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Chemical composition of substrates on the rooting vigor of *Caryocar brasiliense* air layering

Composição química de substratos no vigor de enraizamento de alporques de *Caryocar brasiliense*

Composición química de los sustratos sobre el vigor de enraizamiento de *Caryocar brasiliense* alporques

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ABSTRACT
The definition of vegetative propagation protocols is important for the production of *Caryocar brasiliense* Cambess plants, for the formation of commercial orchards. Therefore, the objective of this study was to evaluate the substrate's chemical characteristics influence on *Caryocar brasiliense* air layering. For this, a randomized block experiment with five substrates was carried out in eight plants. The following substrates were evaluated: Bioplant® commercial substrate; coconut fiber; a mixture of Bioplant® and coconut fiber in (1:1; 1:3; 3:1) proportions. After 150 days, the air layers were cut and evaluations of survival, callusing and rooting percentages, root length, dry and fresh root matter, rooting vigor and lignification were carried out. In laboratory, chemical and physical characterizations of the substrates were undertaken. The results showed that the rooting percentage varied from 40% to 77%. Rooting of *Caryocar brasiliense* air layers is optimized when phosphorus, calcium, magnesium and CEC in the substrate are above 3.0 mg dm^{-3}, 7.0 $cmol_c\ dm^{-3}$, 3.5 $cmol_c\ dm^{-3}$ and 17 $cmol_c\ dm^{-}3$, respectively. Sodium and sodium saturation of the substrate must be below 1.4 $cmol_c\ dm^{-3}$ and 6%, respectively. Strong, positive and significant correlations were observed between rooting and P, Ca, Mg and CEC.

Keywords: cation exchange capacity, nutrients, pequizeiro, plant propagation.

RESUMO
A definição de um protocolo de propagação vegetativa do pequizeiro é importante na produção de mudas que podem ser utilizadas na formação de pomares comerciais. Dessa forma, o objetivo deste trabalho foi avaliar a influência de características químicas de substratos na alporquia de pequizeiro. Para isso, um experimento em blocos ao acaso, com cinco substratos foi instalado em oito pequizeiros. Os substratos avaliados foram: substrato Bioplant®; fibra de coco; mistura de Bioplant® e fibra de coco nas proporções (1:1; 1:3; 3:1). Após 150 dias da instalação, os alporques foram cortados e então avaliadas as porcentagens de sobrevivência, calejamento e enraizamento, o comprimento da raiz, a massa seca e fresca das raízes, o vigor e a lignificação de enraizamento. Os resultados obtidos mostraram taxas de enraizamento variando de 40% a 77%. Os teores ideais de fósforo, cálcio, magnésio e CTC no substrato devem ser superiores a

3,0 mg dm-3, 7,0, 3,5 cmolc dm-3 e 17 cmolc dm-3 respectivamente. O sódio e a saturação de sódio não devem ser superiores a 1,4 cmolc dm-3 e 6% respectivamente. Correlações fortes, positivas e significativas foram observadas entre o enraizamento e os teores de P, Ca, Mg e CTC.

Palavras-chave: capacidade de troca catiônica, pequizeiro, nutrientes, propagação de plantas.

RESUMEN
La definición de un protocolo para la propagación vegetativa de árboles de pequi es importante para la producción de plántulas que puedan ser utilizadas en la formación de huertos comerciales. El objetivo de este estudio fue evaluar la influencia de las características químicas de los sustratos sobre los esquejes de pequi. Para ello, se estableció un experimento de bloques al azar con cinco sustratos y ocho árboles de pequi. Los sustratos evaluados fueron: sustrato Bioplant®; fibra de coco; una mezcla de Bioplant® y fibra de coco en las siguientes proporciones (1:1; 1:3; 3:1). Al cabo de 150 días, se cortaron los esquejes y se evaluaron los porcentajes de supervivencia, callosidad y enraizamiento, longitud de la raíz, masa seca y fresca de la raíz, vigor y lignificación del enraizamiento. Los resultados mostraron tasas de enraizamiento que oscilaban entre el 40% y el 77%. Los niveles ideales de fósforo, calcio, magnesio y CTC en el sustrato deberían ser superiores a 3,0 mg dm-3, 7,0, 3,5 cmolc dm-3 y 17 cmolc dm-3 respectivamente. La saturación de sodio y sodio no debe ser superior a 1,4 cmolc dm-3 y 6% respectivamente. Se observaron correlaciones fuertes, positivas y significativas entre el enraizamiento y los contenidos de P, Ca, Mg y CTC.

Palabras clave: capacidad de intercambio catiónico, árbol pequi, nutrientes, propagación de plantas.

1 INTRODUCTION

Caryocar brasiliense Cambess, commonly known as Pequizeiro, is a tree species that is widely distributed in the Brazilian Cerrado region, particularly in the Center-West and Northern regions. Its fruits are an important food resource for rural and urban populations, and are consumed either in natura or processed into sweets, oils, and juices (Vieira *et al*., 2006), making the species culturally and economically significant.

However, deforestation and excessive extractivism have threatened the perpetuation of this species in natural environments (Martins *et al*., 2015). Thus, there is a need for studies to increase the efficiency of propagating the species. Currently, commercial plants are primarily produced from botanical seeds, which have several disadvantages, including dormancy, leading to low and erratic germination rates (Nasory; Cunha, 2012). Therefore, improving the species propagation is important for its conservation and sustainable use.

Therefore, the establishment of vegetative propagation protocols *for Caryocar brasiliensis* is crucial for the production of seedlings for use in commercial orchards and livestock-forest integration systems. Given the reported low efficiency of propagation via cuttings (Guimarães *et al*., 2019), air layering may be a viable option for obtaining clonal seedlings of this species (Carmona *et al*., 2022).

Air layering is a technique that induces the formation of adventitious roots in stem parts that are still attached to the parent plant. This technique is often more efficient than cutting, as observed in peach trees (Castro; Silveira, 2003), lychee (Lins *et al*., 2015), and jabuticabeira (Danner *et al*., 2006). In air layering, rhizogenesis is favored by a constant supply of water and minerals from the xylem, which remains intact after girdling (phloem removal), as well as the accumulation of photosynthates and hormones produced in leaves and buds (Hartmann *et al*., 2014).

The success rate of air layering is affected by the substrate used in the girdled region. Several authors have reported a significant influence of substrate on the survival, callusing, and rooting characteristics of air layers of different species (Dutra *et al*., 2012). Da Silva *et al*. (2017) studied Basaplant®, sphagnum, and coconut fiber substrates in *Tamarindus indica* L. air layerings and observed average rooting rates of 30%, 65%, and 40% in these substrates, respectively. Lins *et al*. (2015) evaluated the effect of coconut fiber and sphagnum substrates and concluded that the use of coconut fiber can provide satisfactory rooting rates (above 90%) in lychee at certain times of the year (September and November).

Vegetative propagation techniques, such as cuttings and air layering, have been explored as alternative methods for the propagation of native species. Therefore, the present study aimed to investigate the impact of the substrate's chemical composition on the efficacy of air layering as a propagation method for *Caryocar Brasiliense* in the Brazilian Distrito Federal region.

