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LEAF CONCENTRATION OF MACRONUTRIENTS IN OIL PALM PLANTS FERTILIZED WITH PHOSPHORUS, POTASSIUM AND MAGNESIUM IN THE EASTERN AMAZON

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Abstract
The concentrations of nutrients in the leaves allow a better understanding of the nutritional status of oil palm plants, making it a tool for diagnosing the origins of nutritional problems and assisting in fertilizer recommendations. In this sense, the objective of the current research was to evaluate the leaf concentrations of N, P, K, Ca, Mg and S in the oil palm under fertilization with phosphate, potassium and magnesium in edaphoclimatic conditions of Eastern Amazon. The experiment was conducted at the AGROPALMA® Company in the municipality of Tailândia, state of Pará, Brazil. The experimental design used was randomized blocks in a factorial scheme 4 x 2 x 3 x 2, with four levels of phosphorus, two sources of phosphorus (natural phosphate and triple superphosphate), three levels of potassium and two levels of magnesium. Phosphorus fertilization increased the leaf concentrations of N, P, Ca and Mg, providing higher levels when triple superphosphate was applied. However, in adult oil palm plants (12 years old), there was different on leaf concentrations of N, P, K and S between phosphorus sources aphid. Potassium and magnesium fertilization only increased the leaf concentrations of K and Mg, respectively. Fertilization with P, K and Mg promotes adequate leaf concentrations of K, Ca, Mg e S in oil palm plants grown in the Eastern Amazon.

Keywords: *Elaeis guineensis* Jacq. Fertilization. Nutritional diagnosis. Oilseed. Plant nutrition.

1. Introduction

The oil palm (*Elaeis guineensis* Jacq.) is widely cultivated in the Amazon region and known for its high potential in the production of vegetable oil. Brazilian production is capable of producing 340 t of palm oil annually and, still, this quantity is not able to supply the local demand, needing to import the same proportion produced (Viégas et al. 2019). Thus, is essential to apply new management practices to oil palm plantations, which are able to increase the productivity and sustainability of agroecosystems (Matos et al. 2018). The average productivity of the oil palm crop in the eastern Amazon is 17.2 t ha^{-1} of palm clusters, however the crop potential is 25 to 30 t ha^{-1} of palm clusters (Homma and Rabello 2020).

The high productive potential of the oil palm makes this palm demand a high extraction of nutrients to supply its nutritional demands (Viégas et al. 2019). In tropical soils, the high extraction of nutrients can become a limitation for oil palm growth and development, since they are known for their acidity and low natural fertility (Lopes and Guilherme 2007). However, these limitations can be overcome through corrective practices of soil and the addition of fertilizers.

Good fertilizer management is essential for the oil palm's nutritional management, since excessive use is financially disadvantageous and capable of proving pollution to the agroecosystem and low use can cause productivity losses (Woittiez et al. 2018a). Furthermore, the costs of mineral fertilizers in oil palm plantations can reach up to 60 % of production costs (Matos et al. 2017), becoming the efficient use and adequate nutritional management of plants essential.

Mineral fertilizations of N, P, K and Mg are generally necessary in oil palm plantations, as most of the cultivated soils are not able to supply in shough quantity to meet nutritional demand (Woittiez et al. 2018a). It is estimated that in oil palm plantations with an average productivity of 25 t ha^{-1} of bunches of fresh fruits, the nutritional demand is 187 kg ha^{-1} of N, 143 kg ha^{-1} of P_2O_5, 336 kg ha^{-1} of K_2O and 56 kg ha^{-1} of Mg (Franzini et al. 2020). However, is the recommendation of mineral fertilization for oil palm in the state of Pará (Franzini et al. 2020) sufficient to promote adequate leaf concentrations of nutrients in the crop? Incidence of nutrient deficiency such as N, Ca, S, Mn and Zn has been reported in oil palm plantations in the region (Matos et al. 2017). A study carried out in different oil palm plantations in Indonesia found, in most of the plants, deficient and unbalanced of P and K, influencing differently in the productivity of the culture (Woittiez et al. 2018b).

The knowledge of the source and ideal level of fertilizers that provide the adequate balance of nutrients becomes essential for the efficient nutritional management of oil palm. Also, the knowledge of the concentration of nutrients in different phenological stages of plants becomes a tool for understanding the origin of nutritional problems (Viégas et al. 2019). The understanding of oil palm nutrition allows the efficient recommendation of fertilizers, in addition to providing the maximum productive potential of plants.

In this sense, the objective of the current study was to evaluate the nutrition of oil palm plants under phosphorus, potassium and magnesium fertilization in edaphoclimatic conditions of Eastern Amazon.

2. Material and Methods

The study was carried out at the AGROPALMA® Company in the municipality of Tailândia, state of Pará, Brazil (2°56'50'' S and 48°57'12'' W). Tailândia has a tropical rainy climate with no seasonal variation and relative humidity of 84 %. During the period of conducting the experiment, the temperature ranged from 21 to 32.5 ºC and an average annual rainfall was 2,463 mm. During research time the rainfall was monitored with the aid of a rain gauge installed in the experiment area (Figure 1).

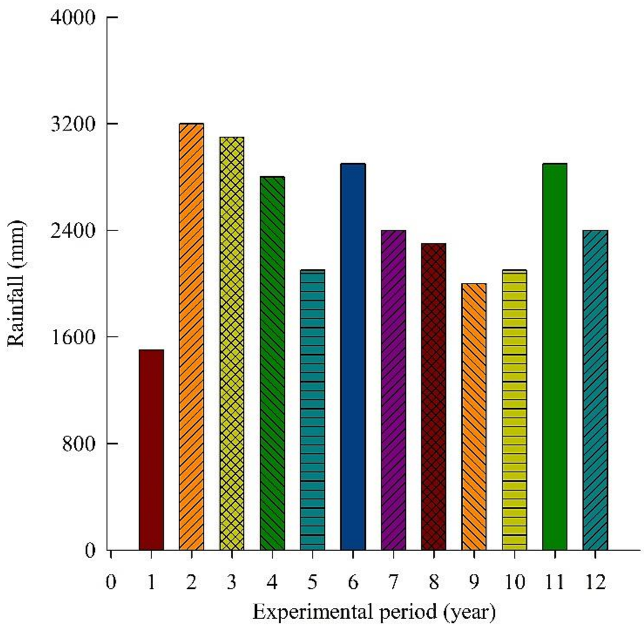

Figure 1. Rainfall (mm) while conducting the study on AGROPALMA®.

The study compromised a randomized blocks design, with four repetitions, in a factorial scheme of 4 x 2 x 3 x 2; four levels of P, two sources of P, three levels of K and two levels of Mg. The sources of mineral P fertilizers evaluated in the study were the commercial source phosphine (rock phosphate- RP; total 33 % P_2O_5 and 42 % CaO) and triple superphosphate (45 % P_2O_5 and 10 % CaO), potassium chloride (60 % K_2O and 47 % Cl) for K and magnesium sulfate (18% Mg) for Mg (Table 2).

Table 1. Chemical and physics characteristics of the soil in 0 - 0.3 m layer of the area before the installation of the experiment.

pH	SOM**	$P_{available}$*	P_{total}	K*	Ca^{+2}*	Mg^{+2}*	Al^{+3}***	sand	Silt	clay
(H_2O)	g kg^{-1}	---- mg dm^{-3} ----			-----------$cmol_c$ dm^{-3}-----------			---------g kg^{-1} --------		
5.20	16.4	12	89	0.04	2.38	0.50	0.02	610	150	240

* extracted with ion exchange resin. ** colorimetric method. SOM - Soil organic matter. *** extracted with KCl 1 mol L^{-1}.

