

Article

Control-Release Fertilizer Improves Growth and Quality of *Cedrela fissilis* Seedlings in Nursery Production

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Abstract

The growth of technical–scientific knowledge is crucial for the conservation of biodiversity and the sustainable management of endangered species, particularly given the limitations in information about high-performance seedling nutrition. Controlled-release fertilizers (CRFs) have strategic advantages in terms of nutrient use efficiency and less need for reapplications. However, their use in the production of native forest seedlings is still little explored. This study aimed to evaluate the effects of applying CRFs in different doses on the growth and quality of cedro-rosa (*Cedrela fissilis* Vell.) seedlings, aiming to identify more efficient fertilization strategies in nurseries. The seedlings showed 100% survival at 150 days. The absence of fertilization resulted in limited growth, while increasing doses promoted significant gains. The dose of 16 g L^{−1} provided greater height and leaf area, while 8 g L^{−1} was sufficient for gains in diameter and robustness index. There was an increase in dry mass and chlorophylls, although stabilized at higher doses, suggesting physiological limits. Doses of between 8 and 16 g L^{−1} of CRF are promising to produce cedro-rosa seedlings, combining gains in growth, quality, and physiological efficiency, making it a viable and sustainable alternative.

Keywords: cedro-rosa; CRF; forest nutrition; forest regeneration



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1. Introduction

Current environmental challenges reflect a critical global scenario marked by rapid climate change, accelerating biodiversity loss, ecosystem degradation, and widespread deforestation [1,2]. In Brazil, biomes such as the Atlantic Forest and the Cerrado have been

experiencing increasing anthropogenic pressure, resulting in habitat fragmentation and heightened vulnerability of various native species [3]. Therefore, it is essential to advance technical–scientific knowledge aimed at biodiversity conservation and the sustainable management of plant species, especially those threatened with extinction.

The preservation of forest species threatened with extinction faces several challenges, including a lack of technical information on seedling production, growth, and diversified silvicultural management, as well as the search for commercially interesting species [4]. Another critical aspect refers to the limited knowledge about the nutritional requirements of these species and appropriate fertility management strategies in nurseries and field conditions [5].

The understanding of nutritional balance, as well as the determination of nutrient use efficiency, can aid in the development of more precise management techniques for these species, directly influencing their performance and survival after planting. Recent studies have shown that the stoichiometric relationship of the soil, especially the relationships between C, N, and P, directly affect the nutrient dynamics of an ecological system [6]. On the other hand, in environments with low natural fertility, the adoption of management strategies that reconcile the gradual availability of nutrients with the physiological demands of the plant becomes essential to avoid losses due to leaching and salinization [7].

In this context, the production of quality seedlings plays a central role in ecological restoration and conservation programs, as the performance of species in the field directly depends on the growth conditions during the nursery phase [8–10]. In Brazil, nutritional management in nurseries involves the application of conventional mineral fertilizers [11]. However, strategies using controlled-release fertilizers (CRFs) have been gaining prominence for promoting the gradual release of nutrients according to temperature and plant demand, favoring continuous and balanced nutrition [12]. Controlled-release fertilizers (CRFs) also offer advantages such as reduced leaching losses, lower reapplication frequency, and improved nutrient use efficiency, due to the presence of semi-permeable layers that regulate their release, as well as reduced residence time and operational costs in nurseries [12–15].

Despite the progress made, there are still significant gaps in defining efficient nutritional practices for the production of high-performance seedlings related to the determination of adequate fertilizer doses associated with morphological and physiological evaluations. Such limitations arise from the specific requirements of each species, particularly regarding the absorption and utilization of nutrients, making it essential to understand these individual demands to promote the initial growth and survival of seedlings in field conditions [16,17].

Among the native forest species that have been garnering increasing scientific and silvicultural interest, the rosewood (*Cedrela fissilis* Vell.) stands out, a species belonging to the Meliaceae family and widely distributed across different Brazilian biomes. It is a deciduous tree of high ecological and economic value, which can reach heights between 10 and 25 m and have a trunk diameter ranging from 40 to 80 cm [18]. Its prominence is associated with the high quality of its wood, widely valued in the national and international markets, due to its light-to-moderate density, good workability, and resistance to attack by wood-destroying organisms. Due to these characteristics, the species has wide applications in civil and naval construction, furniture manufacturing, veneer production, paper and pulp, energy generation, and the extraction of essential oils for the cosmetic industry, in addition to being an option for ecological restoration and reforestation projects [19,20].

This species faces serious risks due to extensive forest loss and the degradation of its natural habitat, often converted into urban areas, pastures, or monocultures [21]. Edapho-climatic factors, such as climate, topography, and soil characteristics, condition its natural

occurrence, which reinforces the need for silvicultural studies aimed at its management and conservation [22]. The historical and unregulated logging of the species contributed to the decline of its natural populations and the local extinction of subpopulations, which justified its categorization as a vulnerable species on the International Union for Conservation of Nature’s (IUCN) Red List [23,24]. In light of the presented information, this study aimed to compare the effects of applying controlled-release fertilizer (CRF) at different doses on the growth and quality of *Cedrela fissilis* Vell. seedlings, with the goal of identifying the most efficient fertilization strategy for producing superior quality seedlings in forest nurseries.

2. Materials and Methods

2.1. Conducting the Experiment

The experiment was conducted in a greenhouse at the Federal Institute of Education, Science and Technology of Espírito Santo (IFES—campus Alegre), located in the district of Rive, municipality of Alegre, ES, under the coordinates 20°45’39.4’’ S and 41°27’25.4’’ W, according to the WGS 84 geodetic reference system.

The region’s climate is Cfa, according to Köppen, and characterized as subtropical warm, with an undefined dry season [25]. During the period of the experiment (24 June to 25 November 2024), average temperatures ranging from 16 °C (minimum) to 23 °C (maximum) were recorded. The average annual relative humidity is approximately 73%, with significant variations throughout the year. During the driest periods, levels can fall below 30%, while during the rainy season humidity frequently exceeds 90% [26].

The greenhouse has an arched roof with a transparent waterproof tarpaulin, sides protected by black shading screens that enable 50% of the light to pass through, and the floor covered with black raffia. Also, it is equipped with benches suspended 80 cm from the ground and an automated irrigation system made up of inverted micro-sprinklers with a flow rate of 160 L h^{−1} and a wet diameter of 9 m, which operated four times a day, lasting 10 min per cycle during the experiment.

