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Articles

Alternative application of sun coral (*Tubastraea coccinea*) in the formulation of substrate for the production of ipê–branco (*Tabebuia roseoalba*) seedlings

Aplicação alternativa de coral–sol (*Tubastraea coccinea*) na formulação de substrato para produção de mudas de ipê–branco (*Tabebuia roseoalba*)

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ABSTRACT

The ipê–branco (*Tabebuia roseoalba*) is valued for its ornamental use, environmental recovery and silvopastoral systems. The quality of the seedlings is essential for successful cultivation and is influenced by the type of substrate used. Organic waste, such as sun coral (*Tubastraea coccinea*), has the potential to improve substrates, reducing costs and promoting seedling growth, as long as it is assessed for quality and toxicity. Indicators such as growth, biomass production, nutritional aspects and the Dickson quality index measure production efficiency in nurseries. The study aimed to evaluate the potential use of alternative application of sun coral as an alternative component in the substrate mixtures, aiming to partially replace conventional inputs and reduce substrate production costs in the production of ipê–branco (*T. roseoalba*) seedlings. For this, ipê–branco seedlings were grown with increasing doses (0, 40, 80, 160 and 320 g m^{-3}) of sun coral added to the commercial substrate in a greenhouse for 270 days. Height, stem diameter, Dickson quality index, shoot and roots biomass production, number of leaves, leaf area, total chlorophyll, root volume, nutrient concentration and heavy metals were assessed. Sun coral application to the substrate showed potential for improving the quality and development of ipê–branco seedlings. Intermediate doses, especially 80 g m^{-3}, stood out for their better performance in DQI, biomass, chlorophyll and root volume, favoring nutrition and photosynthesis. In contrast, high doses (≥160 g m^{-3}) reduced biomass production and promoted nutritional imbalances due to the accumulation of heavy metals and Na^+.

Keywords: Alternative substrates; Invasive coral; Seedling growth; *Tubastraea* spp.; Waste recovery

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RESUMO

O ipê–branco (*Tabebuia roseoalba*) é valorizado por seu uso ornamental, recuperação ambiental e sistemas silvipastoris. A qualidade das mudas é essencial para o sucesso do cultivo, sendo influenciada pelo tipo de substratos utilizado. Resíduos orgânicos, como o coral–sol (*Tubastraea coccinea*), têm potencial para melhorar substratos, reduzindo custos e promovendo o crescimento das mudas, desde que avaliados quanto à qualidade e toxicidade. Indicadores como crescimento, produção de biomassa, aspectos nutricionais e índice de qualidade de Dickson mensuram a eficiência na produção em viveiros. Dessa forma, o objetivo deste estudo é avaliar o potencial uso do coral–sol como componente alternativo nas misturas de substratos, com intuito de substituir parcialmente os insumos convencionais e reduzir os custos de produção do substrato na produção de mudas de ipê–branco (*T. roseoalba*). Para isso, mudas de ipê–branco foram produzidas com doses crescentes (0, 40, 80, 160 e 320 g m^{-3}) de coral–sol adicionados ao substrato comercial, em casa de vegetação, durante 270 dias. Foram avaliadas a altura, diâmetro do coleto, índice de qualidade de Dickson, produção de biomassa da parte aérea e raízes, número de folhas, área foliar, clorofila total, volume de raízes, concentração de nutrientes e metais pesados. A aplicação de coral–sol ao substrato mostrou potencial para melhorar a qualidade e o desenvolvimento de mudas de ipê–branco. Doses intermediárias, especialmente 80 g m^{-3}, destacaram–se pelo melhor desempenho em IQD, biomassa, clorofila e volume radicular, favorecendo a nutrição e a fotossíntese. Por outro lado, doses elevadas (≥160 g m^{-3}) reduziram a produção de biomassa e promoveram desequilíbrios nutricionais devido ao acúmulo de metais pesados e Na^{+}.

Palavras-chave: Substratos alternativos; Coral invasor; Crescimento de mudas; *Tubastraea* spp.; Recuperação de resíduos

1 INTRODUCTION

Tabebuia roseoalba (Ridl.) Sandwith is a tree species belonging to the Bignoniaceae family, popularly known as ipê–branco, which occurs naturally in Bolivia, Colombia, Paraguay, Peru, and Brazil, especially in the Cerrado and in transition areas to the Atlantic Forest, Pantanal and Caatinga (Tropicos, 2024). The ipê–branco is of great economic and ecological importance, especially because of its ornamental landscaping, with its intense white to light pink flowering, which adorns parks, gardens, public sidewalks and streets (Gandolphi e Bittencourt, 2010; Ribeiro et al., 2022). In addition, the species has a number of potential uses, in particular: (i) in projects to recover degraded areas, due to its rapid adaptation to dry and stony soils (Ribeiro et al., 2022); and (ii) in agroforestry systems, due to its characteristics as a facilitating tree in successional processes (Oliveira et al., 2013). These attributes justify the interest in growing the species.

Reforestation projects are successful in many ways, especially the production of high–quality seedlings, as this has a direct impact on the survival and initial development of seedlings after planting (Ehlers e Arruda, 2014; Silva et al., 2022; Wolschick et al., 2016). Thus, the production of high–quality ipê–branco seedlings has a significant impact on the success of projects to recover degraded areas and agroforestry systems with the species. However, the demand for knowledge and technology for native species is high, which can limit commercialization (Almeida et al., 2023; Faria et al., 2016). This is because the recommendations for the composition of substrates for producing ipê–branco seedlings are still uncertain in the literature.

Organic waste has been gaining prominence in the production of tree species in recent years due to its positive contribution to the physical characteristics of the substrate, such as increased water retention capacity, material porosity, particle aggregation, as well as the chemical aspect of the substrate, increasing the macro and micronutrients content (Alonso et al., 2022; Faria et al., 2016; Gabira et al., 2021; Griebeler et al., 2023; Mieth et al., 2019; Silva et al., 2014). The high cost of commercial substrates has led nurserymen to opt for the use of solid urban and/or agro–industrial waste, which highlights the potential of using sun coral (*Tubastraea* spp.). The sun coral has two main invasive species (*T. coccinea* and *T. tagusensis*), originating from the Indo–Pacific, which have spread rapidly on coral reefs, rocky shores and artificial structures in the tropical waters of the Atlantic, especially in Brazil, Caribbean, Gulf of Mexico and Canary Islands (Creed et al., 2021; Oigman-Pszczol et al., 2017). In Brazil, *Tubastraea* spp. was first recorded in the 1980's on oil and gas platforms in Rio de Janeiro state. Currently, its distribution extends over 3,850 km along the Brazilian coast (Creed et al., 2021; Mantelatto et al., 2020). The main reasons for the sun coral invasive success include: (i) its azooxanthellate coral characteristics, which allow it to be independent of light for feeding; (ii) its high reproductive efficiency, both sexually and asexually; and (iii) its accidental transportation on ships and oil platforms, facilitating its spread in different environmental conditions and altering

marine landscapes (Creed et al., 2017, 2021; Mantelatto et al., 2020; Oigman-Pszczol et al., 2017). The negative impacts of the sun coral on ecosystem services include: (i) competition for natural resources with native populations; (ii) facilitation of the invasion of other exotic species; and (iii) economic damage, such as fishing and coastal tourism (Creed et al., 2021; Oigman-Pszczol et al., 2017).

