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Gypsum and lime applications improve soil fertility under coconut cultivation in Eastern Amazon, Brazil

Aplicações de gesso e calcário melhoram a fertilidade do solo sob cultivo de coco na Amazônia Oriental, Brasil

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ABSTRACT

Gypsum and lime application causes chemical modifications in the soil that influence nutrient content, root growth and development of plants. An experiment was carried out in the municipality of Santa Isabel, Pará state, Brazil, to evaluate the chemical changes in the soil and the responses of green dwarf coconut to gypsum and lime at 6 and 12 months after application. The experimental design was completely randomized blocks, with 4 blocks and 7 treatments: T1 = control; T2 = 2000 kg ha^{-1} lime; T3 = 500 kg ha^{-1} gypsum; T4 = 2000 kg ha^{-1} lime + 300 kg ha^{-1} gypsum; T5 = 2000 kg ha^{-1} lime + 500 kg ha^{-1} gypsum; T6 = 2000 kg ha^{-1} lime + 700 kg ha^{-1} gypsum; T7 = 2000 kg ha^{-1} lime and 1000 kg ha^{-1} gypsum. After 12 months of applying the treatments, the combination of gypsum and limestone was used to reduce aluminum saturation, with values of 0% at a depth of 0.0-10 cm of the soil, as well as increments in sulfur contents and base saturation of the soil, with values of 70% at a depth of 0.0-10 cm of the soil; with positive effects on macronutrients concentrations in leaf tissue and on root growth. Application of agricultural gypsum, associated with lime, is efficient to improve the chemical attributes of the soil and the development of green dwarf coconut plants.

Index terms: Liming; calcium sulfate; plant nutrition; *Cocos nucifera*.

RESUMO

A aplicação de gesso e calcário resulta em modificações químicas no solo que influenciam no teor de nutrientes, crescimento radicular e desenvolvimento das plantas. Com o objetivo de avaliar as alterações químicas do solo e respostas do coqueiro anão verde ao gesso e calcário no período de 6 e 12 meses após aplicação, foi realizado experimento no município de Santa Isabel no estado do Pará. O delineamento experimental foi em blocos inteiramente casualizados, sendo 4 blocos e 7 tratamentos: T1= controle; T2= 2000 kg ha^{-1} de calcário; T3= 500 kg ha^{-1} de gesso; T4= 2000 kg ha^{-1} de calcário + 300 kg ha^{-1} de gesso; T5= 2000 kg ha^{1} calcário + 500 kg ha^{-1} gesso; T6 = 2000 kg ha^{-1} calcário + 700 kg ha^{-1} gesso; T7= 2000 kg ha^{-1} calcário e 1000 kg há$^{-1}$ gesso. Após 12 meses da aplicação dos tratamentos, a combinação de gesso e calcário resultou na redução da saturação por alumínio, com valores de 0% na profundidade de 0,0- 10 cm do solo, assim como incrementou os teores de enxofre e aumentou a saturação por bases do solo, com valores de 70% na profundidade de 0,0- 10 cm do solo; apresentou efeitos positivos na concentração de macronutrientes no tecido foliar e no crescimento radicular. A aplicação de gesso agrícola, associada ao calcário eficiente para melhorar os atributos químicos do solo e o desenvolvimento das plantas de coqueiro anão verde.

Termos de indexação: Calagem, sulfato de cálcio, nutrição de plantas, *Cocos nucifera.*

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Introduction

Coconut (*Cocos nucifera* L.) cultivation is very prominent in the Brazilian agricultural market (Fróes *Júnior et al., 2019*) In Brazil, there are 187.5 thousand hectares planted with coconut palms, which account for 1.6 billion fruits (Food and Agriculture Organization of the United Nations - Faostat, 2021). In the national scenario.the North region stands out at the third position in terms of production (Instituto Brasileiro de Geografia e Estatistica - IBGE, 2021).

In this region, coconut trees are usually cultivated in acidic soils with low natural fertility, as is the case of Quartzipsamments. Thus, growth and increase in yield are conditioned on the application of large amounts of mineral fertilizers and on the correction of soil acidity (Silva et al., 2019). The main technique employed to improve the quality of acidic soils with low fertility is the use of lime (Costa et al., 2015), which is already being used alone in coconut crops in the state of Pará (Brasil, Cravo, & Viégas, 2020). Lime applied to the soil provides nutrients, neutralizes pH, and reduces the toxic potential of aluminum (Costa et al., 2015). However, these effects are limited to the superficial layers (Nolla et al., 2020). According to Tiecher et al. (2017), the aluminum toxicity in soil deeper layers can be reduced with correctives that have higher solubility, such as agricultural gypsum, which promotes the reduction of aluminum saturation by forming molecules between S and Al ($AlSO^{4+}$) that are less toxic to plants. Furthermore, the use of gypsum enhances the solubility of Ca and Mg and consequently increases these nutrients in deeper soil layers.

Effects of gypsum and lime application are widely known in the literature (Costa, 2020; Macana, 2023; Crusciol, 2019). It is known that Quartzipsamments are predominantly sandy, with low water and nutrient retention (Brasil, Cravo, & Viégas, 2020), and, considering the scarcity of information on coconut cultivation in the state of Pará, it is imperative to conduct studies that demonstrate whether the use of gypsum associated with lime is capable of altering the fertility of this type of soil and causing changes in the growth and nutritional status of coconut plants. Thus, the objective of this study was to evaluate the effects of gypsum and lime applied separately and together, with different times of reaction in the soil, on the chemical properties of the soil and on the growth and nutritional response of green dwarf coconut plants, cultivated in the state of Pará, Brazil.