The experiment was conducted in a randomized block design (RBD), with five treatments and four replications. Each experimental unit consisted of eight seedlings of *Cedrela fissilis* Vell., totaling 32 seedlings per treatment. Five doses of controlled-release NPK 16-08-12 (+2) fertilizer (0, 4, 8, 12 and 16 g L^{−1} of substrate) were evaluated, with a release period of six months (Table 1) [27].

Table 1. Chemical composition of the controlled-release fertilizer NPK 16-08-12 (+2) with a release time of 6 months.

Macronutrients (%)					
N	P ₂ O ₅	K ₂ O	MgO	S	
16.0	8.0	12.0	2.0	5.0	
Micronutrients (%)					
B	Cu	Fe	Mn	Mo	Zn
0.02	0.05	0.4	0.06	0.015	0.02

Technical information provided by the manufacturer for Nitrogen (N), Diphosphorus pentoxide (P₂O₅), Potassium oxide (K₂O), Magnesium oxide (MgO), Sulfur (S), Boron (B), Copper (Cu), Iron (Fe), Manganese (Mn), Molybdenum (Mo), Zinc (Zn).

The commercial substrate used was obtained from the company Pilar Produtos Agroecológicos, located in the state of Santa Catarina, Brazil, and incubated at Orion Parque, and is composed of pine bark, ash, carbonized rice husk, natural phosphate, NPK fertilizer (0.4, 0.5, and 0.53% N, P, and K, respectively), and dolomitic limestone. The substrate exhibited a pH of 6.4, dry bulk density of 333 kg m^{−3}, moisture content of 49.7%,

and electrical conductivity of 0.098 mS cm^{-1} . In addition, it presented high organic matter (37.4%) and organic carbon (21.6%) contents, as well as a C/N ratio of 54.

Regarding nutrient composition, the substrate contained 0.4% N, 0.5% P, 0.53% K, 0.96% Ca, 0.35% Mg, and 0.25% S. Among the micronutrients, Fe and Mn were present at relatively high concentrations, reaching $14,085$ and 698 mg kg^{-1} , respectively. The substrate also contained Zn (69 mg kg^{-1}), Cu (33 mg kg^{-1}), B (17 mg kg^{-1}), and Mo (1 mg kg^{-1}), providing a broad spectrum of essential nutrients for seedling establishment and early growth.

The fertilizer doses were weighed on an analytical scale and mixed with the substrate. These doses were calculated based on the volume of the planting containers, and the corresponding amounts of fertilizer were applied individually to each container, to guarantee proportionality between the tube volume and the dose established for each treatment. The seedlings were grown in conical plastic tubs with a capacity of 280 cm^3 , and sown directly into these containers, inserting two seeds per tub. The seeds were acquired from the company Arbocenter, located in the state of São Paulo (Brazil) and specialized in the production and commercialization of forest seeds. According to information from the supplier, the batch was collected in July 2023 from five selected mother trees, presenting an estimated germination percentage of 80%, which ensures adequate physiological quality for conducting the experiment. Thinning was conducted 15 days after emergence, keeping only one seedling per pot, prioritizing the strongest and most centralized, to ensure uniform and vigorous growth of the seedlings. A total of 60 days after sowing, the seedlings, originally arranged in flat trays, were spaced out to reduce competition for water and light. Within each treatment, one empty cell was kept between the seedlings, while between different treatments, two empty cells were left.

2.2. Parameters Assessed

2.2.1. Height, Collar Diameter, and Robustness Index

The height of the seedlings was analyzed in centimeters (cm) using a tape measure, measuring from the collar diameter, next to the substrate, to the apical bud. The diameter of the stem was measured in millimeters (mm) with a manual caliper, 1 cm from the level of the substrate. Evaluations took place at 60, 90, 120, and 150 days after sowing.

Based on the data collected, the robustness index (RI) was calculated for each treatment at 150 days after sowing, representing the relationship between height (H) and collar diameter (CD), according to Equation (1).

$$RI = \frac{H}{CD} \quad (1)$$

2.2.2. Dry Mass

A destructive analysis was conducted 120 days after sowing on four seedlings per treatment, selected according to their average height and stem diameter. The plants were removed from the containers, separated into roots (washed to remove the substrate), stems, and leaves, and placed in labeled paper bags. The total dry mass (DM), subdivided into root dry mass (RSM) and shoot dry mass (SPM), was assessed. The samples were dried in an oven with forced ventilation at 65°C for 72 h until reaching constant weight and then weighed on a precision analytical scale.

2.2.3. Leaf Area and Root Attributes

The leaf area (LA) of the seedlings was determined using the LI-3100C leaf area meter (Li-Cor Biosciences, Inc., Lincoln, NE, USA). Root variables, including root length (CR, cm), root area projection (PAR, cm^2), root surface area (ASR, cm^2), mean root diameter

(DMR, mm), and root volume (VR, cm³), were obtained by scanning with a model STD4800 scanner (Seiko Epson®, Suwa, Japan) and analyzed using WinRhizo® software (Regent Instruments, Quebec, QC, Canada, MF version 2024).

2.2.4. SPAD, Chlorophylls (a, b, and Total), and Carotenoids

Chlorophyll indices were analyzed 120 days after sowing using the SPAD 502 PLUS portable colorimetric meter and laboratory analyses. Three leaflets located in the medial region of the third leaf were evaluated. For the SPAD measurement, from the apex to the base. The readings were taken in the greenhouse in the morning.

One seedling per treatment and repetition (32 per species) was collected for the laboratory analyses, with the fourth leaf completely extracted from the apex. Six disks of the leaf limb, preserving the central vein, were removed with a 3.88 mm diameter perforator. The disks were placed in test tubes protected with aluminum foil, identified and submitted to chlorophyll extraction with 2.5 mL of dimethyl sulfoxide (DMSO, 90% purity). The tubes were incubated in a water bath at 65 °C for 60 min. The samples were then transferred to glass cuvettes of 3 cm³ for absorbance spectrophotometric analysis at 480, 649, and 665 nm. From the absorbance readings, the pigment concentrations were calculated using the equations described by [28].

2.3. Statistical Analysis

The data were tested for homogeneity of variance and normality of residuals using the Oneillmathews and Shapiro–Wilk tests, respectively, at a 5% probability level. Upon meeting the requirements, an analysis of variance (ANOVA) was performed using SISVAR 5.6 software [29]. The polynomial regression analysis selected the models with the highest coefficients of determination (R^2) and significant coefficients, also using SISVAR 5.6. The graphs were drawn up in Microsoft Excel 2013. The dose of maximum technical efficiency (DMTE) for seedling production was calculated using the mathematical model-b/2a, obtained by partial derivatives of the adjusted equations.