Table 2. Years, sources and levels of application of fertilizers used in the treatments of the experiment.

Year	Phosphorus								Potassium			Magnesium	
	RP				TSP				KCl			$MgSO_4$	
	P_1	P_2	P_3	P_4	P_1	P_2	P_3	P_4	K_0	K_1	K_2	Mg_0	Mg_1
	--kg ha^{-1}--												
0	35.8	71.5	107.3	143.0	28.6	57.2	85.8	144.4	0	42.9	64.4	0	42.9
1	35.8	71.5	107.3	143.0	28.6	57.2	85.8	144.4	0	71.5	107.4	0	71.5
2	35.8	71.5	107.3	143.0	28.6	57.2	85.8	144.4	0	143.0	214.5	0	143.0
3	35.8	71.5	107.3	143.0	28.6	57.2	85.8	144.4	0	214.5	321.8	0	143.0
4	35.8	71.5	107.3	143.0	28.6	57.2	85.8	144.4	0	286.0	429.0	0	143.0
5	35.8	89.4	143.0	196.6	28.6	71.5	114.4	157.3	0	214.5	429.0	0	143.0
6 to 12	35.8	107.3	178.8	250.3	28.6	85.8	143.0	200.2	0	228.8	457.6	0	171.6

* RP = Rock Phosphate and TSP = Triple superphosphate.

The soil of the experimental area is classified as yellow Oxisol (Gama et al. 2020), low bases saturation, acid and low natural fertility (Rodrigues et al. 2005). Soil samples from the 0-30 cm layer were collected to determine chemical attributes and textural fractions (Table 1).

The experimental area was prepared by removing natural vegetation and burning vegetable waste. The genetic material used in the experiment was the hybrid DELI x La Mé (Category C) from the experimental area of the Institut de Recherches pour les Huiles et Oléagineux. Oil palm seedlings were produced for six months in pre-nurseries and three months in permanent nurseries. After the production of seedlings, planting was carried out in spacing of an equilateral triangle of nine meters in quincunce, resulting in a population of 143 plants ha^{-1}. The experimental plots were composed of six lines with nine plants in each, however, only the twelve central plants of each experimental plot were evaluated. Among the planting lines, cover plants of *Pueraria phaseoloides* (Roxb. Benth.), *Calopogoníum mucunoídes* Desv. and *Pubescens pubescens* Benth were grown throughout the experimental period.

In the preparation of the soil, 300 kg ha^{-1} of partially acidulated natural phosphate (27 % P_2O_5) was applied in the whole experimental area, and 21.45, 42.90 and 71.5 kg ha^{-1} of urea were applied to the first, second and third year of cultivation, respectively. On fifth year of cultivation 14.3 kg ha^{-1} of boráx (20 % B) were applied to all plants in the study.

Plant responses to fertilization were evaluated based on macronutrient concentrations (N, P, K, Ca, Mg and S) on leaves. The nutrient concentrations were determined from leaf analyzes following the methods described in Sarruge and Haag (1974). For this purpose, from the third to the sixth and the twelfth year of age of the plants, leaves 17 were collected in all plants of each useful plot (12 plants) and, in the absence, leaves 9 were collected (Veloso et al. 2020). The extraction of nutrient concentrations on leaves was performed using the sulfuric (N) and nitroperchloric (P, K, Ca, Mg and S) digestion method and the determination by distillation and titration (N), colorimetry (P), flame photometry (K), atomic absorption spectrophotometry (Ca and Mg) and turbidimetry (S) method. After the determination of leaf concentrations, plots of N (x axis) and P (y axis) concentrations were performed as a function of P_2O_5 doses and, also, the line of the universal equation of the nutritional balance of N and P was plotted (Ollagniere and Ochs 1981) to assess the nutritional status of N and P. Based on the universal straight line equation (Ollagnier and Ochs 1981), the optimal P values were calculated as a function of the average N concentrations obtained with the application of phosphine and triple superphosphate.

The results were submitted to preposition tests (homogeneity and normality) and, consequently, analyzed by analysis of variance (F test, $p<0.05$), then, when significant, the Tukey test ($p <0.05$) for qualitative factors (P sources and K and Mg levels) and the regression models were adjusted for the quantitative factor (P levels). All statistical analyzes were performed with the aid of the Sisvar software (Ferreira, 2011).

3. Results

The leaf N concentrations, as a function of P levels, there were quadratic responses from the third to the fifth year and, linear in the sixth and twelfth year of the oil palm (Figures 2A, 2B and 2C). The highest foliar concentrations of N were found in the level of 42.5 and 35.0 kg ha^{-1} of P_2O_5 in the third and fourth year of age of the plants with the concentrations of 25 and 25.7 g kg^{-1} of N, respectively (Figure 2A). While in the fifth year, it reached the highest leaf N concentration of 25.2 g kg^{-1} at the level of 53.9 kg ha^{-1} of P_2O_5 and the concentrations of 24.4 g kg^{-1} of N at the level of 86.4 kg ha^{-1} of P_2O_5 in the twelfth year of age of the plants (Figures 2B and 2C). For the effect of P sources, there were higher leaf N concentrations when triple superphosphate (F1) was used in the third, fourth and fifth year of the oil palm (Figure 2D). Potassium fertilization only increased leaf N concentrations in the fifth and twelfth year of age of the plants, but without difference between the K1 and K2 levels (Figure 2E). Fertilization with Mg only increased leaf N concentrations in the fifth year of age of the plants (Figure 2).

