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Full Length Article

Effect of NPK Fertilization on the Development of Young *Tachigali vulgaris* Plantations

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Abstract

The aim of the study was to evaluate the effect of nitrogen, phosphorus and potassium fertilization on the initial development of *Tachigali vulgaris* plantations for the production of forest biomass. The experiment was set up in the municipality of Igarapé-açu, Pará, Brazil and evaluated over one year. The planting was carried out with 1728 plants at a spacing of 2 m x 3 m and used a completely randomized design with seven fertilization treatments. Measurements included plant height and diameter, as well as leaf nutrient analysis. The results indicated significant growth responses to N, P and K, particularly in height, with plants that received 44.5 $kg.ha^{-1}$ of N showing the greatest increase (534 cm). Potassium also significantly influenced growth, with a notable average increase in height of 77 cm compared to plants without fertilization. Leaf nutrient analysis revealed better nutrient assimilation correlated with fertilizer applications. The study concluded that the combined fertilization of 44.5 $kg.ha^{-1}$ of nitrogen and 50 $kg.ha^{-1}$ of potassium improves the morphological development of *T. vulgaris*, representing an effective strategy for optimizing growth and productivity in forest plantations. These results demonstrate the importance of balanced fertilization for sustainable biomass production using the *T. vulgaris* species.

Keywords: Bioenergy; Fertilization management; Forest biomass; Planted forests; Sustainable wood

Introduction

The species *Tachigali vulgaris* L.G. Silva and H.C. Lima, popularly known as tachi-branco and carvoeiro, is native to South America and has a wide geographical distribution. In Brazil, it occurs from the North to the Southeast, especially in the states of Pará, Amazonas and Tocantins (Carvalho 1994). Its habitat consists of sandy, acidic soils with low chemical fertility and well-drained (Oliveira *et al.* 2006). It stands out for its rapid growth, high biomass production, and wood, which is used to produce thermal energy.

Plantations of the species are usually conducted on soils with low natural fertility and often management practices are not carried out correctly, reducing the productive potential of the stand (Sarcinelli *et al.* 2004). Although forest species can thrive in conditions of low nutrient availability, it is important to adopt silvicultural management practices and carry out soil fertility correction in areas cultivated with *T. vulgaris* to increase the productivity levels of forest sites, as well as maintain it for future rotations (Sousa *et al.* 2016). Management practices in forest plantations should consider the adoption of mineral or organic fertilization so that the soil provides the necessary nutrients and thus provides trees with satisfactory growth (Benites *et al.* 2010; Biagiotti *et al.* 2017).

To understand the factors that control forest growth and the use of natural resources, several studies have already been carried out (Hubbard *et al.* 2004; Yin *et al.* 2004; Teixeira *et al.* 2008; Machado *et al.* 2010). However, studies specifically investigating fertilization management with native Amazonian species are rare.

N is the nutrient found in the highest concentrations in

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higher plants, representing an essential component of proteins, nucleic acids, chlorophyll and many other secondary metabolites. Its role in metabolism has been extensively studied in most cultivated species, especially those with an annual cycle, but few studies have been conducted with forest species in tropical conditions (Jesus *et al.* 2012).

Fast-growing forest species, such as eucalyptus, can respond to fertilization, particularly with N, by increasing leaf area, with a consequent increase in trunk volume (Smethurst *et al.* 2003). In forest stands, the amount of N accumulated can range from 120 to 1.300 kg ha^{-1}, depending on the soil and climate conditions, the genetic material and the production of the stand (Barros *et al.* 1990).

Phosphorus (P) is essential for photosynthesis and plant growth, with leguminous crops highly responsive to phosphate fertilization (Chaudhary *et al.* 2008; Pour *et al.* 2021). Phosphate fertilization has been shown to increase photosynthetic rates and biomass production, especially in the early stages of growth (Fernandez *et al.* 2000; Melo *et al.* 2016; Pour *et al.* 2021). Potassium (K) is crucial for plant metabolism, favoring the synthesis of lipids, carbohydrates and proteins, as well as regulating stomatal movement (Haberman *et al.* 2019; Ragel *et al.* 2019). Studies indicate that photosynthesis in higher plants varies significantly according to K availability (Weng *et al.* 2007; Gerardeaux *et al*. 2009).

According to Crous *et al.* (2015), P has antagonistic effects on K uptake and synergistic on Mg uptake, and Ca has antagonistic effects on K and Mg uptake. Following this theory, fertilization with P (and Ca as an accompanying ion) in plantations with fast-growing forest species can influence the harvest, reducing K uptake and increasing or reducing Mg uptake. However, the effects of P (and Ca) fertilization on Mg and K acquisitions have been tested mainly on agricultural crops and there are no reports on tree species plantations, despite the importance of assessing nutrient dynamic from forest plantations.