3. Results

The cedro-rosa seedlings had a survival rate of 100% at 150 days after sowing, at the completion of the study. The growth curves for height and stem diameter of the seedlings showed a continuous increase for both variables, with greater intensity from 90 days onwards (Figure 1).

The absence of fertilization (control treatment—0 g L⁻¹) resulted in stagnant growth in height and stem base diameter. In contrast, the application of controlled-release fertilizers promoted increases in these variables in all the periods evaluated. The greatest growth in height was observed at a dose of 16 g L⁻¹, while doses of 8 g L⁻¹ were enough to improve development for stem base diameter.

Figure 2 illustrates the adjusted regression models, together with their respective equations and coefficients of determination (R^2), for height and stem base diameter as a function of fertilizer doses, at 150 days after sowing.

Both variables showed a significant quadratic polynomial response ($p < 0.01$), indicating a maximum growth point for these characteristics. Greater seedling growth was observed with the application of controlled-release fertilizer (CRF), especially from 8 g L⁻¹.

Regression analysis showed a significant quadratic response ($p < 0.01$) for the RI , with increasing fertilizer doses resulting in higher H/CD values. This response indicates that height growth increased proportionally more than stem diameter as fertilizer dose increased. Although the H/CD ratio increased, the observed values remained within the

range considered acceptable for forest seedlings, suggesting that fertilization promoted vigorous growth without compromising seedling morphological quality (Figure 3).

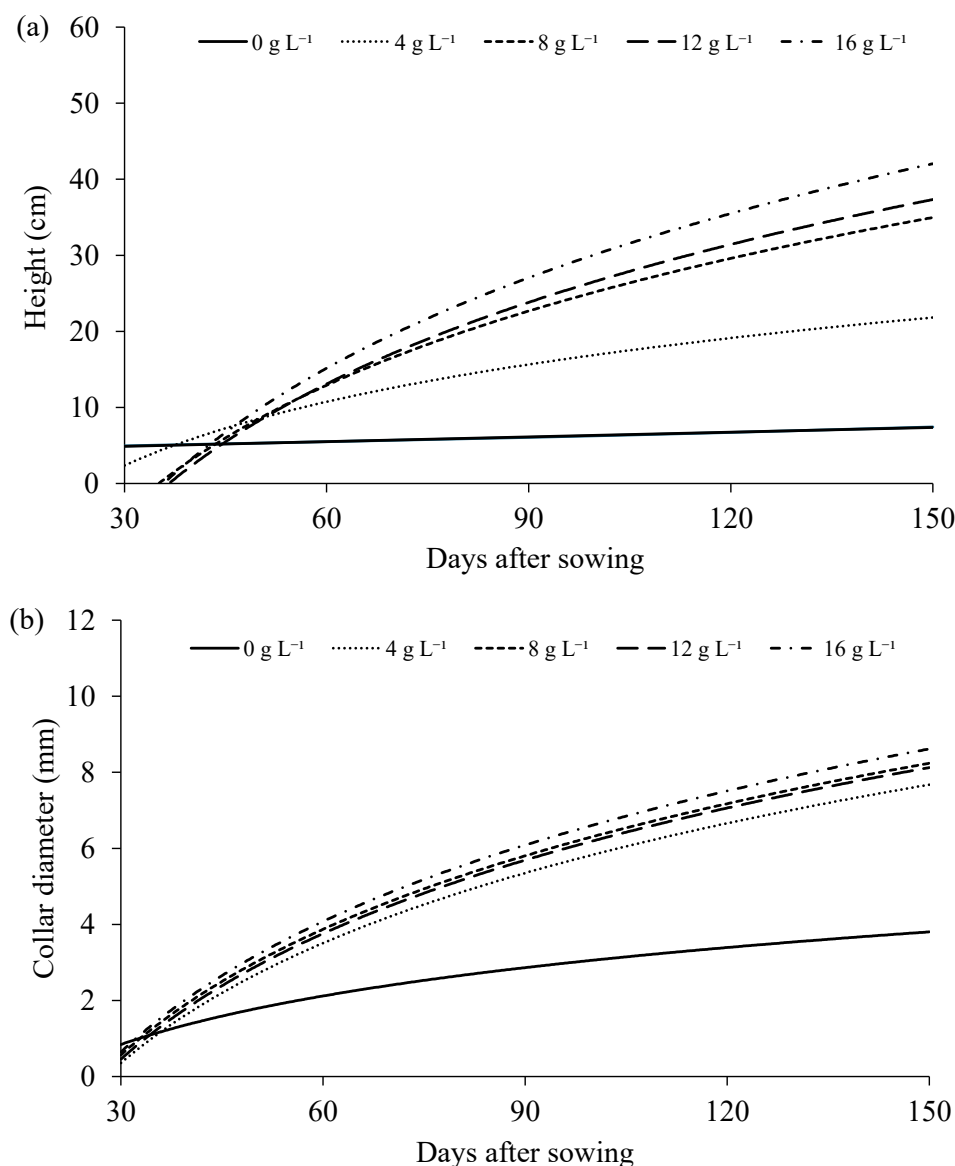


Figure 1. Growth curves in height (cm) (a) and collar diameter (mm) (b) of *Cedrela fissilis* Vell. seedlings from 30 to 150 days after sowing, in a greenhouse in the district of Rive, Alegre, ES.

The adjusted equation showed a high coefficient of determination ($R^2 = 0.9948$), indicating an excellent fit of the model to the experimental data. These results show that fertilization directly influences the robustness of seedlings and is a determining factor in their initial growth.

The polynomial regression analysis showed a significant quadratic pattern ($p < 0.01$) for all the dry mass parameters for the fertilizers released after six months (Figure 4).

The behavior of the curves suggests that the growth of the seedlings responds positively to the increase in doses of fertilizer up to a point of maximum efficiency, followed by a slight tendency towards stabilization, which is more evident for the DMR.

When analyzing the results for dry mass, the controlled-release fertilizers provided the most expressive results, while the control treatment (0 g L⁻¹) showed the lowest values. These results suggest that the availability of nutrients may have favored a greater accumulation of biomass in seedlings.

