AGRONOMY (AGRONOMIA)

Agrária —Revista Brasileira de Ciências Agrárias
ISSN (on line) 1981-0997
v.20, n.4, a4288, 2025
Recife, PE, UFRPE. www.agraria.pro.br
DOI: 10.5039/agraria.v20i4a4288 - Protocol 4288
Subm. 31/05/2025 • App. 05/11/2025 • Pub. 17/11/2025

Phosphorus influence on seedling growth of Caatinga tree species

João Marcos Rodrigues dos Santos[1*], Alessandro Targino Ibiapina de Sousa[1], Ismail Soares[1], Carlos Alberto Kenji Taniguchi [2], Adriana Guirado Artur[1]

1 Universidade Federal do Ceará, Fortaleza, CE, Brasil. E-mail: joaorodriguesestagio.embrapa@gmail.com; mr.alessandro@gmail.com; ismail@ufc.br; driguirado@yahoo.com.br
2 Embrapa Agroindústria Tropical, Fortaleza – CE, Brasil. E-mail: carlos.taniguchi@embrapa.br

ABSTRACT: This study assessed how phosphorus rates affect the growth and nutritional health of seedlings from three native forest species in the Brazilian semi-arid region: *Libidibia ferrea*, *Erythrina velutina*, and *Piptadenia stipulacea*. The experiment was conducted at the Center for Teaching and Research in Urban Agriculture, employing a randomized block design with a 3 × 5 factorial arrangement, involving three tree species (*Piptadenia stipulacea*, *Erythrina velutina*, and *Libidibia ferrea*) and five phosphorus application rates (100, 150, 200, 250, and 300 mg dm^{-3}). Measurements included height, stem diameter, number of leaves, dry biomass, shoot-to-root ratio (SRR), height-to-diameter ratio (HDR), phosphorus use efficiency (PUE), phosphorus accumulation (PA), and the Dickson quality index (DQI). The results showed species-specific responses. *Piptadenia stipulacea* responded more strongly to phosphorus, with notable increases in growth and nutrient absorption. In contrast, *Erythrina velutina* and *Libidibia ferrea* showed minimal changes across treatments. These findings indicate that phosphorus needs differ among native forest species, suggesting that fertilization should be customized to meet each species' specific requirements for optimal seedling production.

Keywords: Brazilian semi-arid region; native forest seedlings; nutrient use efficiency; phosphorus fertilization; seedling quality indices

Influência do fósforo no crescimento de mudas de espécies arbóreas da Caatinga

RESUMO: Este estudo avaliou os efeitos de doses de fósforo sobre o crescimento e o estado nutricional de mudas de três espécies florestais nativas do semiárido brasileiro: *Libidibia ferrea*, *Erythrina velutina* e *Piptadenia stipulacea*. O experimento foi conduzido no Centro de Ensino e Pesquisa em Agricultura Urbana, em delineamento em blocos casualizados, utilizando um esquema fatorial 3 x 5, sendo, três espécies arbóreas (*Piptadenia stipulacea*, *Erythrina velutina* e *Libidibia ferrea*) e cinco doses de fósforo (100, 150, 200, 250 e 300 mg dm^{-3}). Foram determinados altura, diâmetro do caule, número de folhas, biomassa seca, relação altura/raiz (AR), relação altura/diâmetro (AD), eficiência de uso do fósforo (EUF) e o acúmulo de fósforo (AF), bem como o índice de qualidade de Dickson (IQD). Os resultados demonstraram respostas diferenciadas entre as espécies. *Piptadenia stipulacea* apresentou maior responsividade ao fósforo, com incremento significativo no crescimento e na absorção do nutriente. Já *Erythrina velutina* e *Libidibia ferrea* mostraram pouca variação em função das doses aplicadas. Conclui-se que a exigência por fósforo varia entre espécies florestais nativas e que a adubação deve ser ajustada conforme a demanda específica, visando otimizar a produção de mudas.

Palavras-chave: Região semiárida brasileira; mudas florestais nativas; eficiência de uso de nutrientes; adubação fosfatada; índices de qualidade de mudas.

*João Marcos Rodrigues dos Santos. E-mail: joaorodriguesestagio.embrapa@gmail.com (Corresponding author)
Associate Editor: Ricardo Gallo.

INTRODUCTION

Caatinga is a biome exclusive to Brazil, predominantly concentrated in the Northeast region, where a semi-arid climate prevails, characterized by low precipitation, high temperatures, and intense evapotranspiration, resulting in long drought periods (Fernandes et al., 2020). Despite its ecological relevance, this biome is increasingly threatened by human activities, such as deforestation, the conversion of native vegetation into pastures and croplands, and the exploitation of natural resources, which together compromise biodiversity and environmental quality (Kgaphola et al., 2023; Silva et al., 2023; Kooch et al., 2024; Santos et al., 2025). In response, the use of native tree species in reforestation programs has been a common strategy, as these species are naturally adapted to local edaphoclimatic conditions and play a key role in restoring ecological balance (Kemppinen et al., 2020).

However, the success of restoration programs depends not only on the choice of adapted species, but also on appropriate soil fertility management. Among essential nutrients, phosphorus (P) plays a central role in plant metabolism, being involved in photosynthesis, respiration, nucleic acid synthesis, membrane formation, and enzymatic regulation (Hawkesford et al., 2023). As a macronutrient, P frequently limits productivity in natural and agricultural ecosystems (Cong et al., 2020), particularly in semi-arid soils, where its availability is low and mobility is restricted, strongly affecting plant establishment, growth, and survival (Han et al., 2022). Despite its importance, there is still limited knowledge regarding the nutritional requirements of native Caatinga species, especially with respect to phosphorus. This gap hampers the development of adequate fertilization strategies that could improve seedling quality and long-term restoration success.

In this context, species such as *Libidibia ferrea* (Mart. ex Tul.) L.P.Queiroz, *Erythrina velutina* Willd., and *Piptadenia stipulacea* (Benth.) Ducke deserve attention, as they are native to Caatinga, have ecological and economic importance, and are commonly used in restoration initiatives. Understanding their responses to P fertilization may provide valuable insights into their nutritional demands and growth dynamics, contributing to better management practices.