2 MATERIAL AND METHODS

The experiment was conducted on eight adult and uniform *Caryocar brasiliensis* stock plants at Embrapa Cerrados, Distrito Federal, Brazil (15°35'33.7"S 47°44'00.5"W) in October 2020. The climate of the region is Aw, with an average annual rainfall of 1,500 mm (Cardoso *et* *al*., 2014). The selected plants were approximately 20 years old and had homogenous size and characteristics.

Air layering was performed on healthy, lignified stems with a diameter of 20-30 mm using pliers adapted for air layering, resulting in a 3 cm-wide girdling (Carmona *et al*., 2022). The air layering was performed on the lower stems of the plants. In this randomized block design experiment, five treatments (substrates) with four replications each were evaluated, with 10 air layerings in each plot, totaling 200 air layerings. The evaluated substrates were Bioplant® gold-class F commercial substrate, coconut fiber, and mixtures of Bioplant® and coconut fiber in the proportions of 1:3, 1:1, and 3:1. The substrates evaluated in the present experiment were packed in plastic bags measuring 10x20 cm, with a capacity of approximately 300 mL.

After 150 days, the air layerings were removed from the plants 10 cm below the girdling region using a manual saw, and the following characteristics were evaluated: rooting percentages, root length, dry and fresh root mass, rooting vigor, and root lignification.

Air layerings that produced at least one root with a length greater than 1 cm were considered rooted. Root length, measured in millimeters (mm), was determined using a graduated ruler. Fresh root mass was determined by washing the roots, removing them from the air layer, and drying them on paper to eliminate surface water, followed by weighing on a scale. The roots were then dried at 80°C for three days, cooled in a desiccator for two hours, and weighed again to determine dry mass (Maurya *et al*., 2013).

The rooting vigor of each air layer was visually estimated using a scale that ranged from 0 - Presence of calluses, but no root formation; 1 – less than 20% of the calluses emitted roots; 2 – between 21 and 40% of the calluses emitted roots; 3 – between 41 and 60% of the calluses emitted roots; 4 – between 61 and 80% of the calluses emitted roots; 5 – more than 80% of the calluses emitted roots (Carmona *et al*., 2022). The root lignification was evaluated by the following visual scale, according to the percentage of darkened roots in the air layering: 0 – 0%; 1 – 1 to 20%; 2 –21 to 40%; 3 –41 to 60%; 4 – 61 to 80%; 5 – 81 to 100%.

During the experiment, samples of each substrate were collected for laboratory evaluation of chemical characteristics, including available phosphorus (mg dm-3), calcium ($cmol_c\ dm^{-3}$), magnesium ($cmol_c\ dm^{-3}$), potassium ($cmol_c\ dm^{-3}$), sodium ($cmol_c\ dm^{-3}$), cation exchange capacity ($cmol_c\ dm^{-3}$), base saturation (%), and sodium saturation (%) (Table 1) (Embrapa, 2017).

Table 1: Chemical characteristics of the substrates resulted from different mixtures of Bioplant® and coconut fiber, tested in the air layering experiment of *Caryocar brasiliense*. Brasília-DF, 2020-2021. CEC: Cation-exchange capacity; SatNa: Sodium saturation.

Bioplant® content	P (mg dm^{-3})	Ca (cmol$_c$ dm^{-3})	Mg	K	Na	CEC	SatNa (%)
100%	4,2	8,2	3,9	2,2	0,43	17,9	3,0
75%	2,8	4,4	2,8	5,04	1,36	17,1	11,0
50%	2,4	5,6	2,9	5,15	1,46	14,9	11,5
25%	1,7	3,5	2,5	5,4	1,48	14,7	12,0
0%	1,2	1,3	1,8	5,75	1,75	12,6	17,0

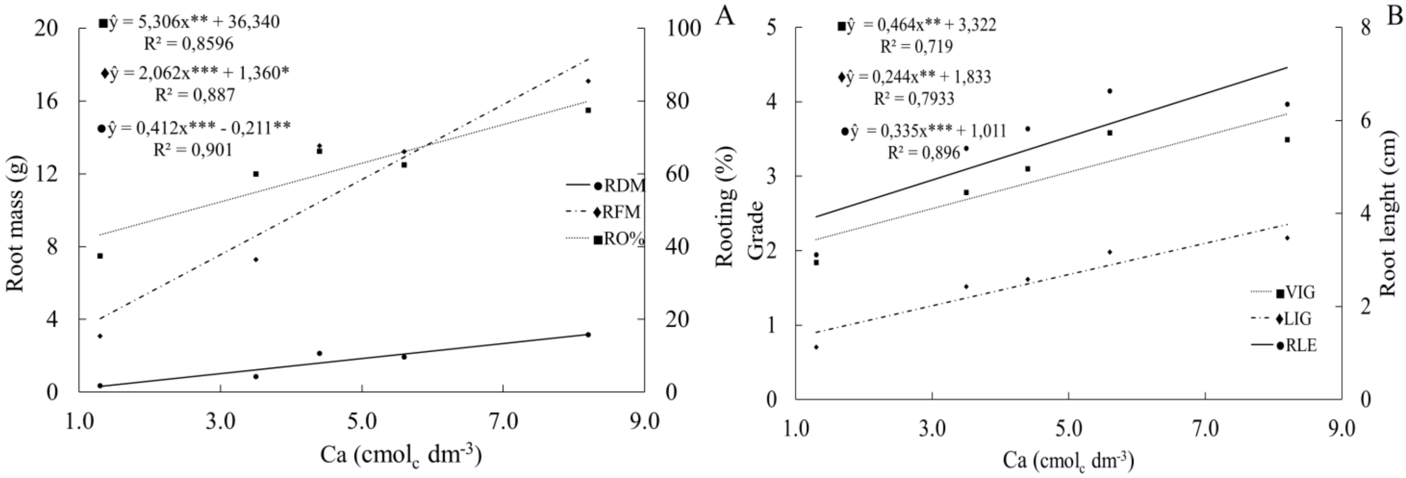
Source: The authors.

The data was tested for normality using the Shapiro-Wilk test and for homogeneity of variance using the Levene test. Regression analysis was performed to determine the relationship between substrate chemical characteristics and air layering parameters. Only significant regressions ($p \leq 0.05$) were reported (Fornes *et al.*, 2013; Mendoza-Hernández *et al.*, 2014). The strength of linear correlation coefficients between variables was classified as very strong (r ± 0.91 to ± 1.00), strong (r ± 0.71 to ± 0.90), medium (r ± 0.51 to ± 0.70), or weak (r ± 0.31 to ± 0.50) (Carvalho *et al.*, 2004). Data analysis was conducted using R software (R Core Team, 2022).

3 RESULTS AND DISCUSSION

The rooting characteristics of air layerings of *C. brasiliense* were found to be positively correlated with the calcium and magnesium content of the substrate (Figure 1 and Figure 2). 100% Bioplant® substrate, which had the highest calcium content (8.2 cmolc dm^{-3}), also showed the highest rooting rate (77.5%), as well as the greatest fresh and dry root masses (17.08g and 3.16g, respectively). Conversely, coconut fiber alone, which had the lowest calcium content (8.2 cmolc dm^{-3}), showed the lowest rooting percentage (37.5%), as well as the lowest fresh and dry root masses (3.08 g and 0.362 g, respectively). These results highlight the importance of calcium content for cell differentiation and rooting development in this species.