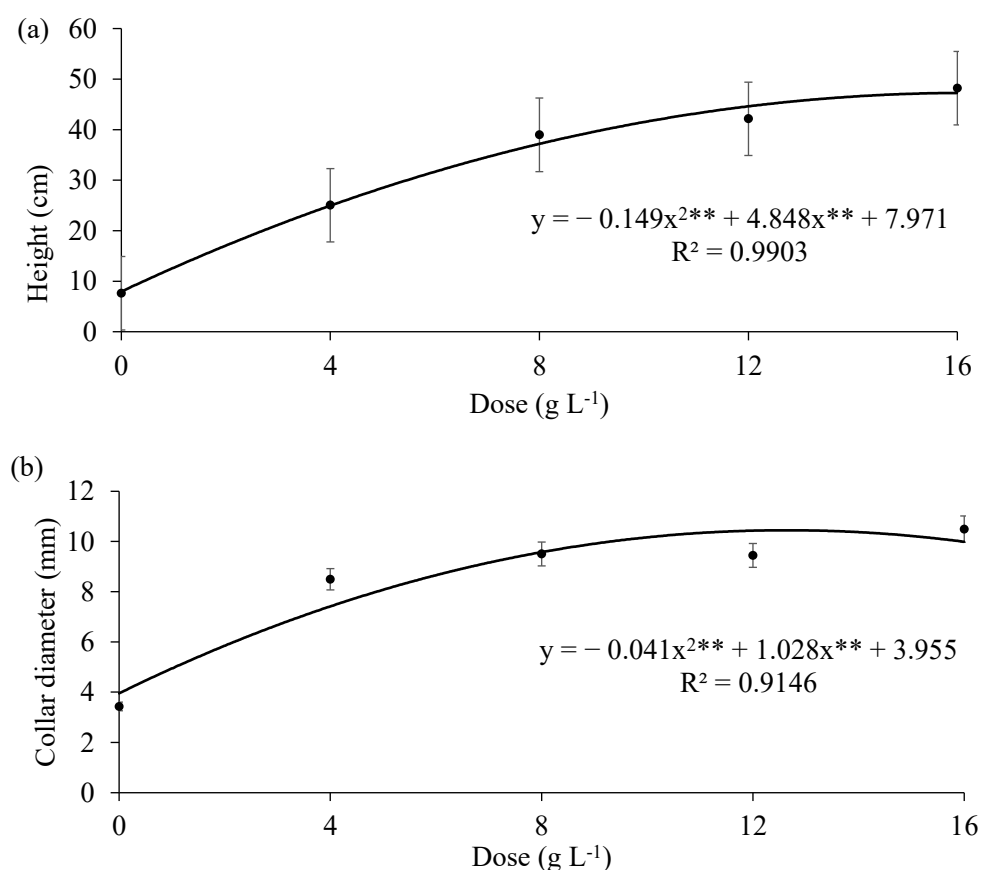


Figure 2. Regression analysis of the doses for height (cm) (a) and collar diameter (mm) (b) of *Cedrela fissilis* Vell. seedlings, at 150 days after sowing, in a greenhouse in the district of Rive, Alegre, ES. **: significant at 1%, by analysis of variance.

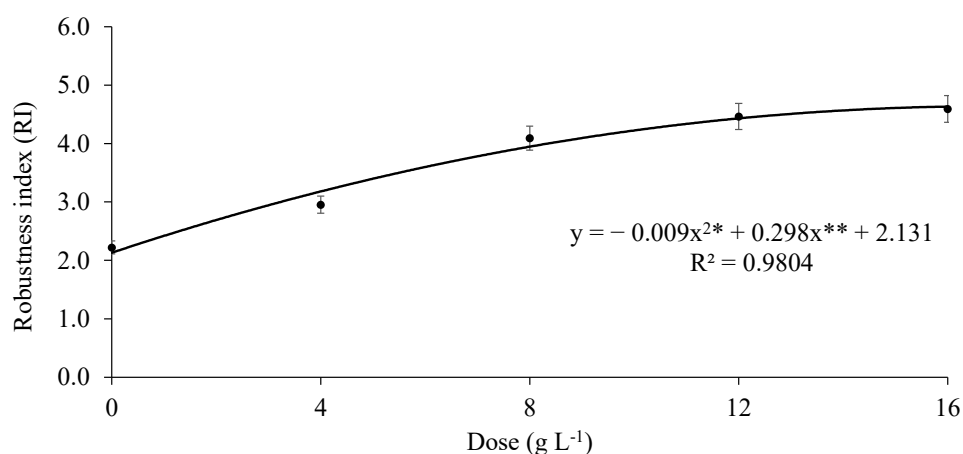


Figure 3. Regression analysis of the doses for the robustness index (RI) of *Cedrela fissilis* Vell. seedlings, at 150 days after sowing, in a greenhouse in the district of Rive, Alegre, ES. **: significant at 1%, and *: significant at 5%, by analysis of variance.

The regression analysis for the leaf area (LA) of the seedlings revealed a significant fit to the quadratic model ($p < 0.01$), with a high coefficient of determination ($R^2 = 0.9867$), suggesting that the variation in leaf area was well explained by the fitted equation (Figure 5).