Organic compounds added to the substrate for seedling production must guarantee quality requirements, such as absence of toxicity and pathogens, local availability and low cost (Alonso et al., 2022), as well as providing gains in growth rates and biomass production (Griebeler et al., 2023). The determination of quality in seedling production can be verified by morphology, such as height, stem diameter, height/stem diameter ratio, shoot and roots dry matter, Dickson quality index (DQI), parameters used worldwide (Menegatti, 2017). However, organic compounds addition can alter the chemical composition of the substrate and, consequently, the nutrients absorption by the seedlings, making nutritional assessment of the different plant organs crucial for gauging the quality of seedling production.

Thus, the hypothesis of this study is that the addition of sun coral (*T. coccinea*) to commercial substrate improves the growth and quality of ipê–branco seedlings at moderate doses but can cause negative effects at high doses due to excess nutrients in the substrate. Therefore, the aim of this study was to evaluate the potential use of sun coral (*T. coccinea*) as an alternative component in the substrate mixtures, aiming to partially replace conventional inputs and reduce substrate production costs in the production of ipê–branco seedlings.

2 MATERIALS AND METHODS

2.1 Study site

The study was conducted in the greenhouse of the Forestry Nursery of the Forestry Institute of the Federal Rural University of Rio de Janeiro, in Seropédica, Rio de Janeiro state, southeastern Brazil (22º 45' 32"S, 43º 41' 50"W; and 33 m altitude).

The predominant climate of the study region is tropical with a dry winter (Aw), characterized by a rainy season in summer and an average temperature of the coldest month of more than 18ºC, according to the Köppen classification (Alvares et al., 2013), with accumulated annual rainfall of 1,294 mm year^{-1} (Oliveira Júnior et al., 2014) and an average annual temperature of 23.9°C (Carvalho et al., 2011). During the study, the greenhouse was controlled at a controlled air temperature of 30 ± 2°C, with a relative humidity of 60% and daily micro-sprinkler irrigation of 8 mm day^{-1}.

2.2 Experimental design and treatments

The study was conducted in a completely randomized design, with increasing doses of sun coral (*Tubastraea coccinea*) added to the commercial substrate. The experiment was set up with five doses (treatments), with three replications, each consisting of five seedlings, totaling 15 seedlings per treatment. The five doses of sun coral applied were: 0, 40, 80, 160, and 320 g m^{-3}. The formulated substrate was made up of 2:1:1 proportions of commercial substrate, composted urban pruning waste and food waste, respectively. The commercial substrate used was Mec Plant, containing 90% biostabilized pine bark and 10% vermiculite, widely used in the production of forest seedlings. The nutritional content of the substrate is shown in Table 1. After mixing the substrate proportions, the doses of sun coral were added.

Table 1 – Total macro and micronutrient contents in the samples of sun coral (*Tubastraea coccinea*)

C	N	P	K	Ca	Mg	Cu	Mn	Fe	Na
(g kg^{-1})						(mg kg^{-1})			
35.0[(1)]	16.0	1.0	0.8	175.0	4.4	90.7	24.0	388.7	896.3

Source: Authors (2025)

In where: [(1)] The values are presented as mean.

2.3 Seedling production and study conduction

The species used in the study was *Tabebuia roseoalba* (Ridl.) Sandwith, popularly known as ipê–branco, classified as a late secondary species according to the successional ecological group. *T. roseoalba* is a species widely used in forest restoration plantations in the Cerrado and Atlantic Forest biomes. The seeds used in the study were collected from mature fruit from mother trees at least 400 m apart. The seeds were sown in single–celled trays filled with washed sand and covered with a shading screen until germination. At 20 days after germination, the most vigorous seedlings with standardized shoots were selected. The seedlings were transferred to polypropylene plastic tubes with a volume of 280 cm^3 and placed in plastic trays suspended 100 cm above–ground. The above–mentioned substrate was homogenized and filled into containers. Immediately, the seedlings were transplanted into the tubes. During the study, the seedlings were irrigated by micro–sprinklers three times a day, totaling 8 mm day^{-1}. In addition, any spontaneous vegetation was controlled manually whenever necessary, ensuring the proper seedlings development.

2.4 Morphological assessment

Growth measurements were carried out monthly until the study end, 270 days after transplanting. The following variables were assessed: total plant height (cm), using a graduated ruler (Digimess, model 600.004, Brazil), stem diameter (mm), using a digital caliper (Mitutoyo, Absolute, Japan) with high precision (±0.01 mm). The data obtained was used to calculate the height/stem diameter ratio (H/D), an indicator commonly used to assess the morphological balance of plants.

The roots volume (cm^3) was determined using the water displacement method, using a graduated cylinder with a capacity of 500 mL and filled with a known initial water volume. The roots, previously washed to completely remove the adhered substrate, were immersed in the cylinder and the displaced volume was recorded. The root volume was calculated by the difference between the final volume of water displaced and the initial water volume, considering volumetric equivalence (1 mL = 1 cm^3).

2.5 Photosynthetic pigment concentration, leaf area and number determination

The photosynthetic pigments concentration was assessed by determining the total chlorophyll index, measured at 270 days after transplanting, using a digital chlorophyll meter (Falker, model CFL–1030, Brazil), according to the method described by Traini et al. (1983). Subsequently, the leaf area per plant was determined using an automatic leaf area meter (Li–Cor, model LI–3100, USA). The total number of leaves per plant was then obtained by direct manual counting.

2.6 Dry matter and seedling quality determination

Plant dry matter production was determined by manually separating the organs into leaves, stems and roots at 270 days after transplanting. The seedlings were cut off close to the surface of the substrate and separated into shoot and root system. The shoot was divided into leaves and stem, with the leaves completely removed from each plant. The roots were carefully washed in running water until the adhered substrate was completely removed. The fractions (leaves, stem and roots) were placed in duly identified paper bags and dried in a forced air circulation oven at 65 ± 1ºC for 96 h. After drying, the fractions were weighed on a digital precision scale (BEL Engineering, Precision balance L, Brazil), with a resolution of 0.01 g. Using this data, the quality of the seedlings was calculated using the Dickson Quality Index (DQI), according to the Equation (1) proposed by (Dickson, Leaf e Hosner, 1960).

$$DQI = \frac{Total\ DM}{\left(\frac{H}{D}\right)+\left(\frac{Shoot\ DM}{Roots\ DM}\right)} \quad (1)$$

where: *DQI* – Dickson's quality index; *H* – height (cm); *D* – stem diameter (mm); *DM* – dry matter (g).

2.7 Nutrient concentration assessment

After fractions drying, the samples were ground in a knife mill and sieved through a 2 mm mesh. They were then stored for chemical analysis of the plant tissue, carried out according to (Tedesco, Volkweiss e Bohmen, 1995). Part of the samples was submitted to sulfuric digestion to determine the N content by the micro–Kjeldahl distillation method, using a distiller (TE–0363, Tecnal, Brazil). Another part was submitted to nitric–perchloric digestion to determine the P, K, Ca, Mg, Cu, Zn, Mn, Fe, and Na contents. P was determined by the colorimetric method described by Murphy; Riley (1962), using a UV–visible spectrophotometer. K and Na were quantified by flame spectrophotometry. The Ca, Mg, Cu, Zn, Mn, and Fe concentrations were analyzed by atomic absorption spectrophotometry.

