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# UAV-Based Vegetation Indices to Evaluate Coffee Crop Response after Transplanting Seedlings Grown in Different Containers

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**Abstract:** Brazil stands out among coffee-growing countries worldwide. The use of precision agriculture to monitor coffee plants after transplantation has become an important step in the coffee production chain. The objective of this study was to assess how coffee plants respond after transplanting seedlings grown in different containers, based on multispectral images acquired by Unmanned Aerial Vehicles (UAV). The study was conducted in Santo Antônio do Amparo, Minas Gerais, Brazil. The coffee plants were imaged by UAV, and their height, crown diameter, and chlorophyll content were measured in the field. The vegetation indices were compared to the field measurements through graphical and correlation analysis. According to the results, no significant differences were found between the studied variables. However, the area transplanted with seedlings grown in perforated bags showed a lower percentage of mortality than the treatment with root trainers (6.4% vs. 11.7%). Additionally, the vegetation indices, including normalized difference red-edge, normalized difference vegetation index, and canopy planar area calculated by vectorization ($cm^2$), were strongly correlated with biophysical parameters. Linear models were successfully developed to predict biophysical parameters, such as the leaf area index. Moreover, UAV proved to be an effective tool for monitoring coffee using this approach.

**Keywords:** remote sensing; sustainable crop production; coffee monitoring; seedling container; UAV



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## 1. Introduction

Brazil is projected to contribute around a third of the world's coffee production, solidifying its position as the leading producer and exporter of coffee [1,2]. The arabica coffee (*Coffea arabica* L.) comprises approximately 70% of Brazil's coffee output, with Minas Gerais standing out as the state with the highest production volume [2]. These statistics underscore the significant economic and social significance of the coffee industry in Brazil.

The regional climate and terrain characteristics of Minas Gerais state provide favorable conditions for coffee production. However, the high productive potential of coffee in these areas necessitates adequate monitoring and the use of technology to ensure high yields. In this context, precision agriculture has become intrinsic to coffee cultivation. Within coffee farming, this approach is known as precision coffee farming, characterized by a collection of methods and technologies that consider the spatial characteristics of both soil and plants, helping coffee growers manage their crops to improve the final product's quality and maximize income [2]. However, this technology cannot be implemented without the farmer's knowledge of the field, and agricultural practices developed across generations are also crucial for successful coffee growing.

Among the different phases of the coffee production cycle, establishing the crop in the field is essential. Therefore, it is important to produce quality seedlings and ensure adequate monitoring after transplanting to ensure a good crop establishment in the field. In this context, conducting studies to evaluate the production of coffee seedlings in different containers, as well as the response of the seedlings after implantation in the field, becomes necessary.

The utilization of different containers for coffee seedling production has been the focus of research studies. Conventional polyethylene bags have some disadvantages, such as potential disintegration, susceptibility to nematode infection, taproot coiling, high substrate demand, and low efficiency in the nursery phase, necessitating a large area and manual planting. Consequently, root trainers and perforated bags have emerged as alternative options. In addition to overcoming the aforementioned disadvantages, both alternatives enable mechanical planting, among other benefits. However, farmers harbor concerns about certain factors, like seedling survival, creating resistance to change due to the high manual labor cost associated with replanting [3–5]. Studies on containers for coffee seedling production have been conducted, most of which have shown superior results in higher-volume containers without necessarily indicating an effect from the container material [6,7]. However, the majority of these studies evaluated the nursery phase, with only a few assessing the performance post-transplanting.

One of the approaches integrated into precision agriculture is remote sensing, defined as the acquisition of information about objects on the Earth's surface without physical contact [8,9]. Due to the well-defined spectral response of plants and their characteristic interaction with electromagnetic radiation, remote sensors find application in agriculture for monitoring purposes. However, there is a lack of studies related to coffee cultivation post-transplanting of seedlings in the field, as coffee is a perennial, complex crop with diverse phenological phases. Furthermore, the emergence of Unmanned Aerial Vehicles (UAV) equipped with remote sensors exacerbates this gap, as UAV images offer higher spatiotemporal resolution compared to satellite images [10]. The challenges related to acquiring spectral information at an appropriate temporal resolution and the expenses associated with obtaining high spatial resolution imagery have been successfully addressed with UAVs [11].

Various studies have employed remote sensing to assess coffee plants, monitor diseases and water stress, and establish correlations among other biotic and abiotic factors using vegetation indices (VIs) measured by orbital sensors [12–14]. Others have utilized multispectral cameras coupled to UAVs to evaluate fruit ripening, seedling mortality, and correlations between field measurements and aerial images [15–23]. However, no studies have utilized remote sensing and UAVs to monitor farming practices, specifically the response of coffee seedlings transplanted in different containers.

To address this gap, a comparative study was conducted, examining indices obtained from aerial imagery in conjunction with field-collected data, including crop growth variables. The study involved graphical analysis of variations over time, correlation analysis, and development of linear models. Within this scope, the study aimed to evaluate the response of coffee plants grown in different containers (root trainers and perforated bags) after transplantation to the field, using VIs generated from multispectral images acquired by UAVs.

## 2. Materials and Methods

### *2.1. Study Area and Experimental Design*

The experimental site is situated within the coffee-growing area of Samambaia Farm, located in Santo Antônio do Amparo, in the Campos das Vertentes region, within the Formiga microregion, southeastern Minas Gerais (MG), Brazil [24]. As the Köppen climate classification modified by [25], the regional climate is categorized as Cwb, a subtropical highland climate that features mainly dry winters and mild summers. Temperature averages fall between 18 °C and 22 °C, accompanied by an average annual rainfall of 1650 mm. The dry season typically lasts from May to September, succeeded by the rainy season, which can persist until late March or early April.

The experimental area (Figure 1) is positioned at geographic coordinates 20°53′29.37″ S and 44°56′4.83″ W and an average altitude of 1010 m, covering an area of 0.28 hectares. The *Coffea arabica* L. cultivar Catuaí IAC-62 was planted. The predominant soil type in the region is classified as red–yellow latosol according to the Brazilian Soil Classification System [26].