Considering the high potential for energy plantations and the recovery of degraded areas, several recent studies have been carried out with *T. vulgaris*, in the most diverse areas, with emphasis on wood technology (Santos *et al.* 2024), ecophysiology and gas exchange (Simões *et al.* 2023), planting spacing (Barros-Junior *et al.* 2022), growth and seedling production (Souza *et al.* 2019). However, studies evaluating the growth of forests planted with the species under chemical fertilization are still rare in the global scientific literature.

Although there are studies on the growth of already established plantations, there is a need for more information on the initial growth of *T. vulgaris* and the ideal nutrient recommendations to speed up this process. Fertilizing with high doses of N, P and K can boost the initial start-up of the crop and facilitate the establishment of plantations of this species.

The study aimed to evaluate the effect of nitrogen, phosphorus and potassium fertilization on the initial development of *Tachigali vulgaris* plantations for the production of forest biomass.

Materials and Methods

Study area

The planting was carried out in an experimental area of the Federal Rural University of Amazonia (UFRA), in the municipality of Igarapé-açu, state of Pará, Brazil. It is located at the geographical coordinates: 01º07'33"S and 47º37'27"W of Greenwich (Fig. 1). According to Costa *et al.* (2013), the region's climate is classified as Am (Köppen classification), with an average annual temperature of 25ºC, annual rainfall reaching 2853 mm, with rainfall concentrated in January to June. The predominant soil in the region is yellow latosol (Rousseau *et al*. 2014).

Planting, experimental design and treatments

The planting of *T. vulgaris* was carried out in February 2016, in an area of 1.44 hectares, in a spacing of 2 m x 3 m (plants x rows), totaling 1728 plants (Fig. 2). To support the fertilization recommendations, a physical-chemical analysis of the soil was carried out in the 0–20 cm and 20–40 cm layers of the planting area (Table 1).

The amounts of fertilizer in each treatment were defined based on recommendations for other fast-growing forest species, such as those of the Eucalyptus genus and *Acacia mearnsii* (Schumacher *et al.* 2013; Silva *et al.* 2013). To supply the necessary amounts of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O), the fertilizers urea, triple superphosphate and potassium chloride were used, where the latter two were represented by the acronyms TSP and KCl, respectively.

The fertilizers mentioned above were used to form the treatments in a factorial arrangement: 0 (no fertilization); N (26 g of Urea); P (19.56 g of TSP); K (30 g of KCl); NP (26 g of Urea and 19.56 g of TSP); NK (26 g of Urea and 30 g of KCl); PK (19.56 g of TSP and 30 g of KCl) and NPK (26 g of Urea, 19.56 g of TSP and 30 g of KCl). The experimental design chosen was entirely randomized, consisting of plots of four plants and four repetitions per treatment, giving a total of 128 plants analyzed in the study. The fertilizers were applied as a top dressing, locally in the area where the tops of the plants protruded, 60 days after planting and repeated after 12 months.

Measurement of morphological variables

In the first year of planting, the diameter of the plants was measured at collar height (DAC), using a digital caliper, considering that the individuals did not have the minimum height for measuring diameter at breast height (DBH),

Table 1: Results of the chemical and physical characterization of the soil in the planting area

Chemical characterization												
Depth (cm)	P	OM	pH	K	Ca	Mg	H+Al	Al	SB	T	V	m
	mg dm^{-3}	g dm^{-3}	$CaCl_2$	mmolc dm^{-3}							%	%
0-20	2,3	18	4,3	0,4	5	1	38	5	6,9	44,9	15	42,0
20-40	2,4	15	4,3	0,4	4	1	30	7	6,1	36,1	17	53,4
Physical characterization												
	Clay HMFS + NaOH		Silt HMFS + NaOH		Sand total HMFS + NaOH				Silt + Clay HMFS + NaOH			
Depth (cm)	g kg^{-1}		g kg^{-1}		g kg^{-1}				g kg^{-1}			
0 – 20	184		90		726				274			
20 – 40	225		111		664				336			

Notes: pH = hydrogen potential; K^+ = potassium; Ca^{+2} = calcium; Mg^+ = magnesium; Al^{+3} = aluminum; H^+Al^{+3} = hydrogen and aluminum; SB = sum of bases of percentage of base saturation; CEC = Cation exchange capacity; P = phosphorus; V = base saturation; m = Al saturation; soil exchangeable K, Na, Ca and Mg contents were determined by atomic absorption spectrophotometry and flame spectrophotometry (Raij *et al.* 2001); HMFS (sodium hexametaphosphate) and NaOH (sodium hydroxide) were the industrial dispersants used by the laboratory to determine the physical analysis of the soil