2.8 Statistical analysis

All the data obtained from the morphological parameters (height, diameter, H/D ratio, number of leaves, leaf area and root volume), dry matter production (shoot, roots and total), seedling quality (DQI), nutritional concentration (N, P, K, Ca, Mg, Cu, Zn, Mn, Fe and Na) and photosynthetic pigments (total chlorophyll) were submitted to regression analysis. The effect of addition doses (0, 40, 80, 160 and 320 g m^{-3}) of sun coral (*Tubastraea coccinea*) on the response variables was evaluated considering dose as a continuous quantitative variable, using its actual values in the regression models (linear or quadratic), without assuming equal spacing between treatment levels. The models were selected using the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC). All models were fitted using the "nlme" package (Pinheiro et al., 2014). The models with the lowest AIC and BIC values were used in the analysis of variance. The results were considered statistically significant when $p < 0.05$.

To assess the effects of the correlation between the response variables and the distribution of sun coral doses, the data was subjected to principal component analysis (PCA) using the "factoextra" (Kassambara e Mundt, 2020) and "FactoMineR" (Lê, Josse

e Husson, 2008) packages. PCA analyses make it possible to explain possible more complex interactions between the variables evaluated and those that contributed most to the differences between treatments. All the analyses carried out in the study were done using RStudio statistical software (R Core Team, 2019).

3 RESULTS AND DISCUSSIONS

3.1 Growth response

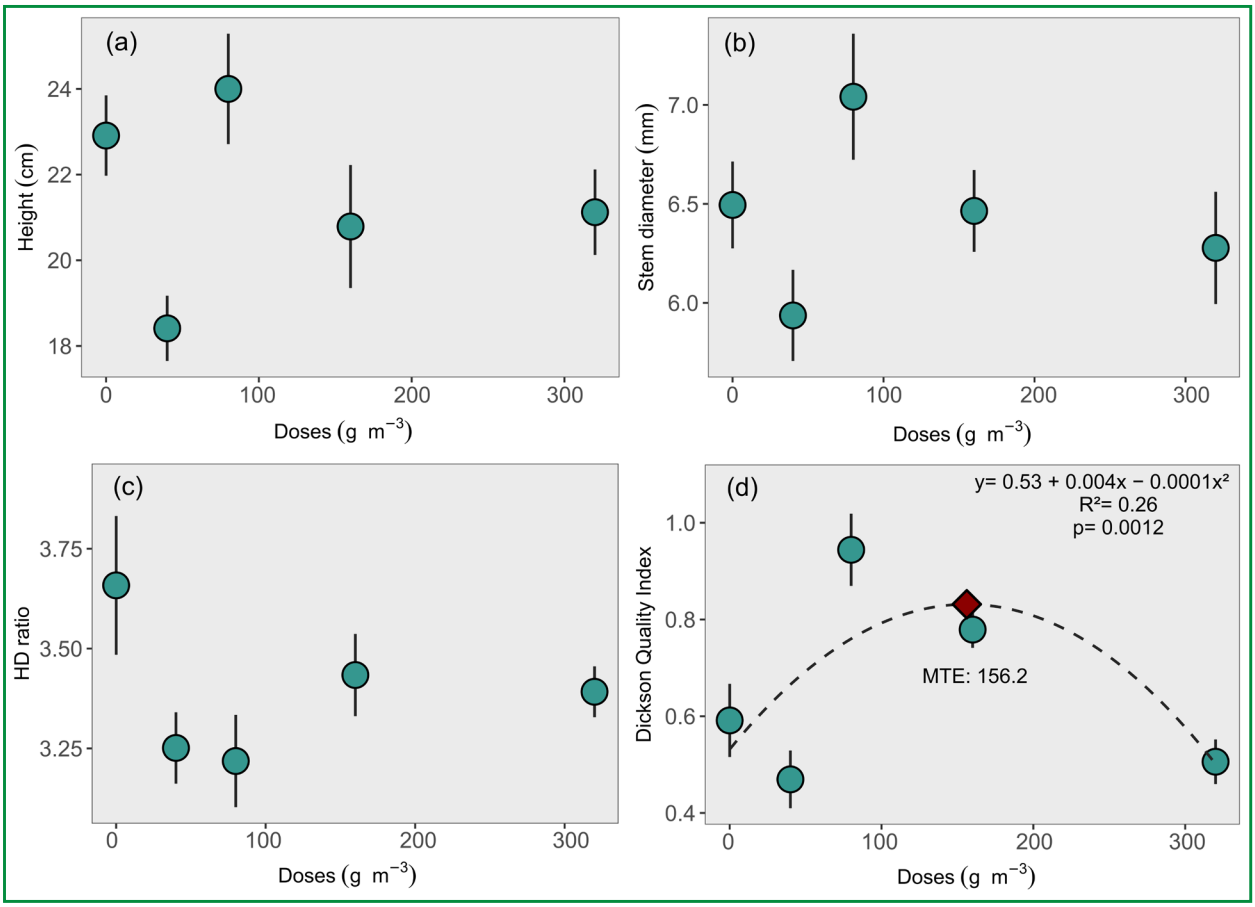
Increasing the doses of sun coral did not influence growth in height, stem diameter and HD ratio (Fig. 1a–c). Although not significant, the highest values for height and stem diameter were found at a dose of 80 g m^3 of sun coral added to the commercial substrate (Fig. 1a, b). Conversely, the lowest height and diameter values were found in the 40 g m^{-3} dose of sun coral.

This pattern may indicate that intermediate doses (80–160 g m^{-3} of sun coral) provide more balanced conditions for initial plant development, corroborating studies that highlight the importance of the substrate's nutritional balance for seedling growth (Alonso et al., 2022; Berghetti et al., 2016; Carneiro, 1995). However, the addition of sun coral influenced the Dickson quality index (DQI), with higher values and maximum technical efficiency at doses of 80 and 156.2 g m^{-3} of sun coral (Fig. 1 d). This result reflects the contribution of the addition of sun coral to improving the quality of seedlings, especially at doses that optimize the physical and chemical conditions of the substrate (Dickson, Leaf e Hosner, 1960).

This pattern demonstrates the potential of using sun coral in the composition of the substrate, since the DQI is one of the most widely used parameters for assessing the quality of forest seedlings, since its determination takes into account the H/D ratio and the distribution of biomass in the different fractions of the seedling, such as total dry matter and the shoot/roots dry matter ratio (Abreu et al., 2019; Carneiro, 1995), thus, high DQI values indicate higher seedling quality. Studies evaluating the

production of ipê–branco seedlings with the addition of: (i) doses of cattle and horse manure (Vieira et al., 2022) and (ii) Cu waste (Silva et al., 2021), found DQI values of 0.13–0.40 and 0.04–0.19, respectively. Our DQI results were considerably higher (0.47–0.94) than those found in the literature, highlighting the potential for using sun coral in the production of forest seedlings, especially for ipê–branco.