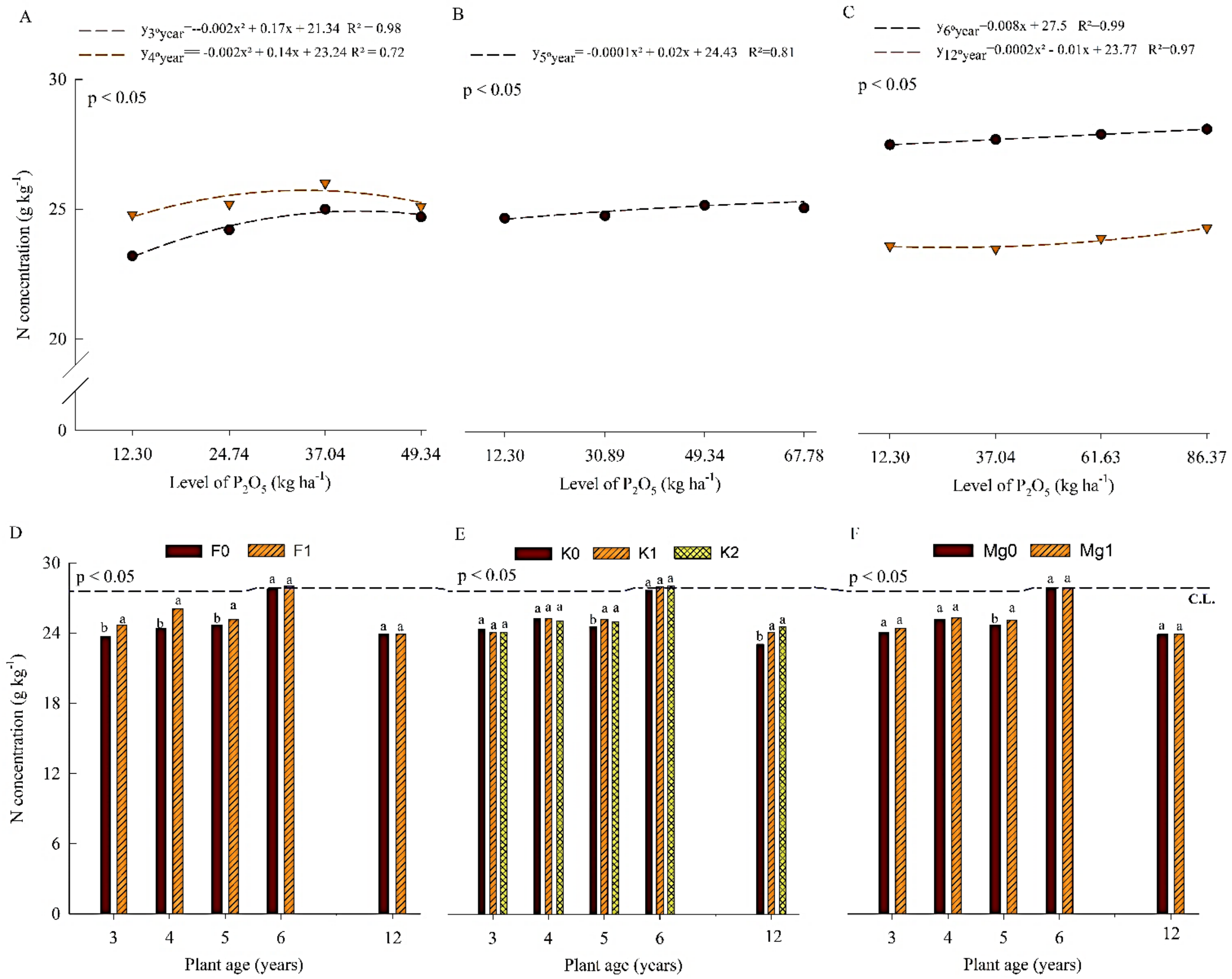

Figure 2. A - Leaf N concentration of oil palm as a function of P levels in the third and fourth; B - in the fifth; C - in the sixth and twelfth year of the plants, from the sources of P; D - F0- phosphine and F1- triple superphosphate; E - levels of K; F – levels of Mg. Equal letters in the columns, comparing fertilization levels

at each age of the plants, are considered statistically equal by the Tukey test (p> 0.05). C.L. - Critical level established for oil palm in Pará state by the method of reduced normal distribution (RND) (Matos et al. 2016).

The application of P levels increased its leaf concentration in a quadratic way in the third, fourth, sixth and twelfth year of age of the plants and, linearly, in the fifth year (Figures 3A, 3B and 3C). The highest leaf concentrations of P were 1.4 g kg^{-1} in the third and fourth year of age with 25 kg ha^{-1} of P_2O_5 (Figure 3A). In the sixth year, the highest concentration was 1.6 g kg^{-1} of P with 62.5 kg ha^{-1} of P_2O_5 (Figure 3C). A similar result was observed in the twelfth year, obtaining a greater concentration (2.0 g kg^{-1} of P) in the level of 62.5 kg ha^{-1} of P_2O_5 (Figure 3C). Regarding the effect of P sources on their leaf concentrations, there were higher values in plants fertilized with triple superphosphate (F1) in the third to sixth year of age (Figure 3D). Potassium fertilization did not significantly influence leaf P concentration (Figure 3E), while magnesium fertilization increased the leaf P concentration only in the fifth year (Figure 3F).

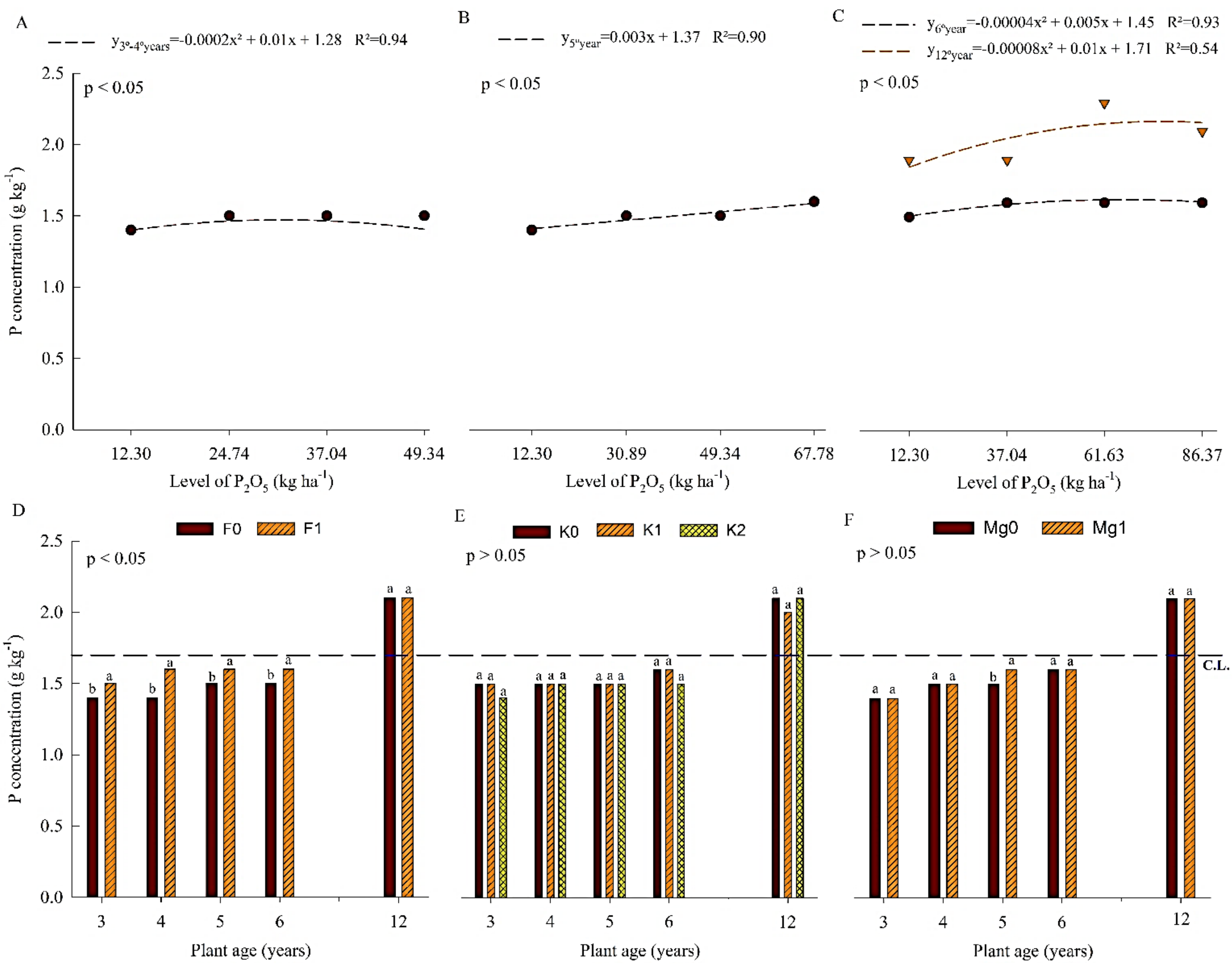

Figure 3. A - Leaf P concentration of oil palm as a function of P levels in the third and fourth; B - in the fifth; C - in the sixth and twelfth year of the plants, from the sources of P; D - F0- phosphine and F1- triple superphosphate; E - levels of K; F – levels of Mg. Equal letters in the columns, comparing fertilization levels at each age of the plants, are considered statistically equal by the Tukey test (p> 0.05). C.L. - Critical level established for oil palm in Pará state by the method of reduced normal distribution (RND) (Matos et al. 2016).