Material and Methods

The experiment was carried out at the Sococo Reunidas farm (1°13'42" S and 48°02'57" W) in the municipality of Santa Izabel do Pará, Pará, Brazil. The experiment was set up in February 2020. Seedlings of the green dwarf coconut variety were planted at spacing of 7.5 x 7.5 x 7.5 m, forming an equilateral triangle. Thus, the experiment consisted of 7 treatments and 4 replicates, totaling 28 experimental plots, each composed of 25 plants. The climate of the region is humid tropical of the Am type according to the Köppen and Geiger classification, with an average monthly temperature of 25 ºC. During the experimental period, annual rainfall and minimum and maximum temperatures (from 21,9 to 32,9ºC) at the site were recorded, and they are shown in Figure 1.

The soil of the experimental area was characterized as *Neossolo Quartzarênico distrófico* (Quartzipsamment) (Santos et al., 2018). To characterize the area before the application of treatments, soil samples were collected at six depths (0-5, 5-10, 10-20, 20-40, 40-60 and 60-80 cm), and their chemical and particle-size characteristics are presented in Table 1. Sample preparation and chemical analysis were performed according to Teixeira et al. (2017).

The experiment was carried out in a completely randomized block design (CRBD) with 4 experimental blocks. Treatments consisted of combined rates of gypsum and lime applied broadcast, as follows: T1 = control; T2 = 2000 kg ha^{-1} lime; T3 = 500 kg ha^{-1} gypsum; T4 = 2000 kg ha^{-1} lime and +300 kg ha^{-1} gypsum; T5 = 2000 kg ha^{-1} lime + 500 kg ha^{-1} gypsum; T6 = 2000 kg ha^{-1} lime + 700 kg ha^{-1} gypsum; T7= 2000 kg ha^{-1} lime + 1000 kg ha^{-1} gypsum. Gypsum rates were calculated based on liming requirements (2000 kg ha^{-1}). The treatments were applied in November 2021, 19 months after setting up the experiment. The gypsum and lime sources used were Dolomitic Limestone (CaO: 36%; PRNT: 91%) and gypsum (Ca: 16%; S: 15%). The fertilization with NPK (10-07-10) was applied once in 2021, at a concentration of 0.5kg per plant. The orchard did not receive any type of specific irrigation, relying solely on rainfall.

Effects of treatments were analyzed at 6 months and 12 months after application of the treatments. For soil fertility analysis, 168 samples were collected at different depths (0-5, 5-10, 10-20, 20-40, 40-60 and 60-80 cm). The soil samples were air-dried and sieved through a 2-mm mesh. The analyses performed were hydrogen potential (pH), potential acidity (H+Al), calcium ion (Ca^{+2}), magnesium ion (Mg^{+2}), aluminum ion (Al^{+3}), potassium ion (K^{+}), available phosphorus (P), sulfur (S), boron (B), copper (Cu), manganese (Mn), and organic carbon (Corg) (Teixeira et al., 2017). After obtaining the results, cation exchange capacity (CEC), base saturation (V%) and aluminum saturation (m%) were calculated.

The material for leaf tissue analysis was collected according to the procedures described by Martin-Prével, Gagnard and Gautier (1984), who recommends the collection of the central leaflets of leaf number 4 for plants up to three years of age. Three leaflets were collected on each side of the central part of the leaf from 16 plants of each treatment, totaling 112 samples. After collection, the material was dried in an oven at 60 ºC until reaching constant mass, and then crushed in a Wiley-type mill (MA 340 model, Marconi, BR).

The nutritional status of coconut plants was evaluated based on the concentrations of macro and micronutrients in the leaf tissue. The macronutrients evaluated were: nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca) and magnesium (Mg), and the micronutrients were: boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn). The analyses were carried out according to Empresa Brasileira de Pesquisa Agropecuária - Embrapa (2000).

Plant growth was measured by height (H), number of leaves (NL), and stem diameter (SD). These measurements were taken with a graduated tape measure and a 5.5-m-long graduated ruler. Sampling was carried out in 16 plants per treatment, totaling 112 plants evaluated.

Growth and development of coconut tree roots were assessed using the rhizotron method (rhizo = root; tron = window), which is a non-destructive analysis (Metcalfe, 2008). In one block, 14 rectangular rhizotrons with height of 105 cm and width of 75 cm were installed. The walls of the rhizotrons are made of transparent acrylic (7.0 mm) with wooden edges, and measurements were performed using a grid profile, each square measuring 10 x 10 cm, with the aid of a graduated tape measure.

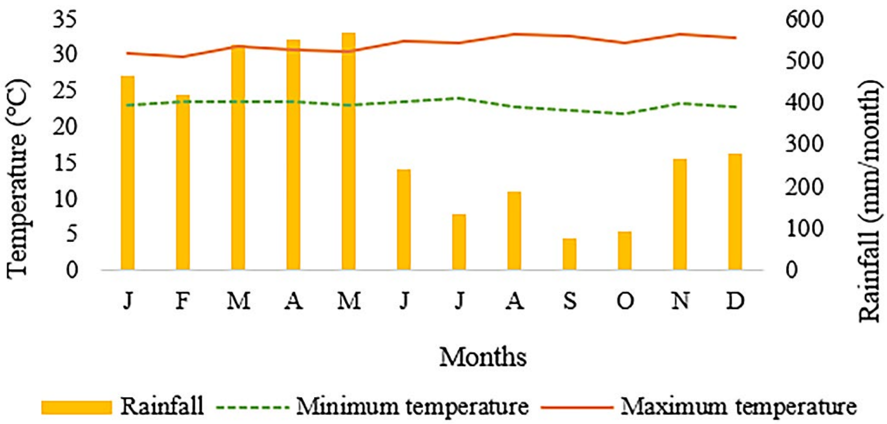

Figure 1: Monthly rainfall and minimum and maximum temperatures atin the site during the experimental period.