Figure 1 – Growth and quality of *Tabebuia roseoalba* seedlings under increasing sun coral doses



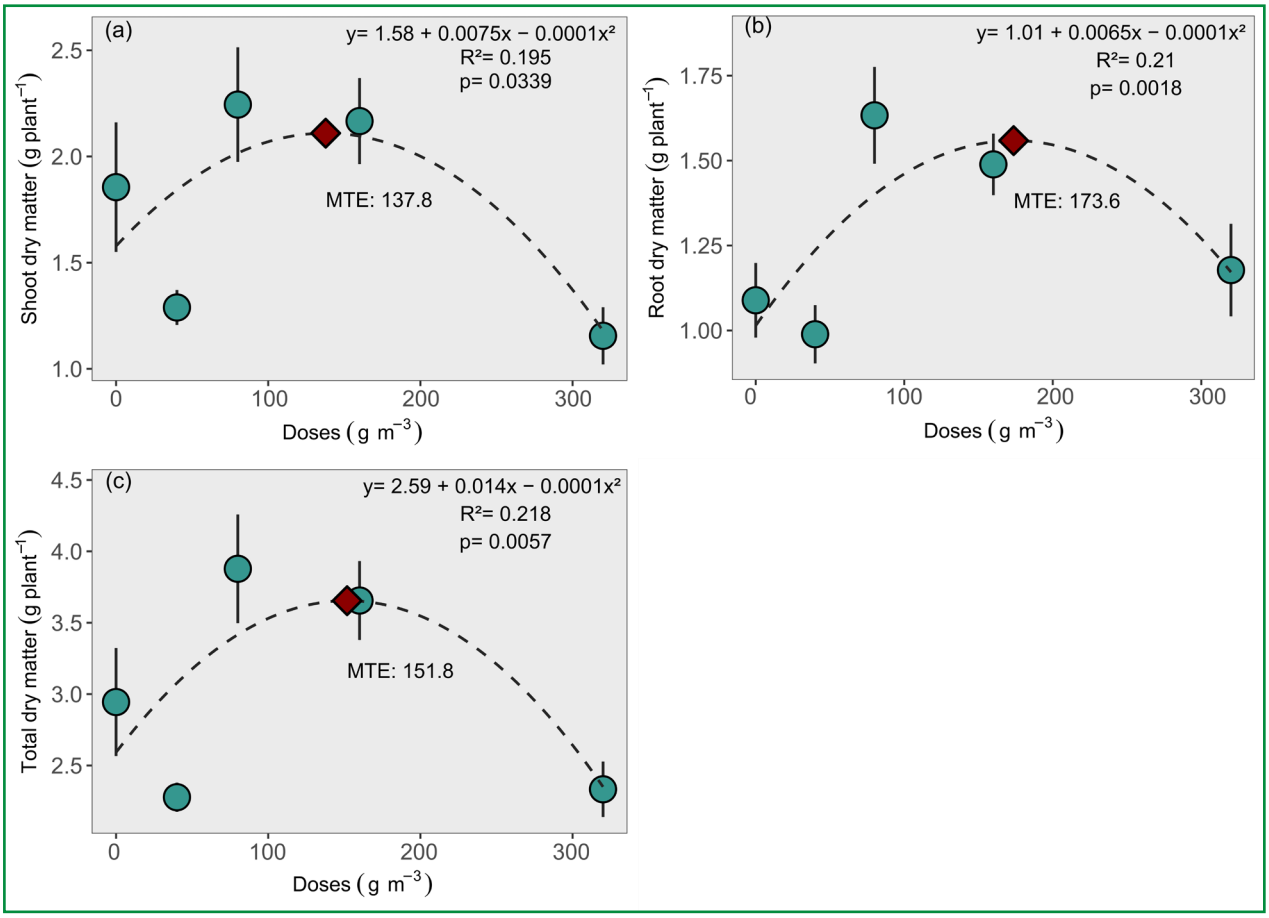
Source: Authors (2025)

In where: Height (a), stem diameter (b), HD – height and stem diameter ratio (c) and Dickson Quality Index of seedlings of ipê–branco (*Tabebuia roseoalba*) produced with increasing doses (0, 40, 80, 160 and 320 g m^{-3}) of sun coral (*Tubastraea coccinea*) added to the commercial substrate; Green circles indicate mean (n = 9); Vertical bars represent the standard error of data for each dose; Dashed lines indicate regressions ($p \leq 0.05$) and equations are described in each panel figure; Reddish diamond represents dose of maximum technical efficiency (MTE).

3.2 Biomass production

Application of doses of sun coral significantly influenced the biomass production of ipê–branco (Fig. 2a–c). The largest shoot, root and total biomass values were found at a dose of 80 g m^{-3} of sun coral added to the commercial substrate.

Figure 2 – Shoot, root, and total dry matter of *Tabebuia roseoalba* seedlings grown with increasing sun coral doses



Source: Authors (2025)

In where: Shoot (a), root (b) and total dry matter (c) of seedlings of ipê–branco (*Tabebuia roseoalba*) produced with increasing doses (0, 40, 80, 160 and 320 g m^{-3}) of sun coral (*Tubastraea coccinea*) added to the commercial substrate; Green circles indicate mean (n = 9). Vertical bars represent the standard error of data for each dose; Dashed lines indicate regressions ($p \leq 0.05$) and equations are described in each panel figure; Reddish diamond represents dose of maximum technical efficiency (MTE).

These results may be associated with the increased availability of nutrients in the substrate, which favors the proximity of ions to the roots, promoting their absorption

and accumulation in metabolically active organs, such as leaves. Consequently, carbon assimilation is enhanced, contributing to protein synthesis and enzyme activation, which benefits photosynthetic processes and favors proper plant development (Berghetti et al., 2016; Griebeler et al., 2023; Taiz et al., 2017). Maximum technical efficiency was observed at doses of 137.8, 173.6 and 151.8 g m^{-3} of sun coral for shoot, root and total biomass, respectively. In addition, high doses of sun coral (>160 g m^{-3}) tended to reduce the biomass production of ipê–branco.

This may have occurred due to the application of plant, animal and/or mineral waste, which can increase the availability of heavy metals, which can cause a decrease in plant growth, by altering cell division, elongation and structure, as well as damage to the roots, a reduction in chlorophyll production and an increase in the production of reactive oxygen species (ROS), due to oxidative damage to plant cells, favoring a decrease in protein, lipid and DNA synthesis (Marschner, 2012; Taiz et al., 2017; Tiecher et al., 2017), resulting in smaller and more vigorous seedlings.

