

## ORIGINAL ARTICLE

## NPK absorption, translocation and usage efficiency in seedlings of *Agonandra brasiliensis* in different substrates

### Eficiência de absorção, translocação e uso de NPK em mudas de *Agonandra brasiliensis* em diferentes substratos

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## ABSTRACT

The practice of controlled-release fertiliser in the nursery phase deserves highlighting because it is potentially capable of reducing the negative effects of available fertilizers, especially regarding losses due to leaching, a factor that maximizes costs and causes environmental damage. The aim of this study was to determine nutrient efficiency for the macronutrients N, P and K in seedlings of *Agonandra brasiliensis* in five different substrates with and without CRF, and relate the nutrient efficiency indices to growth variables. The experimental design was completely randomised in a 2x5 factorial scheme: with and without the addition of 2.0 g L<sup>-1</sup> encapsulated controlled-release fertiliser (CRF) (NPK formulation 18-05-09) and five substrates, with five replications, each replication comprising five seedlings. Substrate 5 (Sub5 - 75% soil + 25% organic substrate (v 3:1)) with CRF is recommended for promoting the efficient absorption, translocation and use of NPK, reflecting in the accumulation of root biomass in *Agonandra brasiliensis*. Plants of *Agonandra brasiliensis* grown in different substrates with no CRF show a distinct behaviour in terms of nutrient efficiency. In Substrate 3 and Substrate 5 with CRF, *Agonandra brasiliensis* is efficient in absorbing, translocating and using nitrogen and phosphorus. These morphophysiological characteristics suggest that plants of *Agonandra brasiliensis* are more vigorous, adapting well after planting even in places where the natural fertility of the soil is low, typical of the region where *Agonandra brasiliensis*, native to northern Brazil, occurs naturally.

**Keywords:** Controlled-release fertiliser; Nutrient efficiency; *Pau-marfim*; Plant nutrition.

## RESUMO

A prática de fertilização de liberação controlada na fase de viveiro merecem destaque por serem potencialmente capazes de reduzir os efeitos negativos dos fertilizantes prontamente disponíveis, principalmente no que se refere as perdas por lixiviação, fator que maximiza os custos e ocasiona danos ambientais. Objetivou-se determinar a eficiência nutricional para os macronutrientes N-P-K em mudas de *Agonandra brasiliensis* com cinco substratos alternativos com e sem FLC, bem como, relacionar os índices de eficiência nutricional com as variáveis de crescimento. O delineamento experimental adotado foi o inteiramente casualizado em esquema fatorial 2x5 sendo eles sem adição e com adição de 2,0 g L<sup>-1</sup> fertilizante encapsulado de liberação controlada (FLC) (formulação NPK 18-05-09) e cinco substratos, com cinco repetições, sendo cada repetição composta por cinco plântulas. O Substrato 5 (Sub5 75% solo+ 25% substrato orgânico (v 3:1)) com FLC é indicado por promover eficiência na absorção, translocação e uso de NPK refletindo no acúmulo de biomassa radicular em plantas de *Agonandra brasiliensis*. Plantas de *Agonandra brasiliensis* desenvolvidas nos substratos alternativos sem FLC apresentam estratégias diferenciadas nos índices de eficiência nutricional. No substrato 3 e substrato 5 com FLC, plantas de *Agonandra brasiliensis* são eficientes na absorção, translocação e uso de Nitrogênio e Fósforo. Estas características morfofisiológicas sugerem que as plantas de *Agonandra brasiliensis* poderão apresentar-se vigorosas, com adaptação no pós-plantio em áreas de restauração florestal, mesmo em locais de baixa fertilidade natural do solo típicos da região de ocorrência natural da *Agonandra brasiliensis* nativa do Norte Brasil.

**Palavras-chave:** Fertilizante de liberação controlada; Eficiência nutricional; *Pau-marfim*; Nutrição vegetal.



## 1. INTRODUCTION

Among the most important species in from Panama to Argentina, including Colombia, Venezuela, Guyana, Suriname, Peru, Bolivia, and Brazil, *Agonandra brasiliensis* Miers ex Benth. & Hook. F., belonging to family *Opiliaceae*, is widely found in the state of Roraima (Smiderle & Souza, 2022; Montenegro et al., 2022).

The species *Agonandra brasiliensis* has been the subject of recent research to demonstrate its economic potential (providing wood for various noble uses) and environmental potential, as it produces fruits that are attractive to wildlife in general (Smiderle et al., 2020, 2021). The various uses associated with it are attractive, but because it is a climax species (adapted to shade), it has slow growth (Montenegro et al., 2022), and after planting, its success and resilience in new conditions is directly related to the nutritional status of the seedlings.

Despite advances in the production of seedlings of native tree species in the north of Brazil, there are still major gaps in our knowledge of how to propagate these species under nursery conditions to produce seedlings for restoration or forest plantations (Smiderle et al., 2024). When establishing forest plantations, whether for commercial purposes or forest restoration, a number of factors affect seedling formation, including the quality of the seeds, volume of the container, type of substrate, fertiliser and management during the production process (Silva et al., 2025).