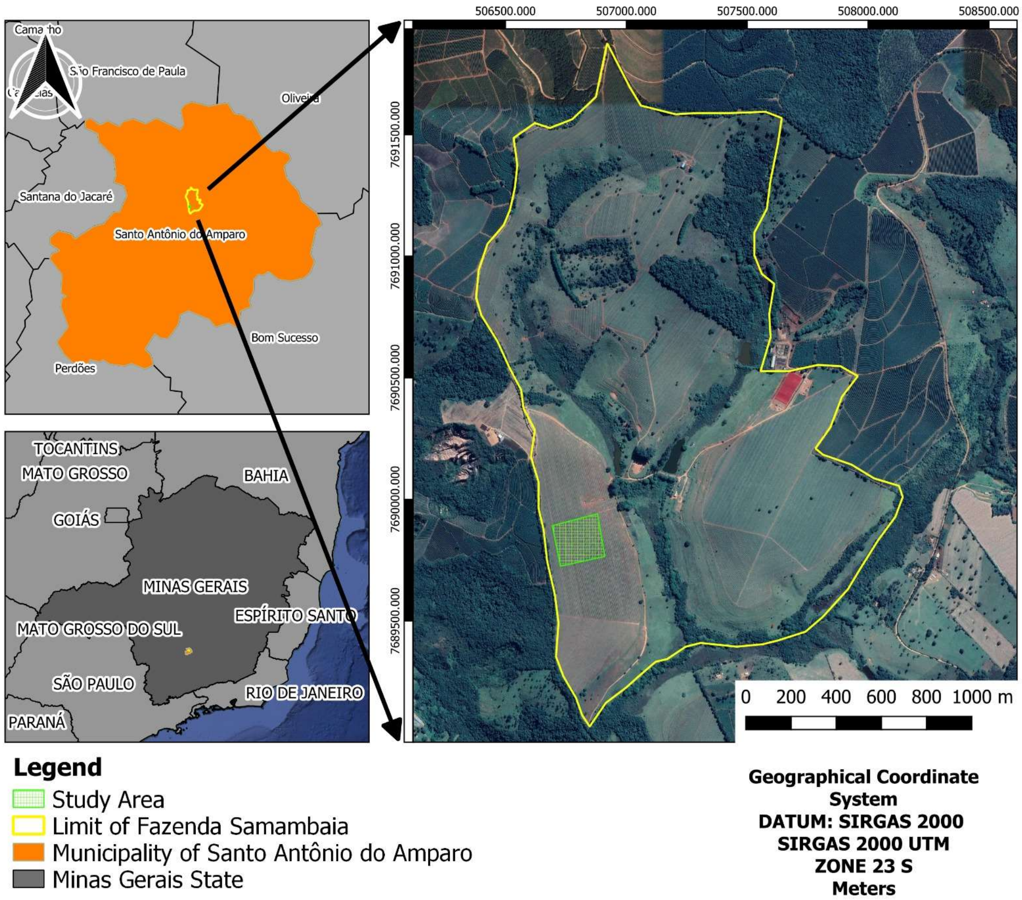


**Figure 1.** Location map of the study area.

### *2.2. Seedlings Production and Transplanting*

The production of coffee seedlings was conducted in a nursery, utilizing two types of containers. The first type was the polyvinyl chloride (PVC) root trainer, which had a volume of 180 mL. The second container was perforated polyethylene bags with a volume of 615 mL. Both containers were filled with a substrate composed of soil and trop-strate, a mixture of vermiculite, coconut fiber, and pine. For clarity in presenting results and discussions, the two container types were referred to as "root trainers" and "perforated bags".

Following seedling production in the nursery, transplantation occurred in the field between November and December 2018. The research was conducted until March of 2020 (16 months of coffee growing evaluation). The seedlings were planted with 50 cm of spacing between plants and 3.8 m between rows in perforated bags using the Mafes transplanter (Gralha model). Three rows were allocated for planting and evaluating seedlings produced in root trainers. Ground control points (GCPs) were utilized to mark sample units, aiding in their identification in the UAV images. Fifteen GCPs were used for each treatment, one for each sample unit (30 in total). The markers were made of cardboard and colored pressed cards.

### *2.3. Unmanned Aerial Vehicles, Flight Plans, and Multispectral Sensors*

The images were captured between 12:00 and 13:00 (local time) to minimize the impact of shadows, utilizing a commercial DJI Matrice 100 UAV equipped with a quadcopter (rotary-wing) design powered by four engines. This UAV was fitted with a Parrot Sequoia multispectral camera. The camera is equipped with an RGB sensor boasting a resolution of 16 megapixels (4608 × 3456) and four supplementary sensors, each with a resolution of 1.5 megapixels (1280 × 960), capturing spectral bands in green (550 nm BP 40), red (660 nm BP 40), red-edge (735 nm BP 10), and near-infrared (790 nm BP 40).

Additionally, the camera incorporates a solar radiation sensor, integrated with a global navigation satellite system (GNSS), as well as a radiometric calibration panel responsible for calibrating electromagnetic radiation (EMR) and standardizing data into reflectance values. Flight planning and configuration, including flight direction (across planting rows), image overlay (80 × 80%), speed (8 m.s$^{-1}$), and altitude (50 m), were managed using the open-source software Precision Flight version 2.0 [27]. Images were captured at intervals of 1.2 s, resulting in a total of 335 scenes and generating an orthomosaic with a Ground Sample Distance (GSD) of 4.85 cm. The flights were conducted bimonthly, as well as the field data collection, resulting in six flights in total.

### *2.4. Processing of Images and Spectral Data*

Following the flights, the images underwent processing using PIX4D Mapper software, Version 4.4.10 [28]. The processing workflow is presented in Figure 2. Subsequently, the generated products were utilized in software applications such as QGIS 3.4.14 Madeira [29] and eCognition Developer 9.0 [30] for generating vegetation indices (VIs), image segmentation, and storing geospatial vector data (shapefiles) representing the sample units, which were also used for vectorized canopy planar-area analysis. This enabled the extraction of VI values from the stored data. The field-measured parameters (crown diameter, chlorophyll, and height) were incorporated into tables detailing the attributes of the vectors.

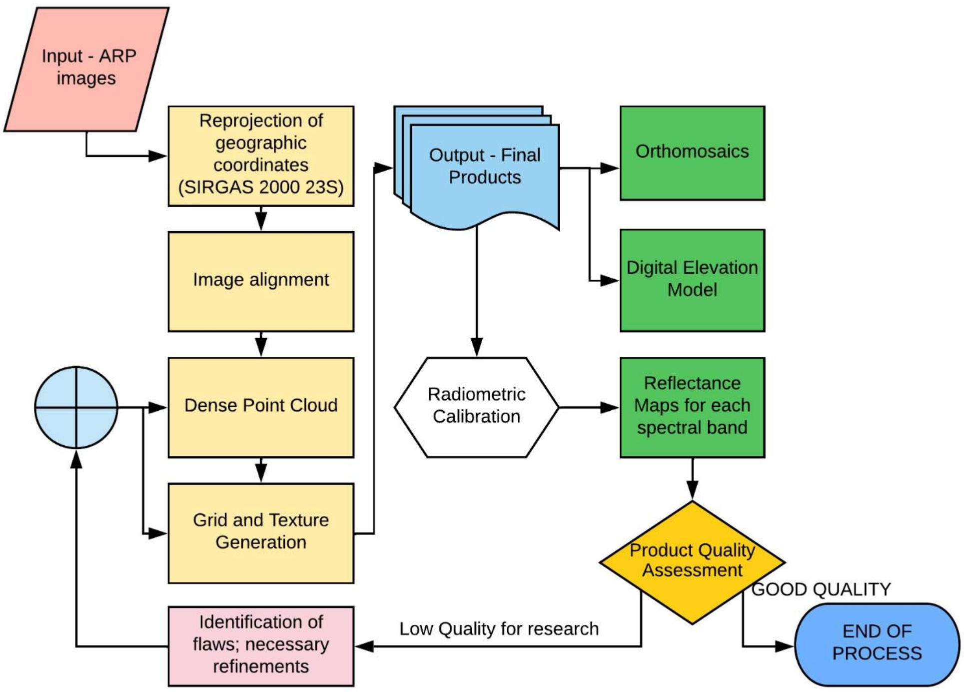


**Figure 2.** Flowchart of the Unmanned Aerial Vehicle (UAV) image processing in the software. ARP: aircraft remotely piloted.

### *2.5. Vegetation Indices*

Vegetation indices were calculated to assess the spectral response of coffee trees transplanted from different containers (Table 1). These indices were selected from the literature to evaluate parameters such as chlorophyll content, nitrogen levels, vigor, water stress, and productivity estimation, among others [31–34].

**Table 1.** Vegetation indices of multispectral images obtained using UAV.

| Vegetation Indices | Equation | Reference |
|---|---|---|
| GNDVI (Green Normalized Difference Vegetation Index) | $\frac{\rho_{nir} - \rho_{green}}{\rho_{nir} + \rho_{green}}$ | [34] |
| NDVI (Normalized Difference Vegetation Index) | $\frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}}$ | [35] |
| NDRE (Normalized Difference Red Edge) | $\frac{\rho_{nir} - \rho_{edge}}{\rho_{nir} + \rho_{edge}}$ | [36] |
| GCI (Green Chlorophyll Index) | $\frac{\rho_{nir}}{\rho_{green}} - 1$ | [32] |
| MSAVI 2 (Modified Soil-Adjusted Vegetation Index 2) | $0.5\ x \left[(2\rho_{nir} + 1) - \sqrt{(2\rho_{nir} + 1)\ x\ 2 - 8\ x\ (\rho_{nir} - \rho_{nir})}\right]$ | [37] |
| MCARI 1 (Modified Chlorophyll Absorption in Reflectance Index 1) | $1.5 \times [2.5(2\rho_{nir} - \rho_{red}) - 1.3(2\rho_{nir} - \rho_{red})]$ | [31] |

$\rho_{green}$ reflectance in the green band; $\rho_{red}$: reflectance in the red band; $\rho_{nir}$: reflectance in the near-infrared band; $\rho_{edge}$: reflectance in the red-edge band.