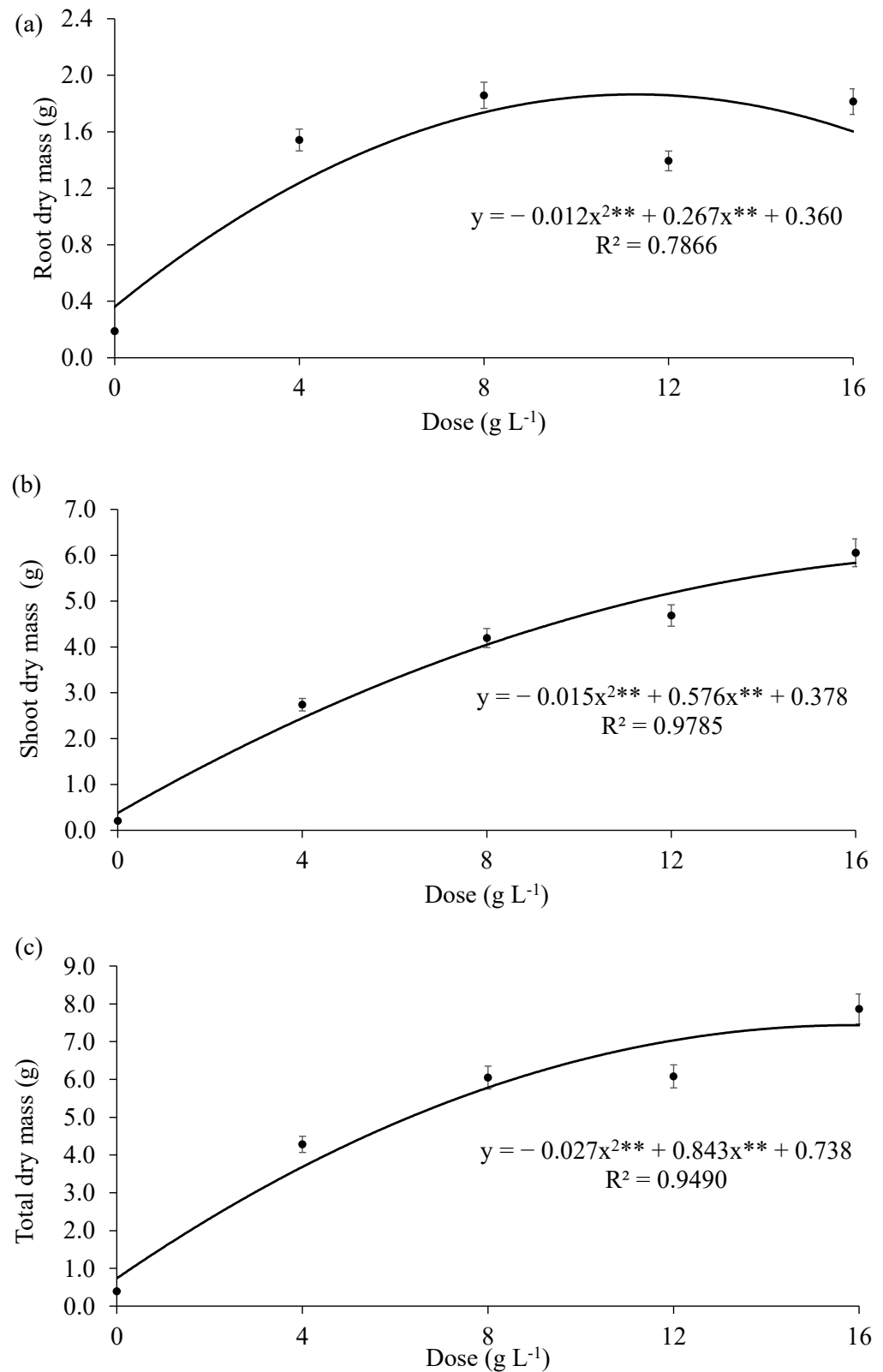


Figure 4. Regression analysis of the doses for root dry mass (RSM) (a), shoot dry mass (SPM) (b), and total dry mass (TSM) (c) of *Cedrela fissilis* Vell. seedlings at 120 days after sowing, in a greenhouse in the district of Rive, Alegre, ES. **: significant at 1%, by analysis of variance.

There was a significant increase in leaf area as the doses increased, reaching values close to 1200 cm² at the highest dose (16 g L⁻¹), which suggests that the supply of nutrients

favored leaf expansion, contributing to greater light interception and, consequently, to the photosynthetic potential of the seedlings.

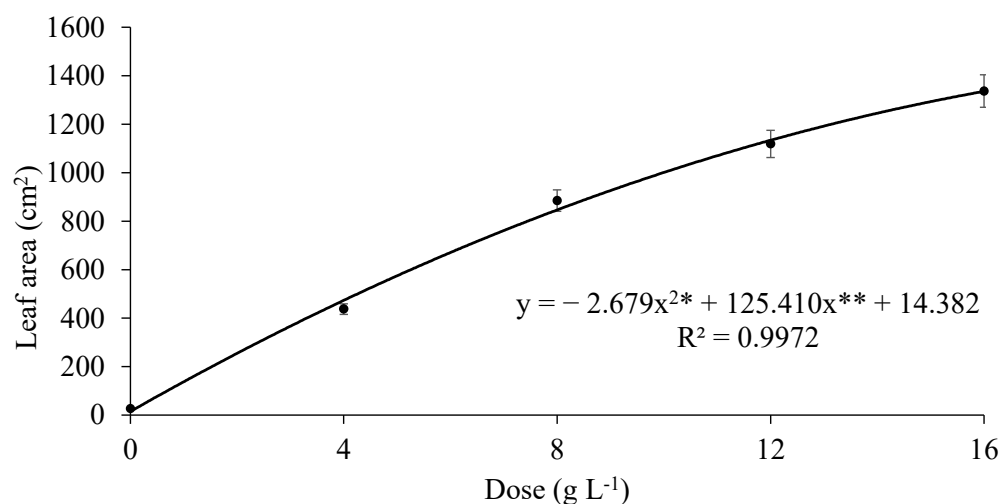


Figure 5. Regression analysis of the doses for leaf area (cm²) of *Cedrela fissilis* Vell. seedlings at 120 days after sowing, in a greenhouse in the district of Rive, Alegre, ES. **: significant at 1%, and *: significant at 5%, by analysis of variance.

The quadratic pattern identified suggests that the leaf area response tends to stabilize at higher doses, suggesting a physiological limit to leaf growth, in which increased fertilization does not result in proportional gains. This trend reinforces the importance of defining optimum doses to maximize growth without wasting fertilizer or negatively impacting seedling development.

The root attributes were adjusted to a quadratic polynomial model ($p < 0.01$) (Figure 6). The absence of fertilization (0 g L⁻¹) results in stagnation in the root development of the cedro-rosa seedlings for all the parameters analyzed.

The regression analysis of the doses of controlled-release fertilizer on the SPAD, chlorophyll-a, chlorophyll-b, total chlorophyll, and carotenoid levels in *Cedrela fissilis* Vell. seedlings at 120 days after sowing indicates that the adjusted models show a quadratic polynomial behavior in most cases, with an initial increase in the levels of these pigments as the doses increased (Figure 7).

The SPAD index, which indicates the relative chlorophyll content, increases with the doses up to a certain point and then tends to stabilize or decrease slightly. The fitted quadratic model is significant ($p < 0.01$), proving that the relationship between the dose and the SPAD index is statistically reliable. The initial increase in the SPAD index indicates a positive effect of the doses on chlorophyll synthesis. The reduction in levels at higher doses may suggest a saturation effect or even a level of toxicity at high concentrations.

Chlorophyll-a concentration increases with the doses up to a certain point, tending to stabilize. For NPK 16-08-12 (+2) at six months of release, the quadratic response was significant ($p < 0.05$), with the model explaining the variation in the data well. These results indicate that chlorophyll responds positively to increasing doses, but there is a physiological limit to its production.

Chlorophyll-b data also fitted the quadratic polynomial model, being most significant for NPK 16-08-12 (+2) with a six-month release ($R^2 = 0.87$). Total chlorophylls showed a similar pattern to chlorophylls a and b, with an initial increase and subsequent stabilization. Both models were significant ($p < 0.01$), with a high fit ($R^2 > 0.89$). The positive response of total chlorophyll to doses indicates that fertilization improved the plants' photosynthetic capacity up to a certain limit.

