tubes with vermiculite). With these results, it can be observed that the modified hydroponic system should not be recommended only in the case of the use of phenolic foam as a substrate, and it can be noticed, during the experiment, that an excessive water accumulation occurred. On the other hand, in the air-conditioned greenhouse system, the upper part of the phenolic foams was dried, and there was no moistening of this part by capillarity, compromising seedling survival. However, it can be observed in this study that there is a need for changes in the modified hydroponic system and in the irrigation system of the greenhouse so that seedling production by cuttings in phenolic foam has greater adaptability of the methodology (Silva et al., 2013).

The remaining leaves help in the maintenance of a transpiratory surface in the cut, so that photosynthesis is maintained and, consequently, the production of carbohydrates, which are essential in rooting; however, the loss of water through transpiration is increased at high temperatures (Benincasa, 2003). This explains the greater fall of these leaves (lesser number of remaining leaves) in the hydroponic environment, where high temperatures were observed (average of 28.4 °C) and there is no spray irrigation system as in the air-conditioned greenhouse. Regarding the root development of the produced seedlings, it can be stated that there was an influence of both the substrate used and the conduction environment. For all root variables analyzed, the use of vermiculite as a substrate yielded better root development; the system that showed the best performance was the modified hydroponic system (Table 2).

Table 2
Root volume, surface area, diameter and length of the largest root of clonal coffee seedlings, grown in phenolic foam and vermiculite, under modified hydroponics and conventional cultivation

	Root volume (mm³)	
	Vermiculite	Foam
Modified Hydroponics	3963.881 Aa	0.000 Ab
Conventional System	1761.437 Ba	487.699 Ab
	Root surface area (mm²)	
	Vermiculite	Foam
Modified Hydroponics	20114.645 Aa	0.000 Ab
Conventional System	5692.955 Ba	1637.599 Aa
	Mean root diameter (mm)	
	Vermiculite	Foam
Modified Hydroponics	0.719 Aa	0.000 Bb
Conventional System	0.693 Ab	0.828 Aa
	Root length (cm)	
	Vermiculite	Foam
Modified Hydroponics	31.540 Aa	0.000 Bb
Conventional System	12.845 Ba	6.920 Ab

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

The highest values of root volume, surface area and length of cutting seedlings produced in tubes with vermiculite in a modified hydroponic system in relation to those produced in a greenhouse, possibly occur as a physiological response of plants to the greater availability of water and nutrients. This availability increases root development, since the plant has mechanisms capable of increasing or decreasing its root system according to its needs (Covre, Partelli, Gontijo, & Zucoloto, 2015). However, the modified hydroponic system was not able to change the root diameter of cutting seedlings, produced in tubes with vermiculite (Table 2).

When the seedlings were cultivated by cuttings in a greenhouse, it was noticed that they presented greater volume and length when produced in tubes with vermiculite. However, the use of phenolic foam was able to keep a similar surface area and increase root diameter in relation to the conventional substrate. As observed in other evaluations, the seedlings produced in phenolic foam in the modified hydroponic system did not survive (Table 2).

The lower development of the root system in the foam may also be related to the degradation process undergone by this substrate, which occurs during the plant cultivation period; thus, nutrient retention time is reduced. Furthermore, the better performance of seedlings in the modified hydroponic system, in terms of root surface area and diameter, may have occurred due to the prompt supply of nutrients during plant absorption (Jordan, Ribeiro, Oliveira, Geisenhoff, & Martins, 2018).

Although the results show an inferiority of the root development in the phenolic foam in some of the characteristics (root volume and length), rooting occurred with the same surface area and larger diameter (Table 2). In the air-conditioned greenhouse system, root length in tubes containing vermiculite was 85.62% greater than those grown in phenolic foam, possibly due to the volume of substrate available for root development, which is greater in the tubes. It is also known that natural pruning occurs, when the roots emerge out of the substrate, and come into contact with oxygen, leading to the death of the exposed tissue (Floss, Silva, Demartelaere, Medeiros, & Preston, 2020).