The indices were calculated in QGIS using the "Raster Calculator" tool and then extracted using the "Zonal Statistics" tool. The vectors were created in the eCognition Developer software following a predefined process tree outlined in [38] and following the concepts of object-based image analysis (OBIA) for UAV, regarding canopy planar area [39,40], encompassing the following sequence of tasks: (a) Image segmentation conducted using "multi-resolution segmentation" and "spectral difference segmentation" algorithms; (b) coffee tree sampling facilitated using the "sample selection" tool; (c) training and classification conducted using the "support vector machine" classifier, incorporating parameters such as brightness, shape, compactness, spectral bands, and VIs; (d) exporting the transformed vectors into the shapefile format (the vectors represented coffee trees canopy planar area).

### *2.6. Seedling Mortality Assessment*

To determine whether there was a difference in "seedling survival" between transplanted seedlings grown in root trainers versus those produced in perforated polyethylene bags, a survey was conducted to count the number of deceased seedlings. This assessment was conducted using eCognition Developer following the methodology outlined in the previous section [38]. The process involved analyzing images from December 2018, corresponding to the period of coffee seedling transplantation, and images from April, which were recorded before the first replanting (gap filling) was conducted in the area. The percentage of seedling mortality was calculated using Equation (1).

$$\%\text{ seedling mortality} = \frac{\text{number of seedlings transplanted in December}}{\text{number of seedlings in April}} \quad (1)$$

### *2.7. Field Sampling*

To assess the response of seedlings cultivated in different containers, field analyses were conducted every 2 months, coinciding with the collection of images on the same day. Throughout these evaluations, the height and canopy diameter of the plants were measured with a graduated measuring tape, and the chlorophyll content was determined using a chlorophyll meter sensor. In the section where coffee seedlings were transplanted into perforated bags, designated as the control, three rows were marked for planting. Each row was divided into five sample units, with each unit comprising an average of five plants. These samples were spaced at intervals of at least 20 plants, resulting in a total of 15 samples. The identical procedure was followed in the area where coffee seedlings were transplanted into root trainers, maintaining a one-row separation from the previously sampled area to minimize border row effects (Figure 3).

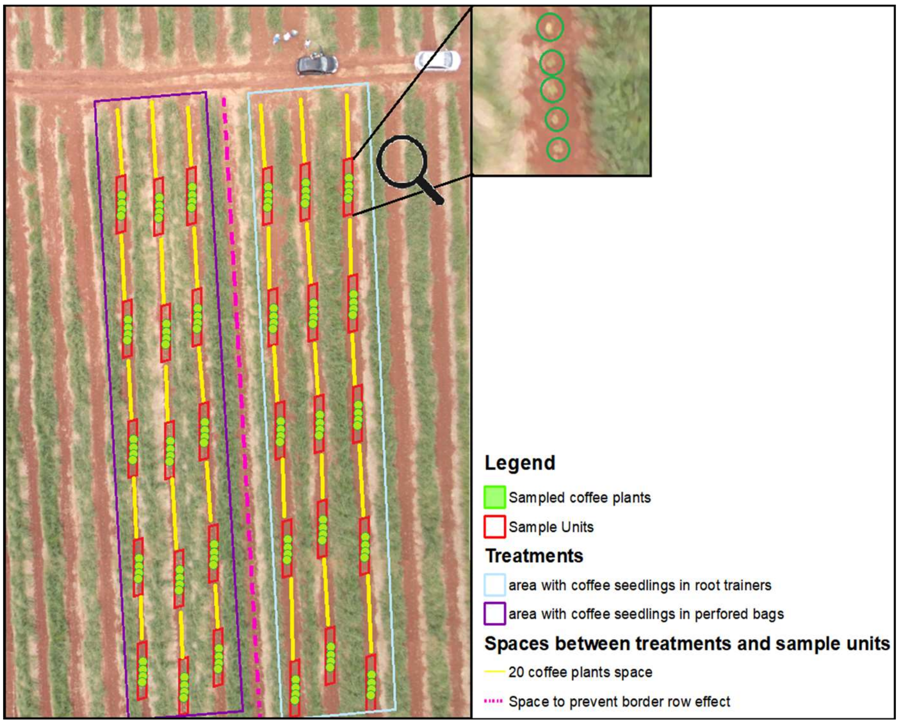


**Figure 3.** Diagram illustrating the coffee plant sampling method for both treatment and control areas.

The chlorophyll measurements were conducted using the atLEAF + chlorophyll meter (FT Green LLC, Wilmington, DE, USA) by attaching the sensor onto the coffee leaf, covering an area of 6 $mm^2$. Subsequently, Equations (2)–(4) developed and described by [41] were employed to estimate the Chlorophyll A and Chlorophyll B content in mg $cm^{-2}$.

$$\text{Total Chlorophyll} = 0.078 \times \text{atLEAF}^{1.63} \quad (2)$$

$$\text{Chl}_\text{a} = -5.774 + 0.430 \times \text{atLEAF} + 0.0045 \times \text{atLEAF}^2 \quad (3)$$

$$\text{Chl}_\text{b} = 0.040 \times \text{atLEAF}^{1.57} \quad (4)$$

where atLEAF is chlorophyll content recorded by the chlorophyll meter (dimensionless), $Chl_a$ is chlorophyll content a ($\mu g/cm^2$) and $Chl_b$ is chlorophyll content b ($\mu g/cm^2$).

The Leaf Area Index (LAI) was calculated following the methodology proposed by [42], which correlates leaf area to the crop area, utilizing plant height and crown diameter, as shown in Equation (5)

$$\text{LAI} = 0.0134 + 0.7276 \times \text{D}^2 \times \text{h} \quad (5)$$

where D represents plant diameter (m) and h represents plant height (m).

### 2.8. Statistical Analysis

The data collected in the field and extracted from images were structured into tables using Microsoft Excel version 16.0, and graphical representations were generated to illustrate the coffee trees' responses.

To assess the distribution of the data, the Shapiro–Wilk test [43] was conducted in SISVAR, indicating a departure from normal distribution. The data were submitted to the Mann–Whitney test [44] for independent and non-parametric variables in the software R version 4.1.3, adopting, in both tests, a significance level of $\rho = 0.05$.

Spearman's rank–order correlation [45]–$\hat{\rho}_s$ was employed to determine the correlation between variables measured in the field and those derived from UAV images. Furthermore, the Pearson's chi-squared ($\chi^2$) test [46], suitable for nominal and non-parametric variables, was utilized to investigate the association between the frequency of seedling mortality observed during transplantation and the container type (root trainer or perforated bag) at a significance level of $\rho = 0.05$.

Additionally, linear models were developed using R [47] to predict physical variables obtained from field sampling based on VIs and digital measurements derived from UAV images.

## 3. Results and Discussion

### *3.1. Coffee Growth Evaluations*

The growth variables of coffee seedlings from perforated bags and root trainers post-transplantation are detailed in Table 2. Table 2 illustrates a bi-monthly increase in LAI (derived from height and diameter) and the canopy planar area calculated via vectorization. There were fluctuations in chlorophyll levels and VIs. However, in September, both LAI and canopy planar area increases were interrupted due to defoliation. Notably, chlorophyll values peaked in July (winter) and hit their lowest point in January (summer).

