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Controlled release fertilizer and tube volume in the production of African mahogany seedlings

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SILVICULTURE

ABSTRACT

Background: The present study verified the effect of controlled-release fertilizer (CRF) doses combined with tube volumes on the initial growth of seedlings of *Khaya anthotheca* and *Khaya grandifoliola*, through evaluations of morphological, physiological, and nutritional characteristics. The experiment was conducted in a factorial arrangement (5 × 2), evaluating the interaction of five concentrations of 15-9-12 CRF and two tube volumes. After 180 days, the morphological parameters of the seedlings were evaluated. Samples of the aboveground and root parts were collected for determination of macronutrients and organic carbon.

Results: Regarding the interaction dose × container volume, for all evaluated characteristics, K. *anthotheca* and *K. grandifoliola* seedlings grown in substrate without the addition of CRF showed the lowest means, while seedlings with higher doses resulted in statistically superior responses for the studied attributes. The multivariate analysis of principal components, concerning the nutrients present in the leaves and roots of *K. anthotheca* and *K. grandifoliola*, allowed for characterizing the groups of nutritional similarities between the CRF doses and the volume of the tubes.

Conclusion: The different doses of CRF resulted in significant variations in the growth of *K. anthotheca* and *K. grandifoliola* seedlings, with the application of the 10 g L^{-1} dose of CRF recommended for both species. The volume of the tubes did not show disparities in the morphological growth characteristics analyzed in the studied species, highlighting the Dickson Quality Index as one of the most accurate measures. The volume of 280 cm^3 stood out, indicating seedlings of better quality.

Keywords: *Khaya anthotheca*; *Khaya grandifoliola*; Forest nursery; CRF; containers.

HIGHLIGHTS

CRF doses influence the initial growth of *K. anthotheca* and *K. grandifoliola* seedlings.
The seedlings grown in substrate with higher doses resulted in superior responses.
Multivariate analysis allowed for characterizing the groups of nutritional similarities.
The type of container did not show a significant impact on seedling growth.

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INTRODUCTION

Among the forest species recognized worldwide for the production of high-quality wood, those belonging to the genus *Khaya* spp. deserve special mention, commonly known as African mahogany (Zanetti et al. 2017). These species present important silvicultural characteristics such as their high resistance to the microlepidopteran *Hypsipyla grandella* Zeller, the main pest of Brazilian mahogany (*Swietenia macrophylla*). The species also have high economic value in the international market and wood technological properties, displays rapid growth and easy adaptation to edaphoclimatic conditions in tropical environments (Ribeiro et al. 2017; Oliveira; Franca 2020).

Despite the many interesting characteristics present in African mahogany species, some factors hinder their cultivation. One of them is seedling production, since seed production does not meet market demand, lacking continuous supply (Araújo et al. 2020; Lucena Junior et al. 2022). Another relevant aspect is the complexity of seed collection, not only due to the large size of the trees but mainly because of the time required for individuals of this species to reach maturity and reproductive stage. Additionally, the short viability period of the seeds and their high value must be taken into account (Silva et al. 2020; Romanoski et al. 2023).

Faced with this reality, it is essential to optimize the production of African mahogany seedlings. The initial stage of a forest implantation process consists of seedling production, which is of paramount importance and considered determinant. This is because the success of a well-established and productive forest is directly associated with the quality of the seedlings used (Roweder et al. 2015). To accelerate this process, the use of traditional fertilizers such as nitrogenous, potassium, and phosphate is common (Min et al. 2021). However, these chemical fertilizers have high solubility in water, resulting in rapid nutrient loss and release (citation needed). Therefore, there is a demand for alternatives to traditional fertilizers that can simultaneously improve nutrient use efficiency, meeting plant needs (Wang et al. 2022).

A safe, economical, environmentally sustainable, and enhanced alternative is the use of controlled-release fertilizers (CRF). These are composed of polymer-coated granules designed to release active nutrients in a controlled manner over a specific period (Aguilera-Rodriguez et al. 2016). This prolongs the duration of nutrient release, synchronizing with the metabolic needs of the plant (Irfan et al. 2018). Additionally, the increased efficiency in nutrient absorption provided by these fertilizers favors the growth of desired species over weeds, reducing operational costs and losses due to leaching, decreasing mortality due to post-planting shock, and optimizing seedling production in a shorter period (Andriguetto et al. 2024; Griebeler et al. 2023).

In addition to fertilization, container size also directly affects seedlings quality, as it influences proper root system formation, protects roots from mechanical damage and dehydration, and contributes to maximum survival and initial growth in the field (Magistrali et al. 2022). The size of the container used in forest nurseries also directly impacts the final cost of the seedlings, as it determines the amount of substrate needed, the space occupied in the nursery, the labor required for transportation, acclimatization, and removal for delivery to the producer, besides influencing the amount of inputs, fertilizers, and water needed (Lima Filho et al. 2019).

The appropriate management of tube volume and seedling quality can be optimized through adequate nutrient supply through fertilization (Cabreira et al. 2019). In this context, the objective of this study was to verify the effect of controlled-release fertilizer (CRF) combined with tube volumes on the initial growth of seedlings of *Khaya anthotheca* and *Khaya grandifoliola*, through evaluations of morphological, physiological, and nutritional characteristics. For this purpose, the hypothesis was tested that it is possible to obtain differences in the growth and quality of African mahogany seedlings with increasing doses of CRF and substrate volumes.

MATERIAL AND METHODS

Plant materials and treatments

Khaya grandifoliola C. DC. and *Khaya anthotheca* (Welw.) C.DC. (Meliaceaes) seeds were acquired through donations from producers of the Brazilian Association of African Mahogany Producers (ABPMA), for seedling production. Two experiments were conducted simultaneously, one for each species. The experimental design used was completely randomized in a factorial scheme (2 × 5), evaluating the interaction of two tube volumes (180 and 280 cm^3) and the five concentrations of controlled release fertilizer (CRF) for 5 months (0, 4, 8, 12 and 16 g L^{-1}). The experimental unit consisted of nine seedlings, with five repetitions, totaling 45 seedlings per treatment. The CRF used was Basacote Plus (15-9-12) for 5 months, and its chemical characterization is presented in Table 1.

For the production of seedlings, the commercial substrate TerraNutri® was used, composed of vermiculite, coconut fiber, decomposed pine bark, and carbonized rice husk (1:2:2:1), with a pH of 6.2, density of 315 kg m^3, moisture content of 58%, and electrical conductivity of 0.6 mS cm^{-1}. The substrate was manually homogenized together with the appropriate doses of CRF before filling the tubes.

Sowing was performed directly in tubes, with two seeds added per container. Thirty days after emergence, thinning was performed, leaving the most vigorous and centrally positioned seedling per container. The seedlings were arranged in a shaded house covered on the sides and top with shading net (shade cloth), allowing 70% of light transmission, a 100-micron plastic sheet above the shade cloth roof, and suspended beds 80 cm above the ground.

The seedlings remained in the shade house for 120 days, and were irrigated five times a day. For an additional 60 days in the hardening-off area, they were irrigated three times a day. The irrigation system was automatic, using sprinklers with a flow rate of 30 liters per hour, with a pressure of up to 15 meters of water column (MCA), wetting an area of 1.5 m^2, fixed on the ceiling at 2 meters height.