In the conventional system (air-conditioned greenhouse), the average root diameter in the phenolic foam (0.828 mm) was greater than in the tubes with vermiculite (0.693 mm). Thin roots are extremely important in the root system, as they are associated with the absorption and transport of water and nutrients.

When evaluating the dry matter weight of the seedlings, it was observed that substrate and cultivation system influenced all the variables analyzed. The best dry matter weight results were observed when using vermiculite as a substrate in the modified hydroponic system (Table 3).

These seedlings had a shoot dry matter weight much higher than those grown in an air-conditioned greenhouse. Leaf dry matter weight increased by 311.97%, and stem dry matter weight increased by 355.10% (Table 4). Root and total dry matter weight followed the same pattern, since the seedlings cut in tubes with vermiculite in the hydroponic system were higher; in addition, the performance of the substrates was similar in the greenhouse. Once again, the death of seedlings cut in phenolic foam in the modified hydroponic system was evidenced (Table 3).

Shoot dry matter (leaves and stem), has a close relationship with the quantity and quality of the leaves. This characteristic is of great importance, since leaves are one of the main sources of photoassimilates for plants (Silva et al., 2013). It is then possible to observe the consistency of the results of this study, with a greater number of leaves and shoot dry matter weight in the treatment with the use of vermiculite in the hydroponic cultivation system, that is, the greater number of leaves under these conditions is related to the greater availability of water and nutrients and, consequently, to a greater seedling growth.

Shoot development and, consequently, dry matter production, is linked to the development of the root system. According to Coelho et al. (2020), seedlings with an underdeveloped root system undergo water stress, as they do not absorb sufficient water to balance losses due to transpiration. However, in this study, the smaller root volume obtained with the use of phenolic foam in the conventional system, was not able to affect the dry matter production of the shoot in these seedlings (Table 3).

Table 3
Leaf dry matter (LDM), stem dry matter (StDM), root dry matter (RDM) and total dry matter (TDM) of clonal coffee seedlings, grown in phenolic foam and vermiculite, under modified hydroponics and conventional cultivation

	LDM (mg)	
	Vermiculite	Foam
Modified Hydroponics	1098.75 Aa	0.000 Ab
Conventional System	266.7 Ba	236.00 Aa
	StDM (mg)	
	Vermiculite	Foam
Modified Hydroponics	221.00 Aa	0.000 Ab
Conventional System	48.56 Ba	38.00 Aa
	RDM (mg)	
	Vermiculite	Foam
Modified Hydroponics	396.50 Aa	0.000 Ab
Conventional System	70.88 Ba	60.66 Aa
	TDM (mg)	
	Vermiculite	Foam
Modified Hydroponics	1716.00 Aa	0.000 Bb
Conventional System	386.15 Ba	334.66 Aa

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

Table 4
Total leaf area (TLA), Leaf area ratio (LAR), specific leaf area (SLA) and specific leaf matter (SLM) of clonal coffee seedlings, grown in phenolic foam and vermiculite, under modified hydroponics and conventional cultivation

	TLA (cm²)	
	Vermiculite	Foam
Modified Hydroponics	21474.66 Aa	0.000 Bb
Conventional System	11858.66 Ba	7049.60 Ab
	LAR (cm²/mg)	
	Vermiculite	Foam
Modified Hydroponics	15.08 Ba	0.000 Bb
Conventional System	30.38 Aa	21.10 Ab
	SLA (cm²/mg)	
	Vermiculite	Foam
Modified Hydroponics	27.91 Ba	0.000 Bb
Conventional System	43.79 Aa	30.24 Ab
	SLM (mg/cm²)	
	Vermiculite	Foam
Modified Hydroponics	0.045 Aa	0.000 Bb
Conventional System	0.023 Ba	0.035 Aa

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

The lowest root dry matter weight was observed by Romero et al. (2017), when using phenolic foam in the formation of *Pinus leiophylla* seedlings. This result was attributed to the fact that the roots penetrated and remained in the foam; thus, removing the root system was difficult and, therefore, these roots were not considered in weighing. The same difficulty was observed in this study in the seedlings formed in phenolic foam in the air-conditioned greenhouse. However, even with this obstacle, the result was similar to that of vermiculite in this environment. Thus, it is possible to infer that phenolic foam can be used as an alternative substrate in this system, as it allows the formation of a well-developed root system.