**Table 2.** Growth variables of coffee seedlings produced in two types of containers perforated bags and root trainers after transplanting.

| | Sampled Months | | | | | |
|---|---|---|---|---|---|---|
| **Coffee Growth Variables** | **May** | **July** | **September** | **November** | **January** | **March** |
| | | | Perforated-bag Treatment | | | |
| Height (cm) | 27.17 * | 32.55 | 33.79 | 43.23 | 47.67 | 62.66 |
| Canopy planar area ($cm^2$) | 521.22 | 798.19 | 592.99 | 1493.36 | 1778.78 | 3782.29 |
| LAI | 0.0362 | 0.0404 | 0.0376 | 0.0906 | 0.1292 | 0.3311 |
| Chlorophyll A ($\mu g/cm^2$) | 33.3175 | 47.8478 | 35.4263 | 37.4145 | 33.4785 | 42.8305 |
| Chlorophyll B ($\mu g/cm^2$) | 22.8253 | 32.5182 | 24.2354 | 25.5561 | 22.9313 | 29.1725 |
| Total chlorophyll ($\mu g/cm^2$) | 56.7625 | 81.9552 | 60.4265 | 63.8125 | 57.0288 | 73.2248 |
| | | | Root-trainer Treatment | | | |
| Height (cm) | 29.73 | 33.66 | 34.47 | 45.17 | 48.88 | 62.25 |
| Canopy planar area ($cm^2$) | 520.14 | 720.87 | 542.92 | 1559.19 | 1763.37 | 4091.52 |
| LAI | 0.0370 | 0.0395 | 0.0359 | 0.0898 | 0.1244 | 0.3305 |
| Chlorophyll A ($\mu g/cm^2$) | 35.0851 | 46.0934 | 35.4470 | 36.8907 | 35.0921 | 41.1585 |
| Chlorophyll B ($\mu g/cm^2$) | 24.0021 | 31.3476 | 24.2460 | 25.2067 | 24.0050 | 28.0558 |
| Total Chlorophyll ($\mu g/cm^2$) | 59.7950 | 78.8964 | 60.4412 | 62.9025 | 59.7898 | 70.3023 |

* Average value of the treatment.

The coffee growth variables during the production cycle showed a linear pattern of increase, mainly in height, canopy planar area, and LAI. The increase in leaf area is crucial for photosynthesis and the production of assimilates by the plant, ensuring a good initial establishment of the crop in the field and, thus, reducing the need for replanting seedlings. This result is consistent with other studies such as [48], evaluating the growth of coffee seedlings, where they observed that seedlings with greater leaf area development and root growth have a greater adaptation to field conditions and consequently result in minor replanting.

The variation of vegetation indices during the study period can be seen in Figure 4. The VI decreases during the dry seasons and increase again during the rainy season. Almost all vegetation indices showed a similar trend over time, with a decline observed from May onwards, reaching their lowest values in September. Notably, indices like MCARI1 and MSAVI2 exhibited higher values in November compared to January.

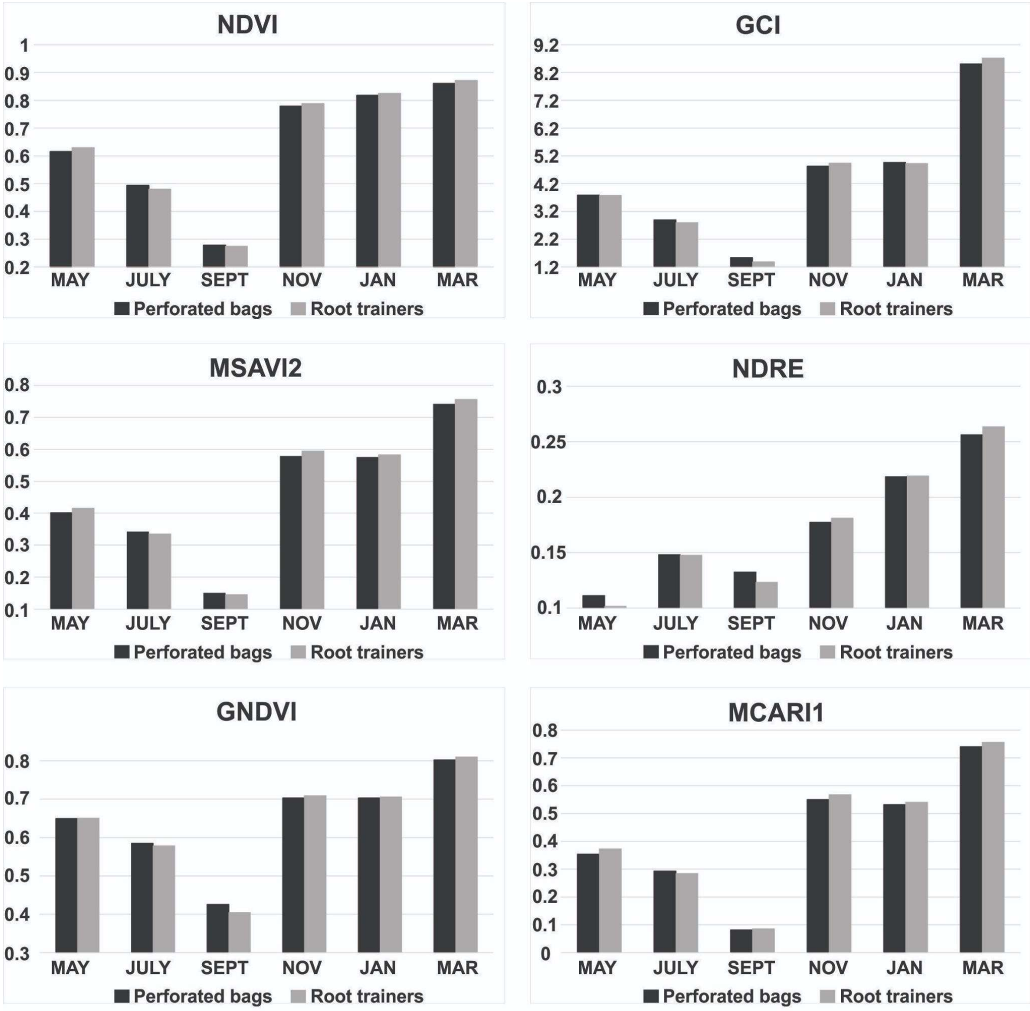


**Figure 4.** Vegetation indices of coffee seedlings produced in two types of containers perforated bags and root trainers after transplanting.

The comparison between seedlings produced in different containers (perforated bags versus root trainers) revealed no significant differences in the majority of variables over time, as shown in Figure 4. Coffee growth variables, such as LAI derived from field measurements of height and diameter, as well as the canopy planar area calculated by vectorization, exhibited a consistent linear increase. These variables experienced a slight decrease in September, notably the canopy planar area, which was likely attributed to defoliation during the dry season and the coffee's slow-growth period in its phenology. The same response pattern depending on the coffee phases was observed in some studies [49–51].

*3.2. Coffee Growth Variables under Different Seedling Containers*

After confirming the non-normal distribution of the data using the Shapiro–Wilk test, the Mann–Whitney test was conducted to assess differences between treatments for all sampled variables. No statistically significant differences were detected in any sampled variable. This outcome corroborates the earlier findings from the temporal analysis.

To assess the correlation between coffee growth variables measured in the field and those derived from UAV images, the Spearman's rank–order correlation coefficient ($\hat{\rho}_s$) was calculated. The results are presented in Table 3. Strong correlations were evident among most variables, except for chlorophyll. All VIs exhibited correlations with growth measures exceeding 0.70. Furthermore, the canopy planar area demonstrated the strongest association with other parameters, particularly with diameter and LAI, both showing ($\hat{\rho}_s$) values above 0.90.