Morphological analysis of seedlings

For the evaluation of seedling growth, the height of the aerial part (H), the stem diameter (D), the height/diameter ratio (HDR), the chlorophyll a index (Cla) and chlorophyll b of the leaves (Clb), the shoot dry mass (SDM), the root dry mass (RDM), the total dry mass (TDM), the shoot/root dry mass ratio (SRR) and the Dickson's quality index (DQI) were measured at 180 days after sowing.

The height of the aerial part was measured using a millimeter ruler (from the base of the seedling to the apical bud), and the diameter with the aid of a digital caliper (precision of 0.01 mm). Total chlorophyll was determined based on readings taken on two leaves per individual non-destructively, using a chlorophyll meter, individually calibrated by the portable ClorofiLOG1030® meter (Falker 2008). To obtain the shoot dry mass (SDM) and the root dry mass (RDM), 12 seedlings were randomly selected for weighing of the plant parts separately after drying in a forced air circulation oven at 70 °C for a period of 72 h. The Dickson quality index was obtained according to the formula presented in Dickson et al. (1960).

Nutritional analysis of seedlings

The aerial and root plant parts that were weighed for biomass determination were then sent to the laboratory for determination of macronutrients. Total N was extracted by sulfuric digestion with titrimetric determination, all other macronutrients (P, S, K, Ca, and Mg) were extracted by Nitro-perchloric digestion, with P and S determined by spectrophotometry, K by flame photometry, and Ca and Mg by atomic absorption spectrophotometry. Finally, organic carbon was determined by oxidation with potassium dichromate and titrimetric determination.

The steps presented in the methodology, from substrate preparation to the analysis of growth and nutritional characteristics, are illustrated by the flowchart in Figure 1.

Statistical Analysis

The statistical analyses were conducted for each species separately. The data were subjected to Hartley's test ($p > 0.05$) and Shapiro-Wilk test ($p > 0.05$) to check the homogeneity of variance among treatments and the normal distribution of errors, respectively. Then, analysis

Table 1: Chemical characterization of the controlled release fertilizer (CRF) Basacote Plus 5 M (15-9-12), provided by the manufacturer.

N	P_2O_5	K_2O	Mg	S	Fe	Cu	Mn	Mo
				%				
15	9	12	1.3	6	0.46	0.05	0.06	0.02

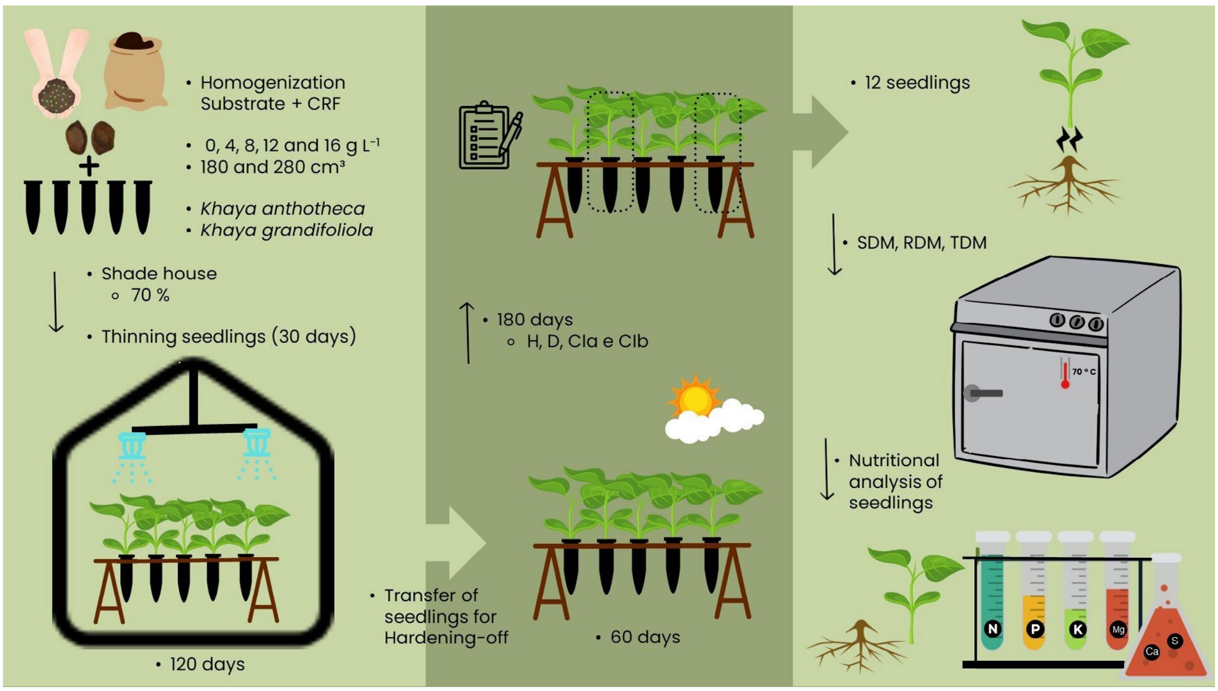

Figure 1: Flowchart of the methodological steps in the study of controlled-release fertilizer (CRF) evaluation and plug volume in the production of seedlings of *Khaya grandifoliola* and *Khaya anthotheca*.

of variance (ANOVA) was performed, and depending on significance, data were compared using Tukey's test ($p < 0.05$). For polynomial regression analyses, equations with significant models ($p > 0.05$) and higher order determination coefficients (R2) were adopted. The mathematical models (-b/2a) were used to determine the dose of maximum technical efficiency (DMTE) for seedling production, which was calculated from the partial derivatives of the adjusted equations. Principal component analysis (PCA) was conducted based on the correlation matrix. Cumulative variance greater than 80% was used as a criterion for PCA. The statistical analyses were performed using the R statistical software, version 4.3.3, with the ExpDes package (R Core Team 2023).

RESULTS

Morphological growth characteristics of *Khaya anthotheca*

According to the analysis of variance, there were significant differences ($p < 0.05$) in the interactions of the tested factors. For the interaction dose × container volume, in all evaluated characteristics, *K. anthotheca* seedlings grown in substrate without the addition of CRF showed the lowest means, while seedlings with higher doses resulted in statistically superior responses for the studied attributes (Table 2).

The variable height (H) showed the same behavior regardless of the tube volume, with the highest means of this variable in seedlings produced at doses of 8, 12 and 16 g L^{-1}, being statistically superior to the other doses tested. The lowest means resulted from the substrate without the addition of CRF (Table 2). For the variable stem diameter (D), seedlings produced in 180 cm^3 tubes showed the highest means at doses of 8, 12 and 16 g L^{-1} with values ranging from 7.37 to 8.30 mm, being statistically superior to the other doses tested. For the 280 cm^3 volume tube, the four doses used (4, 8, 12 and 16 g L^{-1}) were statistically equal and superior, with only the treatment without the addition of CRF being statistically different, with an average of 4.62 mm (Table 2).