From the third to the sixth year of age of the plants, the relationship between N and P leaf concentrations, according to P levels, was below the universal equation. For the twelfth year, the relationship cited was above the universal equation (Figures 4A, 4B and 4C). Phosphorus fertilization caused a change in leaf K concentration in a quadratic way in the different years of age of the evaluated plants

(Figures 5A, 5B and 5C). In the third, fourth and fifth year, the highest leaf concentrations (9.9, 9.6 and 8.2 g kg^{-1} of K) were found when the plants received the lowest P level of 12.3 kg ha^{-1} of P_2O_5 (Figures 5A and 5B). On the other hand, in the twelfth year there was the highest concentration (6.4 g kg^{-1} of K) in the level of 86.4 kg ha^{-1} of P_2O_5 (Figure 5C). For P sources, there was no effect on leaf K concentrations in the different years of evaluation (Figure 5D). Meanwhile, potassium fertilization promoted an increase in the leaf K concentration, raising it above the critical level until the sixth year of age of the plants, but without difference between the K1 and K2 levels (Figure 5E). In all evaluated years, the leaf K concentrations were not influenced by magnesium fertilization (Figure 5F).

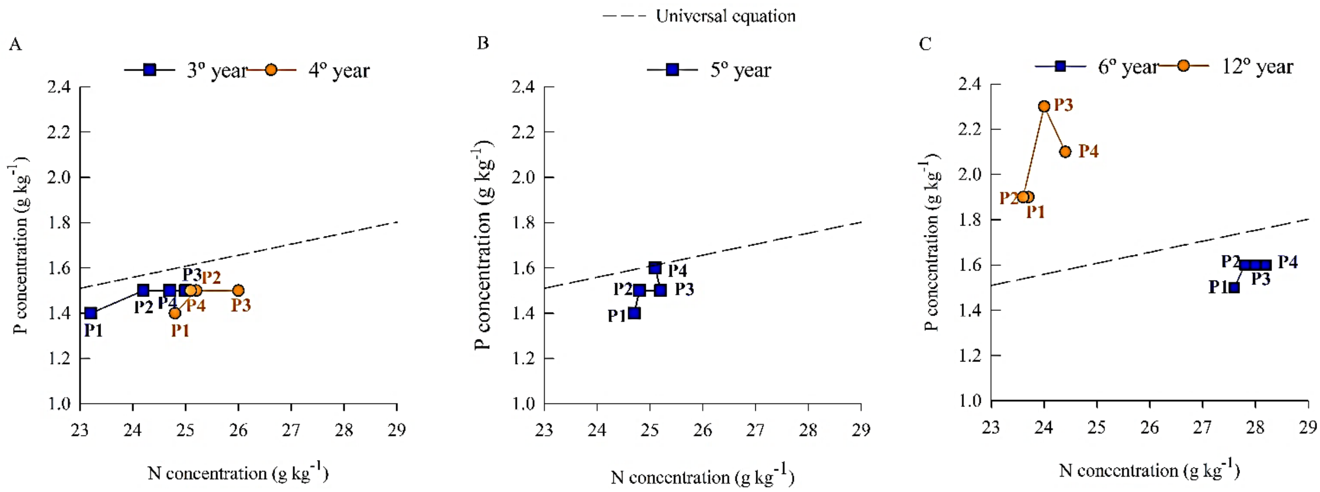

Figure 4. A - Relationship between the N and P leaf concentrations of the oil palm with the application of P to the third and fourth year; B – fifth year; C - sixth and twelfth year of the plant age. Universal line equation [P (g kg^{-1}) = 0.0487 N (g kg^{-1}) + 0.39] determined by Ollagnier and Ochs (1981) for oil palm plants.

For Ca leaf concentrations, there were quadratic responses to P levels in the third, fourth, fifth and sixth year of the oil palm (Figures 6A, 6B and 6C). The highest leaf concentrations of Ca were obtained at levels of 24.7 and 37.0 kg ha^{-1} of P_2O_5 in the third (11.7 g kg^{-1}) and fourth year (11.6 g kg^{-1}), respectively. For the fifth year, the highest leaf concentration of 9.3 g kg^{-1} of Ca was observed in the level of 67.8 kg ha^{-1} of P_2O_5 and, in the sixth year, the highest concentration (10.4 g kg^{-1} of Ca) was observed with 86.4 kg ha^{-1} of P_2O_5. In the case of P sources, the application through triple superphosphate (F1) promoted higher concentrations of Ca in the third, fifth, sixth and twelfth year of oil palm (Figure 6D). Potassium and magnesium fertilizations did not influence leaf Ca concentrations in the different years of age of oil palm plants (Figures 6E and 6F).

Leaf Mg concentrations were influenced, quadratic models, by phosphorus fertilization in the third, fourth, fifth and sixth year of the oil palm (Figures 7A, 7B and 7C). In the third and fourth year, the highest leaf concentrations (2.7 and 2.4 g kg^{-1} of Mg) were verified in the level of 37.0 kg ha^{-1} of P_2O_5 (Figure 7A). For the fifth year, the highest leaf concentration was 2.4 g kg^{-1} of Ca with the level of 67.8 kg ha^{-1} of P_2O_5 (Figure 7B) and, in the sixth year, the highest leaf concentration (2.7 g kg^{-1} of Mg) at a level of 61.6 kg ha^{-1} of P_2O_5 (Figure 7C). For the sources of P, it was found that, with the exception of the fifth year, higher foliar concentrations of Mg when the supply of triple superphosphate (F1) was performed (Figure 7D). There was no effect of potassium fertilization on leaf Mg concentration in the different years of oil palm (Figure 7E). The magnesium fertilization increased the leaf concentrations of Mg in all evaluated years (Figure 7F).

For the effect of phosphorus fertilization on leaf S concentration, there was a positive linear response to the increase in P levels in the third year (Figure 8A) and quadratic response in the twelfth year of oil palm (Figure 8B), obtaining the highest leaf concentration (1.6 g kg^{-1} of S) with 12.3 kg ha^{-1} of P_2O_5 (Figure 8B). Regarding the P sources, there was no effect on the leaf concentration of S in the third and twelfth year of the oil palm (Figures 8C). For the effects of potassium and magnesium fertilization, there were also no significant differences in the leaf concentration of S in the third and twelfth year of age of the plants (Figures 8D and 8E).