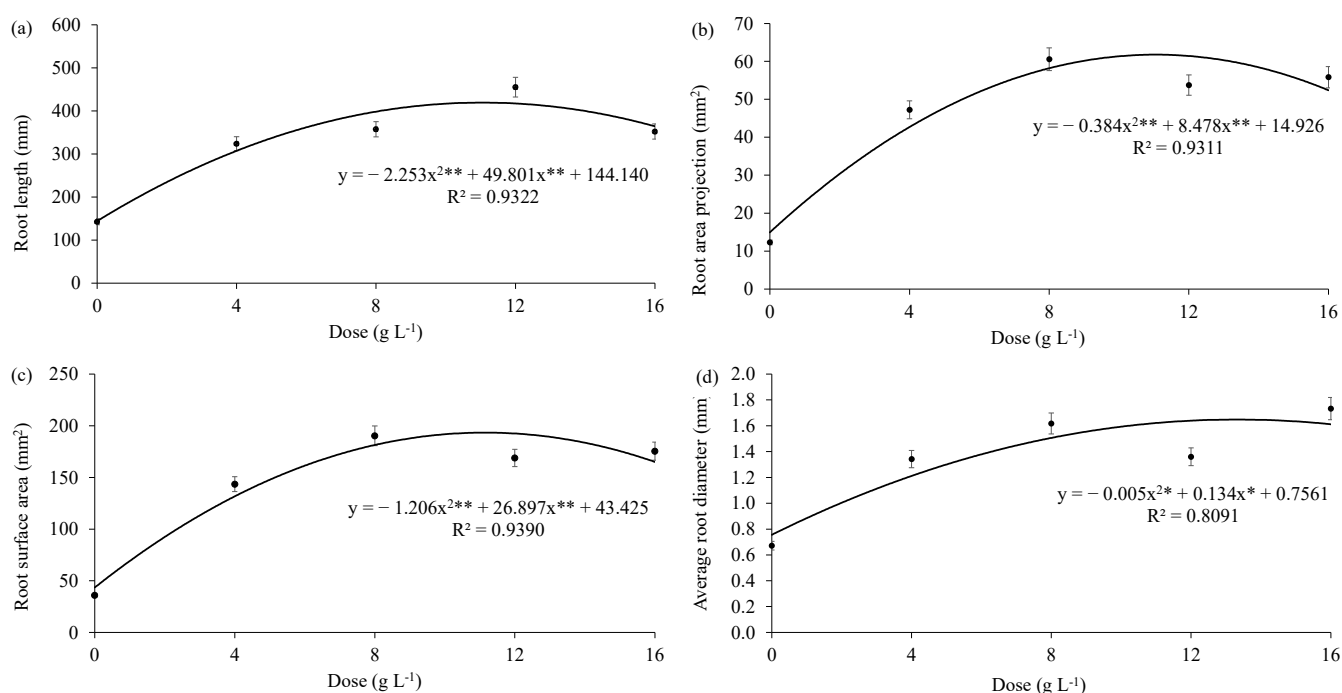


Figure 6. Regression analysis of the doses for the root attributes of *Cedrela fissilis* Vell. (root length (a); root area projection (b); root surface area (c); average root diameter (d)) seedlings at 120 days after sowing, in a greenhouse in the district of Rive, Alegre, ES. **: significant at 1%, and *: significant at 5%, by analysis of variance.

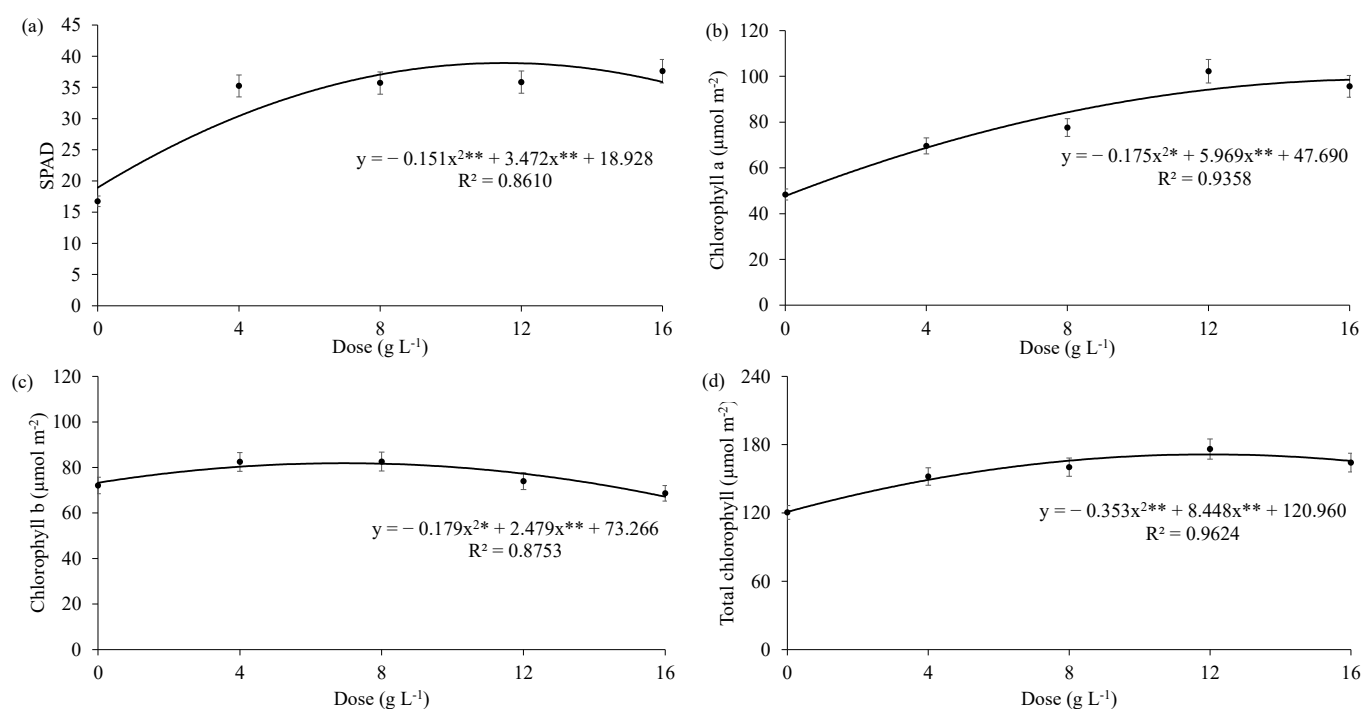


Figure 7. Regression analysis of doses for SPAD (a), chlorophyll a (b), chlorophyll b (c), and chlorophyll total (d) in *Cedrela fissilis* Vell. seedlings, 120 days after sowing, in a greenhouse in the district of Rive, Alegre, ES. **: significant at 1%, and *: significant at 5%, by analysis of variance.