Therefore, this study aimed to evaluate the effects of phosphorus rates on the growth and nutritional status of seedlings of three native Caatinga species. The results are expected to support practical recommendations for phosphorus fertilization in forest nurseries, thereby contributing to reforestation programs, improving seedling vigor, enhancing soil fertility management, and strengthening sustainable restoration initiatives in this unique and ecologically significant biome.

MATERIALS AND METHODS

The experiment was conducted under controlled conditions at the Center for Teaching and Research in Urban Agriculture, Department of Plant Science, Federal University of Ceará (UFC), Fortaleza, Ceará, Brazil (3° 44' 22.571" S, 38° 34' 35.8" W). The greenhouse was kept with natural light and temperature conditions. Soil moisture was maintained at approximately 60% of the pot's water-holding capacity by gravimetric control, with pots weighed daily and water replenished to compensate for evapotranspiration losses.

Seeds of *Libidibia ferrea*, *Erythrina velutina*, and *Piptadenia stipulacea* were collected from forest remnants at the Pici Campus of UFC. To avoid genetic proximity, seeds were obtained from multiple parent trees spaced at least 50 m apart. After collection, seeds were air-dried, stored in paper bags under laboratory conditions (25 ± 2 °C), and sown within three months.

Germination was carried out in polyethylene trays with 162 cells (35 cm^3 per cell), filled with a 1:1 (v:v) mixture of organic compost and washed sand. One seed per cell was sown. Twenty-one days after sowing, seedlings were transplanted into plastic bags (10 × 25 cm) with a 1.0 dm^3 capacity, containing soil previously fertilized according to treatments.

The soil was classified as Oxisol (IUSS, 2022). Samples with disturbed structure were collected from 0–20 cm depth (sandy loam texture) at the Pici Campus (UFC). Its physical and chemical attributes were determined as described by Teixeira et al. (2017) and Donagema et al. (2011): coarse sand = 454 g kg^{-1}, fine sand = 357 g kg^{-1}, silt = 84 g kg^{-1}, clay = 105 g kg^{-1}; Ca^{2+} = 0.7, Mg^{2+} = 0.6, K^+ = 0.15, Al^{3+} = 1.2, H+Al = 3.3 $cmol_c$ dm^{-3}; available P = 16 mg dm^{-3}; organic matter = 10.4 g kg^{-1}; pH = 4.7.

For soil acidity correction, each 32 dm^3 fraction of soil received 27.8 g of calcitic limestone (53% CaO) and 14.8 g of dolomitic limestone (33% CaO, 16% MgO), aiming to increase Ca and Mg saturation to 60% and 20% of CEC, respectively. The soil was incubated for 10 days at 60% of its water-holding capacity.

After incubation, the soils received five phosphorus rates: 100, 150, 200, 250, and 300 mg dm^{-3}, using monoammonium phosphate (60% P_2O_5, 11% N) as the P source. To balance nitrogen across treatments, urea (45% N) was applied to maintain a total of 157 mg dm^{-3} of N. Basal fertilization consisted of 146 mg dm^{-3} of K and 60 mg dm^{-3} of S (applied as potassium sulfate, 50% K, 17% S), plus micronutrients in mg dm^{-3}: 5.0 Zn, 1.5 Cu, 1.5 B, 3.6 Mn, and 0.15 Mo. Fertilizers were thoroughly mixed into the soil before transplanting. No top-dressing fertilization was applied (Bellone & Neves, 2001).

The experimental design was randomized blocks with a 5 × 3 factorial arrangement (five P rates × three species) and six replications. Each plot consisted of six seedlings. Sixty days after sowing, seedlings were evaluated for height, stem diameter, and number of leaves. Dry biomass (shoot, root, and total) was obtained after drying samples at 65 °C to constant weight. Seedling quality indices were calculated: shoot-to-root ratio (SRR), height-to-diameter ratio (HDR), and Dickson Quality Index (DQI) (Gomes et al., 2002).

Phosphorus content in shoots was determined after nitric–perchloric digestion, using spectrophotometry with

molybdenum blue (Donagemma et al., 2011). Phosphorus use efficiency (PUE) was calculated according to Siddiqi & Glass (1981): PUE = (SDW²) / PA, where SDW = shoot dry weight and PA = phosphorus accumulation. Composite soil samples from each treatment were also analyzed for available phosphorus.

Data were subjected to analysis of variance (ANOVA), comparison of means (Tukey's test), and treatment means were analyzed by polynomial regression. Statistical analyses were performed using AgroEstat software (Barbosa & Maldonado Júnior, 2015).

RESULTS AND DISCUSSION

The results of the analysis of variance reveal that the evaluated forest species exhibited significant differences in plant height, number of leaves, and stem diameter. The species exhibited distinct growth patterns in terms of these variables, which were influenced by species and phosphorus rates, with no interaction between them (Table 1).

In the comparison of means for the main effects (species), *Piptadenia stipulacea* exhibited the highest mean height, differing significantly from *Erythrina velutina* and *Libidibia ferrea*, which showed similar heights. Regarding the number of leaves, *Piptadenia stipulacea* also had the highest mean value, followed by *Libidibia ferrea* and *Erythrina velutina*. For stem diameter, *Erythrina velutina* showed the highest value, while *Piptadenia stipulacea* and *Libidibia ferrea* had lower values (Table 1).

Table 1 - Plant height (cm), number of leaves, and stem diameter (mm) of forest seedlings (*Piptadenia stipulacea*, *Erythrina velutina*, and *Libidibia ferrea*) grown under different phosphorus rates incorporated into the soil, evaluated 60 days after sowing.