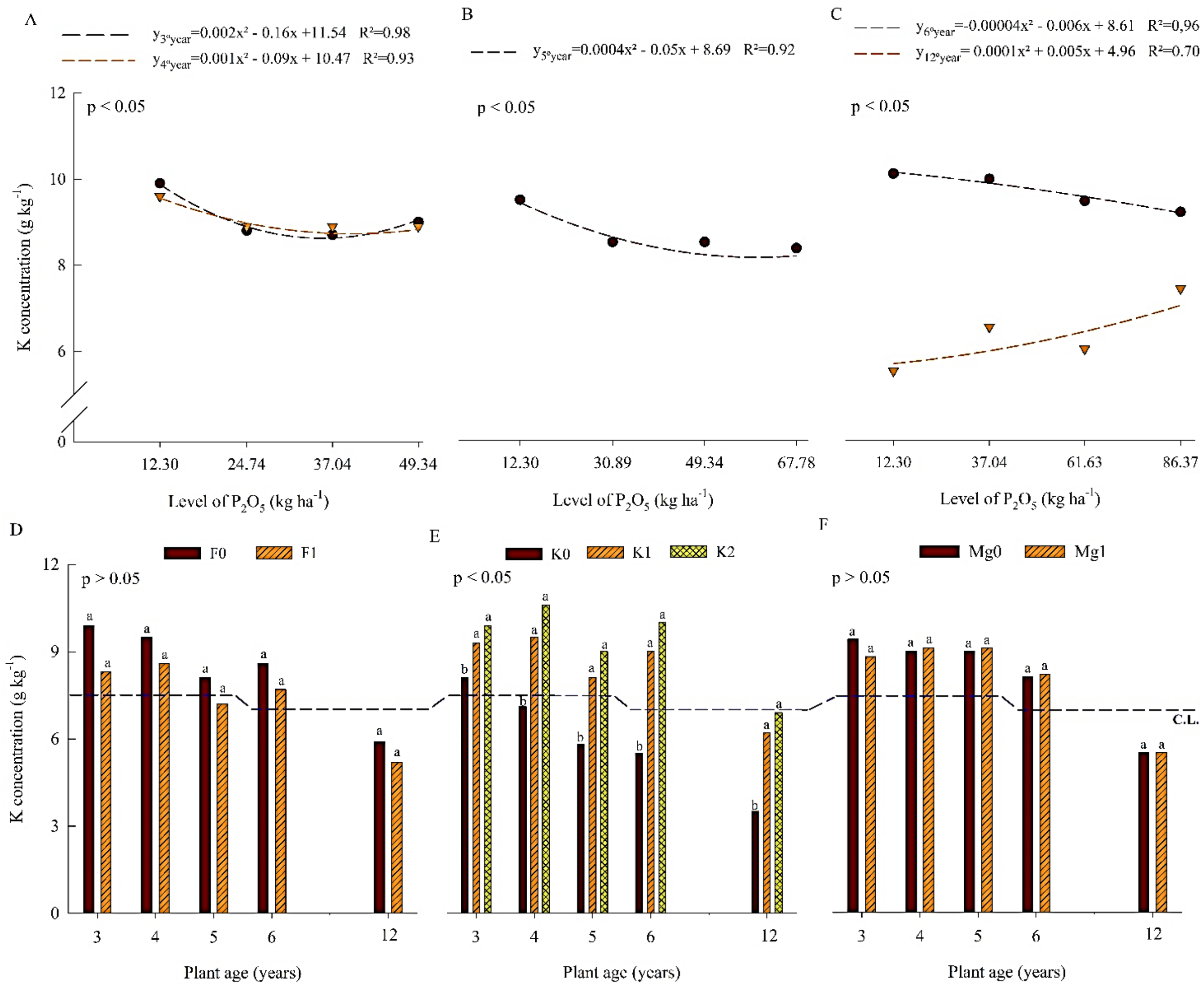

Figure 5. A - Leaf K concentration of oil palm as a function of P levels in the third and fourth; B - in the fifth; C - in the sixth and twelfth year of the plants, from the sources of P; D - F0- phosphine and F1- triple superphosphate; E - levels of K; F – levels of Mg. Equal letters in the columns, comparing fertilization levels at each age of the plants, are considered statistically equal by the Tukey test ($p > 0.05$). C.L. - Critical level established for oil palm in Pará state by the method of reduced normal distribution (RND) (Matos et al. 2016).

4. Discussion

For the leaf N concentrations, a similar result was observed by Viégas et al. (2019), verifying positive responses of leaf N concentration to the increase in P levels applied to oil palm. This fact highlights the importance of phosphorus fertilization on leaf N concentrations in all years of age of the plants, indicating the synergism between P and N for oil palm (Rodrigues et al. 1997). The lower leaf N concentrations verified in plants fertilized with phosphine (F0) until the fifth year were influenced by lower release of this source of P (Franzini and Silva 2012), even using nitrogen fertilization and the cultivation of legumes. A study carried out with oil palm in Pará determined the critical level for the leaf concentration of 27.5 g kg^{-1} of N for plants younger than six years old and 27.8 g kg^{-1} of N for plants older than 6 years old (Matos et al. 2016), indicating that only in the sixth year the plants reached the critical level of this nutrient (Figure 2d). Phosphorus fertilization can interfere on leaf N concentration of oil palm; in their absence, plants tend to have N deficiency, even with nitrogen fertilization (Rodrigues et al. 1997; Viégas et al. 2019). A research carried out in the municipality of Santa Bárbara, Pará sate, in an Oxisol Yellow medium texture, found that the absence of phosphorus fertilization causes a decrease on leaf N concentration in oil palm (Pacheco et al. 1985). P plays a direct role in plant metabolism, providing energy through adenosine triphosphate (ATP) for active ion absorption and protein synthesis, presenting synergism with N (Viégas et al. 2019).

In general, no significant effect was observed on leaf N concentrations by the potassium fertilization of the present study. However, the importance of K in the metabolism of N has been evaluated, pointing out that in cases of K deficiency there is less nitrate assimilation, greater putrescine biosynthesis and changes in amino acids, due to the restriction in protein and pyruvate synthesis (Mirande Ney et al. 2020). A study in Indonesia indicated that K supply in oil palm trees of four and five years of age provided higher leaf N concentrations (Mirande Ney et al. 2020).