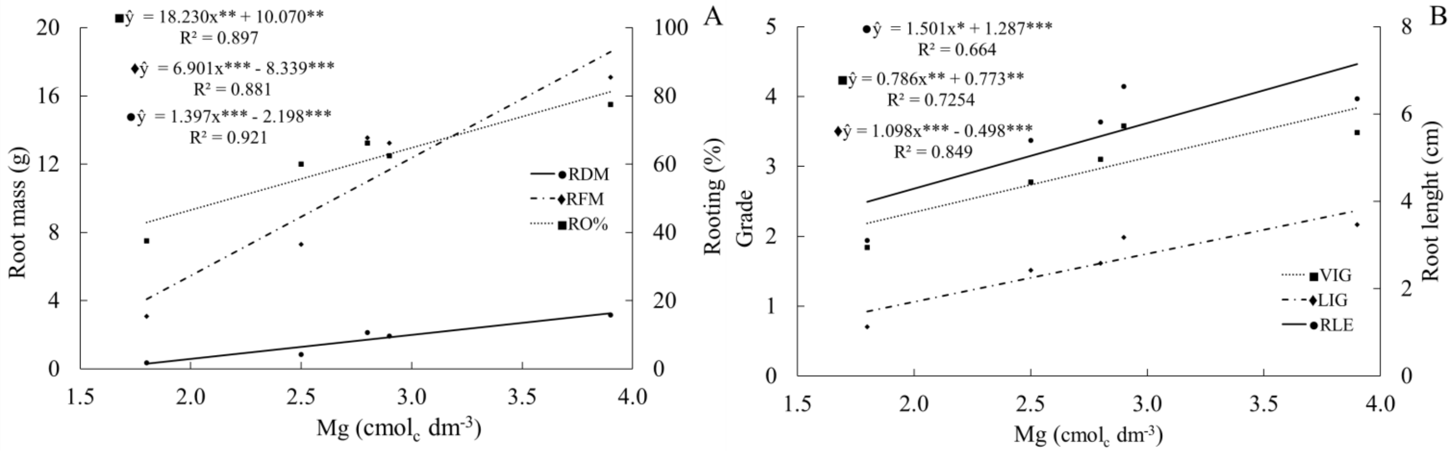
Figure 1: Relationship between calcium (Ca) content in the substrate and: A – rooting percentage (RO%), root fresh mass (RFM), and root dry mass (RDM); B – Lignification (Lig), rooting vigor (Vig) and root length (RLE). Brasília-DF, 2020-2021.



Source: The authors.

The positive correlation between magnesium content and rooting characteristics was also observed, with increasing magnesium content resulting in higher rooting percentage, fresh and dry root masses (Figure 2). Previous studies have also shown that calcium and magnesium are essential nutrients for root growth, as they increase cell division rates and promote root formation. Bakht *et al*. (2015) found that adding calcium and magnesium to the substrate increased the rooting of *Schefflera arboricola* cuttings, while Ichikawa *et al*. (2019) and Cunha *et al*. (2009) observed a positive effect of these nutrients on the rooting of sweet potato and Eucalyptus cuttings, respectively. Calcium has been shown to regulate the activity of enzymes involved in water and nutrient absorption, which could explain its positive effect on the rooting process of cuttings (Giel & Bojarczuk, 2010).

Figure 2: Relationship between magnesium (Mg) content in the substrate and: A – rooting percentage (RO%), root fresh mass (RFM), and root dry mass (RDM); B – Lignification (Lig), rooting vigor (Vig) and root length (RLE). Brasília-DF, 2020-2021.

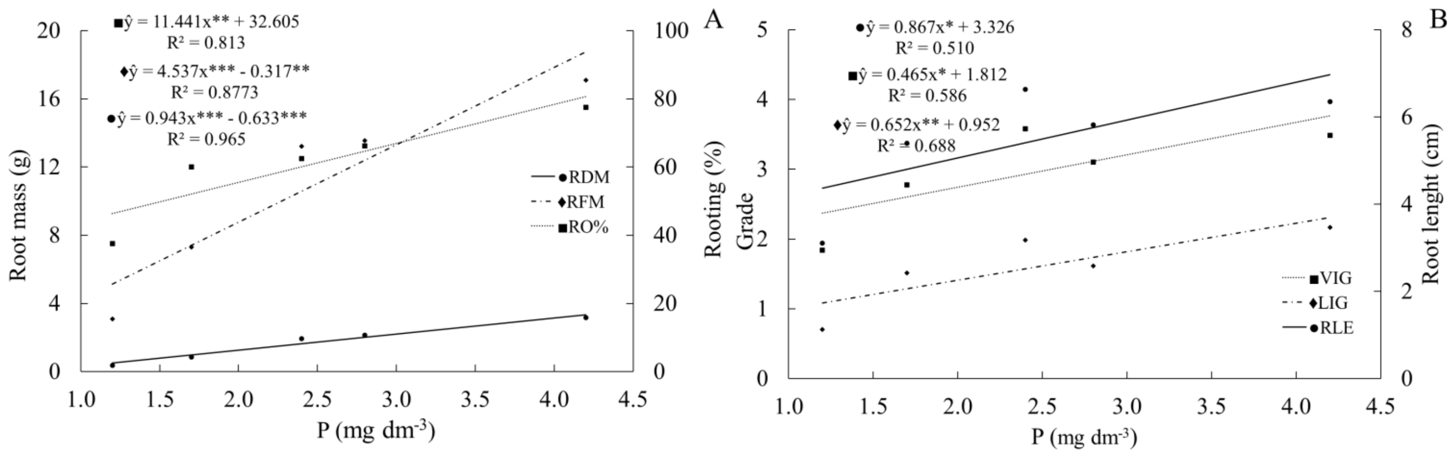


Source: The authors.

In this study, substrates with higher calcium and magnesium resulted in a more robust and vigorous rooting process, which is an essential characteristic for successful transplanting of the plants into the field. This is due to the fact that increased root growth leads to better absorption of water and nutrients from the soil.

Phosphorus content was found to significantly affect all evaluated characteristics (Figure 3), with all variables showing a linear increase with the increasing doses of phosphorus in the substrate. The highest level of phosphorus was observed in Bioplant® substrate, whereas the lowest was observed in coconut fiber (4.2 and 1.2 $cmol_c$ dm^{-3}, respectively). Previous research has also shown that higher levels of phosphorus and potassium in the substrate can result in higher root dry mass in cuttings (Da Silva *et al.*, 2012).

Figure 3: Relationship between phosphorus (P) content in the substrate and: A – rooting percentage (RO%), root fresh mass (RFM), and root dry mass (RDM); B – Lignification (Lig), rooting vigor (Vig) and root length (RLE). Brasília-DF, 2020-2021.