According to Menegatti et al. (2019), the ideal substrate is of uniform composition and low density, with good field capacity, cation exchange, water retention and porosity, but also adequate aeration and drainage and is free from pests and pathogens. In seedling production, enriching the substrate with fertilisers is strongly recommended (Menegatti et al., 2020), since the substrate alone generally does not provide enough nutrients for optimal plant growth (Souza et al., 2020; Rodrigues et al., 2025).

Important among available fertilisers are the controlled-release fertilisers (CLF). These are characterised by their slow release, allowing the ideal amount of nutrients to be absorbed during seedling growth, minimising the risk of deficiency (Souza & Smiderle, 2023; Roubuste et al., 2025) and allowing vigorous seedlings to form in less time, which results in reduced production costs as the seedlings spend less time in the nursery (Menegatti et al., 2019).

The nutrient efficiency of forest species is related to their capacity for absorbing, translocating and utilising nutrients, and can be estimated from nutrient efficiency indices obtained by recording nutrient and dry matter accumulation in the plants (Souza et al., 2020). These indices are an aid for recommending genotypes that are efficient at using nutrients for the different soil conditions in the area (Jimenes et al., 2018).

Variations in nutrient accumulation in forest seedlings have been found (Souza et al., 2020) to a greater or lesser extent in the different plant organs, which can be attributed to differences in nutrient requirements (Menegatti et al., 2021) and to molecular and biochemical factors that modify the levels of nutrient absorption (Paula et al., 2018), as well as reflecting their effective translocation and usage in the various organs (root, stem and leaves).

Forest plantations that are more efficient in absorbing, translocating and utilising certain nutrients can be grown in soils where nutrient availability is low, while less efficient plants, albeit with other characteristics of interest to the market, can be used where nutrient availability is high, avoiding the excessive use of nutritional fertiliser and ensuring better nutrient use by the plant (Martinez et al., 2024), thereby reducing production costs and impacts on the environment.

This scenario reinforces the need to improve the seedling production system, which can be enhanced through nutritional management techniques, such as fertiliser, plants in the nursery phase (Souza et al., 2026), considering nutritional efficiency according to the species. Such procedures may contribute to the early production of *Agonandra brasiliensis* seedlings with adequate nutritional status, which may subsequently become vigorous forest plantations with competitive productive potential.

The aim of this study was to determine nutrient efficiency for nitrogen, phosphorus and potassium in plants of *Agonandra brasiliensis* in five different substrates with and without controlled-release fertiliser, and relate the nutrient efficiency indices to the growth variables.

## 2. MATERIAL AND METHODS

Seeds of *Agonandra brasiliensis* Miers ex Benth. & Hook were collected from 12 mother trees in the Nova Olinda mountains in Boa Vista, Roraima, in March 2022 (2°56'58.99" N, 60°44'48.30" W). The experiment was conducted from September 2022 to June 2023 in the seed analysis laboratory and the screened nursery under 50% luminosity at Embrapa Roraima, located between 2°45'22" N and 60°43'55" W, at an average altitude of 80 metres. According to the classification of Köppen, the climate of the municipality of Boa Vista - RR is of the Am type (tropical monsoon climate), with a mean temperature of 27.2 °C in the warmest month and 23.3 °C in the coldest month, the annual mean being 25.4 °C. The mean annual rainfall is 1808 mm with mean values of 365 mm and 26 mm for the months of higher (June) and lower (February) rainfall, respectively (Alvares et al., 2013).

After obtaining the fruit, they were processed and the seeds sown in a seedbed containing medium-grain washed sand as a substrate for the germination and initial development of the seedlings. Substrate moisture was maintained by automatic irrigation, watering four times daily.

Seedling emergence began approximately 30 days after sowing, and once the seedlings reached an average height of around 12 cm, they were transplanted into polyethylene bags (15 x 35 cm) containing different combinations of substrate: T1 = Sub1 - medium sand (v 1); T2 = Sub2 - 66% soil (sandy loam (25% clay)) + 33% medium sand (v 2:1); T3 = Sub3 - 50% medium sand + 50% organic substrate (v 1:1); T4 = Sub4 - 75% soil + 25% carbonised rice husks (3:1); T5 = Sub5 - 75% soil + 25% organic substrate (v 3:1), in which doses of controlled-release fertiliser (CRF) (NPK formulation 18-05-09) were incorporated into the surface based on each treatment (Table 1).

The organic compost was obtained from the composting process of crop residues from a cupuaçu orchard, in a family agricultural production area in the municipality of Pacaraima/RR, using leaves, branches and twigs with symptoms of witches' broom resulting from phytosanitary pruning, as well as cupuaçu peels and seeds discarded after fruit processing. These residues were shredded using shredders and organized into piles, with layers of vegetable waste interspersed with layers of manure, in a ratio of 3:1, respectively, inside wooden composting compartments with a maximum height of 1.5 meters. The material was turned every 5 days for the first 15 days, and then every 10 days after that period, being watered during the first 14 days. The organic compost obtained from the composting process was stored and subsequently used in this study.