Table 1: Chemical and particle-size characteristics of the Quartzipsamment before setting up the experiment, in the 0-5, 5-10, 10-20, 20-40, 40-60 and 60-80 cm layers.

DEPTH	pH ($CaCl_2$)	pH (SMP)	OM	Corg	S	P	K	Ca	Mg	Al	CEC	V%	m%
			mg dm^{-3}				mmol$_c$ dm^{-3}						
0-5	4.2	6.1	18.5	10.8	7.8	4.0	0.4	6.8	2.0	5.8	49.5	19.3	38.5
5-10	4.1	6.0	16.8	9.8	6.3	3.3	0.3	5.5	1.8	7.3	49.1	16.0	48.2
10-20	4.2	6.1	15.0	8.8	7.3	4.1	0.2	4.8	1.8	7.0	45.8	15.0	50.3
20-40	4.3	6.2	9.0	5.3	9.0	1.6	0.1	3.0	1.0	8.0	39.8	10.8	64.9
40-60	4.3	6.2	6.3	3.3	12.5	1.5	0.1	3.0	1.0	7.0	37.3	11.5	60.9
60-80	4.4	6.5	4.3	2.3	15.0	0.9	0.2	3.3	1.3	5.8	30.6	15.8	54.7

DEPTH	B	Cu	Fe	Mn	Zn	DEPTH	Sand	Silt	Clay
	mg dm^{-3}						g kg^{-1}		
0-5	0.3	0.3	153.8	8.4	1.6	0-5	829	78	93
5-10	0.2	0.2	183.8	6.1	1.0	5-10	842	77	81
10-20	0.3	0.3	228.8	5.1	0.8	10-20	828	96	76
20-40	0.2	0.2	286.3	2.3	0.1	20-40	803	136	61
40-60	0.1	0.1	292.5	1.4	0.1	40-60	798	115	87
60-80	0.1	0.2	278.8	1.8	0.1	60-80	757	111	132

P, Mn, Fe, Cu, Zn – Mehlich-1 extractant; Ca, Mg, K – Resin extractant; B – Hot water method.

Statistical analyses were performed in R software, version 4.2.0. Regression analyses (linear and quadratic) were performed to evaluate the parameters of growth (shoots and roots), nutrition and soil, and the equations were chosen based on the significance of the coefficients. Normality and homoscedasticity assumptions were checked using the Shapiro-Wilk and Bartlett tests, respectively. For all analyses, the dbc function of the ExpDes.pt package was used.

Results and Discussion

Gypsum and lime effects on soil chemical properties

Application of gypsum combined with lime caused significant changes in the chemical properties of the soil at the two times analyzed (Figure 2 and Figure 3). At 6 months after application of the treatments, the main changes observed in the 0-5 cm layer were the increase in Ca and Mg, increase in V%, and reduction in H+Al and Al^+ contents, with consequent reduction in m% (Figure 2).

At 12 months after application of the treatments, more significant changes in the chemical attributes of the soil were observed in the different treatments and depths (Figure 3), when compared to the first evaluation time (Figure 2). The best results were obtained in treatments that associated gypsum and lime, such as T4, T5 and T6 (Figure 3). Although a period of 12 months is short for the total reaction of gypsum (Macana, 2023) and lime, it was possible to observe increments in Ca, Mg, K, S, CEC and V% and reductions in pH, H+Al and Al^+, with consequent reduction in m%. In general, changes were observed up to the 60-80 cm layer (Figure 3).

The results observed for soil chemical properties as a function of lime and gypsum rates are shown in Tables 2 and 3. The variables that had no significant effects according to the regression analysis at 6 months (K, P, S, CEC, Corg, $CaCl_2$, B, Fe, Mn, Zn and Na) and at 12 months (Corg, Cu, Zn and Na) were not presented.