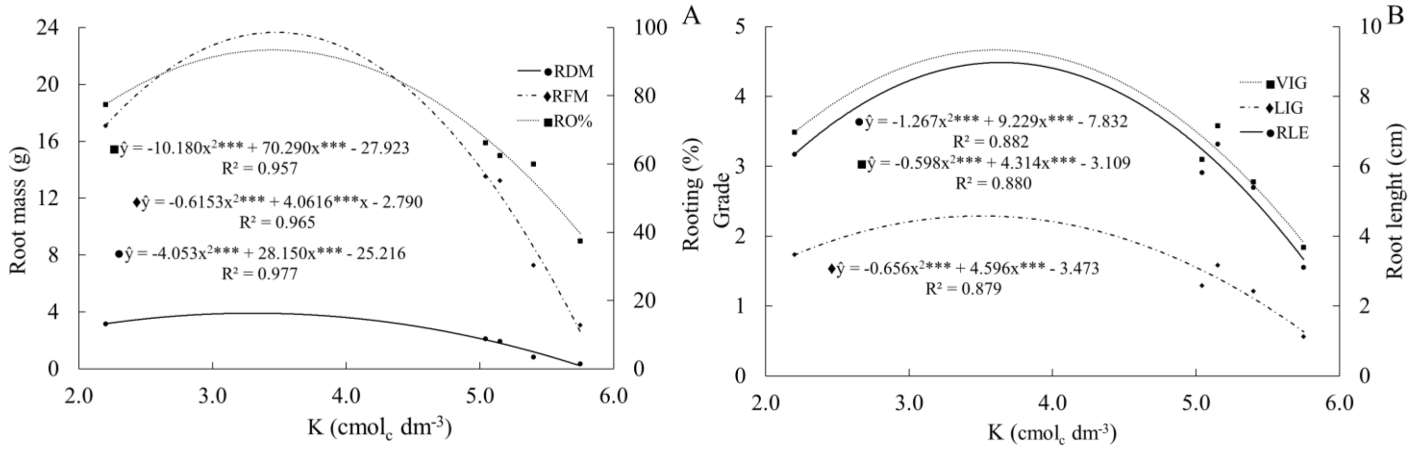


Source: The authors.

Phosphorus is particularly important in the early stages of root development, as it is involved in several key biochemical processes that support root growth. For example, phosphorus is a critical component of nucleic acids, which are essential for DNA replication and cell division. As such, P is necessary for the rapid cell division that occurs during root formation (Zeng *et al*., 2022). Overall, phosphorus acts biochemically on air layer rooting by supporting the cellular processes necessary for root growth, including cell division, energy production, and hormone regulation (Pongrac *et al*., 2020; Khandaker *et al*., 2022). By providing adequate levels of P in the rooting medium, the air layering process can be optimized to promote successful root development (Mahlambi *et al*., 2019).

In addition, quadratic relationships were observed between rooting percentage, fresh and dry root masses, and potassium content in the substrate (Figure 4). The highest potassium content was observed in the coconut fiber alone (5.75 $cmol_c$ dm^{-3}), which resulted in a reduced rooting percentage, below 40%. The optimal estimated potassium content for maximum rooting development of *C. brasiliense* was found to be 3.45 $cmol_c$ K dm^{-3}(Figure 4A).

Figure 4: Relationship between potassium (K) content in the substrate and: A – rooting percentage (RO%), root fresh mass (RFM), and root dry mass (RDM); B – Lignification (Lig), rooting vigor (Vig) and root length (RLE). Brasília-DF, 2020-2021.



Source: The authors.

Pacheco & Franco (2008) reported adequate propagation rates of *Luehea divaricata* via cuttings in substrates with high levels of potassium, phosphorus, and calcium. Consistent with this, our study found that substrates with high levels of calcium, phosphorus, and magnesium resulted in higher rooting percentages, length, and fresh and dry root mass for *Caryocar brasiliense* air layering. However, higher potassium levels, above 4 $cmol_c\ dm^{-3}$, reduced root development in this species. The inhibitory effect of high potassium concentrations on root development may be due to phytotoxicity (Mendoza-Hernández *et al.*, 2014), as excess potassium can stimulate the production of reactive oxygen species that damage cells and tissues and ultimately impair rooting, as reported by Poór *et al*. (2015).

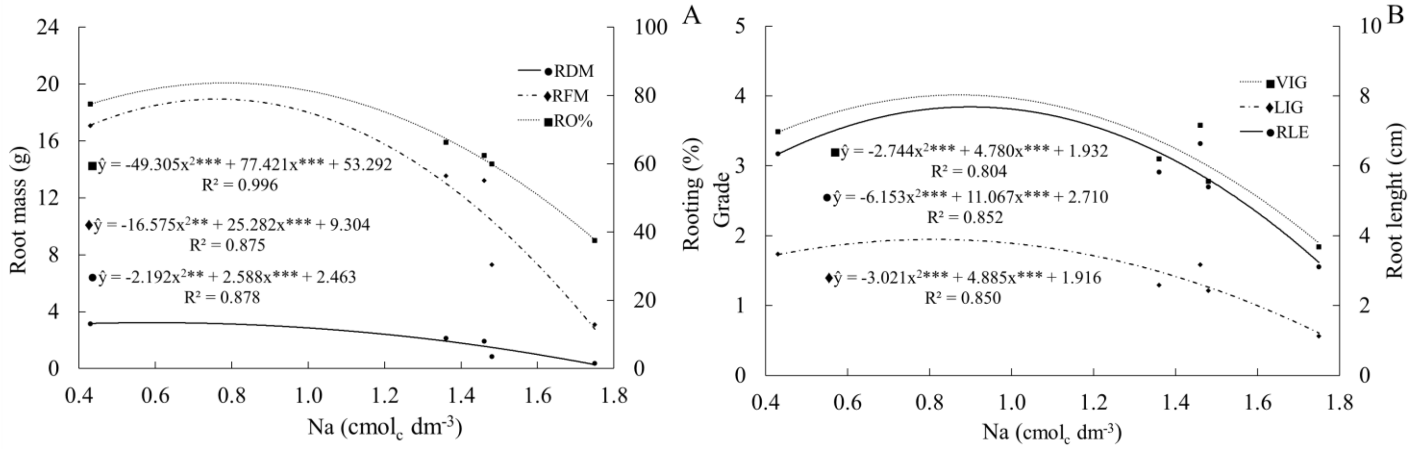
Fornes *et al*. (2013) investigated the effects of sodium and potassium content in substrates on the rooting of *Euonymus japonicus* and *Lavandula angustifolia* cuttings. The study revealed a quadratic relationship between rooting percentage and substrate sodium and potassium content. When the potassium and sodium content exceeded 5 $cmol_c\ dm^{-3}$ and 1.3 $cmol_c\ dm^{-3}$ respectively, the rooting rate decreased by 40%. Similarly, Mendoza-Hernandez *et al*. (2014) found that lower levels of potassium (3.8 $cmol_c\ dm^{-3}$) and sodium (0.86 $cmol_c\ dm^{-3}$) were optimal for *Rosmarinus officinalis* L. cuttings. In our study with *Caryocar brasiliense* air layering, the ideal potassium and sodium content were found to be 4 $cmol_c\ dm^{-3}$ and 1.2 $cmol_c\ dm^{-3}$, respectively. These levels are consistent with those reported by the authors mentioned above (Figures 5 and 6).