A graduated beaker with a capacity of 1,000 mL was used to measure the required amounts of the components used to make up the substrate; after homogenisation, samples of each treatment were separated for later chemical analysis (Table 1).

**Table 1.** Chemical characteristics of the different combinations and proportions of sand, soil, organic compost and rice husks used in cultivating seedlings of *Agonandra brasiliensis*

Treat.	pH	K	P	Ca	Mg	Al	H+Al	OM	Zn	Fe	Mn	Cu	B	S
		-----mg/dm <sup>3</sup> ----		-----cmol/dm <sup>3</sup> -----				dag/kg	-----mg/dm <sup>3</sup> -----					
Sub1	5.7	0.08	0.10	0.01	0.0	0.0	0.0	0.1	0.7	0.4	1.0	0.0	0.0	0.2
Sub2	5.0	12.0	3.12	2.18	2.4	0.1	1.1	1.1	0.9	92.3	16.2	0.6	0.7	9.1
Sub3	5.2	14.0	4.90	10.2	5.0	0.1	0.7	4.2	24.4	93.5	20.9	0.6	0.8	10.7
Sub4	5.5	32.0	8.20	10.0	2.9	0.3	1.3	4.0	23.5	20.3	97.0	3.8	0.8	14.9
Sub5	5.2	92.0	11.2	9.9	1.6	0.2	1.2	4.8	24.3	27.9	21.2	1.0	0.7	25.9

Where: pH in water; Ca<sup>2+</sup> and Mg<sup>2+</sup>: KCl extractor (1 mol L<sup>-1</sup>); K<sup>+</sup> and P: Mehlich 1 extractor; H+Al: SMP extractor; Sub1= medium sand (v 1); Sub2= 66% soil + 33% medium sand (v 2:1); Sub3= 50% medium sand + 50% organic substrate (v 1:1); Sub4= 75% soil + 25% carbonised rice husks (3:1); Sub5 = 75% soil + 25% organic substrate (v 3:1)

The experimental design was completely randomised in a 2x5 factorial scheme, with and without the addition of 2.0 g L<sup>-1</sup> controlled-release fertiliser (CRF) (NPK formulation 18-05-09) and five substrates (Sub), with five replications, each replication comprising five seedlings. Controlled-release fertiliser (CRF) is a product consisting of granules containing a homogeneous combination of nutrients, coated with an organic resin that gradually releases the nutrients for up to six months, making them available during the plant's peak demand phases, preventing losses due to leaching and eliminating the need for split applications from other sources.

The following variables were evaluated 210 days after transplanting (DAT): shoot height (H) (measured with a graduated rule, in cm) and collar diameter (CD) (5 cm from the plant collar, using a digital calliper, in mm). The plants were then divided into roots, stems and leaves and dried in a forced air circulation oven at 65 ± 5 °C to constant weight to determine the individual dry weight (in grams) of the different parts of the plant: shoots (SDW), roots (RDW) and total dry matter (TDW) (in g plant<sup>-1</sup>). The material was then ground and stored.

Samples of the dried and ground material were later used to determine the N, P and K content of the roots and shoots, as per the method described by the Official Network of Soil and Plant Tissue Analysis Laboratories of RS and SC - ROLAS (Brazilian Society of Soil Sciences, 2016).

The nutrient efficiency indices were calculated based on the dry weight and nutrient content of the plant: (a) absorption efficiency = (total nutrient content of the plant)/(root dry weight, [g g<sup>-1</sup>]) (Swiader et al., 1994); (b) translocation efficiency = [(nutrient content of the shoots)/(total nutrient content of the plant)] x 100 [%] (Li et al., 1991); (c) usage efficiency = (total dry weight produced)<sup>2</sup>/(total nutrient content of the plant) [g<sup>2</sup> g<sup>-1</sup>] (Siddiqi & Glass, 1981).

The data related to the characteristics under evaluation that express growth and nutrient efficiency underwent analysis of variance using the F-test; when significant, Tukey's test was carried out at 1% probability using the Sisvar software (Ferreira, 2014).

Principal component analysis was performed using R software version 4.4.2 (R Core Team, 2014).

### 3. RESULTS

The analysis of variance revealed significant differences (Table 2) in height and collar diameter (p<0.01) between the different combinations of substrates with and without the addition of CRF, demonstrating that the different combinations with and without CRF (Table 2) had a direct influence on the growth characteristics of *Agonandra brasiliensis* under nursery conditions at 210 DAT.