For the dry mass of the aerial part (SDM) variable, seedlings produced in 180 cm^3 tubes at doses of 8, 12 and 16 g L^{-1} did not differ statistically from one another, presenting the highest means for this attribute, with average values ranging from 8.18 to 9.91 g per plant. Seedlings produced in the 280 cm^3 tube were statistically superior only in treatments with doses of 8 and 12 g L^{-1}, corresponding to

Table 2: Average values of morphological growth characteristics in relation to five doses of controlled release fertilizer (CRF) in two tube volumes, in the production of *Khaya anthotheca* seedlings at 180 days after sowing.

Variables	Tube (cm^3)	Dose (g L^{-1})				
		0	4	8	12	16
H (cm)	180	15.04 (± 0.63) Ac	23.37 (± 0.95) Ab	27.7 (± 1.13) Aab	28.75 (± 1.72) Aa	29.95 (± 1.31) Aa
	280	18.54 (± 1.18) Ac	25.41 (± 1.24) Ab	31.05 (± 1.38) Aa	28.45 (± 1.21) Aab	26.62 (± 2.24) Aab
D (mm)	180	4.07 (± 0.17) Ac	6.54 (± 0.31) Bb	8.30 (± 0.29) Aa	7.92 (± 0.43) Aa	7.37 (± 0.47) Aab
	280	4.62 (± 0.22) Ab	7.98 (± 0.26) Aa	8.00 (± 0.32) Aa	7.95 (± 0.22) Aa	7.49 (± 0.38) Aa
HDR	180	3.71 (± 0.12) Aab	3.63 (± 0.18) Aab	3.36 (± 0.15) Ab	3.69 (± 0.22) Aab	4.22 (± 0.28) Aa
	280	4.02 (± 0.18) Aa	3.20 (± 0.16) Ab	3.89 (± 0.14) Aab	3.59 (± 0.16) Aab	3.55 (± 0.27) Bab
Cla	180	18.36 (± 0.76) Ac	28.55 (± 2.64) Ab	36.11 (± 2.18) Aab	42.56 (± 2.91) Aa	44.88 (± 2.08) Aa
	280	22.00 (± 0.80) Ac	34.42 (± 2.88) Ab	41.47 (± 2.04) Aab	45.20 (± 1.00) Aa	41.68 (± 3.49) Aab
Clb	180	3.07 (± 0.21) Ac	5.68 (± 0.93) Ac	8.05 (± 1.00) Abc	15.63 (± 3.22) Aab	19.49 (± 3.48) Aa
	280	3.96 (± 0.14) Ac	7.85 (± 0.86) Abc	13.45 (± 2.05) Aab	16.45 (± 1.91) Aa	19.08 (± 3.33) Aa
SDM (g)	180	0.78 (± 0.04) Ac	4.57 (± 0.43) Bb	8.18 (± 0.44) Ba	9.91 (± 0.40) Aa	8.64 (± 0.69) Aa
	280	1.60 (± 0.08) Ac	6.81 (± 0.29) Ab	9.62 (± 0.64) Aa	9.40 (± 0.54) Aa	6.99 (± 0.71) Bb
RDM (g)	180	0.80 (± 0.11) Ab	3.32 (± 0.30) Ba	3.82 (± 0.31) Ba	4.43 (± 0.25) Ba	4.07 (± 0.28) Aa
	280	1.27 (± 0.09) Ad	4.74 (± 0.19) Abc	5.89 (± 0.44) Aa	5.56 (± 0.28) Aab	4.15 (± 0.45) Ac
TDM (g)	180	1.58 (± 0.13) Ad	7.89 (± 0.35) Bc	12.01 (± 0.46) Bb	14.35 (± 0.58) Aa	12.71 (± 0.58) Aab
	280	2.88 (± 0.15) Ac	11.56 (± 0.37) Ab	15.51 (± 0.76) Aa	14.96 (± 0.58) Aa	11.14 (± 0.68) Bb
SRR	180	1.12 (± 0.14) Ab	1.57 (± 0.25) Aab	2.38 (± 0.35) Aa	2.29 (± 0.12) Aa	2.30 (± 0.28) Aa
	280	1.31 (± 0.10) Aa	1.45 (± 0.08) Aa	1.72 (± 0.15) Ba	1.75 (± 0.54) Aa	1.96 (± 0.32) Aa
DQI	180	0.33 (± 0.03) Ac	1.57 (± 0.11) Bb	2.14 (± 0.12) Ba	2.43 (± 0.13) Ba	1.98 (± 0.08) Aab
	280	0.54 (± 0.04) Ac	2.49 (± 0.09) Aab	2.79 (± 0.15) Aa	2.82 (± 0.14) Aa	2.23 (± 0.26) Ab

Height of the aerial part (H), stem diameter (D), height/diameter ratio (HDR), chlorophyll a index (Cla) and chlorophyll b of the leaves (Clb), shoot dry mass (SDM), root dry mass (RDM), total dry mass (TDM), shoot/root dry mass ratio (SRR) and Dickson's quality index (DQI). For each variable, means followed by the same uppercase letter in the column, and lowercase letters in the row, do not differ statistically from each other by Tukey's test ($p < 0.05$). Data presented as: mean ± standard error.

average values of 9.62 and 9.40 g per plant. In both tube volumes, the lowest means were again found in seedlings produced with substrate without the addition of CRF (Table 2). For the root dry mass (RDM) variable, all four doses used (4, 8, 12 and 16 g L^{-1}) were statistically equal and superior in seedlings produced in 180 cm^3 tubes, with only the treatment without the addition of CRF being statistically different and inferior, with an average value of 0.80 g per plant. In the 280 cm^3 tube, only seedlings produced at doses of 8 and 12 g L^{-1} showed the highest means in RDM, being statistically superior to the other treatments. Again, the lowest mean was found in the treatment without the addition of CRF, reaching only 1.27 g per plant (Table 2). For the DQI, in seedlings produced in 180 cm^3 tubes, the two highest doses used (12 and 16 g L^{-1}) were statistically equal and superior to the others. For seedlings produced in 280 cm^3 tubes, doses of 4, 8, 12 g L^{-1} showed the highest statistical values for this parameter. In both container volumes, the lowest statistical values of DQI were the result of seedlings without the addition of CRF.

Concerning the container volume by dose, there was only no statistical difference for the height variable, with all treatments being identical to each other (Table 2). For D, there was a statistical difference only in seedlings produced in tube volumes at a dose of 4 g L^{-1}, with the 280 cm^3 volume statistically superior to the 180 cm^3 (Table 2). Regarding SDM, there was no statistical difference between seedlings produced in tubes at doses of 0 and 12 g L^{-1}, while at doses of 4 and 8 g L^{-1}, the highest average results were obtained in the 280 cm^3 tube and at a dose of 16 g L^{-1} in the 180 cm^3 tube (Table 2). RDM showed no statistical difference between seedlings produced in tubes at doses of 0 and 16 g L^{-1}, while in the other doses, the highest average results were obtained in the 280 cm^3 tube (Table 2).

The DQI showed no statistical difference between seedlings produced in tubes with a dose of 16 g L^{-1} and in substrate without the addition of CRF. However, regarding doses of 4, 8, 12 g L^{-1}, the behavior was different, with seedlings produced in 280 cm^3 tubes showing the highest statistical values for this parameter.