4. Discussion

4.1. Morphological Parameters

Growth in seedling height is related to favorable conditions for development, such as an increase in photosynthetic production [30], which was evident in the *Cedrela fissilis*

Vell. (Cedro-rosa) species, in which increasing doses of controlled-release fertilizer (CRF) promoted significant growth over time. This result is associated with a balanced supply of nutrients, especially nitrogen, phosphorus, and potassium, in appropriate proportions for each stage of development, particularly in the initial phase.

In the production of forest seedlings, native species grown in tubes should have a height of between 20 and 35 cm and a stem base diameter of between 5 and 10 mm to be considered suitable for planting [31]. The results show that it was possible to achieve these standards in 150 days in the nursery with the use of CRF. The *Cedrela fissilis* Vell. seedlings grew to a height of between 24 and 48 cm, which was also reflected in the increase in the diameter of the stem base, resulting in a reduction in production time and optimization of workforce. In a study by [32], the authors investigated the effects of different doses of CRF (15-09-12) on the initial growth of *Cedrela fissilis* and determined that the dose of 7.5 g L^{-1} was the most efficient for height and stem base diameter, with higher doses promoting a slight reduction in height, a behavior also observed in the research.

The doses of maximum technical efficiency (DMTE) were 16 g L^{-1} for height and 12 g L^{-1} for collar diameter in *Cedrela fissilis*. These values highlight the importance of adequate nutrition to optimize seedling growth, ensuring a higher survival rate and better post-planting development. At 150 days, the largest stem base diameters were recorded at doses of 16 g L^{-1} of CRF, ranging from 9.90 to 10.50 mm for *Cedrela fissilis*. Collar diameter is an essential parameter for forest seedlings, as it directly influences their stability and mechanical resistance [33,34] stress that this characteristic is decisive in assessing the ability of seedlings to withstand adverse conditions after planting. The increase in height and collar diameter values recorded in this study demonstrates the efficiency of these fertilizers in supplying nutrients gradually, meeting the requirements of the seedlings throughout the nursery period [35].

Height and collar diameter are fundamental morphological parameters in estimating the development of forest seedlings [36]. Therefore, it is essential to consider the interaction between these variables rather than evaluating them in isolation. The robustness index is widely used to assess seedling sturdiness. Lower H/CD values indicate a greater proportional investment in stem diameter and, consequently, greater mechanical stability, whereas higher values reflect relatively greater height growth, resulting in more slender seedlings [37]. In the present study, the increase in fertilizer doses promoted higher H/CD values, indicating that height growth was proportionally greater than stem diameter growth. Nevertheless, all observed values remained well below the threshold of 10 commonly recommended for forest seedlings, indicating that fertilization did not compromise seedling morphological quality or induce etiolation. The greater biomass accumulation observed at the higher fertilizer doses is likely associated with enhanced photosynthetic capacity resulting from increased leaf area and nutrient availability, supporting vigorous growth while maintaining an adequate height-to-diameter balance [38].

The time seedlings remain in the nursery varies mainly according to the growth characteristics of each species and the expected timing of field planting. In general, this period is approximately five months but may extend to up to 12 months for slower-growing species, such as white sucupira (*Pterodon pubescens*), faveira (*Dimorphandra mollis*), and barbatimão (*Stryphnodendron adstringens*), when cultivated under conventional NPK fertilization programs [39,40].

In the present study, *Cedrela fissilis* seedlings reached the morphological standards recommended for nursery dispatch at 150 days after sowing, corresponding to a production cycle comparable to that commonly reported for native forest species. Compared with the timeframes described in the literature, these results suggest that the use of controlled-release fertilizers can support the production of high-quality seedlings within a competitive

cultivation period without extending nursery residence time. However, because this study did not directly compare different fertilization strategies, it is not possible to attribute any reduction in the production cycle exclusively to the use of controlled-release fertilizer. Therefore, the findings should be interpreted as being consistent with the benefits generally associated with this technology rather than as direct evidence of its superiority over conventional fertilizers.

In addition to their potential to promote early seedling growth, controlled-release fertilizers offer important operational advantages, including gradual nutrient release, reduced nutrient losses through leaching, fewer fertilizer applications, and consequently lower labor requirements and nursery operating costs [41]. Thus, even when the production cycle is similar to that obtained with conventional fertilization strategies, the adoption of controlled-release fertilizers may improve nursery management efficiency and promote greater uniformity in seedling production.

Despite these advantages, one of the main constraints to the adoption of controlled-release fertilizers is their higher initial cost compared with conventional fertilizers. Their cost is estimated to range from 1.3 to 10 times that of traditional fertilizers, depending on the formulation, climatic conditions, and market fluctuations [42]. Nevertheless, Ref. [43] emphasized that the economic feasibility of this technology should be evaluated from a long-term perspective, taking into account improvements in nutrient use efficiency, reduced nutrient losses, lower labor requirements, and increased net production returns, all of which may offset the higher initial investment and justify its adoption in forest nurseries.

4.2. Physiological Parameters

The use of controlled-release fertilizer (CLF) resulted in a significant increase in the allocation of root, shoot, and total dry mass, surpassing the results obtained in the control treatment (0 g L^{-1}). [44] point out that nitrogen is essential for chlorophyll synthesis and is related to photosynthetic metabolism. A deficiency of this nutrient can limit plant growth, resulting in lower shoot and root biomass production. This trend was seen in the control treatment (0 g L^{-1}) for the specie and release times studied, in which the seedlings showed the lowest biomass values.

The shoot dry mass is directly related to the hardiness of the seedlings, as indicated by [16], whose study with *Cedrela fissilis* seedlings, grown with doses between 10.17 and 11.18 g L^{-1} , showed greater resistance to adversity in field conditions. Regarding root dry mass (RSM), according to [45], the root system must be of an adequate size to ensure the efficient supply of water and nutrients to the aerial part of the plant. Ref. [42] point out that this variable is one of the main indicators of survival and initial growth after planting. For cedar, doses between 9.50 and 11.13 g L^{-1} often resulted in greater development of the root system, reinforcing the importance of adjusting fertilization according to the needs of the species.

There is no recommended value for leaf area in the literature, but it is inferred that the larger the leaf area, the higher the photosynthetic rate [46,47], since leaves function as storage centers and sources of phytohormones responsible for plant growth [48].