It can be seen from the result of the means comparison test that plants of *Agonandra brasiliensis* grown in Sub1 with no CRF obtained, measured 43.0% less for plant height compared to the other

substrates with no CRF. However, the values for substrates Sub2, Sub3, Sub4 and Sub5 with no CRF did not differ significantly from each other (Table 2). The collar diameter of plants grown in Sub5 with no CRF was around 4.0 mm, an increase of 35% in collar diameter compared to Sub1 (control treatment) at 210 DAT (Table 2).

When comparing the growth in H and CD between the different substrates with and without added CRF, the plants of *Agonandra brasiliensis* with CRF were superior for these variables. Such results suggest greater efficiency in the absorption and use of nutrients (Table 4) for maintaining the physiological processes that culminate in plant growth, a fact seen in the present study with the above variables (Table 2).

It should be noted that plants of *Agonandra brasiliensis* in Sub5 with CRF tend to be more homogeneous, albeit with a greater accumulation of RDW (Table 4).

It is worth noting that Sub5, with and without CRF, was more efficient for the absorption (AE), using (UE) and translocating (TE) nitrogen from the roots to the shoots. This suggests that the amount of translocated N was efficiently converted into useful photoassimilates for maximising the biomass of the shoots and root system (Table 3) of the plants.

In general, for plants of *Agonandra brasiliensis*, CRF at a dose of 2.0 g L<sup>-1</sup> in the different substrates was sufficient to promote greater efficiency in the absorption and translocation of N (Table 4), directing the conversion of this nutrient to build the cellular machinery that produces energy in the root itself. It is presumed that the energy produced in the cellular machinery was used for a greater proportion of biomass. This explains the superiority in RDW (Table 4) and the poor performance of this variable in the various substrates without CRF (Table 3).

These results also suggest that the root system of *Agonandra brasiliensis* has a high expansion capacity, as evidenced by its superior RDW, as well as the preferential allocation of N to the roots over shoots.

Thus, plants of *Agonandra brasiliensis* grown in Sub5 with CRF are expected to show greater K usage efficiency (Table 4), and consequently greater NR activity and a superior capacity for absorbing and assimilating available nitrate. This would result in an increased capacity for dry weight accumulation, as seen to a greater extent in the roots and shoots of *Agonandra brasiliensis*.

The second quadrant (Figure 1A), where Sub1, Sub2 and Sub4 with CRF are located (Figure 1A), is classified as non-efficient and reactive (NER), i.e. it has values below the mean for the abscissa and above the mean for the ordinate, showing low N absorption, translocation and usage efficiency.

In Figure 1B for phosphorus (P), the first two components (PC1 and PC2) explained 85.4%, with 9% explained by PC2. The relationship between PC1 and PC2 was therefore efficient in splitting the treatments into two groups: one on the right, in which the various substrates with

**Table 2.** Average height and collar diameter in plants of *Agonandra brasiliensis* in different substrates with and without CRF, at 210 days after transplanting

Substrate	Plant height (cm)		Stem diameter (mm)	
	No CRF	With CRF	No CRF	With CRF
SUB1	13.0 bB	33.8 bA	2.6 bB	4.8 aA
SUB2	21.0 abB	33.0 bA	3.6 abB	4.5 aA
SUB3	25.3 aB	38.8 abA	3.4 abB	4.2 aA
SUB4	20.5 abB	35.8 abA	3.6 abA	4.2 aA
SUB5	24.8 aB	46.3 aA	4.0 aB	4.9 aA
CV%	18.31		11.83	
MSD	9.08		0.96	

Lowercase letters (a, b), in a column compare the mean values of the variables between substrates. Uppercase letters (A, B) compare the mean values of the variables with and without CRF (NPK formulation 18-05-09) by Tukey's test at 1% probability. Sub1 = medium sand (v 1); Sub2 = 66% soil + 33% medium sand (v 2:1); Sub3 = 50% medium sand + 50% organic substrate (v 1:1); Sub4 = 75% soil + 25% carbonised rice husks (3:1); Sub5 = 75% soil + 25% organic substrate (v 3:1)

**Table 3.** Average values for shoot dry weight (SDW), root dry weight (RDW) and total dry weight (TDW) in seedlings of *Agonandra brasiliensis* in different substrates with and without CRF, at 210 days after transplanting

Substrate	g plant <sup>-1</sup>					
	SDW		RDW		TDW	
	No CRF	With CRF	No CRF	With CRF	No CRF	With CRF
SUB1	0.63 cB	2.96 bA	1.02 bB	4.08 cA	1.65 dB	7.03 dA
SUB2	1.47 aB	2.86 bcA	2.46 aB	4.73 bA	3.92 aB	7.59 cA
SUB3	0.96 bB	2.68 cA	2.50 aB	3.44 dA	3.45 bB	6.12 eA
SUB4	0.94 bB	2.94 bA	2.50 aB	5.09 bA	3.41 bcB	8.01 bA
SUB5	0.88 bB	3.23 aA	2.20 aB	5.49 aA	3.08 cB	8.72 aA
CV%	5.43		5.18		3.18	
MSD	0.21		0.35		0.34	