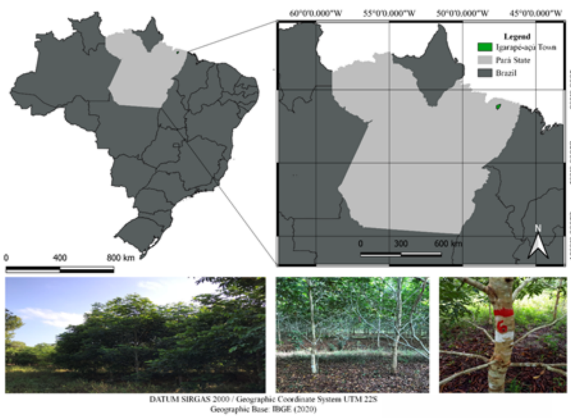

Fig. 1: Location of the municipality of Igarapé-Açú, place of planting of *T. vulgaris*, State of Pará, Brazil

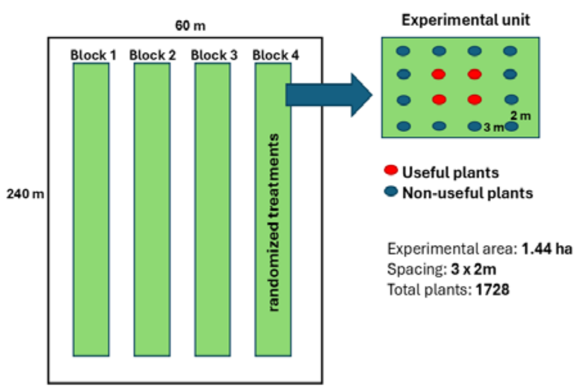

Fig. 2: Experimental design used in the experiment with *T. vulgaris plants*, Igarape-açu, Pará, Brazil

measured 1.3 m from the ground, which was measured from the second year of planting. To obtain the total height, a ruler graduated in centimeters was used, considering the insertion of the last branch of leaves.

Climatic data

A weather station located at latitude 01º07'33"S, longitude 47º37'27"W and altitude 45 m was installed near the experiment site to obtain weather data during the planting evaluation period.

Nutritional diagnosis

This was carried out to monitor the assimilation of fertilizers by the forest and to correct possible deficiencies in the experiment, combined with the results of the soil analysis. The leaves were collected 12 months after planting. From each of the 4 trees in the experimental units, 16 leaves were collected, 4 leaves per quadrant from the tips of the branches in the upper third of the canopy. The levels of nitrogen, phosphorus, potassium, sulphur, calcium, magnesium, copper, manganese, zinc and iron were analyzed, as described by Embrapa (2009).

Statistical analysis

The experimental data was assessed for normality and homogeneity of variance using the Shapiro-Wilk and Bartlett tests, respectively. Subsequently, for the parametric variables, the means of the treatments were subjected to analysis of repeated measures over time to obtain the variance and comparisons of means using the Tukey test, using the statistical software SAS 9.1.3 (SAS 2007). The relationships between the nitrogen, phosphorus and potassium treatments and their interactions on the development in diameter and height of *T. vulgaris* during the study period were analyzed. For the non-parametric variables, the data was evaluated using the Kruskal-Wallis test with Bonferroni and correction using the RStudio software version 1.1.383 (R Core team 2015). All analyses were evaluated at a significance level of 1%.

Results

Rainfall had minimum and maximum values of 34.2 and 510.2, respectively corresponding to times 6 and 4 of the year 2016, showing the seasons of high and low rainfall, characteristic of the Amazonian equatorial climate. Elevated temperatures were observed throughout the year, with

Table 2: Average height development (cm) and interaction over time as a function of the treatments applied to *T. vulgaris* plants, corresponding to the evaluation period of 2 years and 3 months of the experiment