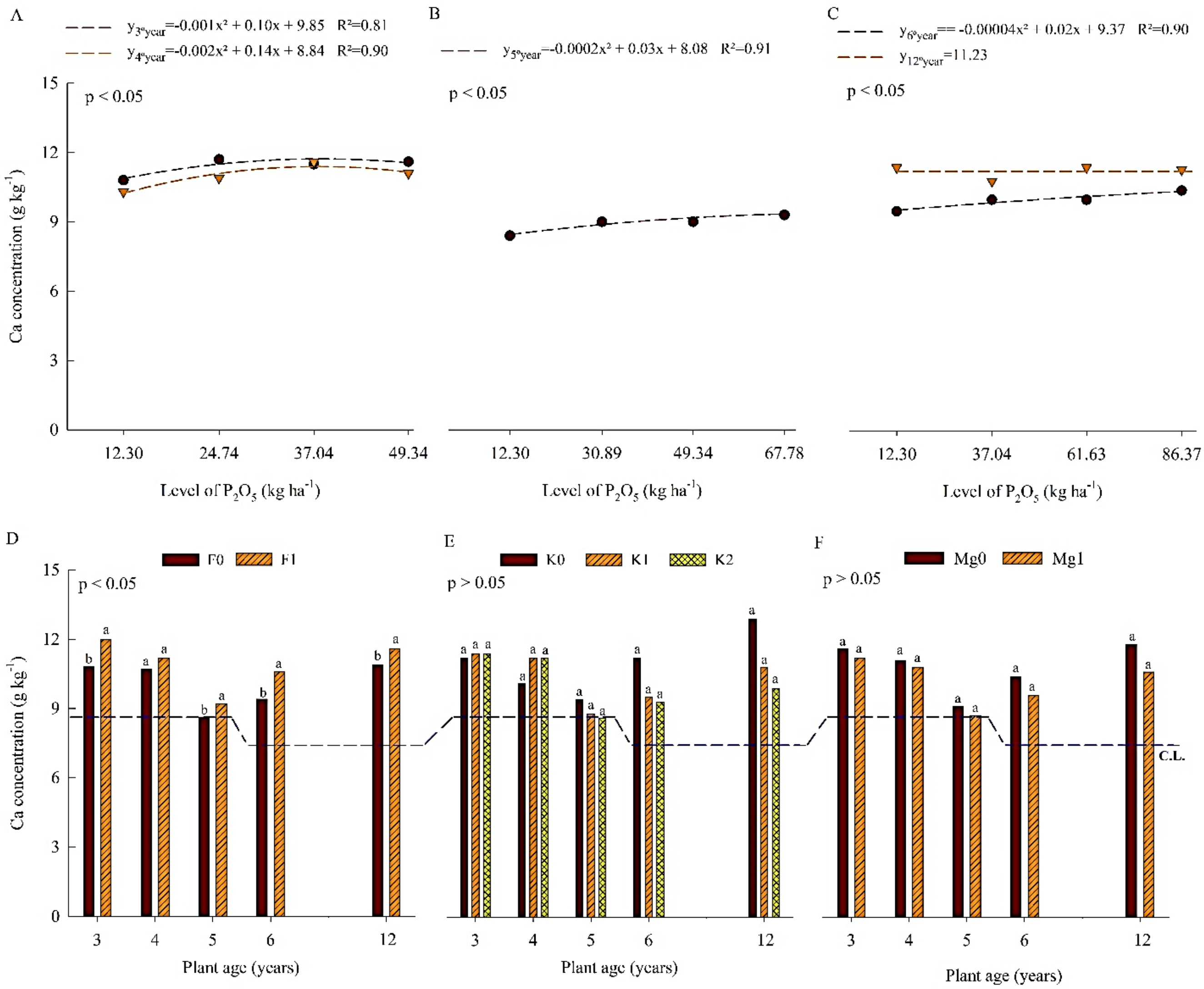

Figure 6. A - Leaf Ca concentration of oil palm as a function of P levels in the third and fourth; B - in the fifth; C - in the sixth and twelfth year of the plants, from the sources of P; D - F0- phosphine and F1- triple superphosphate; E - levels of K; F – levels of Mg. Equal letters in the columns, comparing fertilization levels at each age of the plants, are considered statistically equal by the Tukey test ($p > 0.05$). C.L. - Critical level established for oil palm in Pará state by the method of reduced normal distribution (RND) (Matos et al. 2016).

Assessments of leaf N concentration in oil palm plants in Pará state showed a lack of significant response to magnesium and potassium fertilizations (Viégas et al. 2019). The use of *Pueraria phaseoloides* as soil cover in oil palm plantations, indicated a cycling that varied from 455 kg ha^{-1} of N in the second year of cultivation to 31 kg ha^{-1} of N in the eighth year of cultivation, decrease due to the shading of the oil palm on the legume (Viégas et al. 2021). On the other hand, the N recommendation for oil palm plants in production is 113 kg ha^{-1} of N for 17 t ha^{-1} of expected productivity (Franzini et al. 2020), and this dose can be reduced by the contribution of N cycled by *Pueraria phaseoloides* L.

The leaf P concentrations of current study corroborated with the literature. Viégas et al. (2019) found in oil palm that leaf P concentration responded proportionally to the increase in applied P levels. Studies carried out with oil palm in Pará determined the critical level of 1.7 g kg^{-1} of P (Matos et al. 2016). Thus, the leaf P concentrations of the present study are below the critical level for the crop, except in the twelfth year. This fact indicates that the sources of P did not satisfactorily supply the nutritional demand for this nutrient in the first years of the oil palm. On the other hand, the low P concentration in the soil (Brasil and Cravo 2020) must be considered initially (Table 1) and, additionally, the high adsorption power of the Oxisols, making P unavailable to the plants (Novais et al. 2007).

There was no effect of K levels on the leaf P concentrations of oil palm plants. Viégas et al. (2019) also did not obtain a significant effect of the K supply on the leaf concentration of P of the oil palm. A study conducted in Indonesia with K fertilization on oil palm found no difference in the leaf P concentration in the first year of evaluation, but there were higher concentrations of P with K supply in the second year of plant evaluation (Mirande Ney et al. 2020). In another study, also carried out with Mg fertilization in Pará with oil palm, it was found that the supply of Mg did not alter the leaf concentrations of P (Viégas et al. 2019). This fact corroborates the results found in the present study, although the synergism between P and Mg is mentioned in the literature (Bucher 2018).

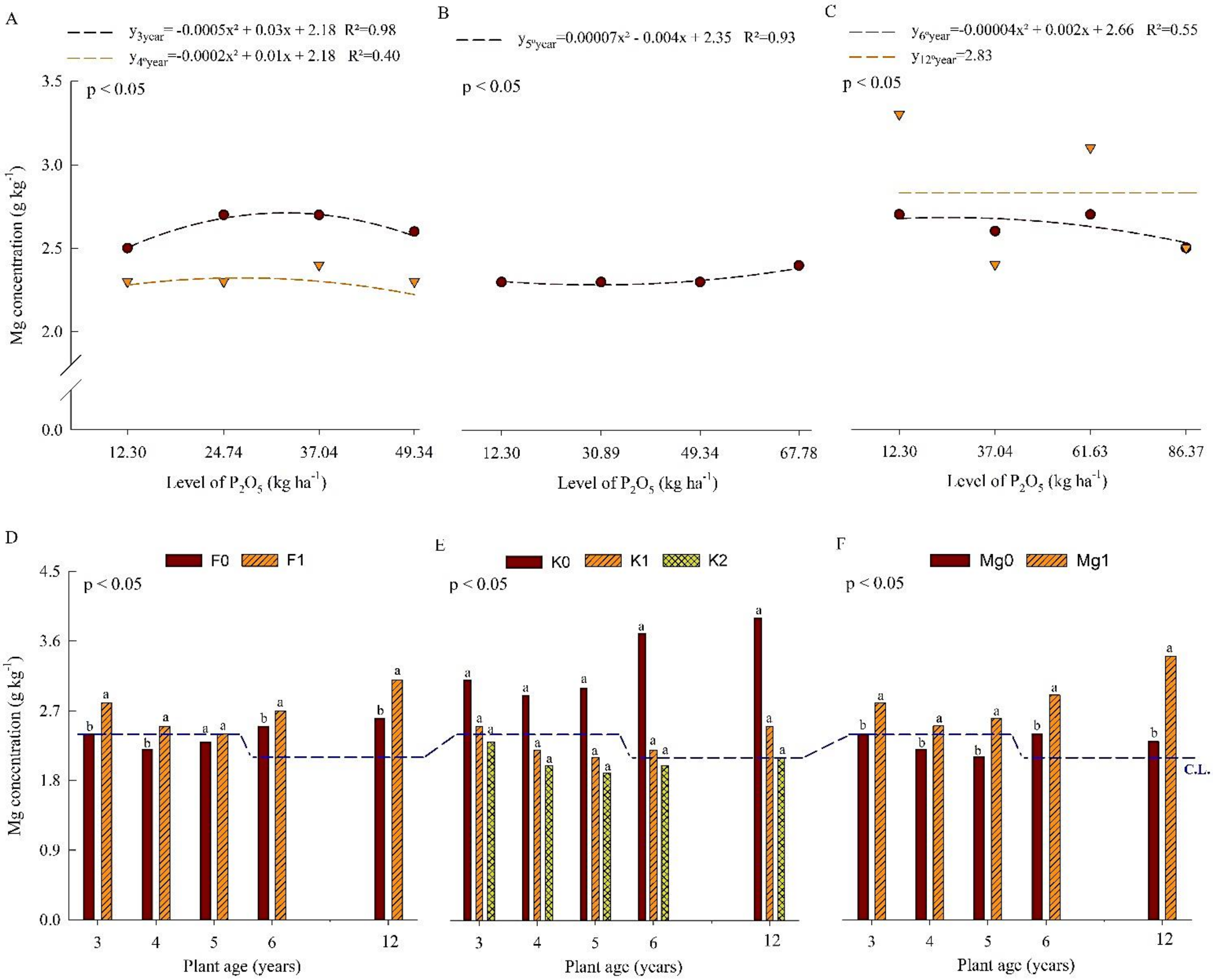

Figure 7. A - Leaf Mg concentration of oil palm as a function of P levels in the third and fourth; B - in the fifth; C - in the sixth and twelfth year of the plants, from the sources of P; D - F0- phosphine and F1- triple superphosphate; E - levels of K; F – levels of Mg. Equal letters in the columns, comparing fertilization levels at each age of the plants, are considered statistically equal by the Tukey test (p> 0.05). C.L. - Critical level established for oil palm in Pará state by the method of reduced normal distribution (RND) (Matos et al. 2016).