The total leaf area and growth parameters of the formed seedlings were influenced by the substrate and the production system used. In the air-conditioned greenhouse environment, there was an increase of 68.21% in the total leaf area (TLA) of the seedlings formed in tubes with vermiculite in relation to the seedlings produced in phenolic foam. In addition, when using tubes with vermiculite in the modified hydroponic system, there was an increase of 81.08% in relation to the seedlings produced in the conventional system (Table 4).

Analyzing the growth parameters, leaf area ratio (LAR) and specific leaf area (SLA), lower values were observed in seedlings cut in tubes with vermiculite in the modified hydroponic system and with the use of phenolic foam as a substrate in the air-conditioned greenhouse. As for specific leaf mass (SLM), the lowest values were obtained in the tubes with vermiculite in the conventional system, but with no significant differences between the substrates in this system (Table 4).

The reduction in leaf area for seedlings formed in phenolic foam, is possibly related to the lower water retention of this substrate under the conditions of the air-conditioned greenhouse.

According to Benincasa (2003), LAR is the ratio between leaf area and total dry matter, and it is a morphophysiological component that represents the area useful for photosynthesis; it is the leaf area necessary to accumulate 1g of dry matter. According to the same author, with plant growth, leaf self-shading increases, leading to a reduction in LAR. Thus, it is possible to explain the reason why the treatment with Vermiculite + Hydroponics yielded the lowest value of LAR, as it was where the greatest growth occurred. The decrease in LAR indicates that, with progressive plant growth, the amount of photoassimilates destined for the leaves is reduced due to the development of other structures (Marques, Peil, Carini, Rosa, & Lago, 2016).

When working with mint propagation by mini-cuttings in different systems, Casais, Borges, Medeiros, Souza and Soares (2020) also observed the lowest LAR values in a hydroponic system, which reinforces the results of this study, that the hydroponic system provides greater seedling growth. In the air-conditioned greenhouse, SLA was lower with the use of phenolic foam. This parameter is given by the ratio between total leaf area and leaf dry matter, and represents the allocation of biomass by area unit (Benincasa, 2003). Lower SLA values may be related to a greater investment of plants in structural components (Mercês et al., 2013). Thus, the lower values found in the seedlings of tubes with vermiculite in a modified hydroponic system, and in those of phenolic foam in the air-conditioned greenhouse can be explained, since the seedlings formed under these conditions showed greater growth in height.

According to Dutra, Massad and Santana (2012), a greater specific leaf matter is important, as it indicates a greater leaf thickness and, consequently, lower water loss. Vermiculite yielded greater specific leaf matter in the modified hydroponic system (95.62% increase) and, in the conventional system, there were no significant differences between substrates.

Regarding the physiological analyses, it was found in this study that the chlorophyll content was affected by substrate and cultivation system. In the seedlings formed in tubes containing vermiculite, there were no significant differences in these levels between the systems used. However, in the air-conditioned greenhouse system, the substrates differed significantly, with a reduction in the contents of chlorophylls a (17.85%), b (30.30%) and total (21.30%) with the use of phenolic foam in relation to vermiculite. Furthermore, as observed in the other evaluations, seedlings cut in phenolic foam under hydroponic conditions did not survive (Table 5).

Table 5
Chlorophyll *a, b* and total of clonal coffee seedlings, grown in phenolic foam and vermiculite, under modified hydroponics and conventional cultivation

	Chlorophyll *a*	
	Vermiculite	Foam
Modified Hydroponics	427.778 Aa	0.000 Bb
Conventional System	400.842 Aa	329.278 Ab
	Chlorophyll *b*	
	Vermiculite	Foam
Modified Hydroponics	166.556 Aa	0.000 Bb
Conventional System	153.368 Aa	106.889 Ab
	Total chlorophyll	
	Vermiculite	Foam
Modified Hydroponics	594.333 Aa	0.000 Bb
Conventional System	554.211 Aa	436.167 Ab

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

Chlorophyll *a* is the main pigment responsible for photosynthesis, giving plants a green color, and chlorophyll *b* is the accessory pigment, with the ability to increase the luminous absorption range of plants. For this reason, its content is extremely important, as it guarantees the success of the photosynthetic process (Casais et al., 2020).