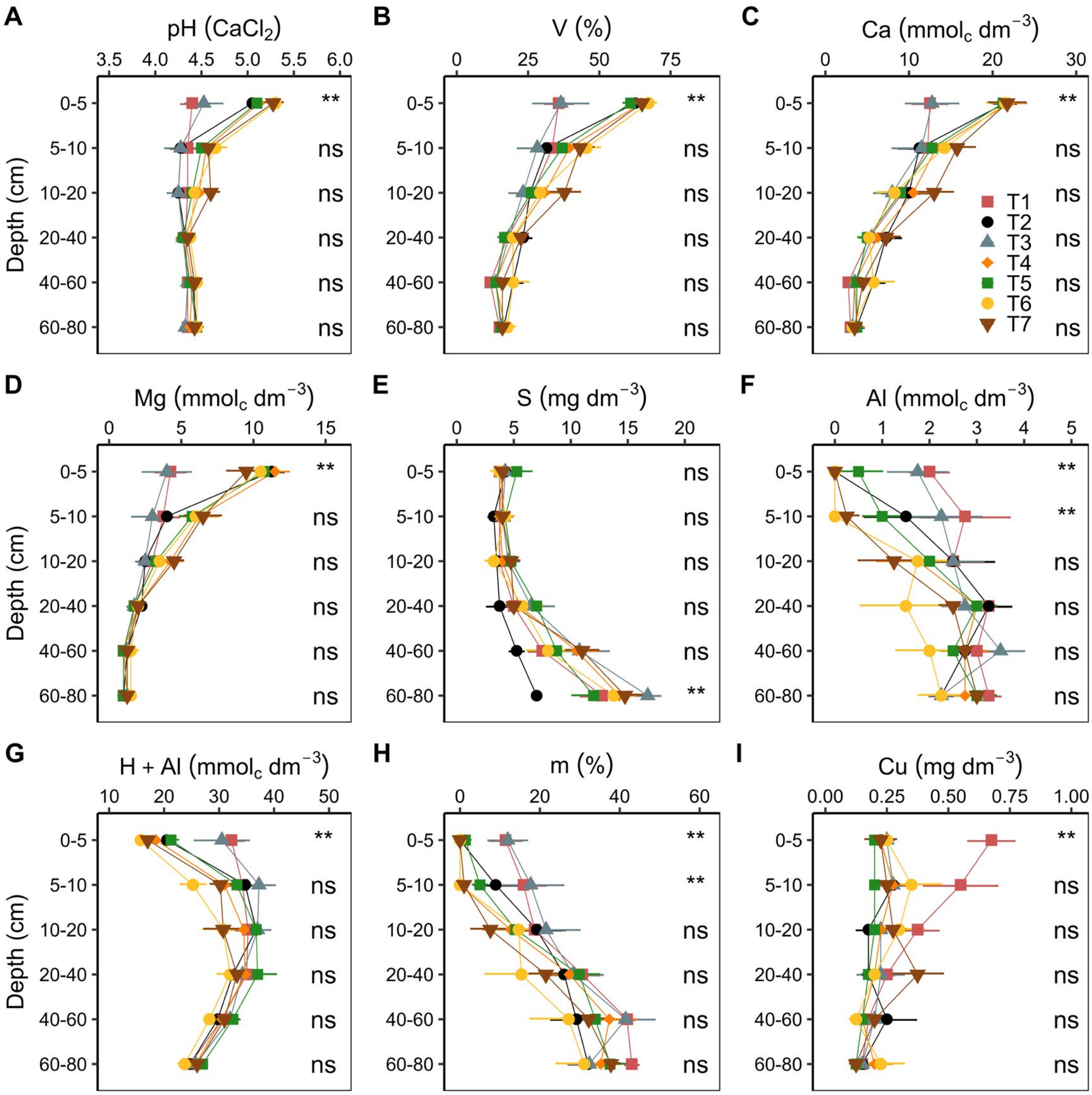

Figure 2: Influence of lime and gypsum rates on hydrogen potential – pH (A), base saturation – V% (B), exchangeable calcium – Ca^{+2} (C), exchangeable magnesium – Mg^{+2} (D), sulfur – S (E), exchangeable aluminum – Al^+ (F), potential acidity – H+Al (G), aluminum saturation – m% (H), copper – Cu (I), in the soil 6 months after application of the treatments. *- significant at $p \leq 0.05$, ** - significant at $p \leq 0.01$ by the F test; R^2 – coefficient of determination; CV – coefficient of variation. Vertical bars indicate standard error of means (n = 4).