Lowercase letters (a, b, c, d, e), in a column compare the mean values of the variables within each substrate. Uppercase letters (A, B) compare the mean values of the variables with and without CRF (NPK formulation 18-05-09) by Tukey's test at 1% probability. Sub1= medium sand (v 1); Sub2 = 66% soil + 33% medium sand (v 2:1); Sub3 = 50% medium sand + 50% organic substrate (v 1:1); Sub4 = 75% soil + 25% carbonised rice husks (3:1); Sub5 = 75% soil + 25% organic substrate (v 3:1)

**Table 4.** Average values for the efficiency of absorption (AE), translocation (TE) and usage (UE) of macronutrients in the different substrates with and without CRF, at 210 days after transplanting, in plants of *Agonandra brasiliensis*

Substrate	AE (mg g <sup>-1</sup> )		TE (%)		UE (g <sup>2</sup> mg <sup>-1</sup> )	
	Nitrogen (N)					
	No CRF	With CRF	No CRF	With CRF	No CRF	With CRF
SUB1	52.57 dB	280.42 cA	21.20 dB	49.37 eA	0.100 cB	0.407 bA
SUB2	174.95 cB	319.32 bA	53.84 cB	51.23 dA	0.298 aB	0.364 cA
SUB3	177.30 cB	317.84 bAww	58.47 bB	59.03 cA	0.241 bB	0.309 dA
SUB4	208.57 bB	326.05 bA	59.14 bB	60.43 bA	0.226 bB	0.441 aA
SUB5	235.56 aB	361.32 aA	61.71 aB	62.68 aA	0.288 aB	0.436 aA
CV%	2.82	--	1.47	--	3.48	--
HSD	14.77	--	1.64	--	0.021	--

Substrate	AE (mg g <sup>-1</sup> )		TE (%)		UE (g <sup>2</sup> mg <sup>-1</sup> )	
	Phosphorus (P)					
	No CRF	With CRF	No CRF	With CRF	No CRF	With CRF
SUB1	6.44 eB	18.93 cA	1.97 eB	4.41 cA	0.180 bB	1.473 eA
SUB2	14.70 dB	16.40 dA	2.37 dB	3.67 eA	0.248 bB	1.195 dA
SUB3	17.86 cB	28.59 aA	2.45 cB	4.60 bA	0.300 bB	2.322 bA
SUB4	20.65 bB	23.22 bA	3.51 bB	4.08 dA	0.631 aB	2.087 cA
SUB5	22.86 aB	27.52 aA	3.96 aB	4.95 aA	0.773 aB	3.182 aA
CV%	2.69	--	3.38	--	9.30	--

Lowercase letters (a, b, c, d, e), in a column compare the mean values of the variables within each substrate. Uppercase letters (A, B) compare the mean values of the variables with and without CRF (NPK formulation 18-05-09) by Tukey's test at 1% probability. Sub1= medium sand (v 1); Sub2 = 66% soil + 33% medium sand (v 2:1); Sub3 = 50% medium sand + 50% organic substrate (v 1:1); Sub4 = 75% soil + 25% carbonised rice husks (3:1); Sub5 = 75% soil + 25% organic substrate (v 3:1)

Table 4. Continued...

Substrate	AE (mg g <sup>-1</sup> )		TE (%)		UE (g <sup>2</sup> mg <sup>-1</sup> )	
	Nitrogen (N)					
	No CRF	With CRF	No CRF	With CRF	No CRF	With CRF
HSD	1.12	--	0.25	--	0.23	--

Substrate	AE (mg g <sup>-1</sup> )		TE (%)		UE (g <sup>2</sup> mg <sup>-1</sup> )	
	Potassium (K)					
	No CRF	With CRF	No CRF	With CRF	No CRF	With CRF
SUB1	50.33 cB	215.37 bA	36.82 dB	64.35 cA	0.101 bB	2.985 cA
SUB2	60.81 cB	189.69 cA	43.64 cB	62.64 cA	0.415 abB	3.098 bA
SUB3	59.29 cB	217.72 bA	48.03 bB	70.98 bA	0.174 abB	3.100 bA
SUB4	90.67 bB	216.70 bA	56.41 aB	76.07 aA	0.344 abB	3.610 aA
SUB5	119.46 aB	258.95 aA	59.56 aA	79.00 aA	0.702 aB	3.633 aA
CV%	7.03	--	3.22	--	18.09	--
HSD	21.3	--	4.47	--	0.57	--

Lowercase letters (a, b, c, d, e), in a column compare the mean values of the variables within each substrate. Uppercase letters (A, B) compare the mean values of the variables with and without CRF (NPK formulation 18-05-09) by Tukey's test at 1% probability. Sub1= medium sand (v 1); Sub2 = 66% soil + 33% medium sand (v 2:1); Sub3 = 50% medium sand + 50% organic substrate (v 1:1); Sub4 = 75% soil + 25% carbonised rice husks (3:1); Sub5 = 75% soil + 25% organic substrate (v 3:1)