The leaf NP ratio is essential for a better understanding of N nutrition, since the critical concentration of N varies according to the P concentration in the leaves (Ollagnier and Ochs 1981). The values that remain distributed below the universal straight equation established by the researchers and predominantly to the left, indicating a deficient phosphate and nitrogen nutrition. On the other hand, the values that were predominantly to the left and above the equation of the straight line indicate satisfactory phosphorus nutrition and deficient nitrogen nutrition. Studies carried out with palm trees grown in the Amazon indicated positive responses of the NP ratio in oil palm (Matos et al. 2016) and coconut tree (Saldanha et al. 2017). The levels P1, P2, P3 and P4 were distributed below the universal equation line except for the twelfth year (Figures 4a, 4b and 4c). A study carried out in Central Amazonia with levels of P and N obtained the NP ratio below the universal line until the third year of the plants, but a balance was found above the universal line, indicating that the N deficiency directly influences the leaf concentration of P (Rodrigues et al. 1997), even though the application of higher level of P did not increase leaf N concentration. This fact may be related to the application of mineral N only in the first three years of the current study, despite the use of legumes, indicating the importance of the supply of N in the nutritional status of P. Based on the line of the universal equation (Ollagnier and Ochs 1981), the optimal leaf concentrations of P were calculated as a function of the average concentrations of N obtained with the application of phosphine and triple superphosphate (Table 3). Considering the P sufficiency range from 1.6 to 2.0 g kg^{-1} for oil palm in Pará (Matos et al. 2016), there were optimal P concentrations in the present study, except for the estimate for the third and fourth year with the application of phosphine (Table 3).

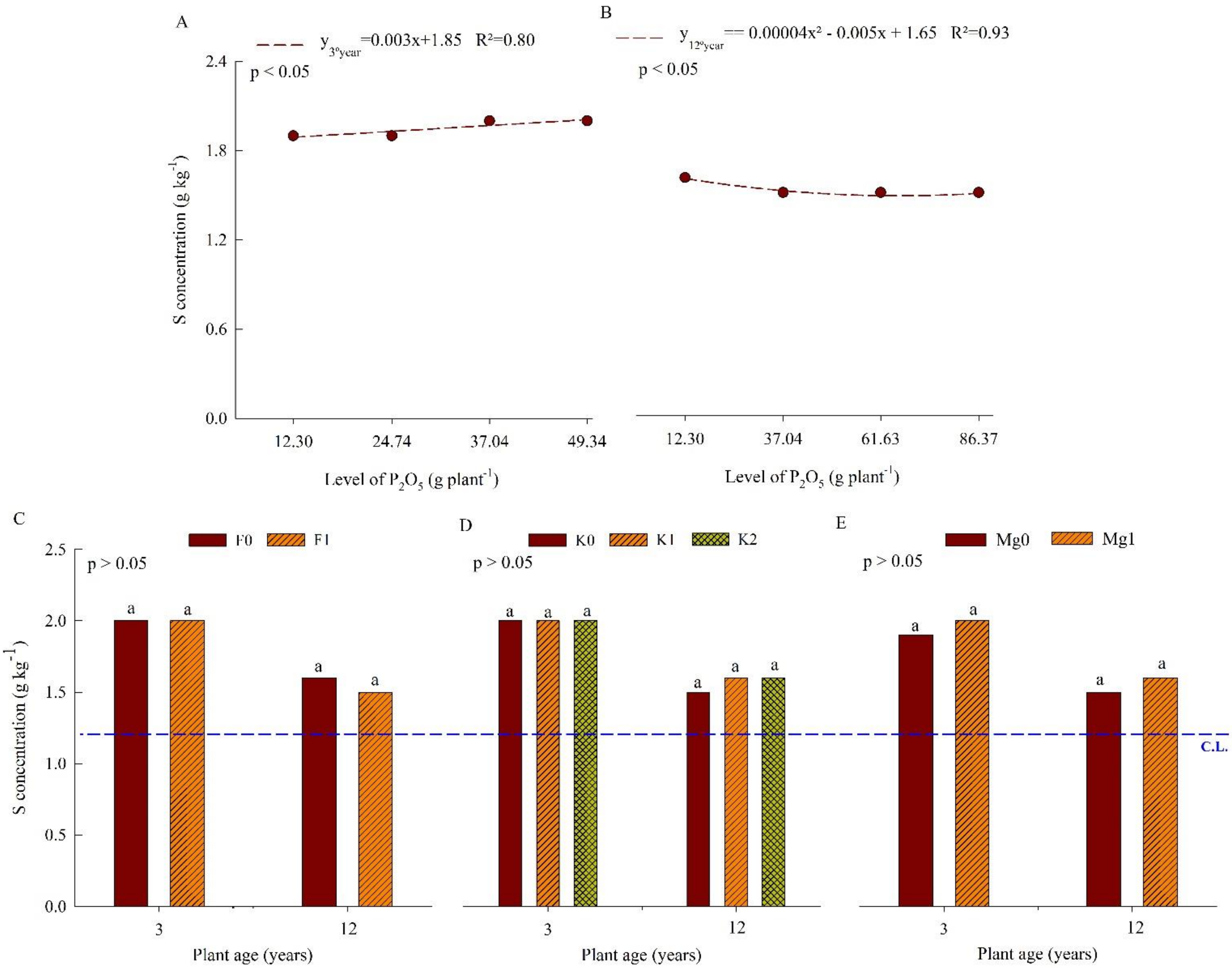

Figure 8. A - Leaf S concentration of oil palm as a function of P levels in the third and fourth; B - in the fifth; C - in the sixth and twelfth year of the plants, from the sources of P; D - F0- phosphine and F1- triple superphosphate; E - levels of K; F – levels of Mg. Equal letters in the columns, comparing fertilization levels at each age of the plants, are considered statistically equal by the Tukey test (p> 0.05). C.L. - Critical level established for oil palm in Pará state by the method of reduced normal distribution (RND) (Matos et al. 2016).

There was a trend to decrease leaf K concentrations by P supply (Figures 5A, 5B and 5C). Decrease on leaf K concentrations with increasing levels of P applied to oil palm is reported in the literature (Pacheco et al. 1985; Viégas et al. 2019). The addition of fertilizers to the soil can increase the leaching of K, caused by its displacement of negative charges by other cations (Ernani et al. 2007). Also, the increase in phosphate concentration in the soil promotes greater availability of Ca, resulting in greater absorption of this nutrient and, consequently, decreasing the absorption of K (Rodrigues et al. 1997).

A study carried out by reduced normal distribution (RND) method in oil palm orchards in Pará determined the critical level of 7.5 g kg^{-1} of K for plants up to the fifth year of age and, for plants from the sixth year of age, the critical level of 7.0 g kg^{-1} of K (Matos et al. 2016). The leaf K concentrations of the current study are in the range of nutritional sufficiency for the crop with the application of the two sources of P, except for the twelfth year of age of the plants. Also, it was observed that the K leaf concentration decreased with the oil palm aging, which can be explained by the increase in nutrient exports by the bunches (Viégas et al. 2019). Viégas et al. (2019) found higher leaf K concentration when oil palm plants received supply of this nutrient, as noted in the current research (Figure 5e). In Indonesia, there was also an increase in the leaf K concentration due to its supply in young (5 years) oil palm plants (Miranda Ney et al. 2020).

Table 3. Optimal P concentration as a function of N concentration and P sources in leaf 17 of oil palm.

Age (years)	N (g kg^{-1})		P (g kg^{-1})		Optimal P concentration	
	RP	TSP	RP	TSP	RP	TSP
3	23.7	24.7	1.4	1.5	1.54	1.59
4	24.4	26.1	1.4	1.6	1.58	1.66
5	24.7	25.2	1.5	1.6	1.59	1.62
6	27.8	28.0	1.5	1.6	1.74	1.75
12	23.9	23.9	2.1	2.1	1.55	1.55

RP – rock phosphate, TSP – triple superphosphate.