C. brasiliense has been found to have limited response to soil liming and fertilization on field conditions (Miranda *et al*., 2016), likely due to the species' adaptation to the nutrient-poor soils of the Brazilian Cerrado, which are particularly deficient in phosphorus and calcium. Such studies typically focus on the effects of fertilization on shoot growth and fruit production, while the response of the plant's root system is often overlooked. In the present study, it is possible that the plant is absorbing and allocating nutrients such as phosphorus, calcium, and magnesium for root development, which may not necessarily lead to significant increases in plant growth and fruit production over the short to medium term.

Based on the findings of this study, elevated levels of nutrients, such as calcium, magnesium, potassium, and phosphorus, in the rooting substrate can lead to a significant improvement in rooting percentage as well as the fresh and dry root mass during the air layering process of *C. brasiliense*. However, further investigations are required to determine the effectiveness of these nutrients during the subsequent growth and development stages of the propagated plants.

A significant effect of substrate sodium concentration on air layer rooting in *C. brasiliense* was observed in this study (Figure 5A). The rooting percentage, root length (Figure 5B), vigor scales (Figure 5B), and dry and fresh mass of roots (Figure 5A) were all significantly reduced at sodium levels higher than 1.2 $cmol_c$ dm^{-3}. This reduction in rooting parameters at higher sodium levels was also reported by Mendoza-Hernández *et al*. (2014).

Figure 5: Relationship between sodium (Na) content in the substrate and: A – rooting percentage (RO%), root fresh mass (RFM), and root dry mass (RDM); B – Lignification (Lig), rooting vigor (Vig) and root length (RLE). Brasília-DF, 2020-2021.



Source: The authors.

Studies have reported that high levels of sodium in the substrate can negatively affect rooting percentage and root length in various plant species, including *Hyptis suaveolens* L. cuttings (Da Silva *et al*., 2012), coffee (Berilli *et al*., 2018), and *Schlumbergera truncata* Haw. cuttings (Zanotti *et al*., 2015).

A linear decreasing relationship was found between sodium saturation in the substrate and the rooting parameters of *C. brasiliense* air layering (Figure 6). The substrate containing coconut fiber exhibited the highest sodium saturation (17%) compared to pure Bioplant® which showed a lower sodium saturation of 3%. The results indicated that increasing the proportion of coconut fiber in the substrate led to a decrease in the rooting percentage of the air layers, with a reduction from 77.5% in a substrate without coconut fiber to 37.5% in a 100% coconut fiber substrate.

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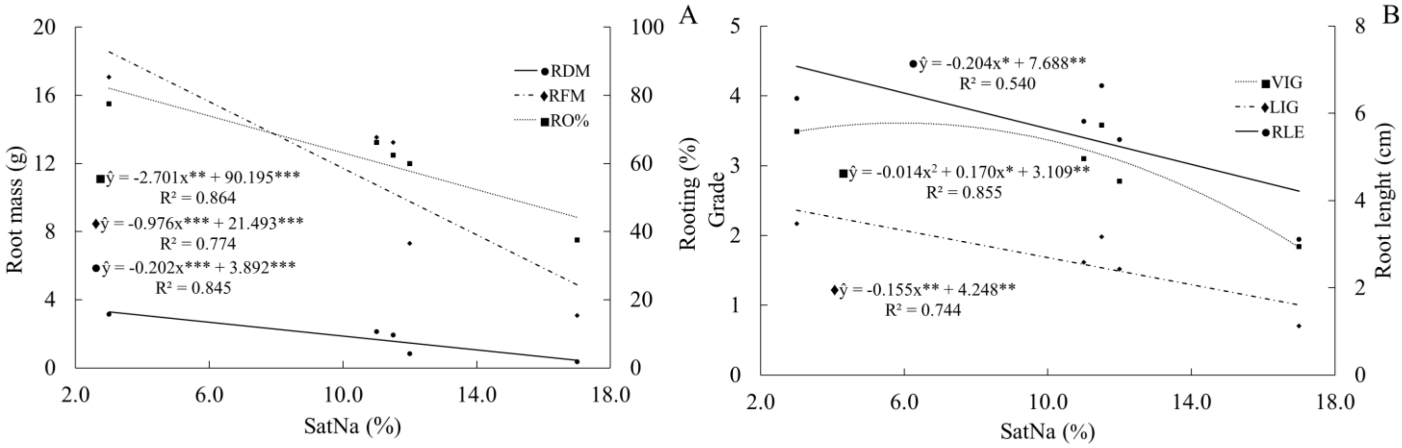
Figure 6: Relationship between sodium saturation (SatNa) content in the substrate and: A – rooting percentage (RO%), root fresh mass (RFM), and root dry mass (RDM); B – Lignification (Lig), rooting vigor (Vig) and root length (RLE). Brasília-DF, 2020-2021.



Source: The authors.

Fornes *et al*. (2013) observed a quadratic relationship between the root dry mass of *Euonymus japonicus* cuttings and the levels of potassium and sodium in substrate mixtures with the highest levels of these nutrients resulting in the lowest rooting rates. Similar results were reported by Zanotti *et al*. (2015) who observed a 6% sodium saturation for the coconut fiber.

The difference in the reported sodium saturation of coconut fiber between this study (17%) and the value reported by Zanotti *et al*. (2015) (6%) may be attributed to the variability in chemical properties, particle size, and distribution during the manufacturing process of the coconut fiber, as noted by ABAD *et al*. (2005). Organic substrate mixtures have been shown to reduce sodium saturation in substrates with high levels of sodium, as noted by Gonçalves *et al*. (2014).

Mendoza-Hernández *et al*. (2014) examined the effect of various levels of potassium and sodium on the rooting of *Rosmarinus officinalis* L. cuttings and found a quadratic relationship between rooting and the doses of both nutrients. Consistent with these findings, the present study also observed a quadratic response in rooting to varying doses of potassium and sodium.

The cation exchange capacity (CEC) represents the total charge on soil particles, serving as an indicator of substrate fertility due to the presence of essential cations such as Ca^{2+}, Mg^{2+}, and K^{+} (Kratz *et al*., 2013). In this study, the CEC of the substrates ranged from 12.6 to 18 $cmol_c$ dm^{-3}. The rooting parameters in *C. brasiliense* air layers, such as fresh and dry mass of roots, were found to have a linear relationship with the CEC of the substrate (Figure 7A).