The regression models and their equations and determination coefficients (R^2) for the four main morphological characteristics of *K. anthotheca* seedlings are presented in figure 2. It can be observed that between doses 8 and 12 g L^{-1} there was a peak in growth for the variables analyzed. Thus for the four morphological characteristics, the dose of maximum technical efficiency (DMTE) was calculated for the tubes with a volume of 180 cm^3 to 280 cm^3, resulting, respectively, in the following values: H = 12.9 g L^{-1} and 9.9 g L^{-1}; D = 10.3 g L^{-1} and 9.3 g L^{-1}; SDM = 13.2 g L^{-1} and 10.3 g L^{-1}; RDM = 11.3 g L^{-1} and 9.4 g L^{-1} (Figure 2).

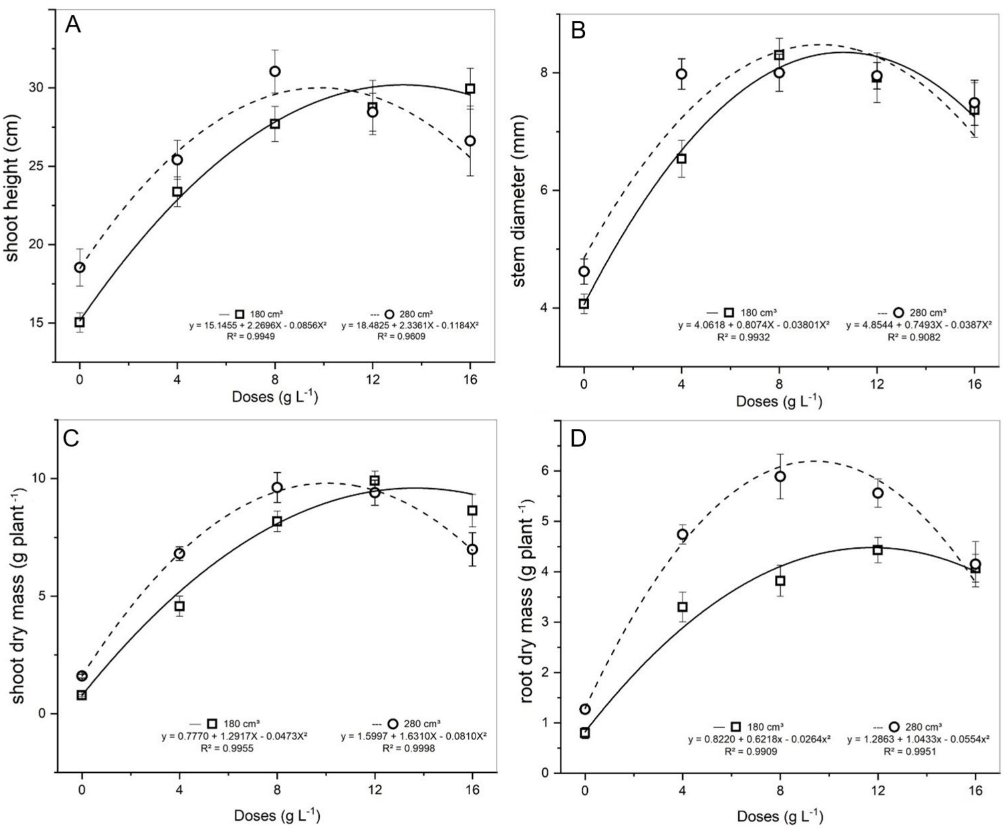

Figure 2: (A) Height (cm); (B) Stem diameter (mm); (C) Shoot dry mass (g $plant^{-1}$); (D) Root dry mass (g $plant^{-1}$) of Khaya anthotheca seedlings as a function of the five doses of CRF under the volumes of 180 and 280 cm^3 tubes at 180 days after sowing.

The relationships between morphological variables, CRF doses, and tube volume can be visualized through Principal Component Analysis (PCA) in Figure 3. The data variability was explained by 78.52% on axis 1 and 13.33% on axis 2, totaling 91.86%. In the first principal component, most variables showed a direct correlation with the growth and quality of *K. anthotheca* seedlings, except for chlorophyll B, HDR and SRR (r = 0.819, -0.130 and 0.761, respectively). Regarding the second component, no direct correlations were observed among the analyzed variables.

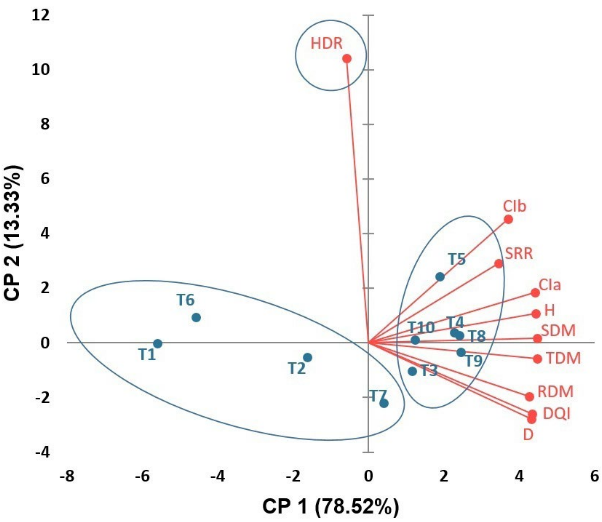

Figure 3: Graphical representation of Principal Component Analysis (PCA) relating dimensions 1 and 2 regarding the development of Khaya anthotheca seedlings at 180 days after sowing, with five doses of controlled-release fertilizer (CRF) and two container volumes. Height of the aerial part (H), stem diameter (D), height/diameter ratio (HDR), chlorophyll a index (Cla) and chlorophyll b of the leaves (Clb), shoot dry mass (SDM), root dry mass (RDM), total dry mass (TDM), shoot/root dry mass ratio (SRR) and Dickson's quality index (DQI). T1(180 cm^3) = 0 g L^{-1}; T2(180 cm^3) = 4 g L^{-1}; T3(180 cm^3) = 8 g L^{-1}; T4(180 cm^3) = 12 g L^{-1}; T5 (180 cm^3) = 16 g L^{-1}; T6(280 cm^3) = 0 g L^{-1}; T7(280 cm^3) = 4 g L^{-1}; T8(280 cm^3) = 8 g L^{-1}; T9(280 cm^3) = 12 g L^{-1}; T10(280 cm^3) = 16 g L^{-1}.

It's possible to observe that the variables were separated into two groups, the first being grouped by treatments with the highest amounts of CRF in both container volumes (T3, T4 and T5; T8, T9 and T10), which influenced the production of Clb, SRR, Cla, H, SDM, TDM, RDM, DQI and D. The second group included only the variable HDR, which was not related to any of the studied treatments. Treatments with the application of the lowest dose (4 g L^{-1}) and without the application of CRF, for both container volumes (T1 and T2; T6 and T7), did not correlate with any analyzed variable, corresponding to the lowest growth and development of *K. anthotheca* seedlings.

Nutrients in the leaves and roots of *Khaya anthotheca*

The multivariate analysis of the principal components, regarding the nutrients present in the leaves and roots of *K. anthotheca*, allowed characterizing the groups of nutritional similarities among the CRF doses and the tube volume (Figure 4).