Analyzed variables			
	Height (cm)	**Number of Leaves**	**Diameter (mm)**
Sources of variation		**F test**	
Species (S)	253.25**	22.84**	2308.42**
Phosphorus rates (P)	1.40^{ns}	2.57*	0.97^{ns}
S x P	0.82^{ns}	1.53^{ns}	1.21^{ns}
CV (%)	11.93	7.66	9.20
Comparison of means for main effects			
	Height (cm)	**Number of Leaves**	**Diameter (mm)**
Forest species			
Erythrina velutina	38.01 b	9.82 c	11.03 a
Piptadenia stipulacea	72.17 a	15.78 a	2.91 b
Libidibia ferrea	40.41 b	13.24 b	2.43 c
Phosphorus rates in mg dm^{-3}			
100	48.98	12.57	5.32
150	49.76	12.71	5.47
200	53.20	13.63	5.65
250	48.58	12.84	5.47
300	50.48	12.99	5.36

Means followed by the same lowercase letter within each column do not differ from each other by the Tukey test, at a 5% probability level. ^{ns}; ** and *: Not significant and significant at 1% and 5% probability, respectively.

Phosphorus is a fundamental element for seedling development and metabolism. It plays an important role in the energy transfer process (ATP formation), contributing to the structure of various organic molecules (such as membranes and carbohydrate esters), and is essential for cell division and photosynthetic processes (Taiz & Zeiger, 2017; Rengel, 2022).

Differences in plant height, stem diameter, and number of leaves between the three species studied support this, align with our results, and suggest that these variables are strongly influenced by the morphophysiological characteristics inherent to each species, as also observed by Azevedo et al.

(2020). Regarding the number of leaves, our results corroborate those of Araújo et al. (2020), who analyzed the influence of phosphorus rates on acacia seedling growth and found an increase in leaf number with increasing phosphorus application rates.

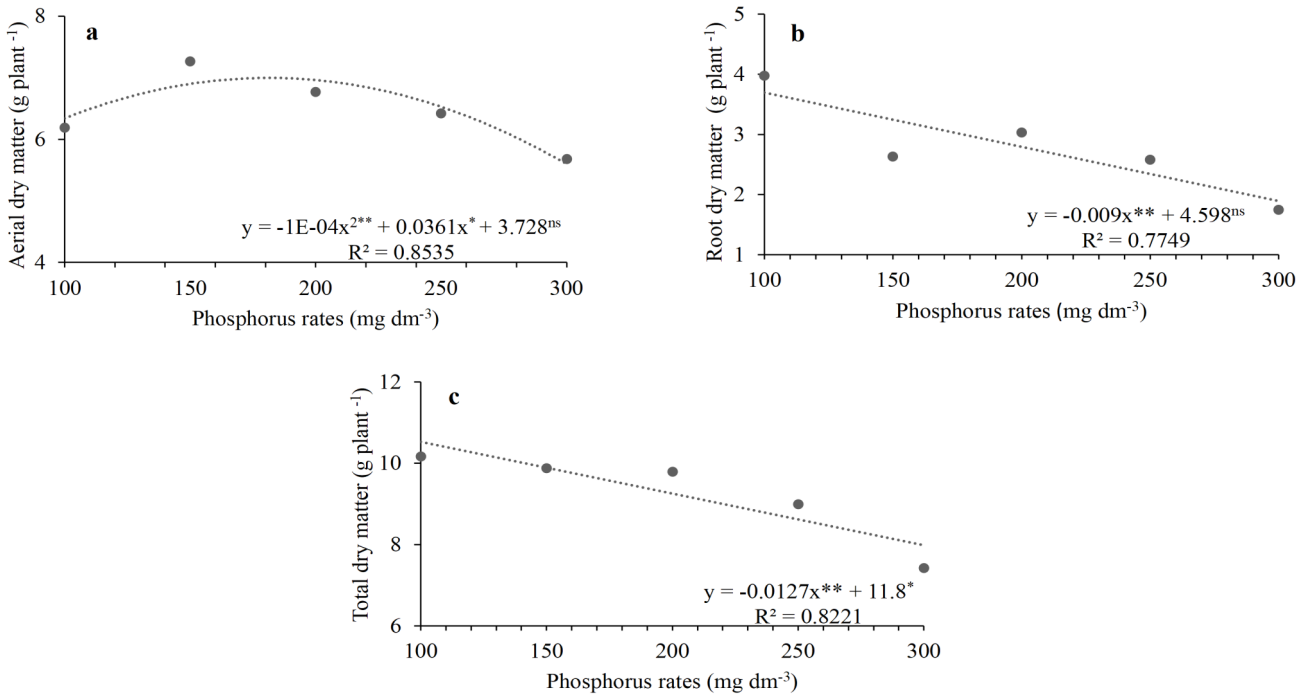
However, our findings for plant height and stem diameter differ from those of Azevedo et al. (2020), who observed an increase in these variables with the application of 150 mg kg^{-1} of phosphorus. The effect of species was highly significant for all variables analyzed. Studies confirm that plant species exhibit considerable variation in their capacity for biomass accumulation in both shoots and roots, depending on their physiology and ecological adaptations (Qi et al., 2019; Zhu et al., 2024).

Aerial dry matter (ADM), root dry matter (RDM), and total dry matter (TDM) were significantly different between the species. The species effect was highly significant for all analyzed variables, indicating that the species differ in their capacity to accumulate biomass, both in the aerial and root systems (Table 2). Figure 1 shows the regression curves between phosphorus rates applied to soil and the production of aerial dry matter (a), root dry matter (b), and total dry matter (c) for *Erythrina velutina*. For ADM (Figure 1a), lower phosphorus rates favored above-ground biomass production, suggesting that increased phosphorus availability may reduce aerial biomass in these species, with an optimal point corresponding to maximum (180.5 mg dm^{-3} / 6.99 g $plant^{-1}$) above-ground biomass accumulation. RDM production was affected by the application of phosphorus rates in the soil. RDM production decreased with the increased phosphorus rates (Figure 1b). In relation to TDM, a decrease in biomass was observed with increased phosphorus rates (Figure 1c).

Table 2 - Production of aerial dry matter (ADM, g $plant^{-1}$), root dry matter (RDM, g $plant^{-1}$), and total dry matter (TDM, g $plant^{-1}$) of forest seedlings (*Piptadenia stipulacea*, *Erythrina velutina*, and *Libidibia ferrea*) grown under different phosphorus rates incorporated into the soil, evaluated 60 days after sowing.