A study carried out with oil palm and magnesium fertilization in Pará also did not observe a significant difference in the leaf K concentrations (Viégas et al. 2019). On the other hand, the literature (Dechen and Nachtigall 2007) points out an antagonism between K and Mg, depending on the concentrations of both. Although there was no response of the leaf K concentrations to Mg fertilization, it was found that the nutrient concentrations are above the critical level (Matos et al. 2016), except in the twelfth year of age of the plants (Figure 5F).

The supply of phosphorus promoted an increase in the leaf Ca concentrations of oil palm (Figures 6A, 6B and 6C). Rodrigues et al. (1997) found an increase in the leaf Ca concentrations with an increase in the applied P levels in oil palm. This increase in leaf Ca concentration is related to the Ca contained in the applied phosphorus sources (Table 2), which increased the availability of the nutrient in the soil. Studies carried out in oil palm orchards in Pará determined the critical level of 8.6 g kg^{-1} of Ca for young plants (<6 years old) and 7.4 g kg^{-1} of Ca for adult plants (≥ 6 years old) (Matos et al. 2016). Thus, the sources of P promoted leaf concentrations of Ca above the critical level for culture in the region (Figures 6D). Similar results were observed in an experiment with oil palm plants in Indonesia (Miranda Ney et al. 2020). Although the concentrations of Ca in relation to potassium fertilization did not differ, there was a tendency of lower leaf Ca concentrations in the fifth, sixth and twelfth year of the plants when the K supply was performed (K1 and K2) (Figure 6E). Ca absorption can be decreased by high concentrations of K^+, Mg^{2+} and N-NH_4^+ (Lima et al. 2018), indicating, at high levels, an antagonism between these nutrients. A study carried out with potassium fertilization in oil palm plants also found a negative correlation between Ca and K (Dubos et al. 2011).

Water is the factor with the greatest influence on the nutrient absorption process, since absorption occurs from its contact with the root surface, depending directly on the concentration of the nutrient in the soil solution (Meurer 2007). Ca is transported, predominantly, by mass flow, taking into account the difference in water potential, with the amount transported of the nutrient resulting from its concentration in the soil solution and the volume of water transpired by the plant (Meurer 2007).

Leaf Mg concentrations (Figures 7A, 7B and 7C) may have been influenced by the increase in Ca concentrations due to the increase in P levels, and it was verified that higher P levels increased leaf Ca concentrations (Figures 6A, 6B and 6C). In research carried out with oil palm in Manaus state, it was also found an increase in leaf Mg concentration with an increase in the level of P (Rodrigues et al. 1997). It was observed greater leaf Mg concentrations with application of triple superphosphate (F1) as P source (Figure

7D). This fact can be explained by the difference between the levels of Ca present in the sources of P, since the phosphine contains 42% CaO and the triple superphosphate presents only 10% CaO (Table 2).

The competition between Ca^{2+} and Mg^{2+} can occur in soils with high levels of Ca, mainly because the soils present lower levels of Mg, justified by the lower retention of Mg by clays and organic matter, leaving this nutrient more conducive to leaching (Lima et al. 2018). Thus, the highest leaf Mg concentration, when the application of triple superphosphate (F1), may have been favored by its lower concentration of Ca in relation to phosphine (F0). A study carried out in oil palm orchards in Pará determined the critical level of 2.4 g kg^{-1} of Mg for young plants (<6 years of age) and of 2.1 g kg^{-1} for adult plants (≥ 6 years of age) (Matos et al. 2016). Thus, the application of triple superphosphate promoted leaf Mg concentrations above the critical level for oil palm in all the years evaluated (Figure 7D).

The lack of response on leaf Mg concentrations in relation to K supply (Figure 7E) was also observed in a study with potassium fertilization in oil palm plants (Miranda Ney et al. 2020). However, there was a trend of lower leaf Mg concentrations with K fertilization in all evaluated years. Pacheco et al. (1985) also observed a decrease in leaf Mg concentration with an increase in the K supply for oil palm. A study evaluating the nutritional status of different oil palm plantations in Benin also found a negative correlation between K and Mg (Koussihouèdé et al. 2020). According to Lima et al. (2018), high levels of K in the soil can reduce the absorption of Mg, and its deficiency can occur under conditions of K/Mg > 4 ratio. The Mg supply increased their leaf concentrations above the critical level for oil palm (Figure 7F). Another fact, according to Viégas et al. (2021), is the presence of legumes in oil palm orchards that can benefit the crop, since the mineralization of organic matter of the soil cover is capable of providing 1 kg $plant^{-1}$ $year^{-1}$ of Mg and thus also contribute to the oil palm nutrition in this cation.

The influence of phosphorus fertilization on leaf S concentrations (Figures 8A and 8B) can be explained by the fact that P promotes greater vegetative growth and, in young plants, the production of bunches is less expressive compared to adult plants, thus lesser export of S occurs through the bunches of those. This fact explains the decrease in leaf S concentration of plants at the twelfth year of age, which, with increased levels of P, produced more bunches (Figure 8D), increased export of S and, consequently, reduced leaf S concentration (Figure 8B). The average organic matter concentration of the soil (MOS) (Table 1) and the climatic conditions (Figure 1) of the present study contributed to a greater mineralization and, thus, a greater release of S for oil palm plants. The use of cover crops may also have contributed to the S-nutrition for oil palm, since the S concentration in the plant tissue varies from 2 to 5 g kg^{-1} of dry matter in most cultivated species (Alvarez et al. 2007).

The leaf S concentrations were not influenced by P sources and K and Mg supply (Figures 8C, 8D and 8E). There is a competition between phosphate and sulfate anions at the colloid sites of the soil, where the former is retained more strongly (Vitti et al. 2018). Thus, high levels of phosphate can promote desorption and greater leaching of S with consequent lesser absorption of this nutrient by plants, especially in sandy soils and region with great rainfall (Figure 1). A study carried out in oil palm orchards in northeastern Pará determined the critical level of 1.3 g kg^{-1} of S for young and adult plants (Matos et al. 2016). Thus, the oil palm plants in the current study were well-nourished in S in the third and twelfth year of age (Figure 8).

S deficiency is commonly observed in Pará's oil palm orchards, mainly caused by the high mineralization rate and high nutrient leaching (Matos et al. 2016), favored by the climate (Figure 1). According to Vitti et al. (2018), the highest proportions of S in the soil are present in organic matter, reaching around 95%. The use of soil cover plants may also have favored the highest leaf S concentrations, since the vegetal residues of these plants contribute to increase the organic matter concentration of the soil and, consequently, the levels of S. In oil palm plantation, it was observed that *Pueraria phaseoloides* L. cycled, on average, 7.1 kg ha^{-1} $year^{-1}$ of S (Viégas et al. 2021). It should be noted that S is an essential element for oilseeds, as it is related to oil biosynthesis and acts in the formation of storage organs of saturated fatty acid (Matos et al. 2019).

5. Conclusions

The leaf concentrations of N, P, Ca and Mg in the oil palm increase with the supply of P, however there was no increase in leaf concentrations of K and S.

The ratio of leaf concentrations of N and P is efficient to evaluate the nutritional status of these nutrients in oil palm.

The P source influences the nutrition of oil palm plants in the early years, mainly with the application of a faster release source (triple superphosphate).

Fertilization with K and Mg increases their leaf concentrations in oil palm plants.

The responses of the leaf concentrations of P, K and Mg indicate the need for adequacy for the recommendation of these nutrients in the eastern Amazon region so that oil palm plants reach adequate levels.

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