Stomatal conductance and density were also influenced by the studied factors. Seedlings cut into tubes with vermiculite in a modified hydroponic system had superior results for both stomatal conductance and density (increase of 302.93% and 12.35%, respectively). In the air-conditioned greenhouse system, stomatal conductance was similar in both substrates (51.77 μmol m^{-2} s^{-1} in vermiculite and 43.98 μmol m^{-2} s^{-1} in phenolic foam), while stomatal density in this system was 7.82% higher in tubes with vermiculite than in phenolic foam (Table 6).

It is observed that stomatal functionality and opening did not differ significantly between treatments. (Table 6). Stomata are the main structures in the regulation of gas exchange in plants. Thus, the increase in stomatal conductance allows a greater CO_2 input, providing higher assimilation rates of this gas, which is essential for the photosynthetic process. There are several factors capable of reducing stomatal conductance, such as: temperature, water deficit, solar radiation, reduced root system, among others (Andrade et al., 2013).

Table 6
Stomatal conductance, density (DEN) and functionality (FUN) and stomatal opening of clonal coffee seedlings, grown in phenolic foam and vermiculite, under modified hydroponics and conventional cultivation

	Stomatal conductance (µmol m^{-2} s^{-1})	
	Vermiculite	Foam
Modified Hydroponics	208.60 Aa	0.00 Bb
Conventional System	51.77 Ba	43.98 Aa
	DEN (stomata/mm²)	
	Vermiculite	Foam
Modified Hydroponics	180.219 Aa	0.000 Bb
Conventional System	160.404 Ba	148.767 Ab
	FUN	
	Vermiculite	Foam
Modified Hydroponics	1.804 Aa	0.000 Bb
Conventional System	1.836 Aa	1.802 Aa
	Stomatal opening (µm)	
	Vermiculite	Foam
Modified Hydroponics	2.576 Aa	0.000 Bb
Conventional System	3.043 Aa	3.127 Aa

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

In the air-conditioned greenhouse, although the phenolic foam possibly underwent greater water restriction in relation to the tubes with vermiculite, a fact observed by the drying of the substrate, it was not sufficient to reduce the stomatal conductance values, indicating that the use of phenolic foam as an alternative substrate should not be discarded. Thus, the possible water restriction observed in seedlings produced in phenolic foam was not able to reduce stomatal conductance. When studying the photosynthetic limitations of coffee seedlings subjected to severe water stress, Peloso, Tatagiba, Reis, Pezzopane and Amaral (2017) observed a reduction in stomatal conductance, differently from this study, in which water restriction was not accentuated. However, the stomatal density response occurs differently from that of conductance; this characteristic is probably more sensitive to water deficiency since, even if the water restriction has not been accentuated, the stomatal density of the seedlings formed in phenolic foam in the air-conditioned greenhouse was reduced when compared to that formed in vermiculite.

Higher stomatal density may be related to the increase in leaf area and, consequently, the increase in CO_2 uptake by plants (Voitsekhovskaja & Tyutereva, 2015). This fact explains why the seedlings cut in tubes with vermiculite presented higher values in a modified hydroponic system, where they also had the largest leaf area.

Conclusions

The survival rate of coffee seedlings is higher in climate-controlled greenhouse conditions compared to the modified hydroponic system.

The innovative production system of coffee seedlings in modified hydroponics in combination with the use of tubes containing vermiculite, in general yields a better seedling development and quality, when compared to the nursery.

The substrate phenolic foam can be used alternatively in the air-conditioned greenhouse system. However, in the modified hydroponic system it is not indicated, as it leads to total seedling mortality.

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