Analyzed variables			
	ADM (g $plant^{-1}$)	**RDM (g $plant^{-1}$)**	**TDM (g $plant^{-1}$)**
Sources of variation	**Teste F**		
Species (S)	96386**	393.94**	10.42**
Phosphorus rates (P)	1.80^{ns}	7.58**	2.49^{ns}
S x P	2.64*	9.84**	5.09**
CV (%)	7.72	28.93	8.42
Comparison of means for main effects			
	ADM (g $plant^{-1}$)	**RDM (g $plant^{-1}$)**	**TDM (g $plant^{-1}$)**
Forest species			
Erythrina velutina	6.46 c	2.79 a	9.25 a
Piptadenia stipulacea	8.79 a	0.25 c	9.04 a
Libidibia ferrea	7.77 b	0.56 b	8.33 b
Phosphorus rates in mg dm^{-3}			
100	7.46	1.56	9.02
150	7.88	1.12	9.01
200	7.91	1.30	9.21
250	7.56	1.13	8.69
300	7.55	0.89	8.45

Means followed by the same lowercase letter within each column do not differ from each other by the Tukey test, at a 5% probability level. ^{ns}; ** and *: Not significant and significant at 1% and 5% probability, respectively.



ns; ** and *: Not significant and significant at 1% and 5% probability.

Figure 1 - Aerial dry matter (ADM, g plant^{-1}) (a), root dry matter (RDM, g plant^{-1}) (b), and total dry matter (TDM, g plant^{-1}) (c) of *Erythrina velutina* seedlings grown under different phosphorus rates incorporated into the soil, evaluated 60 days after sowing.

Species such as *Piptadenia stipulacea* and *Libidibia ferrea*, which exhibited higher values of aerial dry matter, tend to be more efficient in light capture and photosynthesis activity, whereas *Erythrina velutina* accumulated more dry matter in the roots. This pattern may reflect functional differentiation between species, with some allocating more resources to shoots to maximize photosynthesis, while others prioritize root development, a crucial strategy for nutrient acquisition, which may be advantageous under conditions of low soil fertility or water availability (Mayor et al., 2013).

Increasing phosphorus rates did not lead to an increase in aerial, root, or total dry matter production in *Erythrina velutina*; on the contrary, a decreasing trend was observed from 250 mg dm^{-3} onwards, possibly due to phosphorus toxicity or saturation, a condition in which excessive rates are not efficiently absorbed, impairing root growth and compromising overall plant development (Takagi et al., 2020; Zhang et al., 2024).

Significant differences were found between the forest species for the shoot/root ratio (SRR), diameter/height ratio (HDR), and Dickson Quality Index (DQI), indicating that the species differ in their strategies of biomass allocation and growth in height and diameter (Table 3).

For the interaction between species and phosphorus rates, a significant effect was observed only for DQI, indicating that this index was sensitive to the applied rates depending on the species evaluated (Table 3). Regression analysis between phosphorus rates and DQI for *Erythrina velutina* revealed no increase in DQI with higher phosphorus rates, indicating that variations in phosphorus supply did not result in significant changes in the structural quality of seedlings of this species (Figure 2).

Table 3 - Shoot/root ratio (SRR), height/diameter ratio (HDR), and Dickson Quality Index (DQI) of forest seedlings (*Piptadenia stipulacea*, *Erythrina velutina*, and *Libidibia ferrea*) grown under different phosphorus rates incorporated into the soil, evaluated 60 days after sowing.

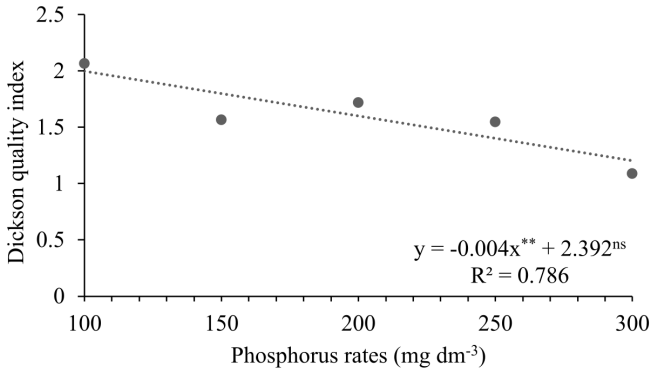
Analyzed variables			
	SRR	HDR	DQI
Sources of variation	**F test**		
Species (S)	71.22**	672.29**	498.01**
Phosphorus rates (P)	0.70^{ns}	0.08^{ns}	5.66**
S x P	0.79^{ns}	0.45^{ns}	6.89**
CV (%)	61.24	13.94	26.70

continued...

Table 3 - Continuation

Comparison of means for main effects			
	SRR	**HDR**	**DQI**
Forest species			
Erythrina velutina	2.56 c	3.46 c	1.59 a
Piptadenia stipulacea	41.79 a	24.96 a	0.14 c
Libidibia ferrea	14.13 b	16.54 b	0.27 b
Phosphorus rates in mg dm^{-3}			
100	22.81	15.09	0.81
150	17.70	15.04	0.66
200	16.32	14.87	0.72
250	20.99	15.13	0.65
300	19.66	14.78	0.51

Means followed by the same lowercase letter within each column do not differ from each other by the Tukey test, at a 5% probability level. ^{ns}; ** and *: Not significant and significant at 1% and 5% probability, respectively.



^{ns}; ** and *: Not significant and significant at 1% and 5% probability.

Figure 2 - Dickson Quality Index (DQI) of *Erythrina velutina* seedlings grown under different phosphorus rates incorporated into the soil, evaluated 60 days after sowing.

The significant effect of species on the variables shoot/root ratio (SRR), height/diameter ratio (HDR), and the structural quality index (DQI) confirms that different forest species adopt distinct biomass allocation and growth strategies, a concept widely documented in literature. Biomass allocation between aerial part and root components is a crucial trait of plant growth and is closely related to environmental adaptation (Fang et al., 2023). *Erythrina velutina* stood out for showing the lowest SRR and HDR values and the highest DQI, indicating a more balanced allocation between shoot and root biomass, which is indicative of better seedling structural quality (Qi et al., 2019).