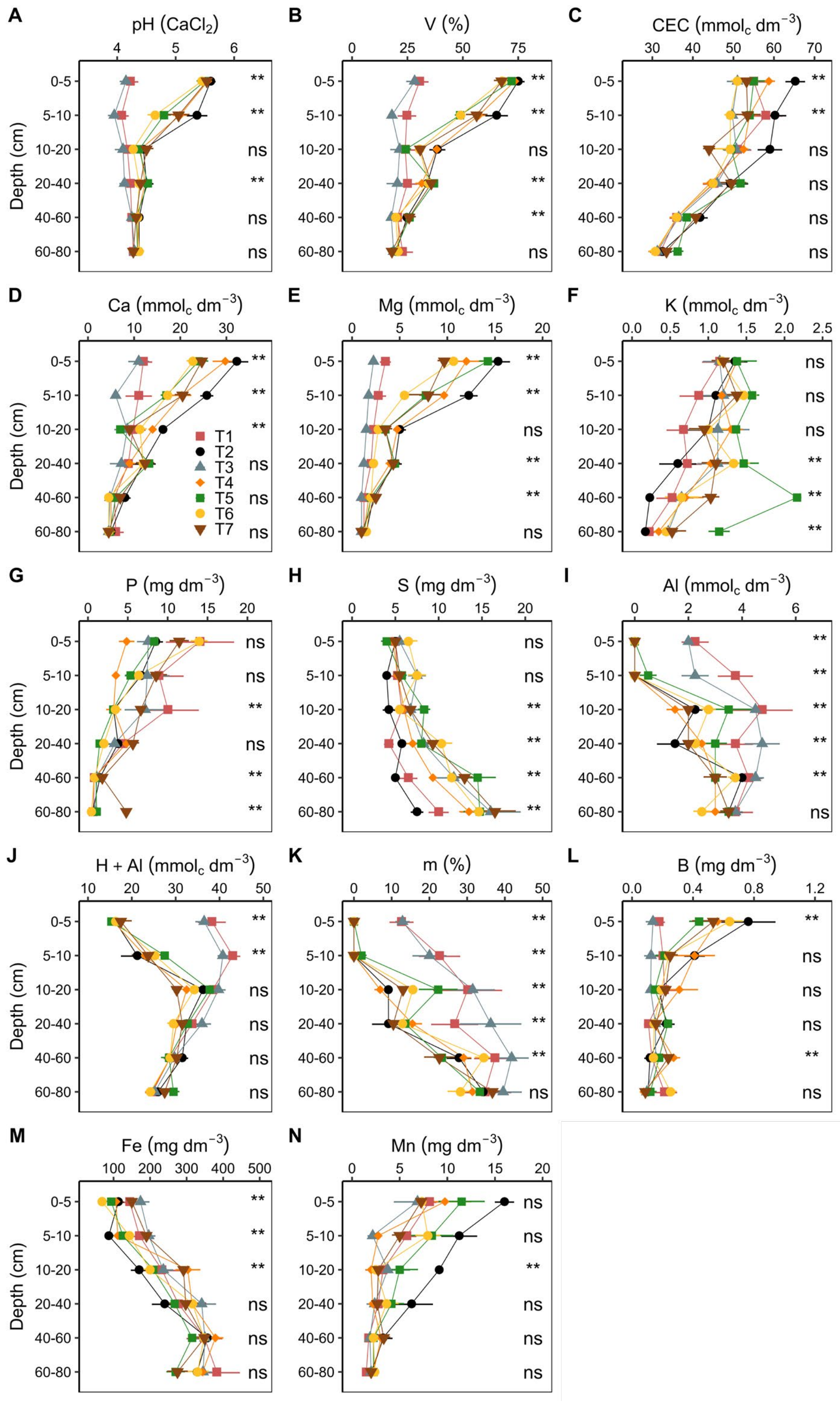

Figure 3: Influence of lime and gypsum rates on hydrogen potential – pH (A), base saturation – V% (B), cation exchange capacity - CEC (C), exchangeable calcium – Ca^{+2} (D), exchangeable magnesium – Mg^{+2} (E), potassium – K (F), available phosphorus – P (G), sulfur – S (H), exchangeable aluminum – Al^{+} (I), potential acidity – H+Al (J), aluminum saturation – m% (K), boron – B (L), iron – Fe (M), manganese – Mn (N), in the soil 12 months after application of the treatments. *- significant at $p \leq 0.05$, ** - significant at $p \leq 0.01$ by the F test; R^2 – coefficient of determination; CV – coefficient of variation. Vertical bars indicate standard error of means (n = 4).

Table 2: Regression equations with significant coefficients of determination ($p \leq 0.01$) between calcium (Ca), magnesium (Mg), base saturation (V%), total acidity (H+Al), exchangeable aluminum (Al^{+}), base saturation (m%), copper (Cu) and sulfur (S) in soil (ŷ), for different depths, and gypsum and lime rates (X), applied to soil surface, at 6 months after application of the treatments.

ŷ	Depth (cm)	Equation	R^2
Ca	0-5	$\hat{y} = 13.85 + 1.29x$	0.41
Mg	0-5	$\hat{y} = 2.75 + 2.79x - 2.25x^2$	0.33
V%	0-5	$\hat{y} = 38.91 + 0.34x$	0.46
H+Al	0-5	$\hat{y} = 31.46 - 2.30x$	0.58
Al	0-5	$\hat{y} = 1.64 - 0.26x$	0.39
	5-10	$\hat{y} = 2.78 - 0.41x$	0.67
m%	0-5	$\hat{y} = 9.93 -1.60x$	0.38
	5-10	$\hat{y} = 17.67 - 268x$	0.6
Cu	0-5	$\hat{y} = 0.80 - 26x + 0.26x^2$	0.72
S	60-80	$\hat{y} = 10.93 + 0.53x$	0.13

Table 3: Regression equations with significant coefficients of determination ($p \leq 0.01$) between hydrogen potential ($pHCaCl_2$), potassium (K), calcium (Ca), magnesium (Mg), total acidity (H+Al), exchangeable aluminum (Al^{+}), cation exchange capacity (CEC), base saturation (V%), base saturation (m%), sulfur (S), boron (B), iron (Fe), manganese (Mn) and phosphorus (P) in soil (ŷ), for different depths, and rates of gypsum and lime (X), applied to the soil surface, at 6 months after application of the treatments.

ŷ	Depth (cm)	Equation	R^2
pH $CaCl_2$	0-5	$\hat{y} = 0.409 + 0.402x - 0.0281x^2$	0.36
pH $CaCl_2$	5-10	$\hat{y} = 4.3 + 0.008x$	0.11
pH $CaCl_2$	20-40	$\hat{y} = 4.2 + 0.024x$	0.12
K	20-40	$\hat{y} = 0.63 + 0.10x$	0.53
K	40-60	$\hat{y} = -0.19 + 0.46 x - 0.041x^2$	0.28
K	60-80	$\hat{y} = -0.18 + 0.31x - 0.029x^2$	0.38
Ca	0-5	$\hat{y} = 11.96 + 5.016x - 0.484x^2$	0.14
Ca	5-10	$\hat{y} = 13.61 + 0.80x$	0.07
Ca	10-20	$\hat{y} = 12.78 - 0.49x$	0.1
Mg	0-5	$\hat{y} = 2.121 + 3.768x - 0.376x^2$	0.18
Mg	5-10	$\hat{y} = 5.62 + 0.294$	0.19
Mg	20-40	$\hat{y} = 2.44 + 0.20x$	0.1
Mg	40-60	$\hat{y} = 1.21 + 0.15x$	0.37
H+Al	0-5	$\hat{y} = 42.77 - 8.711x + 0.717x^2$	0.45
H+Al	5-10	$\hat{y} = 43.5 - 5.77x + 0.44x^2$	0.33

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Table 3: Continuation.