**Table 3.** Statistical correlations between the coffee growth variables and the variables obtained using UAV images of coffee seedlings produced in perforated bags and root trainers.

| VIs (UAV) | Field Variables | | | | | | |
|---|---|---|---|---|---|---|---|
| | Height (cm) | Crown Diameter (cm) | Chlorophyll Content (IRC) | LAI | Chlorophyll A (µg/cm$^2$) | Chlorophyll B (µg/cm$^2$) | Chlorophyll A + B (µg/cm$^2$) |
| | Perforated-bag Treatment | | | | | | |
| GCI | 0.7660 | 0.8930 | 0.1684 | 0.8710 | 0.1535 | 0.1535 | 0.1530 |
| MSAVI | 0.7910 | 0.9040 | 0.1627 | 0.8870 | 0.1494 | 0.1494 | 0.1488 |
| MCARI1 | 0.7860 | 0.8950 | 0.1659 | 0.8780 | 0.1534 | 0.1534 | 0.1529 |
| GNDVI | 0.7600 | 0.8890 | 0.1689 | 0.8660 | 0.1543 | 0.1543 | 0.1537 |
| NDRE | 0.8850 | 0.8600 | 0.2650 | 0.8780 | 0.2570 | 0.2570 | 0.2570 |
| NDVI | 0.7910 | 0.8970 | 0.1070 | 0.8820 | 0.0931 | 0.0931 | 0.0925 |
| Crown area (cm$^2$) | 0.9020 | 0.9390 | 0.2760 | 0.9480 | 0.2700 | 0.2700 | 0.2700 |
| | Root-trainer Treatment | | | | | | |
| GCI | 0.8080 | 0.9100 | 0.1210 | 0.8790 | 0.1193 | 0.1178 | 0.1168 |
| MSAVI | 0.8110 | 0.9150 | 0.0937 | 0.8820 | 0.0907 | 0.0890 | 0.0878 |
| MCARI1 | 0.8030 | 0.9070 | 0.0878 | 0.8730 | 0.0847 | 0.0831 | 0.0818 |
| GNDVI | 0.8070 | 0.9070 | 0.1267 | 0.8770 | 0.1249 | 0.1234 | 0.1225 |
| NDRE | 0.8840 | 0.8780 | 0.2051 | 0.8940 | 0.2011 | 0.1995 | 0.1978 |
| NDVI | 0.8190 | 0.9290 | 0.0749 | 0.8960 | 0.0722 | 0.0705 | 0.0690 |
| Crown area (cm$^2$) | 0.8880 | 0.9340 | 0.2550 | 0.9350 | 0.2530 | 0.2510 | 0.2500 |

The results related to regression metrics and derived errors are presented in Table 4. In the development of linear models, parameters were selected based on their strong correlations, highest coefficient of determination ($R^2$), and relevance to estimation. Specifically, GCI × LAI was chosen.

**Table 4.** Metrics and errors of following scatter plots–GCI × LAI; canopy planar area calculated by vectorization (cm$^2$) × LAI; canopy planar area calculated by vectorization (cm$^2$) × crown diameter sampled in the field—and linear models for the coffee crop planted with seedlings produced in perforated bags and coffee crops planted with seedlings produced in root trainers.

| Model Parameter | Regression Metrics and Errors | | | | |
|---|---|---|---|---|---|
| | MSE | RMSE | MAE | $R^2$ | $\hat{\rho}_s$ |
| | Perforated-bag Treatment | | | | |
| GCI × LAI | 0.003 | 0.056 | 0.041 | 0.775 | 0.871 |
| | Root-trainer Treatment | | | | |
| GCI × LAI | 0.002 | 0.045 | 0.035 | 0.831 | 0.879 |
| | Total Coffee Samples From Both Experiments | | | | |
| Canopy planar area calculated by vectorisation (cm$^2$) × LAI | 0.001 | 0.036 | 0.023 | 0.886 | 0.951 |
| Canopy planar area calculated by vectorisation (cm$^2$) × Diameter (cm) | 35.379 | 5.948 | 4.456 | 0.897 | 0.951 |

Additionally, due to the absence of significant differences between containers and the robust correlation (close to 0.90) observed with field-measured diameter (cm) and LAI in both treatments, a unified linear model was constructed encompassing all sampled coffee trees for the variable "canopy planar area calculated by vectorization" (cm$^2$).

The scatterplots of LAI as a function of GCI, the linear models, and the equations of the line of the seedling planting assessment in the different containers tested in this study, were shown in Figure 5.

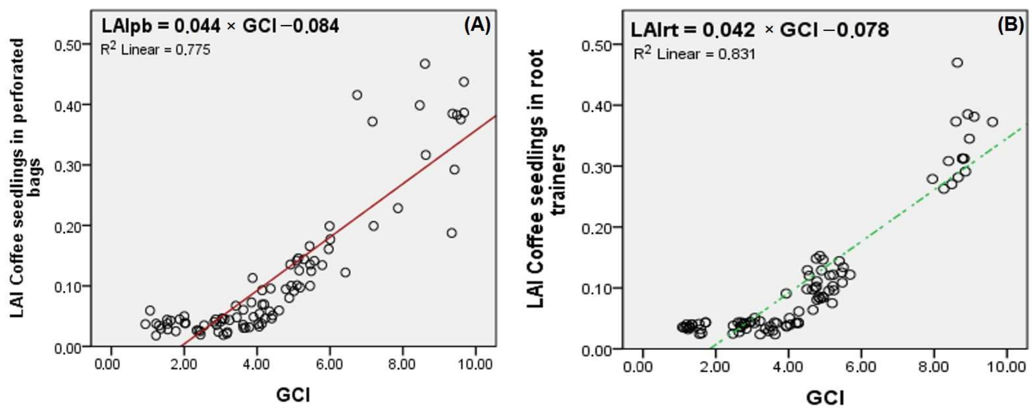


**Figure 5.** Scatterplot, simple linear regression model, and its equation for LAI estimation as a function of GCI for coffee crops planted with seedlings produced in perforated bags (**A**) and seedlings produced in root trainers (**B**).

The $R^2$ values indicate that despite their simplicity, the linear models effectively predict the LAI of coffee plants based on GCI, which typically necessitates field measurements. Post-transplantation, seedlings grown in both perforated bags (A) and root trainers (B) exhibited high $R^2$ values in the model concerning GCI and LAI estimates, exceeding 0.75. Consequently, the simple linear regression models explain more than 75% of the LAI values based on GCI. Notably, the area planted with seedlings from root trainers demonstrated higher $R^2$ values and lower errors ($R^2$ = 0.831; mean squared error (MSE) = 0.002; root mean square error (RMSE) = 0.045; mean absolute error (MAE) = 0.035) compared to seedlings from perforated bags ($R^2$ = 0.775; MSE = 0.003; RMSE = 0.056; MAE = 0.041).

For all samples, disregarding the container type, linear models were developed based on the canopy planar area calculated by vectorization ($cm^2$) to estimate the LAI and crown diameter (cm) of young coffee plants. Figure 6 shows the scatter plots, linear models, and their corresponding equations.