In contrast, *Piptadenia stipulacea* exhibited the highest values for SRR and HDR, but the lowest DQI, suggesting an unbalanced growth pattern, with greater biomass allocation to shoots and limited root development, which negatively impacts seedling structural quality (Zhu et al., 2023), as it reduces stability, and overall field performance. This type of response may be related to the species' physiological characteristics, which prioritize height and diameter growth over root development, which is critical for nutrient and water uptake, especially under limiting environmental conditions.

The significant effect of phosphorus rates on DQI, but not on SRR and HDR, suggests that phosphorus influences seedling structural quality without directly altering biomass allocation patterns in terms of height and diameter. This result is supported by recent studies indicating that phosphorus can affect seedling structure and quality by influencing the growth symmetry between aerial and root components (Toro et al., 2022).

Although increasing phosphorus rates did not enhance DQI, the decreasing trend observed in DQI at higher rates suggests that excessive phosphorus supply may have caused an imbalance between aerial and root growth, compromising seedling structural quality. This supports the notion that excessive supply of nutrients, especially phosphorus, can lead to disproportionate aerial growth relative to the root system, reducing seedling quality (Khan et al., 2023). High

phosphorus rates may inhibit the absorption of other nutrients, such as iron, zinc, and manganese, leading to nutritional imbalances that compromise overall plant health (Santos et al., 2021).

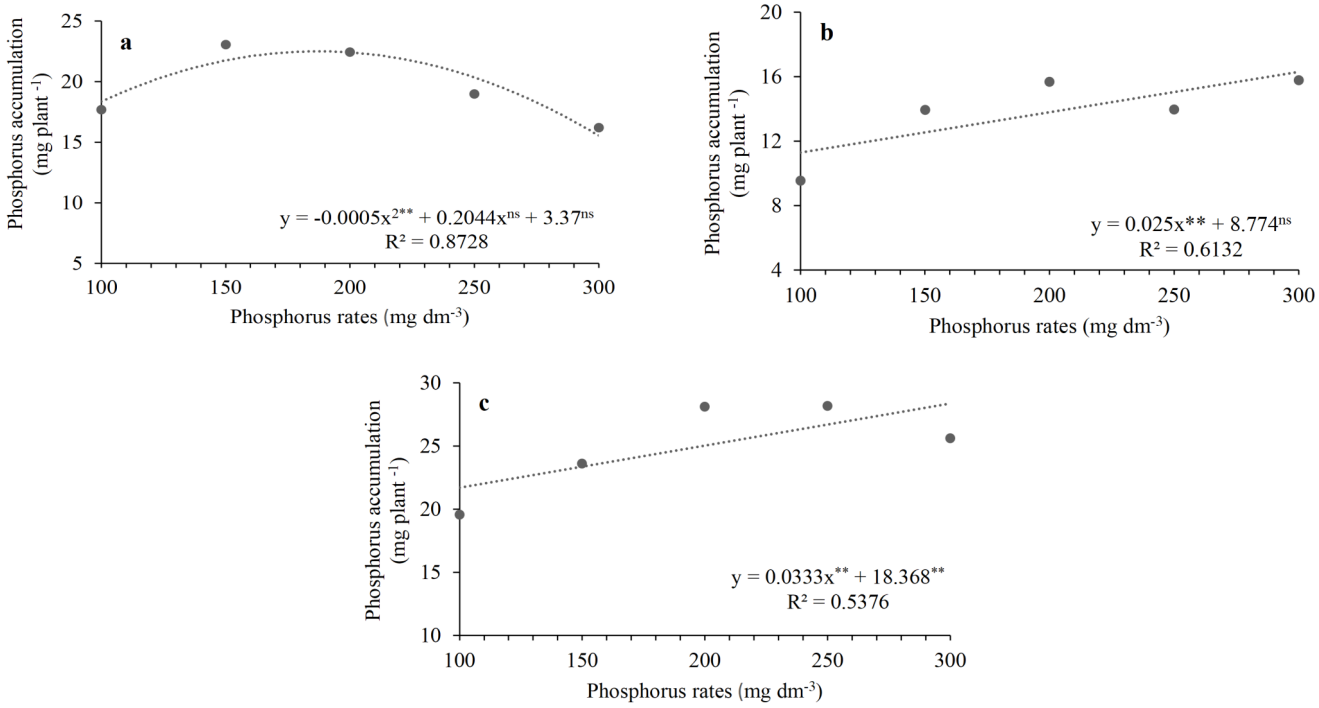
The analysis of variance indicated that both forest species and phosphorus rates had a significant effect on phosphorus content (P), phosphorus use efficiency (PUE), and phosphorus accumulation (PA). Furthermore, significant interaction between species and phosphorus rates was observed for PUE and PA only, suggesting that the response of these variables depends on the specific combination of species and the applied phosphorus rates. Regarding phosphorus content, *Erythrina velutina* and *Piptadenia stipulacea* showed higher values, significantly differing from *Libidibia ferrea*, which had the lowest content. In terms of PUE, *Libidibia ferrea* and *Piptadenia stipulacea* exhibited the highest values, showing greater efficiency in utilizing the applied phosphorus, whereas *Erythrina velutina* had lower efficiency. Phosphorus accumulation was greatest in *Piptadenia stipulacea*, followed by *Erythrina velutina* and *Libidibia ferrea*, highlighting the superior capacity of *Piptadenia stipulacea* to store phosphorus in its tissues (Table 4).

Table 4 - Phosphorus content (P, g kg^{-1}), phosphorus use efficiency (PUE, g^2 mg^{-1}), and phosphorus accumulation (PA, mg $plant^{-1}$) of forest seedlings (*Piptadenia stipulacea*, *Erythrina velutina*, and *Libidibia ferrea*) grown under different phosphorus rates incorporated into the soil, evaluated 60 days after sowing.