ŷ	Depth (cm)	Equation	R^2
Al	0-5	$\hat{y} = 2.607 - 0.8125x + 0.062x^2$	0.47
Al	5-10	$\hat{y} = 4.28 -1.46x + 0.125x^2$	0.55
Al	10-20	$\hat{y} = 4.21 - 0.29x$	0.55
Al	20-40	$\hat{y} = 3.60 - 0.19x$	0.54
Al	40-60	$\hat{y} = 4.46 - 0.20x$	0.47
CEC	0-5	$\hat{y} = 59.857 - 1.062x$	0.2
CEC	5-10	$\hat{y} = 58.57 - 1.11x$	0.36
V%	0-5	$\hat{y} = 24.21 + 14.98x - 1.24x^2$	0.32
V%	5-10	$\hat{y} = 28.89 + 5.62x - 0.28x^2$	0.6
V%	20-40	$\hat{y} = 24.07 + 1.77x$	0.39
V%	40-60	$\hat{y} = 20.17 + 0.5x$	0.5
m%	0-5	$\hat{y} = 14.36 - 4.13x + 0.29x^2$	0.42
m%	5-10	$\hat{y} = 25.43 -7.57x + 0.56x^2$	0.45
m%	10-20	$\hat{y} = 25.18 - 1.70x$	0.41
m%	20-40	$\hat{y} = 26.92 - 2.28x$	0.42
m%	40-60	$\hat{y} = 38 - 1.76x$	0.48
S	10-20	$\hat{y} = 5.17 + 0.25x$	0.48
S	20-40	$\hat{y} = 4.10 + 0.86x$	0.8
S	40-60	$\hat{y} = 5.19 + 1.25x$	0.61
S	60-80	$\hat{y} = 8.62 + 1.16x$	0.57
B	0-5	$\hat{y} = 0.30 + 0.04x$	0.43
B	40-60	$\hat{y} = 0.12 + 0.013x$	0.46
Fe	0-5	$\hat{y} = 143.17 - 5.41x$	0.1
Fe	5-10	$\hat{y} = 188.17 -33.82x + 4.67x^2$	0.21
Fe	10-20	$\hat{y} = 204.53 + 7.50x + 0.11x^2$	0.11
Mn	10-20	$\hat{y} = 5.99 - 0.483x$	0.28
P	10-20	$\hat{y} = 12.85 - 4.23x + 0.46x^2$	0.56
P	40-60	$\hat{y} = 1.40 - 0.28x + 0.04x^2$	0.35
P	60-80	$\hat{y} = 2.27 - 1.41x + 0.23x^2$	0.67

The pH was significantly affected by the treatments at the two times analyzed in the 0-5 cm layer and only at 12 months after application in the 5-10 and 20-40 cm layers (Figure 3A). It can be inferred that the form of application of gypsum and lime in the soil interfered in the results, with greater effects after 12 months of application, time for the reaction of gypsum and lime in the soil profile. For the treatment that received 2000 kg ha^{-1} of lime and 300 kg ha^{-1} of gypsum (T4), the pH was 5.5 and 5.36 in the 0-5 and 5-10 cm layers, respectively; these values are higher than those of the control treatment (T1) and the one that received only gypsum (500 kg ha^{-1}) (T3), which showed values of 4.2 and 4.15, respectively. In this pH range (4.15 to 4.2), the availability of anions such as phosphates and sulfates are reduced and the concentration of Al^{+} is high, which negatively influences plant development (Crusciol, 2019).

The results obtained in this study show that the use of gypsum alone was not efficient in raising the pH. Gypsum alone can cause a variation of only 0.3 units in pH (Meurer, 2010). When combined with lime, gypsum has greater potential to reduce exchangeable soil acidity, which occurs through the reaction of exchange of ligands of iron and aluminum oxides with SO_4^{2-}, which displaces OH^- particles, in addition to releasing basic anions from the dissolution of lime, promoting the partial neutralization of soil acidity (Pivetta et al., 2019). Therefore, the combination of gypsum and lime is essential for cultivation in acidic soils.

The results obtained corroborate those reported by Macana et al. (2023), who tested rates of lime and gypsum alone and together in sandy soils and observed better results of pH with joint application of gypsum (2400 kg ha^{-1}) and lime (2000 kg ha^{-1}) after 33 months.

In relation to V%, significant results were obtained at the two times analyzed. At 12 months after application of the treatments (Figure 3B), the significant effects reached more soil layers, up to 60 cm deep. The treatment that received 2000 kg ha^{-1} lime + 300 kg ha^{-1} gypsum (T4) had V% of 75.25 in the 0-5 cm layer and the treatment that received 2000 kg ha^{-1} lime + 500 kg ha^{-1} gypsum (T5) had values of 37.0 and 26.11 in the 20-40 and 40-60 cm layers, respectively. The control treatment (T1) and the one that received only gypsum (500 kg ha^{-1}) (T3) showed V% around 29% in the superficial soil layers, hence being inferior to the treatments mentioned above, showing an increase of more than 100% in base saturation when gypsum and lime were applied in combination.

The increase in base saturation in subsurface soil layers is justified by the dissolution of the agricultural gypsum molecule ($CaSO_4.2H_2O$), which releases Ca^{+} and SO_4^{2-} molecules into the soil solution. Sulfate has high mobility in the soil and, for having negative valence, it binds to the free cations in the soil solution, making them more available for root absorption (Crusciol et al., 2019). The change in base saturation shows that the treatments with gypsum and lime were efficient in the surface soil layers, as they provided exchangeable bases, mainly Ca^{+} and Mg^{+}, which indicates alkalinization of the soil. This is evident in the results of cation exchange capacity (CEC), which were significant at 12 months after application of the treatments (Figure 3C).