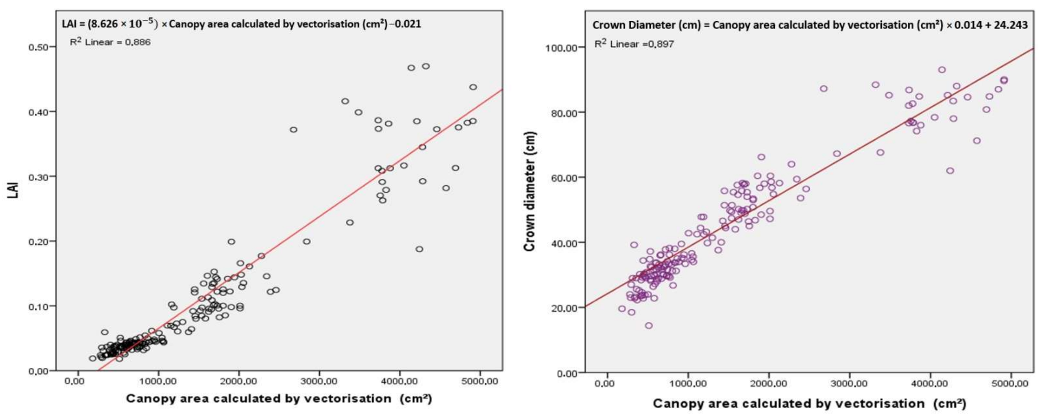


**Figure 6.** Scatterplot, simple linear regression model, and its equations to estimate LAI and crown diameter as a function of canopy planar area calculated by vectorization of coffee plants in formation from both experiments.

The linearity exhibited in Figure 6 suggests that UAV images served as a credible alternative to field measurements. The significance of the linear model predictions is underscored by the $R^2$ values of both models, nearing 0.90. This indicates that the models, based on canopy planar area calculated by vectorization in software ($cm^2$), show approximately 90% of the values for both LAI and crown diameter (cm). However, despite the high $\hat{\rho}_s$ and $R^2$ values, estimating the diameter (cm) using the canopy planar area calculated by vectorization ($cm^2$) resulted in absolute errors (MAE) of approximately 4.5 cm and an

RMSE of 5.948. Notably, the presence of outliers in the scatter plot might have contributed to the elevated MAE and RMSE values. Similar results were reported by [39] who assessed a fast and low-cost technique to estimate canopy volume using UAV images ($R^2 > 0.8$ using pixel-based classification and $R^2 > 0.9$ using OBIA–object-based image analysis). The authors recommend that flights should be conducted at solar noon to avoid shadow interference in algorithms.

### *3.3. Seedling Mortality Survey*

For assessing the number of deceased seedlings, coffee-plant vectors were generated in UAV images obtained immediately after transplanting (December 2018) and before replanting for dead seedlings (April 2019) in areas where seedlings from the two containers were planted in this study. The schematic representation was shown in Figure 7.

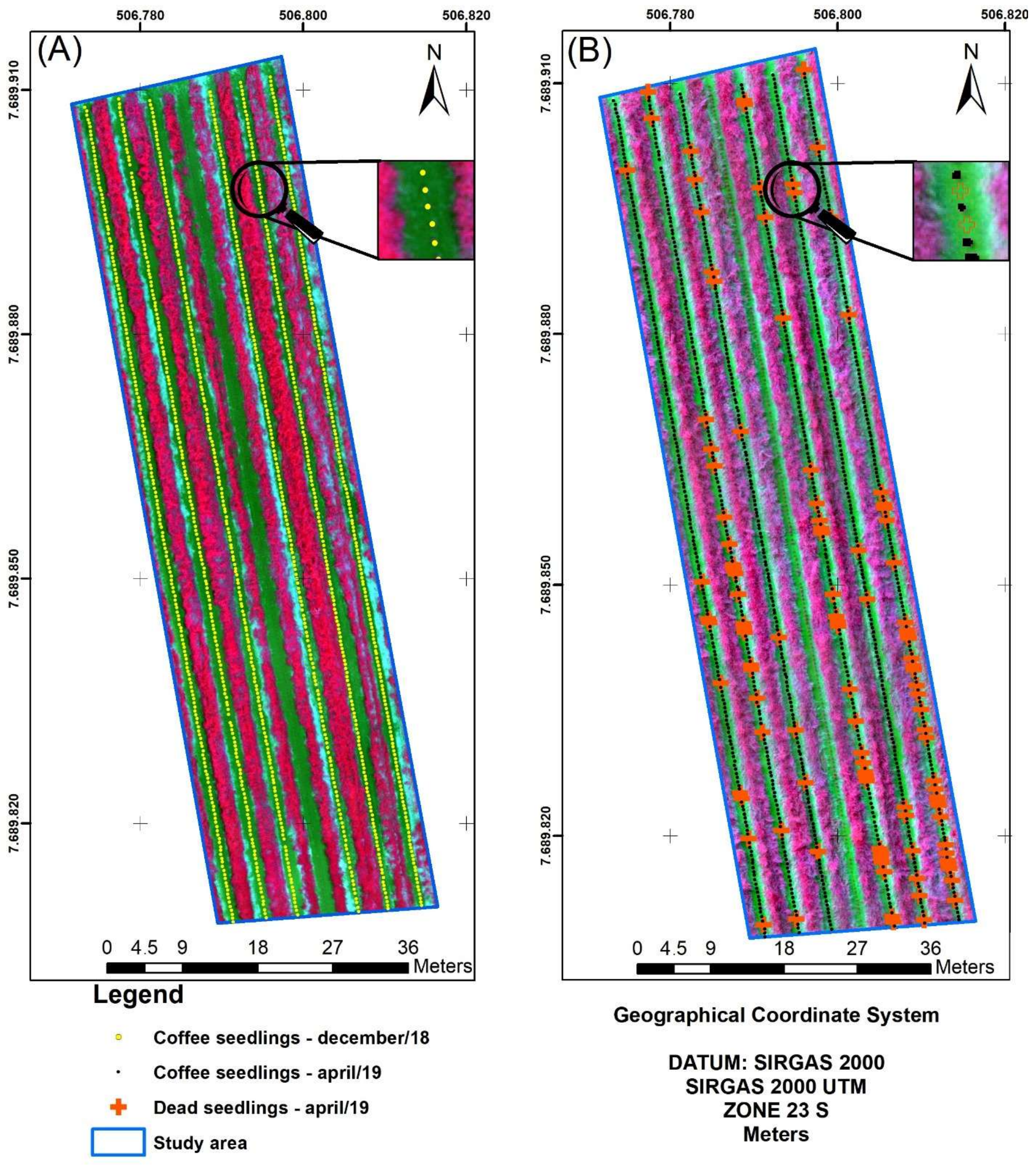


**Figure 7.** Dead seedling assessment, considering coffee crops planted with seedlings produced in perforated bags and seedlings produced in root trainers, using UAV images of December 2018 (**A**) and April 2019 (**B**). The transplanting of seedlings produced in perforated bags was conducted at the 3 rows to the left, while the transplanting of seedlings produced in root trainers was conducted at the 3 rows to the right. The central row was left to prevent border row effects.

Table 5 showed the number of coffee plants planted in both months and the percentage of seed mortality for both studied treatments. The findings indicate that transplanting seedlings from root trainers resulted in a higher number of dead seedlings, indicating lower survival rates compared to seedlings from perforated bags (11.7% vs. 6.3%).

**Table 5.** Quantity of coffee seedlings planted in December 2018 and the remaining ones in April 2019 (before replanting), as well as the dead rating assessment for the studied containers.

| Seedlings Container | Coffee Seedlings—December 2018 | Coffee Seedlings—April 2019 | Dead Seedlings | Failure Rate |
|---|---|---|---|---|
| Perforated bags | 611 | 572 | 39 | 6.4% |
| Root trainers | 613 | 541 | 72 | 11.7% |

A $\chi^2$ test was performed to assess whether the frequency of dead seedlings was significantly associated with the containers, and the results were described in Table 6.

**Table 6.** $\chi^2$ test of independence considering the dead seedlings and the containers (perforated bags and rigid root trainers) used for coffee seedling production.

| Test | Null Hypothesis (H0) | Test Value | Degree of Freedom | Significance Value *p* | Decision |
|---|---|---|---|---|---|
| $\chi^2$ | There is no association between variables | 10,671 [a] | 1 | 0.0011 * | Rejects the null hypothesis (H0); there is an association between variables |

[a] Zero cells (0.0%) had an expected frequency lower than 5; * Significant difference at the level ρ = 0.05.