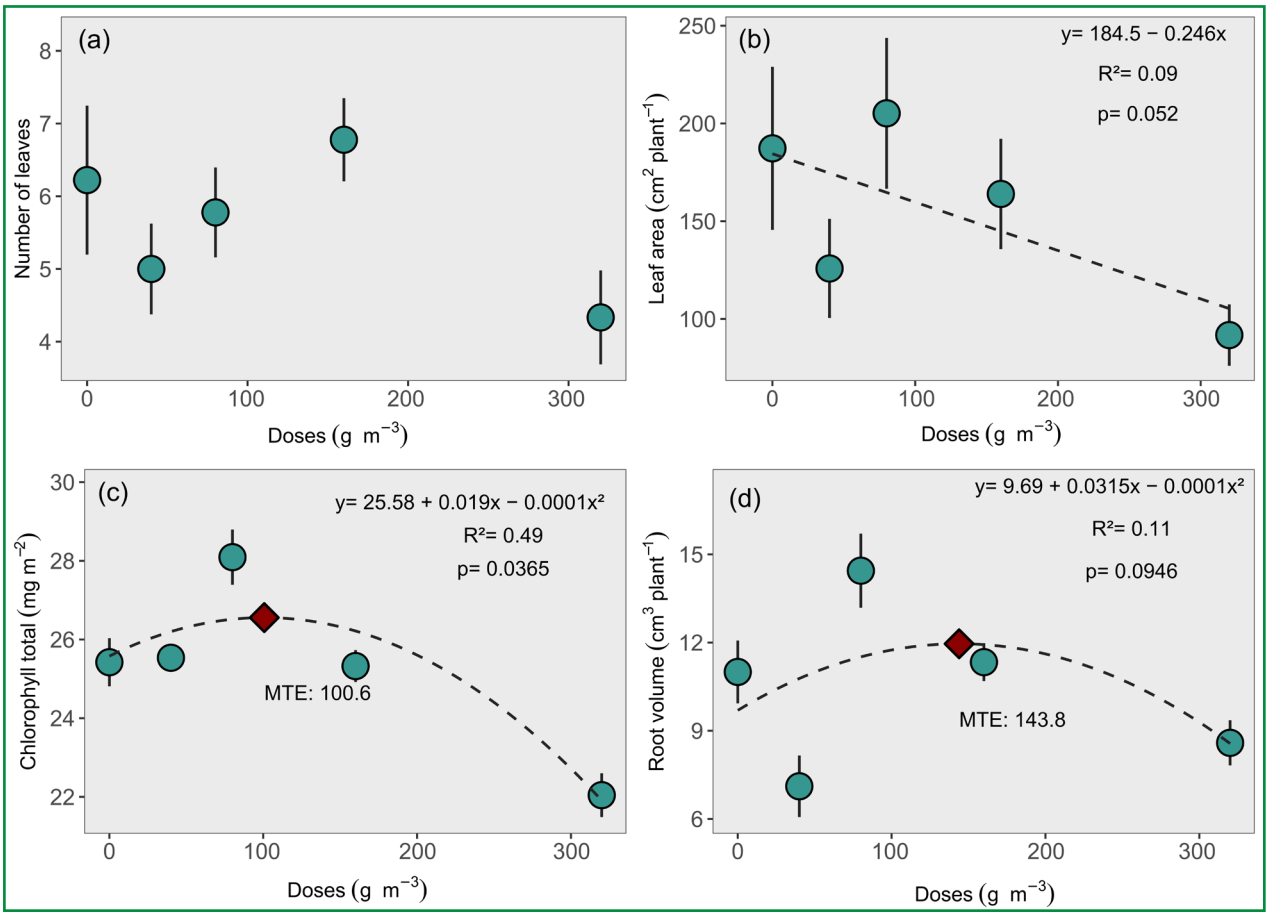
3.3 Morphological and photosynthetic response

The number of leaves was not significantly affected by the addition of sun coral doses to the substrate (Fig. 3a), while a negative linear effect was observed for leaf area as a function of the increase in sun coral doses (Fig. 3b). These results may be due to the increased availability of nutrients due to the sun coral addition, contributing to the allocation of nutrients within the plant, especially N, which has a strong relationship with the leaf area expansion (Ward et al., 2015).

Greater leaf area also favors increased management of natural resources by plants, such as a decrease in gas exchange, especially stomatal closure, contributing to increased water use efficiency in leaves, which can limit water loss from seedlings (Samuelson et al., 2018). In addition, the increase in leaf area may have favored greater resource use efficiency and thus higher concentrations of chlorophyll and chloroplastid proteins, such as RuBisCO, resulting from the greater amount of solar

radiation intercepted by the foliage (Hakamada et al., 2015; Stefano et al., 2018). All these factors have a direct influence on the shoot growth, which can be proven by analyzing the gain in biomass of ipê–branco.

Figure 3 – Leaf traits, total chlorophyll, and root volume of *Tabebuia roseoalba* seedlings grown with increasing sun coral doses



Source: Authors (2025)

In where: Number of leaves (a), leaf area (b), chlorophyll total (c) and root volume (d) of seedlings of ipê–branco (*Tabebuia roseoalba*) produced with increasing doses (0, 40, 80, 160 and 320 g m^{-3}) of sun coral (*Tubastraea coccinea*) added to the commercial substrate; Green circles indicate mean (n = 9); Vertical bars represent the standard error of data for each dose; Dashed lines indicate regressions ($p \leq 0.05$) and equations are described in each panel figure; Reddish diamond represents dose of maximum technical efficiency (MTE).

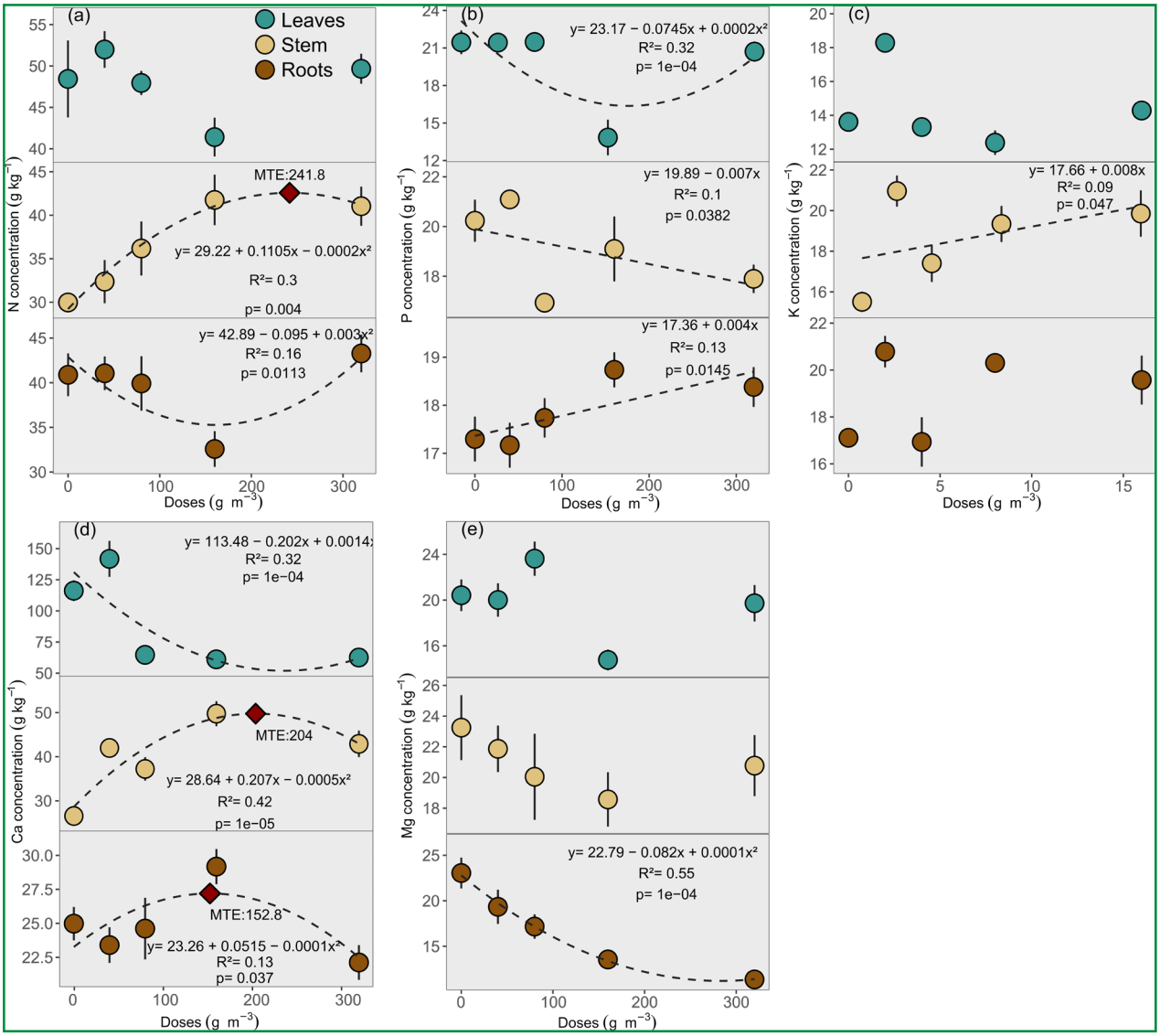
The application of the 80 g m^{-3} doses of sun coral to the substrate provided the highest values of total chlorophyll and root volume, which can be seen in (Fig. 3c, d). The maximum technical efficiency was seen at doses of 100.6 and 143.8 g m^{-3} of sun