Treatments	Time (quarterly)					
	0	1	2	3	4	Tukey's test
T0 (control)	70.25	86.44	123.50	146.75	190.50	a
T1 (26.67 g urea) ***	68.81	93.56	138.88	173.13	223.06	dbc
T2 (19.56 g TSP) ***	67.81	87.38	130.25	154.06	202.06	ca
T3 (30 g KCl) **	64.44	84.88	129.31	160.69	207.44	bca
T4 (26.67 g urea + 19.56 g TSP)	78.56	109.25	156.75	189.56	242.94	d
T5 (26.67 g urea + 30 g KCl) ***	78.31	102.81	148.50	179.44	226.44	db
T6 (19.56 g TSP + 30 g KCl)	75.50	96.81	141.69	182.81	235.44	d
T7 (26.67 g urea +19.56 g TSP + 30 g KCl)	77.25	103.63	151.94	182.63	234.13	db
Treatments	Time (quarterly)					
	5	6	7	8	9	Tukey's test
T0 (control)	246.94	324.06	368.45	426.20	502.85	a
T1 (26.67 g urea) ***	307.25	403.44	464.58	533.81	602.76	dbc
T2 (19.56 g TSP) ***	274.50	356.81	404.62	470.96	536.69	ca
T3 (30 g KCl) **	281,50	374.06	428.24	498.57	580.61	bca
T4 (26.67 g urea + 19.56 g TSP)	336.31	430.94	486.85	562.19	638.57	d
T5 (26.67 g urea + 30 g KCl) ***	304.06	407.38	467.04	535.58	595.84	db
T6 (19.56 g TSP + 30 g KCl)	332.88	440.94	495.29	575.52	654.29	d
T7 (26.67 g urea +19.56 g TSP + 30 g KCl)	314.88	415.81	470.28	531.21	602.43	db

According to Tukey's test; TSP: triple superphosphate; KCl: potassium chloride

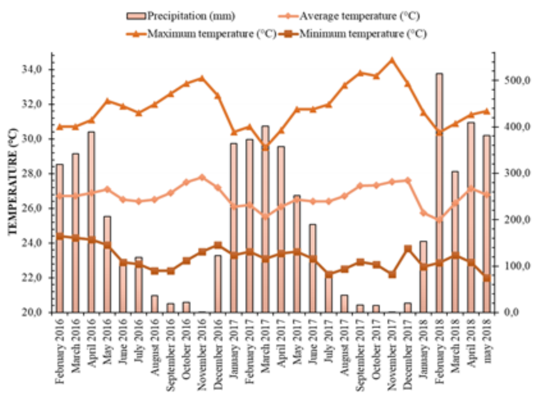

Fig. 3: Meteorological variables obtained during the experiment, Igarape-açu, Pará, Brazil

fluctuations between the hottest and coldest months ranging from 25.3°C to 27.6°C, thus showing a low-temperature range (Fig. 3).

The treatments showed a statistically significant effect for the nitrogen, phosphorus and potassium sources in isolation, and for the N-K combinations on the morphological variable total height of *T. vulgaris* individuals, with no statistical correlation with the measurement intervals in the study, with representation only when analyzed independently (Table 2).

In relation to the application of nitrogen (N), the T. vulgaris plants submitted to the treatment with a dose of 44.5 kg.ha^{-1} of urea showed significant growth in height, with an increase of 534 cm between the first and tenth measurements (time 0 and 9), while the plants in the control treatment had an increase of only 433 cm in the morphological variable in question.

Potassium (K) was also statistically significant in height growth. K is a nutrient that plays a significant role in plant physiology and metabolism, such as protein synthesis, enzyme activation, osmoregulation, photosynthesis, and processes related to stomatal movement (Silva *et al.* 2011). Fig. 4 shows the difference in the height growth of the plants subjected to the potassium fertilization treatments. It is noteworthy that an increase of approximately 77 cm was observed compared to the plants that did not receive fertilization.

Among the treatments that had a positive influence on greater plant diameter growth, the application of N, P and K alone and the N-P and N-K combinations were statistically significant (Table 3). This growth relationship is different from what was observed for height, where potassium fertilization contributed to greater increases, although it did not have a high statistical significance value compared to nitrogen (Fig. 5).

The increase in diameter was not statistically significant, as was the case for total plant height, considering the repeated measurements over time. Fertilizing with 30 g of K for each plant (50 kg.ha^{-1}) contributed to an average increase of 6.84 cm compared to the treatment without fertilization, which was the highest measurement at the end of the study between fertilizer applications. This provides better development due to potassium having various functions in plant metabolism and physiology.

The nutritional analysis of the leaves showed that the levels of some nutrients increased according to the treatments applied (Table 4). Concentrations of P, a highly mobile nutrient in the plant, varied from 0.5 (control) to 0.9 g.kg^{-1} (T7). K concentrations fluctuated between treatments, with indications of a relationship with the doses of fertilizer applied. The highest average leaf K was 3.5 g.kg^{-1} also in treatment T7 (26.67 g urea + 19.56 g TSP + 30 g KCl). Compared to the control (1.7 g.kg^{-1}), there was an increase

Table 3: Average diameter development (cm) and interaction over time as a function of the treatments applied to *T. vulgaris* plants, corresponding to the evaluation period of 2 years and 3 months of the experiment