Consequently, the $\chi^2$ test rejects the null hypothesis (H0) and highlights the association between the seedling container and the number of dead seedlings observed in April 2019. Details regarding this observation, comparing the transplantation methods in this study in relation to seedling survival, are presented in Table 7.

**Table 7.** Cross-tabulation analysis between seedling establishment status and type of studied containers for coffee plants produced in perforated bags and root trainers based on $\chi^2$ test results.

| Seedling Establishment Status | Frequencies | Containers | | Total |
|---|---|---|---|---|
| | | Perforated Bags | Root Trainers | |
| Success | Count * | 572 [a] | 541 [b] | 1113 |
| | Expected Count | 555.6 | 557.4 | 1113.0 |
| | % within establishment | 51.4% | 48.6% | 100.0% |
| | % within container | 93.6% | 88.3% | 90.9% |
| | % Total | 46.7% | 44.2% | 90.9% |
| | Adjusted Residual | 3.3 | −3.3 | |
| Failure (dead seedlings) | Count | 39 [a] | 72 [b] | 111 |
| | Expected Count | 55.4 | 55.6 | 111.0 |
| | % within establishment | 35.1% | 64.9% | 100.0% |
| | % within container | 6.4% | 11.7% | 9.1% |
| | % Total | 3.2% | 5.9% | 9.1% |
| | Adjusted Residual | −3.3 | 3.3 | |
| Total | Count | 611 | 613 | 1224 |
| | Expected Count | 611.0 | 613.0 | 1224.0 |
| | % within establishment | 49.9% | 50.1% | 100.0% |
| | % within container | 100.0% | 100.0% | 100.0% |
| | % Total | 49.9% | 50.1% | 100.0% |

* Different letters significant difference between containers at the level ρ = 0.05.

Figure 8 shows the contrast between the success and failure of coffee seedling establishment. Despite the absence of significant differences in other studied parameters such as VIs and growth variables measured in the field, a notable divergence is observed in seedling survival. Consequently, seedlings from root trainers exhibited a higher number of dead seedlings, signifying lower survival rates compared to seedlings from perforated bags.

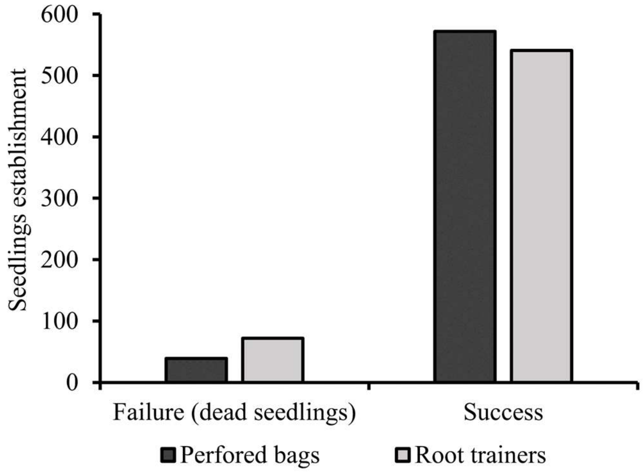


**Figure 8.** Graphical analysis of the difference between failure and success of coffee seedling establishment, after transplanting, considering the containers: perforated bags and root trainers.

## 4. Discussion

This manuscript contributes relevant information that, alongside other studies, can be utilized as a basis for monitoring coffee plants and evaluating them post-transplantation in the field. Additionally, this study offers insights into choosing the optimal container for producing high-quality seedlings with better survival rates in the field. The results presented here are pivotal for planning and decision-making among coffee producers. The utilization of UAV and the integrated multispectral sensor proved efficient in monitoring the effects of transplanting seedlings from different containers.

Coffee growth variables showed a progressive increase throughout the cycle. This temporal variation correlates with augmented dry matter and leaf emissions, stabilizing in September. According to [52], when estimating LAI using equations, an average of 0.27 for coffee seedlings after 15 months was assessed; this is a value similar to those found in this study. Moreover, similar temporal variations in LAI, as reported by [43] in assessments of evapotranspiration and crop coefficients during coffee plant growth, were observed. Notably, a significant reduction in chlorophyll values occurred during the rainy season (January), consistent with [53], who state that under water stress, chloroplasts increase $CO_2$ assimilation to uphold plant physiological functions, thereby heightening the content of photosynthetic pigments due to reduced leaf water content, consequently elevating chlorophyll meter sensor readings during these periods.

The variations in coffee growth variables corresponded to fluctuations in vegetation indices, which mirror the plant's response. These indices decline during the dry season and rise during the rainy season. The dry season, overlapping with winter, a period of stress where photoassimilates prioritize root growth overshoots, explains the drop in VI values [54–56].

The findings of this study corroborate with [57], which assessed temporal changes in the wood biomass of Arabica coffee plants using Landsat-5 images, revealing the lowest values of NDVI, soil-adjusted vegetation index (SAVI), and field-measured LAI in August and September. Similar water deficit effects were noted in [58], where a decrease in NDVI values was observed using a moderate-resolution imaging spectroradiometer (MODIS) sensor for coffee plants grown under full sunlight. Additionally, Ref. [59] reported the lowest crop coefficient values in June, July, and August, coinciding with the dormancy phase of coffee plants characterized by reduced vegetative activity.

Some indices, such as MCARI1 and MSAVI2, exhibited higher values in November compared to January. These indices might be more responsive to flowering in this experimental area, corroborating with [60], which also observed increased biomass and consequent index elevation from mid-October onward.

The temporal dynamics of VIs calculated in this study agree with the findings from [60], where NDVI measured using a MODIS sensor evaluated coffee plants' temporal changes during seedling production, growth, and pruning, proposing an agrometeorological–spectral monitoring model. Similar trends in coffee plant variations using VIs have been reported in other studies [57,58,61]. Hence, even during seedling growth and initial months after transplantation, coffee plants exhibit response patterns associated with their phenological phases, as described by [62]. Young coffee plants demonstrate distinct responses compared to mature trees, particularly in the first 3 years, where most photoassimilates drive plant growth, resulting in lower biomass and, subsequently, lower VI values [60,63], as observed in the results of this study.

Most vegetation indices exhibited a similar temporal variation, decreasing from May with the lowest values reached in September. Similar VI responses were documented by [58,60,61], aligning with the coffee phenology proposed by [62]. Notably, NDRE demonstrated distinct behavior compared to other indices, showing a more linear variation over time with no decrease in September or only a slight drop in January. This pattern reflects the dynamics of growth variables. NDRE, commonly associated with ripeness and vegetation pigments, including chlorophyll (strongly linked to vegetative vigor), is widely used in crop monitoring. The consistent increase in this index from September onwards suggests a correlation with the phenological behavior of coffee plants, which experience heightened growth and ripening after that month.

Based on the results presented, no significant differences were found for most studied coffee growth variables across the evaluated treatments. These findings agree with the values observed in the temporal analysis. Many studies on coffee plants grown in different containers focus on seedlings in the nursery stage and do not assess performance after transplanting. In addition to measuring differences between container materials, most studies, like [3,5], evaluate the effects of volume and substrate. They generally identify better results in polyethylene bags or root trainers with larger volumes and commercial substrates compared to mineral soil.

In a study examining coffee plants after transplanting in the field [6], seedlings grown in polyethylene bags and in 50 and 120 mL root trainers using different substrates were evaluated. Considering the studies cited in the previous paragraph, which found no significant differences between coffee seedlings grown in polyethylene bags and those in 120 mL root trainers, it can be concluded that 180 mL root trainers (as used in this research) could be a viable alternative to perforated bags. However, container volume should be carefully considered, as opting for root trainers with lower volumes may result in less substrate and compromise root development.