Analyzed variables			
	P (g kg^{-1})	**PUE (g^2 mg^{-1})**	**PA (mg $plant^{-1}$)**
Sources of variation		**F test**	
Species (S)	99.74**	98.06**	96.74**
Phosphorus rates (P)	7.55**	9.48**	10.63**
S x P	1.71ns	5.10**	3.30**
CV (%)	13.37	18.86	14.66
Comparison of means for main effects			
	P (g kg^{-1})	**PUE (g^2 mg^{-1})**	**PA (mg $plant^{-1}$)**
Forest species			
Erythrina velutina	3.03 a	2.15 c	19.67 b
Piptadenia stipulacea	2.84 a	3.18 b	25.02 a
Libidibia ferrea	1.77 b	3.18 a	13.78 c
Phosphorus rates in mg dm^{-3}			
100	2.15	4.18	15.60
150	2.57	3.30	20.20
200	2.79	2.98	22.07
250	2.67	3.00	20.37
300	2.57	3.12	19.21

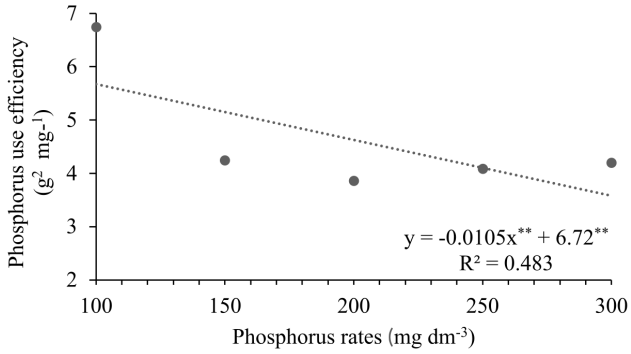
Means followed by the same lowercase letter within each column do not differ from each other by the Tukey test, at a 5% probability level. ns; ** and *: Not significant and significant at 1% and 5% probability, respectively.

The regression analysis between applied phosphorus rates and phosphorus accumulation in the forest species *Erythrina velutina*, *Libidibia ferrea*, and *Piptadenia stipulacea*. Showed no significant effect for *Erythrina velutina* (a) and *Libidibia ferrea* (b), indicating that increasing phosphorus availability did not result in substantial improvements in nutrient uptake and storage. In contrast, for *Piptadenia stipulacea* (c), the regression was significant, suggesting that this species responds positively to higher phosphorus availability in the soil, with increased accumulation of the nutrient in plant tissues (Figure 3). The regression analysis between phosphorus rates and phosphorus accumulation efficiency for *Libidibia ferrea* indicated that increasing phosphorus availability in the soil did not result in significant changes in the species' capacity to efficiently accumulate the nutrient (Figure 4).



ns; ** and *: Not significant and significant at 1% and 5% probability.

Figure 3 - Phosphorus accumulation (PA, mg plant^{-1}) for seedlings of *Erythrina velutina* (a), *Libidibia ferrea* (b), and *Piptadenia stipulacea* (c) grown under different phosphorus rates incorporated into the soil, evaluated 60 days after sowing.



ns; ** and *: Not significant and significant at 1% and 5% probability.

Figure 4 - Phosphorus use efficiency (PUE, g^2 mg^{-1}) of *Libidibia ferrea* seedlings grown under different phosphorus rates incorporated into the soil, evaluated 60 days after sowing.

The results indicate that both phosphorus content in plant tissues and phosphorus use efficiency are influenced by species characteristics. *Piptadenia stipulacea* showed the highest values of phosphorus content, phosphorus accumulation (PA), and phosphorus use efficiency (PUE), while *Libidibia ferrea* had the lowest values. These findings are consistent with studies demonstrating that different species vary in their capacities for phosphorus uptake, translocation, and allocation within plant tissues (Qi et al., 2019).

Erythrina velutina, in turn, showed a more balanced growth profile, although with lower phosphorus use efficiency compared to the other species. This suggests that, although this species accumulates phosphorus reasonably well, its capacity to utilize this nutrient is more limited, possibly due to a less efficient absorption system or lower physiological plasticity in response to phosphorus availability (Zalamea et al., 2016). The observed variation among species in phosphorus content and PUE is a significant factor that can guide fertilization management strategies. Species with higher phosphorus use efficiency may require lower nutrient concentrations to achieve satisfactory levels of growth and accumulation (Turner et al., 2018).

This not only contributes to more cost-effective practices but also supports environmentally sustainable resource management by minimizing excess phosphorus application and potential environmental impacts.

CONCLUSION

This study demonstrated that the response of native Caatinga species to phosphorus fertilization varies according to specific growth patterns, biomass allocation strategies, and nutrient use efficiency.

Piptadenia stipulacea exhibited the highest total biomass and phosphorus accumulation, indicating a strong capacity to store phosphorus in its tissues.

Erythrina velutina showed a more balanced growth profile, with high structural quality and substantial root development, although its phosphorus use efficiency was lower.

Libidibia ferrea had intermediate biomass production but high phosphorus use efficiency, suggesting efficient utilization of available phosphorus.

Soil phosphorus rates influenced growth and phosphorus accumulation differently between the species. For *Erythrina velutina*, the optimal phosphorus rate to maximize aboveground biomass was approximately 180 mg dm^{-3}, above which growth declined, indicating potential nutrient saturation. For *Libidibia ferrea*, growth and phosphorus use efficiency were adequate at 150–200 mg dm^{-3}, whereas *Piptadenia stipulacea* responded positively to higher phosphorus rates, with optimal accumulation observed at approximately 200–250 mg dm^{-3}.

Therefore, the recommended phosphorus rates for nursery fertilization are approximately 180 mg dm^{-3} for *Erythrina velutina* and 150–200 mg dm^{-3} for *Libidibia ferrea*. These species-specific recommendations can improve seedling quality, enhance phosphorus use efficiency, and support more sustainable and cost-effective restoration practices in the semi-arid Caatinga biome.