Treatments	Time (quarterly)					
	0	1	2	3	4	Tukey's test
T0 (control)	0.76	1.09	2.18	3.16	3.78	A
T1 (26.67 g urea) ***	0.69	1.10	2.39	3.11	3.96	Ab
T2 (19.56 g TSP) ***	0.74	1.12	2.59	3.38	4.18	Ab
T3 (30 g KCl) **	0.73	1.22	2.67	3.56	4.86	Ab
T4 (26.67 g urea + 19.56 g TSP)	0.73	1.29	2.94	3.68	4.95	B
T5 (26.67 g urea + 30 g KCl) ***	0.71	1.29	2.86	3.61	4.45	Ab
T6 (19.56 g TSP + 30 g KCl)	0.75	1.29	3.01	3.83	5.03	B
T7 (26.67 g urea +19.56 g TSP + 30 g KCl)	0.81	1.39	2.86	3.67	4.73	Ab
Treatments	Time (quarterly)					
	5	6	7	8	9	Tukey's test
T0 (control)	8.03	11.33	13.63	17.40	20.43	A
T1 (26.67 g urea) ***	9.53	13.64	16.25	20.02	23.14	Ab
T2 (19.56 g TSP) ***	8.13	12.64	14.82	18.08	20.99	Ab
T3 (30 g KCl) **	11.06	16.77	19.46	23.86	27.28	Ab
T4 (26.67 g urea + 19.56 g TSP)	10.23	14.72	17.88	21.48	24.45	B
T5 (26.67 g urea + 30 g KCl) ***	10.56	15.41	17.95	21.72	24.77	Ab
T6 (19.56 g TSP + 30 g KCl)	11.37	15.92	18.29	21.46	24.27	B
T7 (26.67 g urea +19.56 g TSP + 30 g KCl)	11.32	15.50	17.80	20.82	23.38	Ab

Significance levels: '***' 0.1%; '**' 1%; '*' 5%. Different letters in the last column differ statistically according to Tukey's test; TSP: triple superphosphate; KCl: potassium chloride

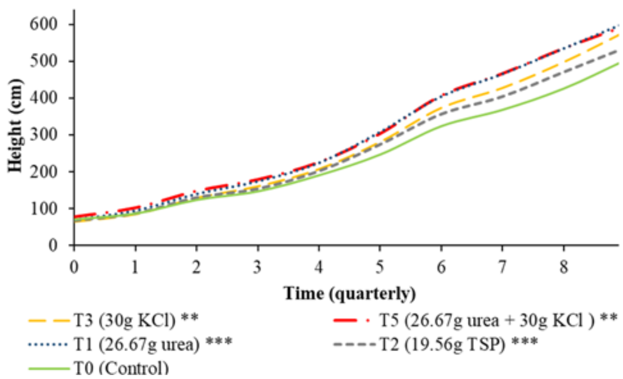

Fig. 4: Height growth over the evaluation time of *T. vulgaris* trees under commercial fertilizer doses of urea, triple superphosphate, potassium chloride and their combinations, referring to the treatments that obtained statistical significance

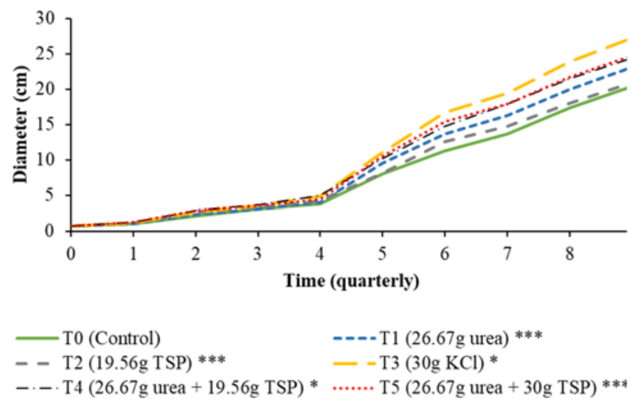

Fig. 5: Diameter growth over the evaluation time of *T. vulgaris* trees under commercial fertilizer doses of urea, triple superphosphate, potassium chloride and their combinations, referring to the treatments that obtained statistical significance

of approximately 105% on the highest average. For micronutrients, the results obtained in treatments T3 (30 g KCl), with 257.3 mg/kg of Fe and 236.1 mg/kg of Zn and T5 (26.67 g urea + 30 g KCl), with 94.2 mg/kg of Mn, stand out. The other micronutrients varied widely between the treatments.