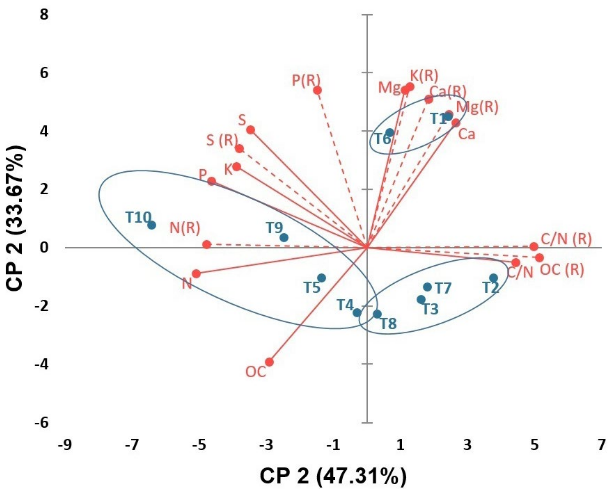

Figure 4: Graphical representation of Principal Component Analysis (PCA) correlating the concentrations of macronutrients, organic carbon, and C/N ratio in leaf and root tissues of *Khaya anthotheca* seedlings at 180 days after sowing. Dotted lines represent nutrients in the roots, and solid lines represent foliar nutrients. T1(180 cm^3) = 0 g L^{-1}; T2(180 cm^3) = 4 g L^{-1}; T3(180 cm^3) = 8 g L^{-1}; T4(180 cm^3) = 12 g L^{-1}; T5 (180 cm^3) = 16 g L^{-1}; T6(280 cm^3) = 0 g L^{-1}; T7(280 cm^3) = 4 g L^{-1}; T8(280 cm^3) = 8 g L^{-1}; T9(280 cm^3) = 12 g L^{-1}; T10(280 cm^3) = 16 g L^{-1}.

The data variability was explained by 47.31% on axis 1 and 33.67% on axis 2, totaling 80.98%. It is observed that both for leaves and roots, the values of macronutrients followed the same pattern. Through PCA, it was possible to observe the formation of three distinct groups. The first group was formed by treatments without the application of CRF in both tube volumes (T1 and T6), obtaining correlation only with the nutrients Mg and Ca. The second group formed by treatments with the lowest doses of CRF (4 and 8 g L^{-1}) in both tube volumes (T2, T3 and T7, T8), presenting correlation with the C/N ratio. The third group was composed of treatments with the highest doses of CRF (12 and 16 g L^{-1}), regardless of container volumes (T4, T5 and T9, T10), resulting in a direct correlation with N, P, S, while the C/N ratio showed opposite correlation to the treatments.

Morphological growth characteristics of *Khaya grandifoliola*

According to the analysis of variance, there were significant differences ($p < 0.05$) in relation to the interactions of the tested factors. Regarding the dose × container volume interaction, all evaluated characteristics of *K. grandifoliola* seedlings grown in substrate without the addition of CRF showed the lowest means, disregarding the relations (HDR and SRR), while seedlings with higher doses resulted in superior responses for the studied attributes (Table 3).

The variable height (H) presented the same behavior regardless of the tube volume used, with the highest means of this variable in seedlings produced at doses of 8, 12 and 16 g L^{-1}, which were statistically superior to the other treatments. The lowest means resulted from the substrate without the addition of CRF (Table 3). For the stem diameter variable (D), the four doses of CRF used (4, 8, 12 and 16 g L^{-1}) in seedlings produced in 180 cm^3 tubes were statistically equal and higher to the treatment without CRF addition, with an average of 4.68 mm. Seedlings produced in 280 cm^3 tubes had the highest means at doses of 8, 12 and 16 g L^{-1}, with values ranging from 7.69 to 8.80 mm, and they were statistically superior to the other treatments (Table 3).

In the same manner as the above-ground height variable (H), the above-ground dry mass (SDM) showed the same behavior regardless of the tube volume used, with the highest means of this variable in seedlings produced at doses of 8, 12 and 16 g L^{-1}, which were statistically superior to the other treatments. The lowest means also resulted from the substrate without the addition of CRF (Table 3). For the root dry mass variable (RDM), all four doses used (4, 8, 12 and 16 g L^{-1}) were statistically equal and higher in seedlings produced in 180 cm^3 tubes, with only the treatment without CRF addition statistically distinct and inferior, with an average value of 0.08 g $plant^{-1}$. In the 280 cm^3 tube, seedlings produced with doses of 8, 12 and 16 g L^{-1} had the highest means in RDM, and they were statistically superior to the other treatments. Once again, the lowest mean was found in the treatment without CRF addition, reaching only 1 g $plant^{-1}$ (Table 3).

Regarding the DQI, seedlings produced in 180 cm^3 tubes had the highest means in treatments using doses of 12 and 16 g L^{-1} of CRF, with both being statistically equal and superior to the others. In the 280 cm^3 tubes, there was a statistical difference only in seedlings produced without the addition of CRF (Table 3).

As for the container volume × dose interaction, only in seedlings produced in tubes with a dose of 8 g L^{-1}, there was a statistical difference in height (H), while for D, there was a statistical difference only in seedlings produced in tubes with a dose of 12 g L^{-1}. In both morphological growth characteristics, the 280 cm^3 tube was statistically superior to the 180 cm^3 tube (Table 3). For SDM, there was no statistical difference between seedlings produced in tubes with doses of 0 and 16 g L^{-1}, while with doses of 4, 8 and 12 g L^{-1}, the

Table 3: Average values of morphological growth characteristics in relation to five doses of controlled release fertilizer (CRF) in two tube volumes, in the production of *Khaya grandifoliola* seedlings at 180 days after sowing.