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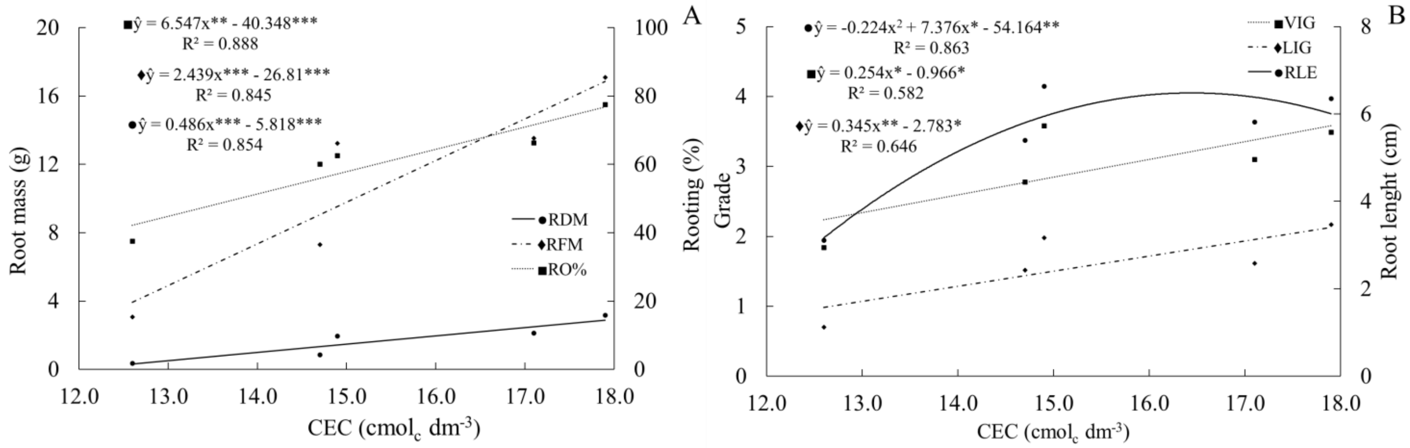
These findings indicate that the availability of potassium, calcium, and magnesium in the substrate for the rooting process of *C. brasiliense* is influenced by higher CEC levels. Therefore, the selection of an appropriate substrate for plant propagation should consider the importance of these nutrients. The presence of these cations may create more favorable conditions for the development of adventitious roots, which is an essential factor in successful plant propagation (Mahlambi *et al*., 2019). According to Penningsfeld (1983), a suitable substrate should have a CEC value above 12 $cmol_c\ dm^{-3}$.

A quadratic relationship was identified between CEC and root length, with the peak value at 16.5 $cmol_c\ dm^{-3}$ (Figure 7B). These findings align with those reported by Chen *et al*. (2003), who observed that CEC levels exceeding 20 $cmol_c\ dm^{-3}$ constrained root length development.

The reduced root length, fresh and dry mass observed in substrates with higher proportions of coconut fiber (Figure 7A and B) can be attributed to the lower CEC of these substrates. The lower CEC of the coconut fiber-containing substrates may have compromised their ability to supply essential nutrients like calcium, potassium, and magnesium, necessary for root development. Mahlambi *et al*. (2019) reported that substrate mixtures may not always be beneficial, and their combination may lead to a decrease in CEC.

Figure 7: Relationship between cation exchange capacity (CEC) in the substrate and: A – rooting percentage (RO%), root fresh mass (RFM), and root dry mass (RDM); B – Lignification (Lig), rooting vigor (Vig) and root length (RLE). Brasília-DF, 2020-2021.



Source: The authors.

According to Pacheco and Franco (2008), a higher substrate CEC can result in an increase in the dry mass of the aerial part of cuttings. These authors also suggested that CEC can be a reliable parameter when selecting a substrate, as it indicates the amount of nutrients, present in the substrate. Similar findings were observed in the present study, where CEC played an important role in both the initial phase of air layering rooting and the final phase of seedling production, as evidenced by its positive correlation with rooting percentage and root fresh and dry mass.

Significant and positive correlations were found between the air layering variables (Table 2). Rooting exhibited a very strong and positive correlation with callus formation, lignification, root length, rooting vigor, and the dry and fresh mass of roots. In contrast, Chen *et al*. (2021) did not observe significant correlations between callus formation and rooting, suggesting that callus formation is not a necessary precursor to rooting in this species.

In terms of substrate composition, a significant, positive and strong correlation was observed between rooting and the phosphorus, calcium, magnesium and CEC (r=0.935; r=0.919; r=0.940; r=0.940, respectively). Conversely, there was a strong negative correlation between rooting and the sodium saturation (r= -0.908).

Cunha *et al*. (2009) reported significant and positive correlations between the rooting and the levels of phosphorus, magnesium, and potassium in the substrate, while negative correlations were observed with the calcium concentration. Similarly, in the present study, positive and significant correlations were found between rooting and the levels of phosphorus, calcium, and magnesium. Roehrdanz *et al*. (2019) reported a positive correlation between the levels of phosphorus and potassium in the substrate and root dry mass, while a negative correlation was observed for magnesium. In the present study, a very strong, positive and significant correlation was found between rooting and magnesium content.

The study revealed a strong, negative, and significant correlation between the sodium saturation and the root length, as well as the dry and fresh mass of roots. Furthermore, the sodium saturation showed a strong negative correlation with the levels of phosphorus, calcium, and magnesium, while it showed a positive correlation with the levels of potassium and sodium. The observed correlations reinforce the findings of the regression analysis, where higher levels of P, Ca, Mg, and CEC in the substrate led to better rooting percentages, while higher levels of sodium saturation resulted in a reduction in this parameter (Table 2).

Table 2: Pearson's linear correlation coefficients for air layering parameters and chemical composition of substrates. Brasília-DF, 2021. SUV: Survival percentage; CAL: Calousing percentage; RO%: Rooting percentage. LIG: Lignification scale; RLE: Root length; VIG: Rooting vigor; RFM: Root fresh mass; RDM: Root drymass; P: phosphorus; Ca: Calcium; Mg: Magnesium; K: Potassium; Na: Sodium; CEC: Cation exchange capacity; NatSat: Sodium saturation.

	SUV	CAL	RO%	LIG	RLE	VIG	RFM	RDM	P	Ca	Mg	K	Na	CEC	NaSat
SUV	1	0,25	0,47	0,53	0,51	0,61	0,74	0,80*	0,71	0,59	0,60	-0,44	-0,28	0,56	-0,58
CAL		1	0,89*	0,89*	0,93*	0,87*	0,77	0,67	0,72	0,73	0,70	-0,47	-0,56	0,75	-0,73
RO%			1	0,95*	0,89*	0,88*	0,93*	0,89*	0,93*	0,91*	0,94*	-0,66	-0,70	0,94*	-0,90*
LIG				1	0,97**	0,98**	0,93*	0,87*	0,92*	0,95**	0,90*	-0,79	-0,81	0,81*	-0,95**
RLE					1	0,99**	0,88*	0,81*	0,84*	0,86*	0,79	-0,69	-0,71	0,73	-0,87*
VIG						1	0,92*	0,85*	0,89*	0,90*	0,84**	-0,74	-0,74	0,75	-0,91*
RFM							1	0,98**	0,98**	0,94*	0,94*	-0,71	-0,68	0,90*	-0,93*
RDM								1	0,98**	0,91*	0,94*	-0,67	-0,61	0,91*	-0,89*
P									1	0,96**	0,98**	-0,77	-0,73	0,91*	-0,95**
Ca										1	0,97**	-0,89*	-0,88*	0,82*	-0,99**
Mg											1	-0,81*	-0,79	0,90*	-0,96**
K												1	0,97**	-0,49	0,90*
Na													1	-0,49	0,89*
CEC														1	-0,79
NaSat															1

Source: The authors.