Discussion

During the period of lowest rainfall, plants that received potassium fertilization followed by combined fertilizers showed higher growth rates, with *la ninã* being recorded for the year 2016 (Lim and Hendon 2017). Dias and Marenco (2016) evaluated the effect of rainfall seasonality on the growth of trees of 28 species in terra firme tropical forest in central Amazonia and concluded that the region's mild dry season is not long enough to deplete water from the soil beyond the reach of the root system, which allows trees to grow at constant rates throughout the year. In this study, growth also remained constant, even during periods of lower rainfall, and was not zero during the evaluation period. In a study to assess the growth in trunk diameter of *Eucalyptus grandis* trees and its relationship with climatic variables and mineral fertilization. Sette *et al.* (2010) concluded that climatic variables influenced growth rates, where higher rainfall led to reductions in increments.

Laclau *et al.* (2009), evaluating *Eucalyptus saligna* plants observed that fertilization with 140 kg.ha^{-1} of K_2O in sandy loam soils resulted in an increase in height of 370 cm at 36 months compared to unfertilized plants. For this study, the difference in height growth between the first and last measurements is 517 cm for the plants that received 30 g of potassium (K), equivalent to 50 kg.ha^{-1}. The foliar concentrations were also higher according to the results in Table 4, showing that the plants assimilated the potassium

Table 4: Nutritional diagnosis of *T. vulgaris* plant leaves one year after planting

	plant tissue analysis									
Treatments	N	P	K	Na	Ca	Mg	Fe	Zn	Cu	Mn
	g/Kg						mg/Kg			
T0 (control)	16,1	0,5	1,7	1,3	3	0,6	72,8	137,8	7,8	44,3
T1 (26.67 g urea)	23,6	0,8	2,1	1,6	3,9	1	37,5	25,8	6,8	74,9
T2 (19.56 g TSP)	20,7	0,7	1,8	1	3,6	1,1	51,4	25,7	4	105
T3 (30 g KCl)	18	0,7	3,2	1,5	2,9	0,7	257,3	236,1	6,9	44,8
T4 (26.67 g urea + 19.56 g TSP)	21,3	0,7	1,6	1,1	4,6	1	33,9	22,1	4,8	76,8
T5 (26.67 g urea + 30 g KCl)	21,4	0,6	2,4	0,8	3,7	0,6	34,7	19,8	5,1	94,2
T6 (19.56 g TSP + 30 g KCl)	24,8	0,8	2,4	1,1	4,4	0,7	44,4	23,5	3,7	71,7
T7 (26.67 g urea +19.56 g TSP + 30 g KCl)	26,4	0,9	3,5	1,1	2,7	0,6	30,8	20,2	6,5	57,7

Nutrients assessed in the nutritional diagnosis: nitrogen (N); phosphorus (P); potassium (K); sodium (Na); calcium (Ca); magnesium (Mg); iron (Fe); zinc (Zn); copper (Cu) and manganese (Mn). The values shown in the table were obtained using descriptive statistics (averages)

that was made available through fertilization. High external concentrations of K tend to promote contingency supply of the nutrient, causing wide variations in vacuolar concentrations, where it is stored.

Potassium is the second most important macronutrient in terms of plant absorption and is essential for the activation of enzymes involved in respiration and photosynthesis. In tropical soils, potassium levels are low (< 1.5 mmolc.dm^{-3}), making it important to use potassium fertilizers for correction and supplementation (Benites *et al.* 2010), as was the case in this study, which obtained only 0.4 mmolc.dm^{-3} of K in the soil. K deficiency can reduce apical dominance, plant development in general and delay fruiting, with implications for fruit size and color (Costa *et al.* 2017).

One of the positive points of fertilizing with K is the fact that it is present in ionic form (K+) in plant tissue and returns to the soil shortly after the plant leaves have senesced (Parente *et al.* 2016). In this way, most of the K is recycled, which explains its effect over time on plant development. Ferreira *et al.* (2011) state that the availability of nutrients for plants in production systems depends on the fertility of the soil and the speed at which waste degrades because, in intensive cultivation, the K absorbed by the plants remains in the plant tissue for most of the time and is not eroded or leached. Climate variables such as temperature and local humidity affect the rate at which K is released into the soil. The authors point out that because this nutrient is absorbed in enormous quantities, around 80% returns to the soil during the decomposition of organic matter, and the harvested material, such as grains and seeds exports the additional 20%.

The N-K combination resulted in a 18.5% increase in total plant height compared to those without fertilization in the last measurement. In work carried out by Jesus *et al.* (2016), similar results were observed for *Eucalyptus globulus* seedlings, where fertilization with N-P had an influence on seedling growth and, therefore an important development strategy in the seedling production stage. Height, considered a characteristic that expresses the quality and vigor of the plant, can be used as a reference to predict growth potential, both in forest nursery conditions and during definitive planting in the field. In this sense, fertilizing with N and P contributed positively to obtaining T. vulgaris plants of better silvicultural quality and superior results could be observed when compared to plants without fertilization, even during periods of low rainfall.