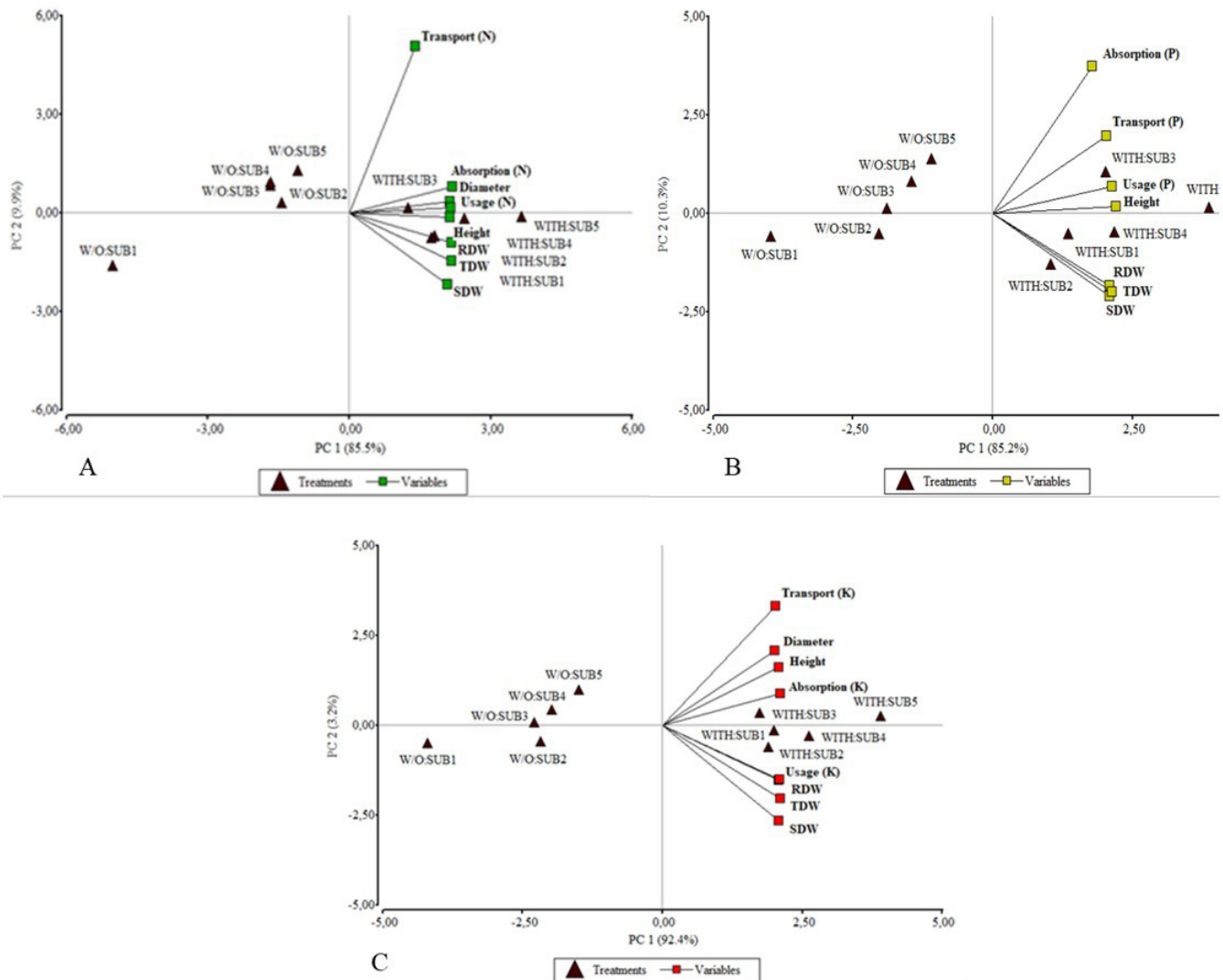


Figure 1. Principal component analysis of the variables for the different substrates with and without CRF, and the nutrient efficiency of nitrogen (A), phosphorus (B) and potassium (C) at 210 DAT, in plants of *Agonandra brasiliensis*

CRF were more closely related, and a group on the left, comprising the substrates with no CRF.

On the other hand, the best K usage efficiency can be seen in the second quadrant, in Sub1, Sub2 and Sub4 with CRF, for RDW, SDW and TDW (Figure 1C); classified as having high K usage and low efficiency in absorbing and translocating potassium (Figure 1C).

#### 4. DISCUSSION

Considering the relationship between the chemical characteristics of the substrate of each treatment without FLC addition on plant growth at 210 DAT, it is observed that sub 1 presented lower values for height and collar diameter (H and DC). This result can be understood according to the materials used in the composition of the substrates of each treatment. Sub 1, consisting of sand, which is a substrate devoid of mineral nutrients. This treatment may have compromised the production of various enzymes, proteins, and other compounds (Smiderle et al., 2021).