In the correlation analysis, strong correlations were observed between all variables except for chlorophyll. The weak correlations observed between chlorophyll levels and most calculated VIs in this research could be attributed to random leaf sampling. Even within a single coffee tree, leaves that are more exposed might suffer from burning and chlorosis during cooler periods or endure harsher conditions in hot summers. However, leaves positioned inside the canopy area may be more protected from such factors or receive reduced solar radiation, potentially affecting the behavior of their photosynthetic pigments.

All vegetation indices demonstrated a correlation with growth measures exceeding 0.70, indicating that VIs can be a viable option for estimating certain coffee growth variables using this approach. Moreover, the variables that exhibited higher values both when growing seedlings in perforated bags and when growing seedlings in root trainers in the canopy planar area were calculated by vectorization ($cm^2$), NDVI, and NDRE. However, the latter resulted in the lowest correlation value, with crown diameter among the studied VIs.

Considering the observed relationship between growth variables and vegetation indices, the generated models yielded favorable results for the studied treatments. Consequently, it is possible to use and recommend such linear models for estimating the coffee leaf area. In the literature, some studies have developed linear models to estimate crop-growth parameters such as height, diameter, and LAI, combining these measures, with results similar to the findings of this study. For instance, Ref. [63] reported $R^2$ values close to 0.8 and 0.9 for maize and potatoes, respectively, when using their models to estimate LAI based on SAVI, MSA-VI, the transformed soil-adjusted vegetation index (TSAVI), and the perpendicular vegetation index (PVI) derived from QuickBird satellite images. However, in sorghum, $R^2$ values of 0.85 and 0.81 were observed when estimating LAI using NDVI and EVI, respectively, from multispectral images acquired by UAV [64].

Studies on perennial crops have reported good $R^2$ values and correlations between growth variables measured and those measured by UAV, particularly involving forest species [65,66]. In coffee cultivation, a similar UAV approach was undertaken by [19], with high $R^2$ values for height and diameter (0.87 and 0.95, respectively), which were variables used to calculate LAI. However, there is still a scarcity of studies employing VIs to estimate this variable in coffee plants. This may be attributed to the saturation of indices such as NDVI when LAI reaches higher values [67]. According to [68], no significant results were obtained when using NDVI, SAVI, green vegetation index (GVI), and ratio vegetation index (RVI) to estimate LAI, although they reported a good correlation of the parameter with the blue and green spectral bands. Additionally, Ref. [69] achieved an $R^2$ of 0.78 for LAI based on the NDVI measured using a MODIS sensor after several calibrations and adjustments. However, various VIs were calculated in this study, and the coffee plants were young, implying that their LAI values were low. Consequently, the $R^2$ values of the proposed models are considered good in regression models.

An important point to highlight is related to the possible existence of autocorrelation in the data due to temporal analysis. In this study, this fact was not a limiting factor since the objective was to characterize the variations over time and observe the existing correlations between the variables studied. Other studies also conducted monitoring and evaluation of plant response over time and did not observe problems with autocorrelation in the analysis [19,70]. In future studies, especially those with long time series that require temporal analysis, the use of autocorrelation analysis may be necessary and recommended.

Studying the response and survival of coffee seedlings in the field becomes crucial, primarily due to the high investment and need for a robust establishment of the crop. In this context, coffee seedlings transplanted from perforated polyethylene bags exhibited a higher survival rate than seedlings produced in root trainers, as indicated by the lower number of dead seedlings in the field. This difference may primarily be attributed to the volume of substrate, which is considerably lower in the root trainers than in the perforated polyethylene bags tested in this study, affecting not only the nutrition of the plants but also their ability to retain water during higher temperatures.

The literature lacks studies utilizing vegetation indices and Unmanned Aerial Vehicles for this approach, with agronomic studies typically relying on in situ field measurements. For instance, Ref. [71] evaluated the survival of Topázio cultivar coffee seedlings produced in plastic bags and 120 mL and 50 mL root trainers after transplanting, comparing conventional to no-till planting, where dry Brachiaria was managed on the soil, previously planted between rows. The study observed that seedlings grown in plastic bags exhibited a higher survival rate than those grown in root trainers 138 days after planting (DAP). However, the difference for the root trainer with a higher volume (120 mL) was significantly smaller in conventional planting in dystrophic red–yellow argisol. In no-till planting, a clear difference in seedling survival was observed from 30 days after planting, with percentages reaching 100%, 91.62%, and 40.62% for plastic bags and 120 mL and 50 mL root trainers, respectively, after 138 days.

Another study by [71] focused on seedling survival in different planting seasons for the Acaiá Cerrado cultivar, grown in plastic bags and 120 mL root trainers in different soil types. On all dates, seedlings produced in perforated bags demonstrated a higher survival rate. However, in seasons with unfavorable climatic conditions, the percentage of seedling survival after transplanting from root trainers reached its lowest value (12.50%), in contrast to 90% for seedlings grown in plastic bags in dystrophic red latosol. In dystrophic red–yellow argisol, the difference in seedling survival was lower (97.50% for plastic bags versus 67.50% for root trainers), also highlighting the impact of soil factors. Therefore, substrate volume emerged as a critical factor for seedling survival in periods of stress for coffee plants.

While the increase in seedling survival in perforated bags corroborates with the findings of the present study, the difference in the percentage of seedling mortality is lower in this study (6.4% for perforated bags versus 11.7% for root trainers). Hence, the volume of the root trainers used in this study (180 mL) demonstrated a positive effect on performance. However, replanting represents an increase in labor costs, with an approximate cost of USD 200,000 per hectare for the farm where this research was conducted. Consequently, both containers were interesting alternatives to conventional polyethylene bags, with root trainers proving advantageous for the nursery phase and perforated bags for seedling survival.

This study aimed to evaluate the coffee plant's response after transplanting seedlings grown in different containers, based on multispectral images acquired by UAVs. The results confirmed that this methodology can be used to assess the impacts of transplanting seedlings produced in different containers. As a recommendation for future research, it is important to highlight the relevance of incorporating analyses on how extreme weather events and climate change can affect these processes. Climatic variability and an increase in the frequency of extreme events, such as prolonged droughts and heavy rainfall, can significantly impact plant development and transplant efficacy, necessitating adaptive strategies for coffee management. Therefore, it is recommended to conduct in-depth research on the coffee root system's resilience to these adverse conditions. Regarding UAVs, research with other multispectral cameras and hyperspectral cameras could be conducted to assess other coffee responses, primarily related to chlorophyll or flowering, and how these processes are influenced by climate change. Additionally, the use of artificial intelligence (such as machine learning and deep learning, among other AI tools) would represent new research alternatives for UAV image segmentation and the identification of features allowing volume estimation, fruit ripening, harvest prediction, identification of damage caused by extreme weather events, and development of adaptive management strategies.

## 5. Conclusions

The findings presented in this study are indispensable for the planning and decision-making processes of coffee producers. The utilization of UAVs and coupled multispectral sensors proved effective in monitoring coffee plants, enabling the assessment of the impacts of transplanting seedlings produced in different containers.

No significant differences were observed between transplanting seedlings produced in root trainers and perforated bags concerning coffee growth variables and responses of vegetation indices.

Linear models were successfully developed to predict LAI as a function of the GCI for seedlings produced in both containers tested in this study, achieving $R^2$ values above 0.75. Additionally, when aggregating all data on coffee plants, linear models for LAI and crown diameter ($cm^2$) estimation, as a function of canopy planar area calculated by vectorization ($cm^2$) in software, yielded $R^2$ values close to 0.90.

Seedlings grown in perforated bags exhibited lower seedling mortality than those grown in root trainers (6.4% vs. 11.7%, respectively). The mortality of coffee plants was found to be related to the type of container used for seedling production.

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