coral for total chlorophyll and root volume of ipê–branco, respectively. This pattern may be related to the greater production of fine roots (≤2 mm in diameter), which act directly as a strategy to increase the contact area between roots and soil, and especially access to nutrients. This is due to the greater transfer of photoassimilates to the root system, which activates the emission of fine roots (Lee et al., 2016). With a greater number of fine roots, the seedlings increase the possibility of absorbing nutrients, such as P, especially through the activation of high–affinity P transporters (PHT1 family), promoting root growth, seeking sites richer in nutrients, a phenomenon described in P studies with forest species (Fan et al., 2021; Kulmann et al., 2023; Zhang, Wen e Ding, 2017). In addition, the large N content in the sun coral substrate (16 g kg^{-1}) may have favored its availability in the solution, promoting the activation of N transporters (NRT1.1) in the root system, increasing N absorption by the roots (Krouk et al., 2010; Remans et al., 2006). Part of the N absorbed is translocated to growing organs, such as the leaves, collaborating with photosynthetic processes, since photosynthetic capacity is directly related to the concentration of N in the leaves (Moriwaki et al., 2019; Taiz et al., 2017). Thus, the higher the absorption and N concentration in the leaves, the higher the photosynthetic pigments concentrations, such as chlorophylls (Stefano et al., 2018).

3.4 Nutritional response

Application of doses of sun coral significantly influenced the concentration of P and Ca in the leaves, N, P, K and Ca in the stem and N, P, Ca and Mg in the roots of ipê–branco (Fig. 4a–e). Increasing the doses of sun coral in the substrate had a quadratic effect on the concentration of N and Ca in the stem and Ca in the roots of ipê–branco (Fig. 4a,d). The maximum technical efficiency of N and Ca in the stem was seen at doses of 241.8 and 204 g m^{-3} of sun coral, respectively (Fig. 4a,d).

Figure 4 – Macronutrient concentrations in leaves, stems, and roots of *Tabebuia roseoalba* seedlings grown with increasing sun coral doses



Source: Authors (2025)

In where: Nutritional concentration of N (a), P (b), K (c), Ca (d) and Mg (e) of seedlings of ipê–branco (*Tabebuia roseoalba*) produced with increasing doses (0, 40, 80, 160 and 320 g m^{-3}) of sun coral (*Tubastraea coccinea*) added to the commercial substrate; Green circles indicate mean (n = 9); Vertical bars represent the standard error of data for each dose; Dashed lines indicate regressions ($p \leq 0.05$) and equations are described in each panel figure; Reddish diamond represents dose of maximum technical efficiency (MTE).

In the roots, the maximum technical efficiency of Ca was observed with the addition of 152.8 g m^{-3} of sun coral. These results show that the increased availability of N may have favored the formation of plant tissues, since N is an essential component

of amino acids, used in proteins (Taiz et al., 2017). In the stem, these proteins play a role in the formation and maintenance of cell structures, contributing to the elasticity and mechanical strength of the stem, as well as the synthesis of enzymes and carrier proteins that regulate the flow of nutrients and assimilates through the phloem (Castro-Rodríguez et al., 2017). Ca is a critical structural component of cell walls, acting in the formation of calcium pectates and its increase can contribute to the mechanical stability of the stem, rigidity and elasticity of the cells, helping to support the stem (Rocha, Toit e Gonçalves, 2019; Taiz et al., 2017). In contrast, increasing the addition of sun coral led to a decrease and increase in P in the stem and roots of ipê–branco, respectively (Fig. 4b). This shows that P absorption occurred, but P transport at high doses of sun coral was not efficient. This may be linked to a mechanism used by plants to adapt to P requirements, with the replacement of phospholipids by galactic and/or sulfolipids in cell membranes, which allocates smaller amounts of P to structural compounds and makes P available for the plant's energy production (ATP and NADPH) (Lambers et al., 2006).

Meanwhile, the concentration of K in the stem increased linearly with the application of doses of sun coral (Fig. 4c). Increased K concentrations can contribute to the ionic and osmotic balance, directly impacting the growth and functionality of the stem. This is because K acts as the main cation involved in controlling cell osmotic potential and activating enzymes related to cell metabolism, which facilitates cell division and elongation, contributing to stem growth (Santos et al., 2021), and can increase the efficient use of water by plants, especially in the nursery phase (Gonçalves, 1995). Increasing the doses of sun coral to the substrate had a negative quadratic effect on the concentration of P and Ca in the leaves and N and Mg in the roots of ipê–branco (Fig. 4a, b, e). Increasing the doses of sun coral did not influence the N, K and Mg concentration in the leaves, Mg in the stem and K in the roots of ipê–branco (Fig. 4a, c, e).

These results show that the ipê–branco seedlings already had enough nutrients for the photosynthetic apparatus to function optimally. An excess of nutrients in the nursery phase, such as N, can cause excessive vegetative growth, resulting in more fragile plants that are susceptible to pests and diseases, a decrease in lignification,

making the wood less dense and more susceptible to physical damage and nutritional imbalance, leading to a deficiency of other nutrients, especially P and K (Graciano et al., 2006; Kulmann et al., 2022). In contrast, excess Mg can cause ionic antagonism with K and Ca, reducing their absorption and the concentration of these ions in the leaves, leading to a nutritional imbalance and possibly causing chlorosis (Rocha, Toit e Gonçalves, 2019). Therefore, high doses of sun coral (≥8 g kg^{-1}) should be avoided.