Furthermore, when the substrate is divided into small proportions of alternative substrates, it allows for better substrate aeration and good drainage. The promotion of the use of this material is based on its limited cost and ease of availability in some regions (Cavalcante et al., 2021). Organic compost, in different combinations of agricultural by-products, has the main function of improving water retention, in addition to providing macro and micronutrients; thus increasing their availability to plants and, consequently, improving seedling performance (Abaurre et al., 2021). This fact was evidenced in the present research for the substrates Sub3 = 50% medium sand + 50% organic substrate (v 1:1) and Sub5 = 75% soil + 25% organic substrate (v 3:1).

Smiderle et al. (2020), evaluating initial growth of *Agonandra brasiliensis* seedlings in response to different levels of shading and doses of controlled-release fertiliser, determined that a 2 g L<sup>-1</sup> dose of CRF and cultivation in a greenhouse under 50% luminosity maximises the growth of *Agonandra brasiliensis* and ensures the plant makes the best use of the inputs.

The addition of CRF guarantees nutrient availability, with the environment promoting efficient nutrient usage by the plants (Smiderle et al., 2020). N, present in the CRF formulation used in the above study, is an essential component of the photosynthetic system, used in the biosynthesis of chlorophylls and rubisco activity (Menegatti et al., 2021). This indirectly influences the maintenance of satisfactory rates of carbon assimilation (Pires et al., 2024). It is expected that plants of *Agonandra brasiliensis* fertilised with CRF exhibit a high production of photoassimilates and greater total dry matter (TDW) accumulation, as was seen in the present study (Table 3). This relationship can be shown by using the results obtained for shoot, root and total dry weight (Table 3), which showed a greater increase in plants grown with CRF compared to those grown with no CRF.

The greater TDW with the use of CRF shows that for the evaluated period, after pricking out, and referred to as initial plant growth, is actually the time when plants of *Agonandra brasiliensis* require readily available nutrients to maintain the physiological processes that determine energy conversion into plant biomass.

Similar results were obtained by Smiderle et al. (2020) with *Agonandra brasiliensis*, Souza & Smiderle (2023) with *Cordia alliodora*, Smiderle et al. (2023) with *Hymenaea courbaril* and Souza et al. (2018) with *Pochota fendleri*. They reported an increase in the total biomass of native forest seedlings in the northern Amazon area when using CRF in the nutritional management of plants in both a greenhouse and a screened nursery under 50% luminosity, demonstrating and underlining the efficiency of this type of fertiliser in the production of native forest seedlings.

The root system is responsible for the ability of the plants to absorb water and nutrients from the soil solution into the interior of the plant. Therefore, it is an important organ when vigorous plants for different soil conditions in forest plantations are to be recommended (Huang et al., 2016).

The absorption capacity of the roots may be the result of a series of metabolic processes related to genetic factors that limit the efficiency of N translocation, resulting in a higher concentration of nutrients in the roots in Sub5 with CRF (Table 4) and promoting greater root biomass (Table 3).

According to Menegatti et al. (2020), aspects that are intrinsic to the genotype, such as the expression, presence and activation of transporters, enzymes and proteins, control and regulate the absorption, translocation and use of nutrients.

Furthermore, nutrient use efficiency can vary between genotypes of the same species (Menegatti et al., 2021). The genotype with the highest nutritional efficiency is the one that, when fertilized with the lowest doses of a given nutrient, maximizes its conversion into biomass; a fact which was verified in the present study as seen in Table 3.

In general, efficient absorption refers to the ratio between the total content of a given nutrient in plant tissue and the dry mass of roots, while nutrient utilization efficiency is defined as the ratio between the total dry mass of the plant and the total accumulation of a given nutrient (Martinez et al., 2024).

Determined nutrient efficiency indices can be used as a criterion for recommending genotypes that are efficient in using the ions available in the soil (Pires et al., 2024). When determining the nutrient efficiency of the plants under evaluation, significant differences were recorded for efficient absorption, translocation and use of N, P and K within and between the different substrates, with and without CRF (Table 4).

According to Menegatti et al. (2020), nutrient translocation is due to the presence, expression and activity of certain ion transporters, based on their affinity for the available nutrient. This may or may not favour the entry of certain elements into the xylem (for transport), resulting in greater or lesser shoot vigour.

The plants of *Agonandra brasiliensis* showed different average values for the nutrient efficiency of phosphorus (P) between the different substrates with and without CRF (Table 4). According to Table 1, P is not a limiting element to the growth of *Agonandra brasiliensis* (Table 3).

However, despite the nutrient (P) being required in small quantities, as in the case of *Agonandra brasiliensis*, sufficient levels are essential to maintain plant metabolism, such as the formation and integrity of cell membranes, the process of cellular energy production and transfer involving ATP, and the metabolism of carbohydrates.