Although not statistically significant, there were negative correlations between rooting and the levels of potassium and sodium in the substrates. The lower rooting percentages observed in the air layering at higher doses of potassium and sodium could be due to an increase in substrate salinity, which can cause toxicity and reduce rooting vigor. This finding is consistent with the results reported by Roehrdanz *et al*. (2019) who observed a negative correlation between substrate salinity and root dry mass, and suggested that substrates with low salinity may promote better growth of seedlings. Fornes *et al*. (2017) also reported a phytotoxic effect of substrates with high salinity, which was attributed to an excess of sodium and potassium.

The correlation analysis revealed a very strong and positive correlation between CEC and the air layering rooting parameters, namely rooting percentage and root fresh and dry masses ($r = 0.9442$, $r = 0.9089$, and $r = 0.9149$, respectively), indicating that air layering has a greater propensity to root in substrates with higher CEC (Table 2). The observed correlations also suggest that a higher CEC value is dependent on the adequate availability of essential nutrients such as calcium and magnesium, as these two elements showed a significant correlation with CEC ($r > 0.8$).

Positive and significant correlations were observed between root length and root fresh mass ($r = 0.61$) by Costa *et al*. (2021). Abksari *et al*. (2017) reported significant and positive correlations between the root dry mass and levels of phosphorus ($r = 0.76$), potassium ($r = 0.88$), and magnesium ($r = 0.56$), which is consistent with the findings of the present study.

4 CONCLUSIONS

The optimal development of rooting in *Caryocar brasiliense* air layers is achieved when the substrate's phosphorus, calcium, and magnesium contents are above 3.0 mg dm^{-3}, 7.0 $cmol_c$ dm^{-3}, and 3.5 $cmol_c$ dm^{-3}, respectively, and the cation exchange capacity is above 17 $cmol_c$ dm^{-3}. The ideal potassium content of the substrate should be between 3.0 and 4.0 $cmol_c$ dm^{-3}. It is recommended to keep the sodium content and sodium saturation of the substrate below 1.4 $cmol_c$ dm^{-3} and 6%, respectively, to avoid phytotoxicity. Based on the results, the Bioplant® commercial substrate is a suitable choice for the air layering process in *C. brasiliense*.

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REFERENCES

ABAD, M. *et al*. Physical properties of various coconut coir dusts compared to peat. **HortScience**, Alexandria, v.40, n.7, p.2138-2144, 2005. Available from:< https://doi.org/10.21273/HORTSCI.40.7.2138>.

ABOKSARI, H. A. *et al*. Application of bio-fertilizer for *Pelargonium peltatum* growth in new organic substrates. **Journal of Plant Nutrition**, New York, v. 41, n.2, p.137-149, 2018. Available from: <https://doi.org/10.1080/01904167.2017.1381733>.

BAKHT, B. *et al*. Interactive effect of calcium and magnesium on growth of *Schefflera arboricola* cuttings. **Pure and Applied Biology**, Quetta, v.4, n.4, p.568-574, 2015. Available from: <http://dx.doi.org/10.19045/bspab.2015.44016>.

BERILLI, S. D. S. *et al*. Effect of substrate treated with tannery sludge on growth and anatomy of conilon coffee cuttings. **Journal of Experimental Agriculture International**, Hoogly, v.22, n.4, p. 1-10, 2018. Available from: < https://doi.org/10.9734/JEAI/2018/40670 >.

CARDOSO, M. R. D. *et al*. Classificação Climática de Köppen-Geiger para o Estado de Goiás e o Distrito Federal. **Acta Geográfica**, Boa Vista, v.8, n.16, p.40-55, 2014. Available from: <http://rigeo.cprm.gov.br/bitstream/doc/15047/1/1384-9805-1-PB.pdf>.

CARMONA, R. *et al*. Air layering in *Caryocar brasiliense*-effect of stem diameter. **Ciência Rural**, Santa Maria, v.52, n.9, p.1-7, 2022. Available from: <https://doi.org/10.1590/0103-8478cr20201040 >.

CARVALHO, F. D. *et al*. **Estimativas e implicações da correlação no melhoramento vegetal**. Pelotas: UFPEL, 2004. 142p.

CASTRO, L. A. S.; SILVEIRA, C. A. P. Propagação vegetativa do pessegueiro por alporquia. **Revista Brasileira de Fruticultura**, Cruz das Almas, v.25, n.2, p.368-370, 2003. Available from: <https://doi.org/10.1590/S0100-29452003000200051>.

CHEN, J. *et al*. Rooting foliage plant cuttings in compost-formulated substrates. **HortTechnology**, Alexandria, v.13, n.1, p.110-114, 2003. Available from: <https://doi.org/10.21273/HORTTECH.13.1.0110>.

CHEN, W. *et al*. Factors involved in the success of *Castanea henryi* stem cuttings in different cutting mediums and cutting selection periods. **Journal of Forestry Research**, Heidelberg, v.32, n.4, p.1627-1639, 2021. Available from: <https://doi.org/10.1007/s11676-020-01208-5>.

COSTA, R. M. *et al*. Quality of pre-sprouted sugarcane seedlings grown on substrates with decomposed babassu palm stem. **Pesquisa Agropecuária Tropical**, Goiânia, v.51, 2021. Available from: <https://doi.org/10.1590/1983-40632021v5166587>.

CUNHA, A. C. M. *et al*. Influência do estado nutricional de minicepas no enraizamento de miniestacas de eucalipto. **Revista Árvore**, Viçosa, v.33, n.4, p.607-615, 2009. Available from: <https://doi.org/10.1590/S0100-67622009000400003>.

DA SILVA, M. S. C. *et al*. Substrates and indolebutyric acid (IBA) concentrations in air-layering rooting of Tamarind tree. African **Journal of Agricultural Research**, Lagos, v.12, n.39, p.2926-2932, 2017. Available from: <https://doi.org/10.5897/AJAR2017.12561>.

DA SILVA, R. C. *et al*. Efeito da composição de substratos no enraizamento de estacas de *Hyptis suaveolens* (L.). **Revista Brasileira de Ciências Agrárias**, Recife, v. 7, n. 2, p. 219-225, 2012. Available from: <https://doi.org/10.5039/agraria.v5i3a1245>.

DANNER, M. A. *et al*. Enraizamento de jabuticabeira (*Plinia trunciflora*) por mergulhia aérea. **Revista Brasileira de Fruticultura**, Cruz das Almas, v.28, n.3, p.530-532, 2006. Available from: <https://doi.org/10.1590/S0100-29452006000300043>.

DUTRA, T. R. *et al*. Ácido indolbutírico e substratos na alporquia de umbuzeiro. **Pesquisa Agropecuária Tropical**, Goiânia, v. 42, n. 4, p. 424-429, 2012. Available from: <https://doi.org/10.1590/S1983-40632012000400010>.

FORNES, F. *et al*. Assessment of biochar and hydrochar as minor to major constituents of growing media for containerized tomato production. **Journal of the Science of Food and Agriculture**, London, v.97, n.11, p.3675-3684, 2017. Available from: <https://doi.org/10.1002/jsfa.8227>.