The application of nitrogen (N) contributed positively to the vegetative development of the plants during the evaluation period of the experiment, as can be seen in the leaf diagnosis results (Table 4). As the greatest development occurs in the first phases of the plant's life, which are attributed to the period of greatest absorption and metabolization of nitrogen (Belapart *et al.* 2013; Borin *et al.* 2017), explaining its significance in this study.

Plants respond well to nitrogen fertilization, with the most visually expressive external effect of nitrogen being abundant green vegetation. However, an excess of N can be harmful, so the dose applied to the crop must be well balanced with the amount of other nutrients. *T. vulgaris* showed significant growth (Table 2), with an increase of 534 cm between the first and tenth measurements (time 0 and 9), with the application of 44.5 kg.ha^{-1} of urea, while the plants without fertilization had an increase in height of 433 cm.

Corroborating the results found in this study, Ciriello *et al.* (2014), evaluating the effect of N doses on the growth of the native Brazilian tree species Guanandi (*Calophyllum brasiliense* Cambèss), observed that the dose of 80 kg.ha^{-1} of N during planting was effective in providing superior initial growth for the species. This dose is almost four times higher than the dose of N applied to *T. vulgaris* plants in this study, in the form of urea fertilizer (44.5 kg.ha^{-1}).

Phosphate fertilization made a significant contribution to height growth, with an increase of around 7% when compared to the plants without added nutrients in the last measurement of the study, in addition to having an increase between the beginning and the last measurement of 468.88 cm. The low available P content in the soil (2.3 mg.dm^{-3}) tends to influence the plants response to mineral fertilization with this nutrient which, according to Raij (1991), is often reported to be deficient in tropical soils. Several studies have highlighted the importance of P in the initial growth phase of fast-growing forest species (Maeda and Bognola, 2012; Stahl *et al.* 2013; Dias *et al.* 2014). The response to the application of phosphate fertilizer was expected due to the low availability of this nutrient throughout the soil profile, in addition to the acidity contributing to P adsorption, favoring the availability of the nutrient through fertilization. P is known to be an essential element for plant development. (Rodrigues *et al.* 2016). Ca supplementation *via* TSP (12 to 14% of TSP is composed of Ca) may also have contributed. The *T. vulgaris* showed a clear response to the addition of Ca *via* TSP, since the nutrient's exchangeable content in the soil was below the lower supply limit (20 mmolc.dm^{-3}), and it is important to note that the soil's acidity was not corrected, which could be another factor reducing the nutrient's availability to the plants in the soil solution.

Another factor that may have contributed to the increase in height observed in the plants that were fertilized with phosphorus refers to an intrinsic characteristic of the adaptation potential and hardiness of *T. vulgaris*, which is that it is tolerant of soils with high acidity (Sarcinelli *et al.* 2004; Oliveira *et al.* 2006), since increased acidity tends to reduce the availability of phosphorus for plants.

Low pH values favor an increase in the concentration of aluminum (Al) in the soil solution (Chen *et al.* 2015; Rodrigues *et al.* 2017). High concentrations of Al inhibit root growth, with negative consequences for water and nutrient absorption and plant development (Cherubin *et al.* 2016). The reduction in the plant's root system can reduce the absorption of nutrients, especially phosphorus, which moves through the soil by the diffusion mechanism (Frazão *et al.* 2019).

The fact that K provided better development for planting *T. vulgaris*, this result can be explained by the fact that this nutrient has various functions in the metabolism and physiology of plants, which can be exemplified in studies such as that by Biagiotti *et al.* (2017), when studying the application of K to *Corymbia citriodora* plants, from 6 to 24 months after planting, observed the maximum growth in diameter (2.89 cm) of the plants with the dose of 52.9 kg.ha^{-1} of K, at six months. At 9 months, the maximum growth in diameter (3.83 cm) was estimated with 57.4 kg.ha^{-1} of K. At 12 months, there was a quadratic effect of the treatments, with maximum development (5.98 cm) estimated with a dose of 62 kg.ha^{-1} of K_2O. Thus, the authors concluded that, up to 12 months, biomass production and morphological development parameters of *C. citriodora* were favored by K fertilization. Melo *et al.* (2016) found that the doses of potassium fertilization that most contributed to optimal growth rates of *E. grandis* x *E. urophylla* hybrid clones in low-fertility soils were 104 and 184 kg.ha^{-1} of KCl. This may be related to the high levels of K in the leaves of the plants that received higher levels of potassium fertilization.