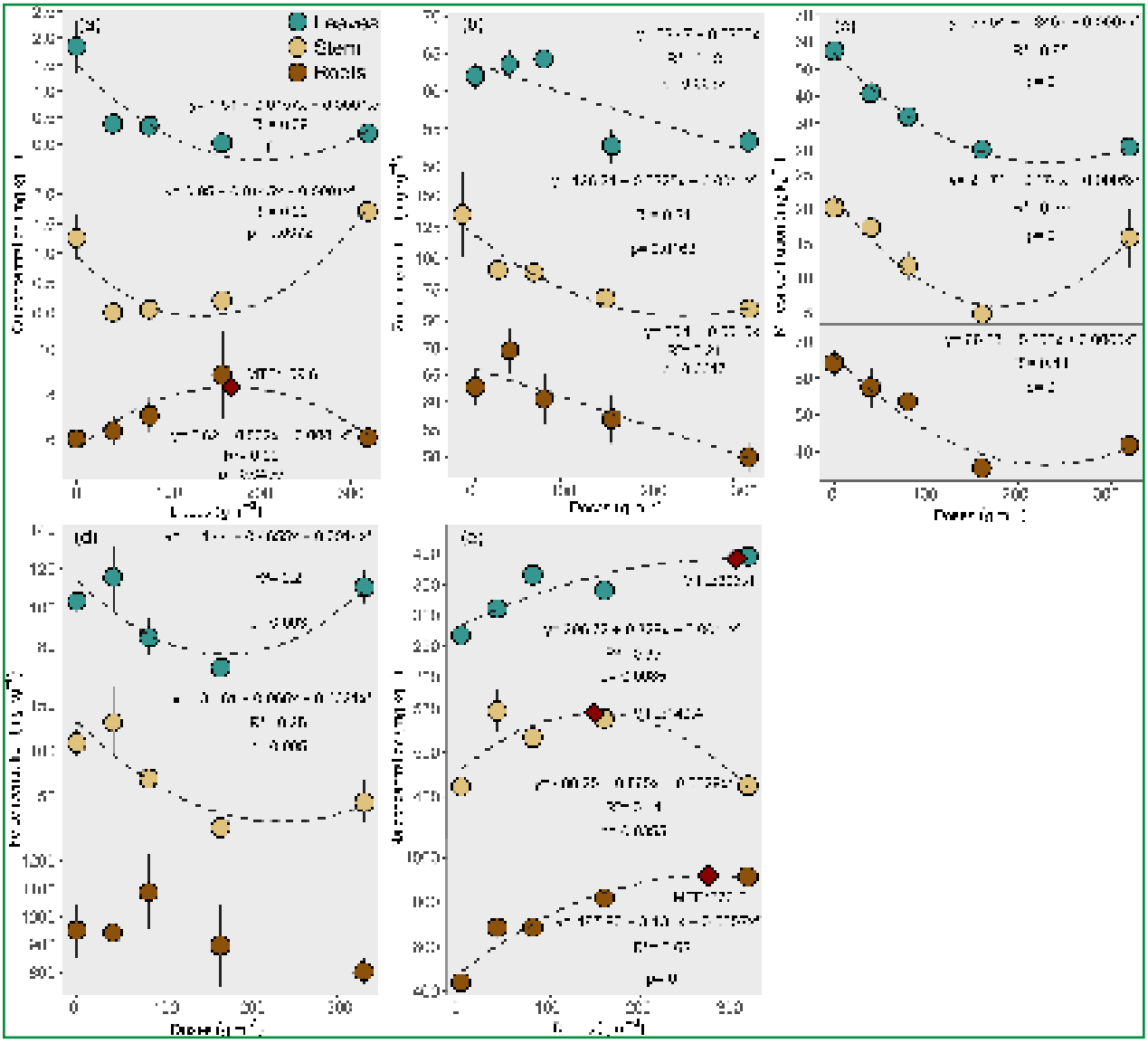
Application of doses of sun coral significantly influenced the Cu, Zn, Mn, Fe and Na concentration in the leaves, stem and roots, except Fe in the roots (Fig. 5a–e). Increasing the addition of sun coral linearly decreased the concentration of Zn in the leaves and roots (Fig. 5b). Increasing the doses of sun coral to the substrate had a negative quadratic effect on Cu, Mn and Fe concentration in the leaves, Cu, Zn, Mn and Fe in the stem and Mn in the roots of ipê–branco (Fig. 5a–d).

These results can be considered positive, since the presence of heavy metals in forest seedlings can have negative effects on plant growth and development. Heavy metals can reduce growth by interfering with cell division and cell elongation (Lovato et al., 2024). Roots are commonly the most affected and can suffer structural damage, reducing their capacity to absorb water and nutrients (Tiecher et al., 2017). Interference in the absorption and translocation of nutrients can lead to nutritional deficiency, caused by altered permeability and integrity of cell membranes. As a result, chlorosis and necrosis can be seen, which compromises photosynthesis and other vital functions (Marschner, 2012; Taiz et al., 2017).

Conversely, the concentration of Na in the leaves and stem and Cu and Na in the roots increased quadratically with the application of sun coral doses (Fig. 5a, e). Maximum technical efficiency of Na in the leaves and stems was seen at doses of 306.8 and 149.4 g m^{-3} of sun coral, respectively. In the roots, the maximum technical efficiency of Cu and Na was observed with the addition of 169.6 and 276.2 g m^{-3} of sun coral, respectively. High Na levels were to be expected given the sun coral's environment of origin, i.e. marine waters. As Na is one of the main ions in marine ecosystems, it tends

to be present in relatively high concentrations in the tissues of these organisms. Thus, with the increased availability of Na in the substrate, absorption and accumulation may occur in the organs of the ipê–branco.

Figure 5 – Micronutrient and sodium concentrations in leaves, stems, and roots of *Tabebuia roseoalba* seedlings grown with increasing sun coral doses



Source: Authors (2025)

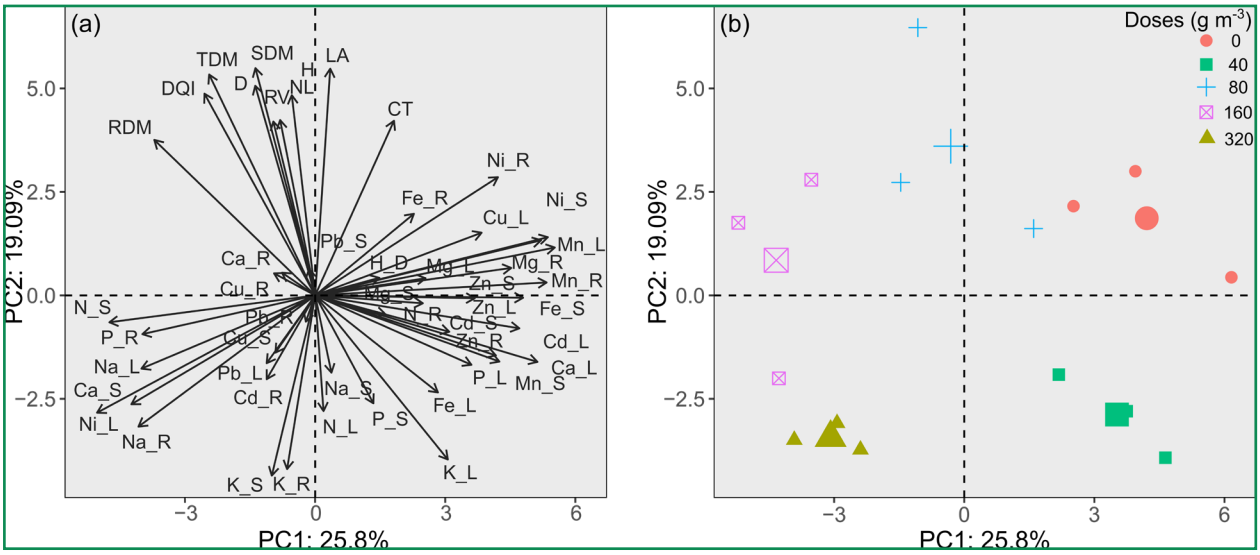
In where: Nutritional concentration of Cu (a), Zn (b), Mn (c), Fe (d) and Na (e) of seedlings of ipê–branco (*Tabebuia roseoalba*) produced with increasing doses (0, 40, 80, 160 and 320 g m^{-3}) of sun coral (*Tubastraea coccinea*) added to the commercial substrate; Green, beige and brown circles represent mean nutritional concentration of leaves, stems and roots, respectively (n = 9); Vertical bars represent the standard error of data for each dose; Dashed lines indicate regressions ($p \leq 0.05$) and equations are described in each panel figure; Reddish diamond represents dose of maximum technical efficiency (MTE).