Variables	Tube (cm³)	Dose (g L^{-1})				
		0	4	8	12	16
H (cm)	180	18.08 (± 0.70) Ac	25.89 (± 1.28) Ab	25.95 (± 1.54) Bab	31.16 (± 0.96) Aa	27.41 (± 1.68) Aa
	280	18.41 (± 1.05) Ac	27.50 (± 0.65) Ab	32.83 (± 1.46) Aa	31.29 (± 1.82) Aab	30.25 (± 1.57) Aab
D (mm)	180	4.68 (± 0.11) Ab	7.02 (± 0.38) Aa	7.87 (± 0.49) Aa	7.76 (± 0.25) Ba	7.29 (± 0.47) Aa
	280	4.37 (± 0.09) Ac	7.32 (± 0.21) Ab	8.53 (± 0.36) Aab	8.80 (± 0.50) Aa	7.69 (± 0.30) Aab
HDR	180	3.86 (± 0.15) Aa	3.74 (± 0.15) Aa	3.34 (± 0.18) Ba	4.04 (± 0.13) Aa	3.81 (± 0.18) Aa
	280	4.22 (± 0.25) Aa	3.79 (± 0.12) Aa	3.91 (± 0.22) Aa	3.65 (± 0.24 Aa	3.93 (± 0.14) aa
Cla	180	20.08 (± 1.94) Ab	23.80 (± 1.91) Bb	36.70 (± 2.95) Ba	42.32 (± 2.38) Aa	35.89 (± 3.54) Ba
	280	22.09 (± 1.47) Ab	38.04 (± 0.71) Aa	43.27 (± 0.90) Aa	41.47 (± 2.26) Aa	45.64 (± 2.68) Aa
Clb	180	4.35 (± 0.83) Ab	4.60 (± 0.40) Ab	9.36 (± 1.39) Aab	13.59 (± 1.98) Aa	14.67 (± 3.64) Aa
	280	4.05 (± 0.28) Ab	7.13 (± 0.69) Ab	10.12 (± 1.14) Ab	10.80 (± 2.07) Ab	18.55 (± 2.38) Aa
SDM (g)	180	1.49 (± 0.08) Ac	5.16 (± 0.21) Bb	7.84 (± 0.34) Ba	7.93 (± 0.66) Ba	7.34 (± 0.93) Aab
	280	1.80 (± 0.12) Ac	7.15 (± 0.59) Ab	9.64 (± 0.71) Aa	10.35 (± 0.58) Aa	8.46 (± 1.03) Aab
RDM (g)	180	1.00 (± 0.08) Ab	3.26 (± 0.21) Ba	3.84 (± 0.26) Ba	3.78 (± 0.34) Ba	3.08 (± 0.31) Ba
	280	1.42 (± 0.10) Ac	4.87 (± 0.41) Ab	5.50 (± 0.42) Aab	6.45 (± 0.51) Aa	5.07 (± 0.57) Aab
TDM (g)	180	2.50 (± 0.15) Ac	8.42 (± 0.32) Bb	11.69 (± 0.55) Ba	11.71 (± 0.90) Aa	10.43 (± 1.08) Bab
	280	3.22 (± 0.15) Ad	12.02 (± 0.90) Ac	15.14 (± 0.59) Aab	16.80 (± 0.77) Ba	13.54 (± 0.84) Abc
SRR	180	1.57 (± 0.11) Aa	1.64 (± 0.11) Aa	2.09 (± 0.10) Aa	2.24 (± 0.27) Aa	2.57 (± 0.37) Aa
	280	1.33 (± 0.12) Aa	1.54 (± 0.13) Aa	2.05 (± 0.39) Aa	1.72 (± 0.19) Aa	2.19 (± 0.48) Aa
DQI	180	0.47 (± 0.03) Ac	1.59 (± 0.09) Bb	2.18 (± 0.12) Bb	1.90 (± 0.17) Ba	1.68 (± 0.18) Aab
	280	0.59 (± 0.03) Ac	2.28 (± 0.17) Aab	2.61 (± 0.13) Aa	3.27 (± 0.30) Aa	2.32 (± 0.19) Ab

Height of the aerial part (H), stem diameter (D), height/diameter ratio (HDR), chlorophyll a index (Cla) and chlorophyll b of the leaves (Clb), shoot dry mass (SDM), root dry mass (RDM), total dry mass (TDM), shoot/root dry mass ratio (SRR) and Dickson's quality index (DQI). For each variable, means followed by the same uppercase letter in the column, and lowercase letters in the row, do not differ statistically from each other by Tukey's test ($p < 0.05$). Data presented as: mean ± standard error.

highest average results were obtained in the 280 cm^3 tube (Table 3). As for RDM, only seedlings produced without the addition of CRF did not show statistical differences between containers, while all four doses used (4, 8, 12 and 16 g L^{-1}) of seedlings produced in 280 cm^3 tubes were statistically superior to those produced in 180 cm^3 tubes (Table 3).

The DQI showed no statistical difference between seedlings produced in both tubes in substrates with 16 g L^{-1} and without the addition of CRF. However, concerning doses of 4, 8, 12 g L^{-1}, the behavior was different, with seedlings produced in 280 cm^3 tubes showing the highest statistical values for this parameter.

The regression models and their equations and determination coefficients (R^2) for the four main morphological characteristics of *K. grandifoliola* seedlings are presented in figure 5. The results indicate that a peak in growth occurred between doses of 8 and 12 g L^{-1} for the analyzed variables. Thus, for the four morphological characteristics, the dose of maximum technical efficiency (DMTE) was calculated for the tubes with a volume of 180 cm^3 of 280 cm^3, resulting, respectively, in the following values: H = 11.5 g L^{-1} and 10.6 g L^{-1}; D = 10.1 g L^{-1} and 10.3 g L^{-1}; SDM = 11.4 g L^{-1} and 10.7 g L^{-1}; RDM = 9.5 g L^{-1} and 10.3 g L^{-1} (Figure 5).

The relationships between morphological variables, CRF doses and tube volume can be visualized through Principal Component Analysis (PCA) in Figure 6. Data variability was explained by 75.47% on axis 1 and 13.29% on axis 2, totaling 88.76%. In the first principal component, similar to *K. anthotheca* species, most variables showed a direct correlation with seedling growth and quality, except for chlorophyll b, HDR and SRR (r = 0.740, - 0.375 and 0.612 respectively). In reference to the second component, no direct correlations were observed among the analyzed variables.

It's possible to observe that the variables were separated into two groups, with the first grouped by treatments with the highest amounts of CRF in both container volumes (T3, T4 and T5; T8, T9 and T10), which influenced the production of Clb, SRR, Cla, H, SDM, TDM, RDM, DQI and D. The second group encompassed only the variable HDR, which was not related to any of the studied treatments. Treatments with the application of the lowest dose (4 g L^{-1}) and without the application of CRF, for both container volumes (T1 and T2; T6 and T7), did not correlate with any analyzed variable, corresponding to the lowest growth and development of *K. grandifoliola* seedlings.