The more efficient P usage shown by plants of *Agonandra brasiliensis* in Sub5 with CRF may be related to the need for phosphorus for biochemical reactions, as well as the more efficient redistribution and mobilisation of P from the vacuoles to the growth points as needed (Menegatti et al., 2022).

It is evident that with the addition of CRF to the different substrates, plants of *Agonandra brasiliensis* are efficient in translocating P to the shoots; thus ensuring the nutrient is supplied to the photosynthetically active sites of the plant. This allows for energy production needed in carbon metabolism, while indirectly favouring greater biomass production, as seen in the present study (Table 3).

A similar result to that obtained for P was seen for potassium (K): plants of *Agonandra brasiliensis* were more efficient in the use of this nutrient compared to the different substrates with no CRF (Table 4). According to Souza et al. (2020), there is a close relationship between the use of K (i.e. between the total potassium content of the

tissues) and plant growth, due to the need for adequate amounts of K in the cytoplasm to maintain the various processes involving nitrogen metabolism.

Potassium influences the metabolic processes associated with incorporating mineral nitrogen in the form of nitrate, either by activating the enzyme nitrate reductase (NR) or by signalling the transcription and expression of genes related to the nitrate transporters responsible for N absorption (Souza et al., 2019).

According to Menegatti et al. (2022), the translocation of N from the roots to the shoots is facilitated by optimal concentrations of K<sup>+</sup> and NO<sup>3-</sup>, with K<sup>+</sup> acting as a counterion in the xylem sap, favouring NO<sup>3-</sup> transport to the shoots. On the other hand, at concentrations higher or lower than the needs of the plant, the transport of both nutrients is restricted, leading to accumulation in the root system, as was seen in the present study (Table 3).

When selecting the principal components, it is important to choose those with an eigenvalue greater than 1.0 and that concentrate the most significant variation in the data, so that it is possible to carry out a divergent grouping between the variables (Maia et al., 2024), as shown by the data from this study.

Maia et al. (2024) state that values for the first principal components greater than 70% are sufficient to explain the total variance between the variables. This is shown in Figure 1A, where the first two components (PC1 and PC2) together explain approximately 95.40% of the original variability of the results, of which, PC1 explained 85.5% and PC2 explained 9.9%. Since the differences in NPK absorption, translocation and usage efficiency in plants of *Agonandra brasiliensis* in the different substrates were grouped in the first quadrant, where Sub3 and Sub5 with CRF are located, they are considered efficient and responsive (ER) for CD with values above the average for the two Cartesian axes. As such, substrates Sub3 and Sub5 proved to be efficient in the absorption, translocation and use of nitrogen.

The diameter of the collar (CD), which is located in the aerial part of the plant, is usually responsible for the flow of nutrients from the roots to the shoots (Casali et al., 2011; Piccin et al., 2017; Kulmann et al., 2021), and is related to the absorption of N by the roots and the efficient use of the nutrient in the shoots (Table 3 and Table 4).

In the first quadrant for plant height in Sub5 with CRF, P was shown to be efficient for absorption, translocation and usage. The absorption, transport and redistribution of phosphorus in the plant can occur due to the action of several transporters in the cells, with distinct molecular structures, locations and functions (Shukla et al., 2016).

It is known that as plants grow, new roots are emitted, absorbing part of the P present in the soil solution, which increases the percentage of P in that organ (Xuan et al., 2017) and explains the presence of P in the root system. In young plants, most of the P present in the roots is redistributed to the growing organs of the shoots (H), especially the branches and leaves (Li et al., 2020; Herschbach et al., 2022), as seen in the present study (Figure 1B).

As for nutrient efficiency of the NPK under test, in general Sub3 and Sub5 can be recommended for the production of seedlings of *Agonandra brasiliensis*. In the first quadrant, potassium (K) was shown to be efficient for absorption and translocation, reflecting in greater plant height (H) and greater CD in Sub3 and Sub5 with CRF. These morpho-physiological characteristics suggest that plants of *Agonandra brasiliensis* from these treatments are more vigorous. It is expected that they would adapt well after planting even in places where the natural fertility of the soil is low, typical of the region where *Agonandra brasiliensis*, native to northern Brazil, occurs naturally.

## 5. CONCLUSIONS

Substrate Sub5 with CRF is recommended for promoting better efficiency in the absorption, translocation and use of NPK, as reflected in the accumulation of root biomass in plants of *Agonandra brasiliensis*. However, plants in different substrates with no CRF show a different behaviour for the nutrient efficiency indices.

In Sub3 and Sub5 with CRF, plants of *Agonandra brasiliensis* are efficient in the absorption, translocation and usage of nitrogen and phosphorus.

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## AUTHOR CONTRIBUTIONS

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AGS: conceptualization, data curation, data analysis, research, data validation, data presentation design, original manuscript writing; RAM: methodology, review; W.F.A: conceptualization, methodology, review; JNS: review; FCS: methodology, review; EUA: review; OJS: conceptualization, research, project management, supervision, review