Thus, the application of increasing doses of the fertilizer resulted in a significant increase in the leaf area of both species studied, consequently increasing the photosynthetic area. This increase enabled the plants to capture a greater amount of sunlight, promoting greater production of glucose and other energy compounds essential for metabolic processes. Therefore, there was an accelerated growth of the species analyzed. This resulted in greater root growth, positively impacting the absorption of water and nutrients, essential factors for the survival and initial performance of the seedlings in the field.

The chlorophyll content is indicative of the amount of nitrogen in the leaves and serves as a basis for identifying its deficiency, which can occur due to excess of water and the leaching of nitrogen from the soil [49].

The results indicate that there is an increase in SPAD values along with the dose of fertilizers, suggesting greater chlorophyll production. This effect can be attributed to the continuous supply of essential nutrients, such as nitrogen and magnesium, by CRF. The fertilizer used contained 16% nitrogen and 0.06% magnesium, which are fundamental elements for the pigmentation and biosynthesis of chlorophyll, directly contributing to its formation and efficiency [48].

However, the data show that there is a reduction in this parameter as the dose of maximum technical efficiency (DMTE) is exceeded, which for the cedro-rosa seedlings was 11.70 g L^{-1} . The decline in the SPAD index at higher doses may be associated with an excess of fertilizer, particularly potassium, which is the second most present element in the formulation used. High concentrations of potassium can interfere with the absorption of magnesium by plants, as pointed out by [50], causing a saline effect in the substrate and negatively impacting parameters essential to plant metabolism.

SPAD is a dimensionless indicator used to assess the concentration of chlorophyll in leaves and is directly associated with the efficiency of photosynthesis and plant development [51,52]. Moreover, the presence of nitrogen significantly influences this index [53]. Higher levels of nitrogen promote an intense green color in the leaves [54], a desirable characteristic both for esthetic reasons and for its functional and physiological importance. Thus, greener plants tend to have higher SPAD values. Moreover, higher nitrogen levels improve the photosynthetic capacity of plants, favoring the synthesis of carbohydrates and resulting in greater production of plant biomass [55]. This study confirmed this direct relationship between increased nitrogen and higher SPAD values.

The levels of chlorophylls (a, b, and total) increased with fertilization, reflecting an improvement in the photosynthetic capacity of the seedlings, with doses between 8 and 12 g L^{-1} promoting the best results. Higher fertilizer rates did not result in additional gains and, in some cases, led to a reduction in pigment levels. These responses may reflect a decline in the physiological efficiency of the plants at excessive fertilizer rates, although specific physiological assessments are required to confirm the mechanisms involved, particularly those related to stress.

Chlorophylls a and b play a crucial role in converting light radiation into chemical energy, resulting in the formation of ATP and NADPH [56], which are responsible for energy storage. Therefore, providing adequate doses of fertilizers can increase the concentration of these pigments and improve the efficiency of the photosynthetic process, promoting greater plant development. Carotenoids are fundamental in protecting photosystems, as they dissipate excess energy, preventing the photo-oxidation of chlorophylls [48].

The fertilizer used had a higher concentration of N (16%), and it was expected that the treatments that received fertilization would have higher chlorophyll concentrations, especially at higher doses. The supply of these doses favors the absorption and accumulation of nitrogen by the plants. As this element is essential for chlorophyll synthesis [57], its intensification was predictable.

Studies indicate that total chlorophyll is a fundamental indicator of the photosynthetic capacity of plants and is directly associated with greater efficiency in capturing light and producing biomass [58]. A study conducted by [59] tested five doses of CRF (19-06-10) on *Annona cacans* seedlings over 180 days in the nursery. The results indicated increases in photosynthetic pigments, showing the direct impact of the fertilizer on this aspect, as observed in this research.

The gradual nutrient release promoted by controlled-release fertilizers likely enhanced the synchronization between nutrient availability in the substrate and the nutritional demand of the plants throughout the cultivation period. This synchronization favors greater nutrient use efficiency by maintaining a continuous supply of essential elements, particularly nitrogen and magnesium, which are directly involved in chlorophyll biosynthesis, photosynthetic enzyme activity, and the maintenance of the photosynthetic apparatus [60,61]. In systems with gradual nutrient supply, such as CRFs, plants tend to maintain higher photosynthetic activity, reflected in higher levels of chlorophyll and carotenoids, favoring growth and biomass accumulation. The continuous availability of nitrogen reduces nutritional limitations throughout development, promoting greater efficiency in nutrient use and better physiological performance [62].

The positive effects observed on plant growth and photosynthetic pigment concentration are consistent with the increased nutrient availability provided by the controlled-release fertilizer, particularly nitrogen (N), potassium (K), and magnesium (Mg), which are directly involved in chlorophyll synthesis, photosynthetic activity, and plant growth. However, although the observed response pattern is consistent with the effects of nutrient supply from the fertilizer, it was not possible to establish a direct relationship between the uptake of specific nutrients and the morphophysiological responses of the plants. Therefore, inferences regarding the underlying nutritional mechanisms should be interpreted with caution. Future studies incorporating substrate fertility assessments and mineral nutrient analyses of plant tissues will enable more robust relationships to be established between nutrient availability, plant nutrient uptake, and the observed morphophysiological responses, thereby providing a more comprehensive understanding of the effects of controlled-release fertilizers.

Although higher doses of controlled-release fertilizer promoted greater seedling growth, increasing fertilizer application rates also result in higher production costs, since controlled-release fertilizers are considerably more expensive than conventional soluble fertilizers [12,13]. From a commercial nursery perspective, the adoption of higher application rates should therefore be based not only on morphophysiological performance but also on economic viability, considering the balance between the additional growth obtained and the increase in production costs. In this context, fertilizer doses close to DMTE may represent a more economically efficient alternative to produce satisfactory seedling quality, especially for large-scale nursery operations. Since an economic analysis was beyond the scope of the present study, future research should evaluate fertilizer use efficiency and cost–benefit relationships to define economically optimal application rates for seedling production.

5. Conclusions

The use of controlled-release fertilizers (CRFs) proved to be an effective strategy for improving the morphophysiological performance of *Cedrela fissilis* seedlings under nursery conditions. Fertilizer doses between 8 and 16 g L^{−1} promoted significant gains in seedling growth and physiological attributes, demonstrating the potential of this technology for nursery production. However, the selection of the most appropriate application rate for commercial operations should also consider economic aspects, particularly the cost–benefit relationship associated with increasing fertilizer doses. Furthermore, the effects of these improvements on seedling survival, establishment, and growth after outplanting remain to be validated under field conditions. Therefore, future studies should integrate economic analyses with field evaluations under different soil and climatic conditions to establish comprehensive recommendations for the use of controlled-release fertilizers in the production of *C. fissilis* seedlings.

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