The increase in Na in plant tissue can be beneficial, as Na can partially replace the physiological functions of K that operate in the plant vacuole, such as osmotic control and enzymatic reactions, as they are essential for enabling adenosine triphosphatases (ATPases) (Marschner, 2012). In addition, Na improves the plant's water balance and water use efficiency (WUE), contributing to the maintenance of turgor and cell expansion (Laclau et al., 2024; Mateus et al., 2021). Studies report positive effects of partially replacing K with Na in the growth of Eucalyptus spp., elucidating the cost reduction with NaCl fertilization, rather than KCl (Mateus et al., 2019; Mateus et al., 2021; Laclau et al., 2024).

3.5 Principal component analysis

Principal component analysis (PCA) was carried out considering only the first two components, since the sum of principal components (PC) 1 and PC 2 explained 44.9% of the original variability of the data (Fig, 6a, b), showing that PCA was able to simplify the complexity of the data without losing essential information.

Figure 6 – Principal component analysis of growth, quality, and nutritional traits of *Tabebuia roseoalba* seedlings grown with increasing sun coral doses



Source: Authors (2025)
In where: Relation between principal component 1 (PC1) and principal component 2 (PC2) for parameters (a): H – height; D – stem diameter; HD – height and stem diameter ratio; DQI – Dickson quality index; SDM – shoot, RDM – root, TDM – total dry matter; NL – number of leaves; LA – leaf area; CT – chlorophyll total; and RT – root volume; nutritional concentration in L – leaves; S – stem; R – roots, and their relationship with the treatments of seedlings of ipê–branco (*Tabebuia roseoalba*) produced with increasing doses (0, 40, 80, 160 and 320 g m^{-3}) of sun coral (*Tubastraea coccinea*) added to the commercial substrate.

PC1 explained 25.8% of the variability and made it possible to observe the pattern of the effect of the doses of sun coral on the response variables, especially through two groupings, contrasted with each other: (i) doses of 160 and 320 g m^{-3} of sun coral, distributed to the left of the spatial distribution; and (ii) doses of 0 and 40 g m^{-3} of sun coral, located to the right of the spatial distribution of the PCA. The application of the 160 and 320 g m^{-3} doses of sun coral showed a strong relationship with the response variables of the nutritional concentration of Na in the leaves, N and Ca in the stem and P and Na in the roots. This pattern may indicate a nutritional imbalance at higher doses, particularly due to excessive Na accumulation, which can negatively affect nutrient uptake and plant growth (Taiz et al., 2017).

In contrast, the lower doses (0 and 40 g m^{-3}) had a strong relationship with nutritional concentration and growth variables. This increased nutrient uptake at these low rates may be related to competitive interactions among cations, particularly between Mg^{2+}, Ca^{2+}, and K^{+}, which can reduce the uptake of other nutrients, such as Mg. This indicates that moderate additions can optimize nutritional balance, while higher rates may induce antagonistic effects and reduce nutrient use efficiency (Mateus et al., 2019; Taiz et al., 2017). High doses of sun coral were strongly associated with specific nutritional variables, such as Na in the leaves, N and Ca in the stem, and P and Na in the roots. These results show that high doses can promote an increase in the concentration of Na, Ca and P, due to the greater availability of these nutrients in the substrate (Mendonça et al., 2024). However, the absorption and accumulation of nutrients in specific organs shows that the nutritional translocation was not efficient, reducing the concentration in other metabolically active organs, such as the leaves, which can reduce photosynthetic activity (Aguilar et al., 2024; Berghetti et al., 2021), reducing the concentration of chlorophyll (Kulmann et al., 2020), as we can see in our results (Fig. 3c).

PC2 explained 19.09% of the variability in the data and was efficient in separating the treatment of applying the 80 g m^{-3} dose of sun coral to the substrate, with the

response variables of: (i) growth, such as height (H) and stem diameter (D); (ii) seedling quality, such as DQI; (iii) biomass production, such as shoot, roots and total; (iv) morphology, such as leaf area (LA), number of leaves (NL) and root volume (RV). These results show that the intermediate dose of sun coral (80 g m^{-3}) in the substrate is recommended for the production of ipê–branco seedlings. This is because the plants showed higher growth values, such as height and stem diameter, reflecting the higher shoot and roots biomass production and, especially, leaf number and area. This pattern can be attributed to the adequate availability of nutrients in the substrate, ensuring absorption in sufficient quantities for full photosynthetic activity, increasing the capture and absorption of light in different regions of the spectrum in the initial phases of photosynthesis, with the efficiency of absorbed energy used for the photochemical reactions responsible for the production of plant biomass (Berghetti et al., 2021; Kulmann et al., 2020), reflecting an increase in seedling quality, contributing to higher DQI values. Thus, the use of alternative sources of nutrients in the substrate, such as sun coral, in adequate quantities, can favor financial and environmental savings, especially by reducing the use of peat, chemical substrates and fertilizers (Griebeler et al., 2023). In addition, it promotes the appropriate use of an exotic species that has invaded the Brazilian coast.

4 CONCLUSIONS

Application of doses of sun coral to the commercial substrate showed the potential to optimize the growth and quality of ipê–branco seedlings, especially at the intermediate dose (80 g m^{-3}), with maximum technical efficiency in various parameters, such as total biomass, total chlorophyll and root volume, reinforcing its effectiveness in producing vigorous seedlings.

The 80 g m^{-3} dose of sun coral promoted development in height, stem diameter and biomass, as well as providing the highest Dickson quality index (DQI), showing an improvement in the physical and chemical conditions of the substrate, demonstrating

the viability of sun coral as an alternative component in substrate mixtures. which can partially replace conventional inputs and reduce the production costs of the substrate for forest seedlings production, especially ipê–branco.Low (≤40 g m^{-3}) and high doses of sun coral (≥160 g m^{-3}) reduced biomass production and nutritional imbalance caused by the availability and absorption of heavy metals.

This condition can compromise seedling growth, highlighting the importance of proper dose management. The multivariate analysis revealed that intermediate doses were more associated with positive responses in terms of growth, quality and nutrition, while high or low doses showed limitations in these parameters. Thus, the use of sun coral should be oriented towards optimized doses, guaranteeing sustainability and performance in the forest nursery.

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