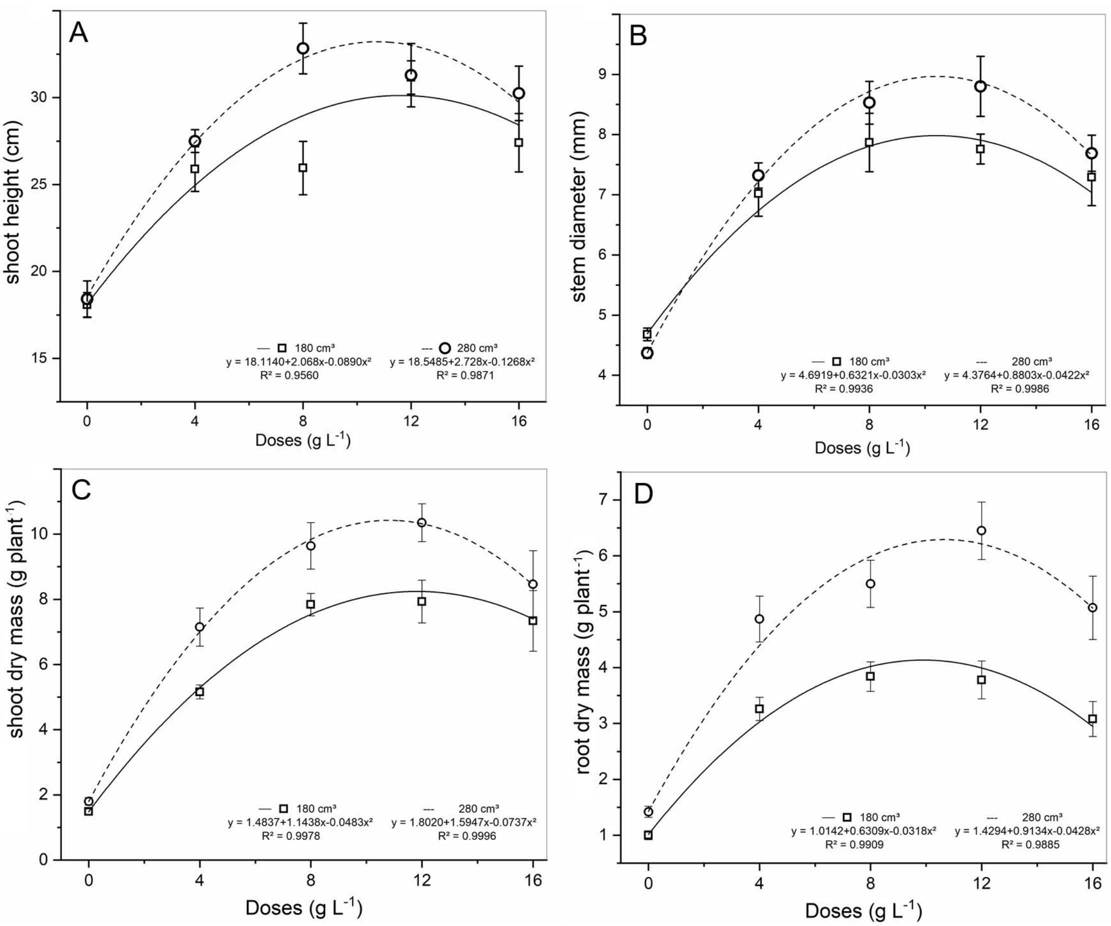

Figure 5: (A) Height (cm); (B) Stem diameter (mm); (C) Shoot dry mass (g $plant^{-1}$); (D) Root dry mass (g $plant^{-1}$) of *Khaya grandifoliola* seedlings as a function of the five doses of CRF under the volumes of 180 and 280 cm^3 tubes at 180 days after sowing.

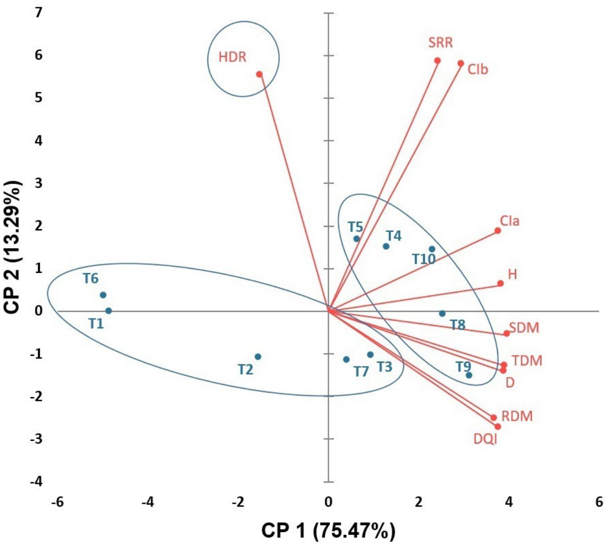

Figure 6: Graphical representation of Principal Component Analysis (PCA) relating dimensions 1 and 2 regarding the development of *Khaya grandifoliola* seedlings at 180 days after sowing, with five doses of controlled-release fertilizer (CRF) and two container volumes. Height of the aerial part (H), stem diameter (D), height/diameter ratio (HDR), chlorophyll a index (Cla) and chlorophyll b of the leaves (Clb), shoot dry mass (SDM), root dry mass (RDM), total dry mass (TDM), shoot/root dry mass ratio (SRR) and Dickson's quality index (DQI). T1(180 cm³) = 0 g L^{-1}; T2(180 cm³) = 4 g L^{-1}; T3(180 cm³) = 8 g L^{-1}; T4(180 cm³) = 12 g L^{-1}; T5 (180 cm³) = 16 g L^{-1}; T6(280 cm³) = 0 g L^{-1}; T7(280 cm³) = 4 g L^{-1}; T8(280 cm³) = 8 g L^{-1}; T9(280 cm³) = 12 g L^{-1}; T10(280 cm³) = 16 g L^{-1}.

Nutrients in the leaves and roots of *Khaya grandifoliola*

The multivariate analysis of principal components, regarding the nutrients present in the leaves and roots of *K. grandifoliola*, allowed for characterizing the groups of nutritional similarities between the CRF doses and the volume of the tubes (Figure 7).

The variability of the data was explained by 51.26% on axis 1 and 28.93% on axis 2, totaling 80.19%. It is observed that both for leaves and roots, the values of macronutrients followed the same pattern. Through PCA, it was possible to observe the formation of three distinct groups. The first group was formed by treatments without the application of CRF in both tube volumes (T1 and T6), correlating only with the nutrients Mg and Ca. The second group consisted of treatments with the lowest doses of CRF (4 and 8 g L^{-1}) in both tube volumes (T2, T3 and T7, T8), showing correlation with the C/N ratio. The third group was composed of treatments with the highest doses of CRF (12 and 16 g L^{-1}), regardless of the container volumes (T4, T5 and T9, T10), resulting in direct correlation with N, P, S, while potassium (K) and organic carbon (OC) showed opposite correlations to the treatments.

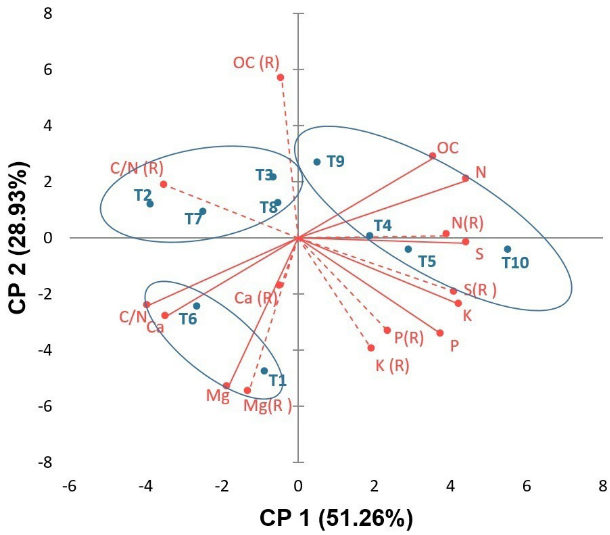

Figure 7: Graphical representation of Principal Component Analysis (PCA) correlating the concentrations of macronutrients, organic carbon, and C/N ratio in leaf and root tissues of *Khaya grandifoliola* seedlings at 180 days after sowing. Dotted lines represent nutrients in the roots, and solid lines represent foliar nutrients. T1(180 cm³) = 0 g L^{-1}; T2(180 cm³) = 4 g L^{-1}; T3(180 cm³) = 8 g L^{-1}; T4(180 cm³) = 12 g L^{-1}; T5 (180 cm³) = 16 g L^{-1}; T6(280 cm³) = 0 g L^{-1}; T7(280 cm³) = 4 g L^{-1}; T8(280 cm³) = 8 g L^{-1}; T9(280 cm³) = 12 g L^{-1}; T10(280 cm³) = 16 g L^{-1}.