Studies have shown that the application of K, in the form of potassium chloride, promotes greater diameter development. For example, in a study conducted by Sette Junior *et al.* (2010), the application of 140 kg.ha^{-1} of K_2O in a *Eucalyptus grandis* plantation on a medium-textured red-yellow latosol (200 g.kg^{-1} of clay) promoted an increase in diameter of 4.14 cm in contrast to plants that did not receive potassium fertilization.

Fertilizing with N at a dose of 26.67 g or 44.5 kg.ha^{-1}, ranked third in terms of growth compared to the other fertilizations. Research shows that nitrogen is among the most limiting nutrients for plant growth, as can be seen in a study carried out on *Hymenaea courbaril*, in which the stem diameter of plants grown without N was reduced by 21% compared to individuals that received the nutrient (Nascimento *et al.* 2014). Nitrogen fertilization can significantly alter the soil environment and can even increase carbon storage by plants since it promotes the formation of chlorophyll, found in plant leaves, which in turn combines CO_2 + H_2O to form the sugars that the plant needs for its growth and the production of grains and fruit (Shryock *et al.* 2014).

As with height, P fertilization contributed to an increase in the diameter of *T. vulgaris* plants, although much less than other fertilizer applications, with an increase of 3% more when compared to those without fertilization (Fig. 5). The addition of Ca *via* TSP (12 to 14% of Ca) may also have had a positive effect together with the addition of P, both present in the composition of TSP (Dias *et al.* 2020). This contribution could be observed in phosphate fertilization in *Eucalyptus camaldulensis*, which promoted growth in diameter of 5.6 cm, considering the treatment with fertilization with P at a dose of 120 kg.ha^{-1} in relation to plants without the addition of mineral fertilizer (Costa *et al.* 2012). The same was corroborated in *Pinus taeda* plantations, where the application of P, starting at 75 kg.ha^{-1}, combined or not with nitrogen and potassium, led to the formation of trees with larger diameters in their initial development phase (Moro *et al.* 2014).

Treatments with N-P and N-K nutrient combinations were statistically significant, contributing to an increase of approximately 20% for both fertilizations at the end of the last measurement in this study. This response may have occurred due to the synergy between nutrients in plant metabolism. N uptake is impaired by P deficiency, a condition that has been observed in scientific literature. Santos *et al.* (2015) made a considerable contribution to science by evaluating the efficiency of N use by cotton genotypes under P application. In the study cited above, genotypes grown under low phosphorus supply conditions showed higher nitrogen concentration in leaves, suggesting a synergistic relationship between these nutrients. This is consistent with the results of this study, where the positive interaction between nitrogen and phosphorus benefited plant diameter growth. Phosphorus indirectly affects nitrogen uptake by reducing leaf area (Santos *et al.* 2015), which is linked to nitrogen uptake. A larger leaf area increases the transpiration rate, and the flow of water absorbed by the plant, influencing the uptake of nutrients from the soil, especially nitrogen (Bonfim-Silva and Monteiro, 2010; Han *et al.* 2015).

The correlation between K and N is also observed in soils with high K levels, where N stimulates vegetative growth, increasing K levels in the aerial part of plants and promoting the use of reserves of this nutrient in the soil. K plays a crucial role in the functioning of enzymes involved in plant development, also facilitating the absorption of N, which results in improved vegetative growth (Debbarma *et al.* 2017).

In *Eucalyptus grandis* plantations, it was observed that the greatest responses to fertilization with N and K occurred in the first year, with doses of 4.3 kg.ha^{-1} of N and 20 kg.ha^{-1} of K, respectively, indicating the possibility of reducing the number of applications without compromising productivity or increasing losses due to deep drainage (Silva *et al.* 2013). In a study by Jesus *et al.* (2016), when fertilizing *Eucalyptus globulus* seedlings with N and K, observed a significant increase of 72% in plant diameter compared to unfertilized seedlings, highlighting the positive impact of nutrients on the initial growth of seedlings.

Conclusion

Based on the results of this study, combined fertilization of 44.5 kg.ha^{-1} of nitrogen and 50 kg.ha^{-1} of potassium is recommended until the third year of planting as an effective silvicultural management strategy to promote greater development of the morphological variables height and diameter in *T. vulgaris* plantations, resulting in larger trees. This approach can optimize the growth and productivity of the species, contributing to the sustainability and profitability of forest plantations.

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Author Contributions

LFP and PHOS planned the experiments, LFP and PHOS interpreted the results, WLSA, MTP, and RLPN made the write-up, MARS, LFSD, JFBRS and CADP made corrections and suggestions to the text and LFP statistically analyzed the data, LFP and PHOS made illustrations.

Conflict of Interest

All authors declare no conflict of interest.

Data Availability

Data presented in this study will be available on a fair request to the corresponding author.

Ethics Approval

Not applicable to this paper.

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