ACKNOWLEDGMENTS

The authors thank the Federal University of Ceará for the structural support provided for the development of this study. J.M.R.S. also thanks FUNCAP (Ceara Foundation to Support Scientific and Technological Development) for the scholarship grant under process number BMD-0008-01029.01.08/23 and CAPES (Coordination for the Improvement of Higher Education Personnel) for the financing of the research (code 001).

COMPLIANCE WITH ETHICAL STANDARDS

Author's contributions: Conceptualization: JMRS, ATIS; Data curation: JMRS, ATIS; Formal analysis: JMRS, ATIS; Funding acquisition: JMRS; Investigation: ATIS; Methodology: ATIS; Project administration: IS; Resources: JMRS; Software: CAKT; Supervision: IS, AGA; Validation: IS, CAKT, AGA; Visualization: JMRS, CAKT, AGA; Writing – original draft: JMRS, ATIS, CAKT, AGA; Writing – review & editing: JMRS, IS, CAKT, AGA.

Conflict of interest: The authors declare that there is no conflict of interest, whether professional or financial, that could have influenced the article.

Funding: The Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001, the Fundação Cearense de Apoio ao Desenvolvimento Científico e Tecnológico (FUNCAP) (BMD-0008-01029.01.08/23) and the Universidade Federal do Ceará.

LITERATURE CITED

Araújo, M.S.; Custódio, J.P.C.; Santos, B.F.A.; Pelá, A.; Coneglian, A. Growth and nutritional efficiency of Acácia seedlings in response to phosphate fertilization. Revista Brasileira de Ciências Agrárias, v.15, n.2, p.e7305, 2020. https://doi.org/10.5039/agraria.v15i2a7503.

Azevedo, S.R.V.; Sousa, G.G.; Ferreira, M.B.; Dutra Júnior, M.P.; Rocha, I.C.A.; Medeiros, J.R.; Pinto, M.G.C.; Santos, R.V. Influence of phosphorus on initial growth and production of fresh biomass of legumes. Journal of Experimental Agriculture International, v.42, n.2, p.51-59, 2020. https://doi.org/10.9734/jeai/2020/v42i430499.

Barbosa, J.C.; Maldonado Júnior, W. Experimentação agronômica e AgroEstat: sistema para análises estatísticas de ensaios agronômicos. Jaboticabal: Multipress, 2015. 396p.

Bellone, A.F.J.; Neves, E.J.M. Calagem e adubação em espécies florestais plantadas na propriedade rural. Colombo: Embrapa Florestas, 2001. 6p. (Embrapa Florestas. Circular Técnica, 54) https://www.infoteca.cnptia.embrapa.br/bitstream/doc/306311/1/CT0054.pdf. 26 Aug. 2025.

Cong, W.F.; Suriyagoda, L.D.B.; Lambers, H. Tightening the phosphorus cycle through phosphorus efficient crop genotypes. Trends in Plant Scence, v.25, n.10, p.967-975, 2020. https://doi.org/10.1016/j.tplants.2020.04.013.

Donagema, G.K.; Campos, D.V.B.; Calderano, S.B.; Teixeira, W.G.; Viana, J.H.M. Manual de métodos de análise de solos. 2.ed. Rio de Janeiro: Embrapa Solos, 2011. 230p. (Embrapa Solos. Documentos, 132). https://ainfo.cnptia.embrapa.br/digital/bitstream/item/77712/1/Manual-metodos-analis-solo-2.ed.pdf. 13 May. 2025.

Fang, T.; Rao, M.; Chen, Q.; Liu, S.; Lai, J.; Chen, T.; Ye, D. Different biomass allocation strategies of geophytes and non-geophytes along an altitude gradient. Ecological Indicator, v. 146, e109805, 2023. https://doi.org/10.1016/j.ecolind.2022.109805.

Fernandes, M.F.; Cardoso, D.; Queiroz, L.P. An updated plant checklist of the Brazilian Caatinga seasonally dry forests and woodlands reveals high species richness and endemism. Journal of Arid Environments, v.174, p.e104079, 2020. https://doi.org/10.1016/j.jaridenv.2019.104079.

Gomes, J.M.; Couto, L.; Leite, H.G.; Xavier, A.; Ribeiro, S.L. Parâmetros morfológicos na avaliação da qualidade de mudas de *Eucalyptus grandis*. Revista Árvore, v.26, n.6, p.655-664, 2002. https://doi.org/10.1590/S0100-67622002000600002.

Han, Y.; White, P.J.; Cheng, L. Mechanisms for improving phosphorus utilization efficiency in plants. Annals of Botany, v.129, n.3, p.247-258, 2022. https://doi.org/10.1093/aob/mcab145.

Hawkesford, M.J.; Cakmak, I.; Coskun, D.; De Kok, L.J.; Lambers, H.; Schjoerring, J.K.; White, P.J. Functions of macronutrients. In: Rengel, Z.; Cakmak, I.; White, P.J. (Eds.). Marschner's mineral nutrition of plants. 4.ed.

London: Academic Press, 2023. Chap. 6, p.201-281. https://doi.org/10.1016/B978-0-12-384905-2.00006-6.

IUSS Working Group WRB. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. 4.ed. Vienna: International Union of Soil Sciences (IUSS), 2022. 236p. https://files.isric.org/public/documents/WRB_fourth_edition_2022-12-18.pdf. 03 May. 2025.

Kemppinen, K.M.S.; Collins, P.M.; Hole, D.G.; Wolf, C.; Ripple, W.J.; Gerber, L.R. Global reforestation and biodiversity conservation. Conservation Biology, v.34, n.5, p.1221-1228, 2020. https://doi.org/10.1111/cobi.13478.

Kgaphola, M.J.; Ramoelo, A.; Odindi, J.; Kahinda, J-M. M.; Seetal, A. Apportioning human-induced and climate-induce land degradation: a case of the greater sekhukhune district municipality. Applied Sciences, v. 13, n. 6, e3644, 2023. https://doi.org/10.3390/app13063644.

Khan, F.; Siddique, A.B.; Shabala, S.; Zhou, M.; Zhao, C. Phosphorus plays key roles in regulating plants, physiological responses to abiotic stresses. Plants, v.12, n.15, p.e2861, 2023. https://doi.org/10.3390/plants12152861.