FORNES, F. *et al*. Compost versus vermicompost as substrate constituents for rooting shrub cuttings. **Spanish journal of agricultural research**, Madrid, v. 11, n. 2, p. 518-528, 2013. Available from: <https://doi.org/10.5424/sjar/2013112-3304>.

GIEL, P.; BOJARCZUK, K. Effects of high concentrations of calcium salts in the substrate and its pH on the growth of selected rhododendron cultivars. **Acta Societatis Botanicorum Poloniae**, Warszawa, v. 80, n. 2, 2011. Available from: <https://doi.org/10.5586/asbp.2011.021>.

GONÇALVES, E. O. *et al*. Crescimento de mudas de *Ateleia glazioviana* em substratos contendo diferentes materiais orgânicos. **Floresta e Ambiente**, Seropédica, v. 21, p. 339-348, 2014. Available from: <https://doi.org/10.1590/2179-8087.029213>.

GUIMARÃES, R. N. *et al*. Vegetative propagation of pequi (souari nut) by cutting. **Ciência Rural**, Santa Maria, v.49, n.2, 2019. Available from: <https://doi.org/10.1590/0103-8478cr20180579>.

HARTMANN, H. T. *et al*. **Plant propagation: principles and practices.** 8th ed. New Jersey: Prentice Hall, 2014. 559p.

ICHIKAWA, E. *et al*. Enraizamento de mudas de batata-doce submetidas a nutrição suplementar com cálcio e fósforo no substrato. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, v.23, n.11, p.860-868, 2019. Available from: <https://doi.org/10.1590/1807-1929/agriambi.v23n11p860-868>.

KHANDAKER, M. M. *et al*. Effects of Indole-3-Butyric Acid (IBA) and rooting media on rooting and survival of air layered wax apple (*Syzygium samarangense*) CV Jambu Madu. **Brazilian Journal of Biology**, v. 82, 2022. Available from: <https://doi.org/10.1590/1519-6984.256277>.

KRATZ, D. *et al*. Propriedades físicas e químicas de substratos renováveis. **Revista Árvore**, Viçosa, v.37, p.1103-1113, 2013. Available from: <https://doi.org/10.1590/S0100-67622013000600012>.

LINS, L. C. R. *et al*. The lychee tree propagation by layering. **Revista Brasileira de Fruticultura**, Cruz das Almas, v.37, n.2, p.480-487, 2015. Available from: <https://doi.org/10.1590/0100-2945-112/14>.

MAHLAMBI, N. *et al*. Effects of Propagation Media and Branch Orientation on Rooting of Guava (*Psidium guajava* L.) Shoots Propagated by Air Layering in a Sub-tropical Environment. **Journal of Experimental Agriculture International**, Hoogly, v.41, n.4, p.1-9, 2019. Available from: <https://doi.org/10.9734/JEAI/2019/v41i430404>.

MAHLAMBI, N. *et al*. Effects of propagation media and branch orientation on rooting of guava (*Psidium guajava* L.) shoots propagated by air layering in sub-tropical environment. **J Exp Agric Int**, v. 41, n. 4, p. 1-9, 2019. Available from: <https://doi.org/10.9734/JEAI/2019/v41i430404>.
MARTINS, W. A. *et al*. Estaquia e concentração de reguladores vegetais no enraizamento de *Campomanesia adamantium*. **Revista de Ciências Agrárias**, Lisboa, v.38, n.1, p.58-64, 2015. Available from: <**https://doi.org/10.19084/rca.16869**>.

MAURYA, R. P. *et al*. Studies on the Propagation of Jamaican Ackee (*Blighia sapida* L.) by Air-layering. **HortScience**, Alexandria, v.48, n.10, p.1298-1300, 2013. Available from: <https://doi.org/10.21273/HORTSCI.48.10.1298>.

MENDOZA-HERNÁNDEZ, D.*et al*. Compost and vermicompost of horticultural waste as substrates for cutting rooting and growth of rosemary. **Scientia Horticulturae**, Amsterdam, v.178, n.23, p.192–202, 2014. Available from: <https://doi.org/ 10.1016/j.scienta.2014.08.024>.
MIRANDA, R. F. *et al*. Crescimento do pequizeiro em resposta a irrigação e adubação. **Revista Cultura Agronômica**, Ilhas Solteira, v.25, n.4, p.351-360, 2016. Available from: <https://doi.org/ 10.32929/2446-8355.2016v25n4p351-360>.

NASORY, D. C.; CUNHA, M. F. Quebra da dormência e emergência de plântulas de sementes de pequi, *Caryocar brasiliense*. **Revista Verde de Agroecologia e Desenvolvimento Sustentável**, Mossoró, v. 7, n. 1, p. 46, 2012. Available from: <https://dialnet.unirioja.es/servlet/articulo?codigo=7410343>.

PACHECO, J. P.; FRANCO, E. T. H. Substratos e estacas com e sem folhas no enraizamento de *Luehea divaricata* Mart. **Ciência Rural**, Santa Maria, v.38, n.7, p.1900-1906, 2008. Available from: <https://doi.org/10.1590/S0103-84782008000700015>.

PENNINGSFELD, F. Kultursubstrate für den Gartenbau, besonders in Deutschland:—Ein kritischer Überblick. **Plant and Soil**, Dordrecht, v.75, n.3, p.269-281, 1983. Available from: <https://doi.org/10.1007/BF02369967>.

PONGRAC, P. *et al*. Effect of phosphorus supply on root traits of two *Brassica oleracea* L. genotypes. **BMC Plant Biology**, v. 20, p. 1-17, 2020. Available from: <https://doi.org/10.1186/s12870-020-02558-2>.

POÓR, P. *et al*. Salt stress-induced production of reactive oxygen-and nitrogen species and cell death in the ethylene receptor mutant Never ripe and wild type tomato roots. **Plant Physiology and Biochemistry**, v. 97, p. 313-322, 2015. Available from: <https://doi.org/10.1016/j.plaphy.2015.10.021>.

R CORE TEAM. **R: A language and environment for statistical computing. R Foundation for Statistical Computing**, Vienna. 2022. ISBN 3-900051-07-0. Available from: https://www.R-project.org>.

ROEHRDANZ, M. *et al*. Co-composted hydrochar substrates as growing media for horticultural crops. **Scientia Horticulturae**, Amsterdam, v.252, n.27, p.96-103, 2019. Available from: <https://doi.org/10.1016/j.scienta.2019.03.055>.

VIEIRA, R. F. *et al*. **Frutas nativas da região Centro-Oeste do Brasil**. 1. ed. Brasília: Embrapa Recursos Genéticos e Biotecnologia, 2006. 320p.

ZANOTTI, R. F. *et al*. Propagação de *Schlumbergera truncata* (Haw): alternativas ao uso do xaxim. **REVISTA AGRO@ MBIENTE ON-LINE**, Boa Vista, v.9, n.3, p.337-341, 2015. Available from: <https://doi.org/10.18227/1982-8470ragro.v9i3.226>.

ZENG, J. *et al*. Effects of scion variety on the Phosphorus efficiency of grafted *Camellia oleifera* seedlings. **Forests**, v. 13, n. 2, p. 203, 2022. Available from: <https://doi.org/10.3390/f13020203>.