DISCUSSION

This study confirms the hypothesis that CRF doses influence the initial growth of *K. anthotheca* and *K. grandifoliola* seedlings, with doses between 8 to 12 g L^{-1} providing significant gains for the measured variables, especially H, D, SDM and RDM. The observed benefit in the analyzed variables was attributed to the appropriate dose of controlled-release fertilizers (CRF), while the type of container did not show a significant impact on seedling growth during the evaluation period.

CRFs present advantages in reducing production costs due to decreased labor, by reducing operations and optimizing space, water, and energy (Irfan et al. 2018). Our results are aligned with several scientific studies in specialized literature, which investigated forest species, both native species with potential for restoration and exotic species aimed at wood production. All these studies indicate that seedlings grown with adequate doses of controlled-release fertilizers (CRF) show superior development compared to those that did not receive the fertilizer (Rosa et al., 2018; Silva et al., 2019; Silva, 2022). In the present study, it was possible to observe how CRF improved the growth of *K. grandifoliola* and *K. anthotheca* seedlings, as evidenced by the significant increase in aerial and root biomass production.

According to Smiderle et al. (2021), aerial height, along with stem diameter, are crucial morphological parameters for estimating the growth of forest seedlings. Araújo et al. (2020), when evaluating the effect of nitrogen and phosphorus doses on the initial growth and nutrition of African mahogany seedlings, concluded that the application of 200 mg dm^{-3} of P, combined with the addition of 100 mg dm^{-3} of N, provided maximum growth in seedlings. In our study, the dose of maximum technical efficiency (DMTE) for both species was using the dose of 10 g L^{-1} of 5-month Basacote Plus CRF (15-9-12). Dry mass production, both of roots and aerial parts, is a crucial variable for describing seedling growth and quality. It is believed that the higher the total dry mass (TDM) value, the better the quality of the produced seedling, which directly influences the survival and growth of plants after transplantation in the field (Faria et al. 2017).

The Dickson Quality Index (DQI) is recognized as an effective indicator of seedling quality, as it considers robustness (HDR) and the balance of biomass distribution (SRR) in its calculation (Caldeira et al. 2005; Caldeira et al. 2007), reflecting the results of various important morphological characteristics in quality assessment. The higher the DQI value, the better the quality of the produced seedling (Souza et al. 2017). In this context, the present study demonstrates that, according to the DQI results, the seedlings that statistically presented better quality were those treated with doses of 8 to 12 g L^{-1} of CRF and grown in 280 cm^3 tubes for both species (Tables 2 and 3).

Chen et al. (2016) asserts that the chlorophyll content of leaves is highly correlated with the amount of nitrogen present in the leaves, thus allowing to assess deficiency of this nutrient. According to Souza Terassi et al. (2023), high chlorophyll levels indicate good nutrient assimilation by the plant. In the present study, treatments that did not receive CRF incorporation into their substrate presented the lowest chlorophyll content results, reflecting reduced amounts of nitrogen in both aerial and root parts. As CRF doses increased throughout the treatments, an increase in chlorophyll and nitrogen levels was observed in both parts of the plant. Furthermore, higher CRF doses promoted an increase in biomass production in the aerial part and, consequently, in organic carbon.

Regarding seedling ruggedness for field planting, Caldeira et al. (2013) state that the lower the quotient obtained by dividing the height by the dry mass of the aerial part, the more rugged the seedling will be, and the greater its survival should be after field planting. Thus, based on this principle, for *K. anthotheca*, seedlings produced with 12 g L^{-1} of CRF, regardless of tube volume, showed a lower quotient in the H/SDM relationship, resulting in values of 2.90 and 3.02, respectively, while for *K. grandifoliola*, seedlings produced with 8 (180 cm^3) and 12 g L^{-1} (280 cm^3) of CRF obtained lower ratios, 3.30 and 3.02, respectively. This is consistent with previous studies that claim that the root system is not the sole indicator of better seedling development in the field, as Haase (2008) demonstrates that root mass does not always reflect root fibrosity, as a seedling with many fine roots may have the same mass as a seedling with a more developed taproot.

In terms of nutritional analyses, an increase in phosphorus (P) stimulates plant metabolic activity (Pereira; Peres 2016), while potassium (K) plays essential roles in osmotic processes, protein synthesis, regulation of stomatal opening and closing, membrane permeability, pH control, and activation of about 60 enzymatic systems (Sustr et al. 2019), contributing to the overall development of all plant parts. In this context, both phosphorus and potassium exhibited a greater correlation with treatments receiving the highest doses of CRF, in both the leaves and roots of African mahogany seedlings, regardless of the container used, resulting in greater seedling growth. This is because these nutrients were more abundant in the fertilizer formulation (Table 1).

Seedlings produced without the addition of CRF showed a direct correlation with magnesium and calcium elements, regardless of the species. This is due to the low percentage of magnesium available in the CRF formulation compared to other nutrients, resulting in a lack of correlation with treatments receiving the fertilizer. The correlation of calcium with treatments without the addition of CRF is explained by its absence in the fertilizer formulation.

The C/N and CO ratio of the root of both species correlated with seedlings produced using the lowest doses of CRF (4 and 8 g L^{-1}). As suggested by Pugnaire and Valladares (2007), in environments where there is nutritional restriction, plants tend to invest in more extensive root systems, thus becoming more efficient in nutrient absorption. In the present study, African mahogany seedlings produced with the highest doses of CRF showed an opposite relationship between organic carbon in the root system in both species, as greater nutrient availability stimulates an increase in dry mass of the aerial part and, consequently, of organic carbon, albeit to a lesser extent in the roots (Marco et al. 2019).

Based on the results obtained in this study, a positive influence of CRF use on the growth and quality of *K. anthotheca* and *K. grandifoliola* seedlings was detected, especially with the application of an average of 10 g L^{-1} of Basacote Plus 15-9-12 5M. As for the tube volume, no significant differences were observed for most of the analyzed variables. However, although the tube volume did not show statistically significant differences among the analyzed variables, the use of 280 cm^3 tubes is recommended to produce higher quality seedlings, as indicated by the DQI.

It is worth noting that the nutritional analyses of the leaves and roots were essential for understanding and interpreting the growth results of both African mahogany species seedlings under different doses of CRF. Notably, higher concentrations of calcium (Ca) and magnesium (Mg) were associated with seedlings that showed lower growth in the evaluated morphological characteristics. These results suggest a possible relationship between the accumulation of these specific nutrients and a limitation in seedling development, highlighting the importance of proper nutritional balance for the optimal growth of these species.

CONCLUSIONS

The different doses of CRF resulted in significant variations in the growth of *K. anthotheca* and *K. grandifoliola* seedlings, with the application of the 10 g L^{-1} dose of CRF recommended for both species. Seedlings without CRF application (0 g L^{-1}) showed the lowest values in all evaluated morphological characteristics.

The volume of the tubes did not show disparities in the morphological growth characteristics analyzed in the studied species, highlighting the Dickson Quality Index as one of the most accurate measures. The volume of 280 cm^3 stood out, indicating seedlings of better quality.

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