Kooch, Y.; Kartalaei, Z.M.; Amiri, M.; Zarafshar, M.; Shabani, S.; Mohammady, M. Soil health reduction following the conversion of primary vegetation covers in a semi-arid environment. Science of the Total Environment, v.921, p.e171113, 2024. https://doi.org/10.1016/j.scitotenv.2024.171113.

Mayor, J.R.; Wright, S.J.; Turner, B.L. Species-specific responses of foliar nutrients to long-term nitrogen and phosphorus addition in a lowland tropical forest. Journal of Ecology, v.102, n.1, p.36-44, 2013. https://doi.org/10.1111/1365-2745.12190.

Qi, Y.; Wei, W.; Chen, C.; Chen, L. Plant root-shoot biomass allocation over diverse biomes: A global synthesis. Global Ecology and Conservation, v.18, p.e00606, 2019. https://doi.org/10.1016/j.gecco.2019.e00606.

Rengel, Z.; Cakmak, I.; White, P.J. Marschener's mineral nutrition of plants. 4. ed. London. Academic Press, 2023. 816p. https://doi.org/10.1016/C2019-0-00491-8.

Santos, E.F.; Pongrac, P.; Reis, A.R.; Rabêlo, F.H.S.; Azevedo, R.A.; White, P.J.; Lavres, J. Unravelling homeostasis effetcs of phosphorus and zinc nutrition by leaf photochemistry and metabolic adjustment in cotton plants. Scientific Reports, v.11, p.e13746, 2021. https://doi.org/10.1038/s41598-021-93396-1.

Santos, J.M.R.; Pereira, A.P.A.; Moniz, T.C.D.; Henrique, G.S.; Barbosa, F.L.A.; Nascimento, I.V.; Queiroz, A.S.; Artur, A.G.; Silveira, M.R.S.; Costa, M.C.G.; Sousa, H.H.F.; Dias, C.T.S.; Ferreira, O.P.; Fregolente, L.G.; Souza Filho, A.G.; Oliveira, Filho, R.L.; Mota, J.C.A. Biochar as a strategy to mitigate greenhouse gases in degraded drylands of the brazilian semiarid region: carbon stocks and CO_2 fluxes. Journal of Plant Nutrition and Soil Science, v.0, p.1-13, 2025. https://doi.org/10.1002/jpln.70016.

Siddiqi, M.; Glass, A. Utilization index: a modified approach to the estimation and comparison of nutrient utilizations efficiency in plants. Journal of Plant Nutrition, v.4, n.3, p.289-302, 1981. https://doi.org/10.1080/01904168109362919.

Silva, B.F.; Rodrigues, R.Z.S.; Heiskanen, J.; Abera, T.A.; Gasparetto, S.C.; Biase, A.G.; Ballester, M.V.R.; Moura, Y.M.; Piedade, S.M.; Silva, A.K.O.; Camargo, P.B. Evaluating the temporal patterns of land use and precipitation under desertification in the semi-arid region on Brazil. Ecological Informatics, v.77, p.e102192, 2023. https://doi.org/10.1016/j.ecoinf.2023.102192.

Taiz, L.; Zeiger, E.; Møller, I.M., Murphy, A.F. Fisiologia e desenvolvimento vegetal. 6.ed. Porto Alegre, 2017. 888p.

Takagi, D.; Miyagi, A.; Tazoe, Y.; Suganami, M.; Kawai-Yamada, M.; Ueda, A.; Suzuki, Y.; Noguchi, K.; Hirotsu, N.; Makino, A. Phosphorus toxicity disrupts rubisco activation and reactive oxygen species defence systems by phytic acid accumulation in leaves. Plant Cell Environment, v.43, n.9, p.2033-2053, 2020. https://doi.org/10.1111/pce.13772.

Teixeira, P.C.; Donagemma, G.K.; Fontana, A.; Teixeira, W.G. Manual de métodos de análise de solo. 3.ed. Brasília: Embrapa, 2017. 574p. http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1085209. 03 May. 2025.

Toro, L.; Pereira-Arias, D.; Perez-Aviles, D.; Vargas, G.; Soper, F. M.; Gutknecht, J.; Powers, J. S. Phosphorus limitation of early growth differs between nitrogen-fixing and no- N-fixing dry tropical forest tree species. New Phytologist, v.237, n.3, p.766-779, 2022. https://doi.org/10.1111/nph.18612.

Turner, B.L.; Brenes-Arguedas, T.; Condit, R. Pervasive phosphorus limitation of tree species but not communities in tropical forests. Nature, v.555, p.367-370, 2018. https://doi.org/10.1038/nature25789.

Zalamea, P-C.; Turner, B.L.; Inverno, K.; Jones, F.A.; Sarmiento, C.; Dalling, J.W. Seedling growth responses to phosphorus reflects adult distribution patters of tropical trees. New Phytologist, v.212, n.2, p. 400-408, 2016. https://doi.org/10.1111/nph.14045.

Zhang, K.; Zheng, D.; Gu, Y.; Xu, J.; Wang, M.; Um, B.; Wen, S.; Tang, T.; Rengel, Z.; Shen, J. Utilizing soil organic phosphorus for sustainable crop production: insights into the rhizosphere. Plant and Soil, v.498, p.57-75, 2024. https://doi.org/10.1007/s11104-023-06136-x.

Zhu, H.; Bing, H.; Wu, Y.; Sun, H.; Tian, X.; Zhou, J. Species-dependent phosphorus acquisition strategy modulates soil phosphorus cycle in the subalpine forest of Eastern Tibetan Plateau. Applied Soil Ecology, v.195, p.e105253, 2024. https://doi.org/10.1016/j.apsoil.2023.105253.

Zhu, J.; Jiang, L.; Chen, L.; Jin, X.; Xing, C.; Liu, J.; Yang, Y.; He, Z. Tree seedling growth allocation of Castanopsis Kawakamii is determined by seed-relative positions. Frontiers in Plant Science, v.14, p.e1099139, 2023.