The highest CEC values were observed in the treatment that received lime alone (2000 kg ha^{-1}) (T2), 65.34 to 60.26 mmol dcm^{-3} in the 0-5 cm and 5-10 cm layers, respectively. These values can be explained by the increase in Ca promoted by liming. Therefore, lime has an effect on the transformation of hydrogen-blocked CEC into effective CEC, which increases its concentrations in the soil (Rheinheimer et al., 2018).

Ca and Mg contents showed significant results at the two times analyzed. For the time of 6 months after application of the treatments (Figure 2C and 2D, respectively), the results were significant in the 0-5 cm layer, with concentrations of 22 mmol dcm^{-3} Ca and 12 mmol dcm^{-3} Mg. The treatment that had these values received 2000 kg ha^{-1} lime + 300 kg ha^{-1} gypsum (T4).

For the time of 12 months after application of the treatments (Figure 3D and 3E), in the treatment that received only lime (2000 kg ha^{-1}) (T2), the significant effects reached more soil layers, up to 60 cm deep for Mg and 20 cm deep for Ca. This accumulation of Ca^{2+} is an important factor to be observed, because Ca has low solubility in the soil, with greater concentration in the 0-10 cm layer in sandy soils (Centeno et al., 2017).

In the superficial layers, the treatment that received only lime (2000 kg ha^{-1}) (T2) and the one that received 2000 kg ha^{-1} lime + 500 kg ha^{-1} gypsum (T5) had values ranging from 12 to 15 mmol dcm^{-3} for Mg and from 25 to 32 mmol dcm^{-3} for Ca, respectively. Ca^{2+} mobility in surface was due to the addition of gypsum in the system. According to Bayer (2019), this movement is due to the effect of SO_4^{2-} in binding to Ca^{2+}, forming the $CaSO_4^0$ ion pair, which neutralizes the charge of Ca^{2+} and prevents this compound from binding to soil charges, leaving it available in the soil solution, which facilitates its movement in the soil profile and absorption by plants.

The Ca^{2+} concentrations found in this study are within the range of average values (15 to 35 mmol dcm^{-3}) for soils in Pará (Brasil, Cravo, & Viégas, 2020). Thus, the addition of gypsum and lime in the system made it possible to obtain sufficient concentrations of Ca up to 60 cm deep in the soil, promoting greater availability of this nutrient to green dwarf coconut plants.

Mg^{2+} contents in the soil remained within the appropriate range (5 to 15 mmol dcm^{-3}) (Brasil, Cravo, & Viégas, 2020) up to 40 cm deep in the soil. For Mg, the effect was similar to that of Ca^{2+} as a function of gypsum application. At 12 months, it was possible to verify the effect of gypsum in displacing Mg^{2+}) up to 40 cm deep in the soil.

K^+ contents were significant only at 12 months after application of the treatments (Figure 3F), with decreasing values in the subsurface layers of the soil (> 20 cm). This reduction may have been caused by the imbalance of Ca, Mg and K, resulting in the leaching of K in the form of K^+ (Malavolta, 2006). Another explanation for the reduction of K^+ is the low availability of this nutrient in the surface layers of the soil, where there may be the formation of an ion pair with SO_4^{2-} ions ($K_2SO_4^0$), thus increasing its mobility in the soil profile (Bayer, 2019).

P contents were significant only at 12 months after application of the treatments (Figure 3G). In the 0-20 and 20-40 cm layers, the treatment that received 2000 kg ha^{-1} lime and 1000 kg ha^{-1} gypsum (T7) showed higher values (1.1 mg dm^{-3}) compared to the others. This behavior can be explained by the sandy texture of the studied soil, which causes lower P adsorption and, consequently, less P available to plants in the superficial layers (Vinha et al., 2023).

The results for S content were significant at the two times analyzed. For the time of 6 months after application of the treatments (Figure 2E), the significant result was observed in the 60-80 cm layer of the soil; for the treatment that received only gypsum (500 kg ha^{-1}) (T3), this behavior can be justified by the leaching of this nutrient in the soil profile, due to its high mobility.

At the second evaluation time, significant results were observed for S in four subsurface soil layers (>20 cm) (Figure 3H). The behavior of S was linear in each layer and increasing in the soil profile. The use of gypsum as a chemical conditioner in the subsurface root environment provides SO_4^{2-}, which will be available in the soil solution and will move more easily. Another factor that may have influenced the S contents in the deeper layers of the soil is the presence of iron and aluminum oxides, with a great capacity for SO_4^{2-} adsorption (Crusciol, et al., 2019).

Al^+, H+Al and m% contents showed a reduction at the two times analyzed as a function of the gypsum and lime rates applied broadcast. At 6 months after application of the treatments (Figure 2F, 2G and 2H), the results showed a significant effect in the surface layers, proving that it is possible to observe results in the first layers of the soil 6 months after application of gypsum and lime. The values found were 0 to 2 mmol dm^{-3} of Al^+, 20 to 30 mmol dm^{-3} of H+Al and 20% of aluminum saturation in the treatment that received 2000 kg ha^{-1} of lime + 300 kg ha^{-1} of gypsum (T4).

The results observed at 12 months after application of the treatments (Figure 3I, 3J, 3K) were more pronounced, as well as significant for five soil depths. Al^+ and m% did not show significant results in the 60-80 cm layer due to the application of the treatments. For H+Al, the significant effect occurred only in the superficial layers (0-5 and 5-10 cm). These results show the capacity of SO_4^{2-} to form an ion pair with Al^+ ($AlSO_4^+$), a compound that is less toxic to plants; this behavior occurred in almost the entire soil profile, reducing aluminum concentrations. The control treatment and the treatment that received only gypsum showed concentration of 5 mmol dm^{-3}, considered high when compared to the treatments that received gypsum and lime together, which showed a reduction of up to 100% in Al^+ concentration. In all treatments that received gypsum and lime, Al^+ concentration was reduced to 0% in the surface layers of the soil.

This reduction in Al^+ concentration can be explained by the increase in the ionic strength in the soil solution in subsurface, i.e., with the application of the treatments there was greater availability of basic ions (Ca, K and Mg) in the soil solution, causing a decrease in Al^+ activity. Another important factor is the increase of Ca^{+2} in the charge complex, causing a reduction in m%, which is the most important variable in the control of aluminum toxicity for plants (Vargas et al., 2019). These results corroborate those reported by Macana et al. (2023), who worked with gypsum and lime rates alone and together in sandy soils and obtained significant results for Al^+ at 6 months and 18 months after application of the treatments.

Copper was the only micronutrient that showed a significant effect at 6 months after application of the treatments (Figure 2I), with a concentration of 0.73 mg dm^{-3} for the control treatment, while the other treatments had an effect on the reduction of Cu concentration, but the results were not significant.

At 12 months after application of the treatments, the micronutrients that showed significant effects were B, Fe and Mn (Figure 3L, 3M, 3N). Mn^{2+} showed an effect only in the 10-20 cm layer, with higher concentrations in the treatment that received only lime (2000 kg ha^{-1}) (T2) and lower concentrations in all treatments with gypsum and lime. This occurred because the availability of Mn^{2+} decreases with the increase in pH (Meurer, 2010).

B showed an effect at two different soil depths (0-5 and 40-60 cm), with significant effect only in the liming treatment. This concentration in distinct layers, without a clear pattern in the soil profile, can be explained by the texture of the soil, which has low clay content, favoring the leaching of water-soluble B to deeper layers (Santos et al., 2021).

Fe^{+3} showed significant results at three depths of the soil profile (0-10, 10-20 and 20-40 cm), with lower values for treatments that received 2000 kg ha^{-1} lime + 500 kg ha^{-1} gypsum (T5) and 2000 kg ha^{-1} lime + 700 kg ha^{-1} gypsum (T6). This result is due to the increase in pH, since alkaline media favor reduction of Fe^{+3} solubility in the soil solution (Macana et al., 2023).

Gypsum and lime effects on the nutritional status of plants

Regarding the nutritional status of the young plants of green dwarf coconut analyzed, the results obtained in this study show that the application of gypsum combined with lime influenced the concentrations of macro and micronutrients in their tissue, as well as the chemical properties of the soil. The changes observed were distinct for the two times analyzed.

Regarding the macronutrients observed in the leaf tissue, N concentrations were influenced by the treatments only in the evaluation carried out 6 months after application of the treatments (Figure 4A), while P, K and Mg were influenced by the treatments in the evaluation carried out at 12 months after application of the treatments (Figure 4B, 4C and 4E).

N concentrations in the leaf tissue increased with the addition of gypsum and lime in the system, which is evidenced by the increasing linear model, represented by the equation $y = 20 + 0.746x$, with a coefficient of determination of 59%. The treatment with the highest value was the one that received 2000 kg ha^{-1} lime + 700 kg ha^{-1} gypsum (T6), with a value of 26 g kg^{-1} N, above the one considered adequate according to Lins and Viégas (2020), which is 20 g kg^{-1} for young coconut plants. Ideal amounts of N in the plant promote greater development, increase leaf growth and structure, and enable greater biomass production and consequently greater fruit development; in addition, N is part of the chlorophyll molecule, a constituent of proteins, nucleic acids, and vitamins (Fernandes, Souza, & Santos, 2018). The combined application of gypsum and lime in the amount mentioned above increased N absorption by the plants, due to the increases in root growth and in the SO_4^{2-} content available in the soil, thus reducing the amount of NO^{3-} leached (Crusciol et al., 2019).

P concentrations in the leaf tissue at 12 months after application of the treatments decreased with the addition of gypsum and lime, which is evidenced by the decreasing linear model, represented by the equation y = 125 - 0.0113x, with a coefficient of determination of 33%. (Figure 4B). The treatment that received 2000 kg ha^{-1} lime + 700 kg ha^{-1} gypsum (T6) showed a value of 1.19 g kg^{-1} P in the leaf tissue, which is close to the adequate level according to Lins and Viégas (2020) which is 1.2 to 1.4 g kg^{-1} for young coconut plants. This shows that the joint use of gypsum and lime in the above-mentioned amounts would not cause a significant reduction of this nutrient in young dwarf coconut plants.

K concentrations in the leaf tissue, at 12 months after application of the treatments, were quadratically influenced by the treatments (Figure 4D). The quadratic model showed that the treatment that received 2000 kg ha^{-1} lime + 300 kg ha^{-1} gypsum (T4) allowed the highest increase in K content, around 13.3 g per kg^{-1} dry matter, equivalent to an increase of 12.52% when compared to the control treatment (Figure 4D). From the rate of 363 kg ha^{-1} gypsum, K concentrations decreased by 0.019 g kg^{-1} for each 1 kg gypsum applied (Figure 4D).

The maximum K concentration achieved with the addition of lime and gypsum is below to that considered adequate according to Lins and Viégas (2020), which is 18 to 21 g kg^{-1} for young coconut plants. This improvement in K concentration may be related to the increase in soil pH caused by gypsum and lime added to the system. Increase in pH in surface and subsurface layers causes greater K^+ fixation and lower leaching losses in the soil profile (Meurer, 2010)

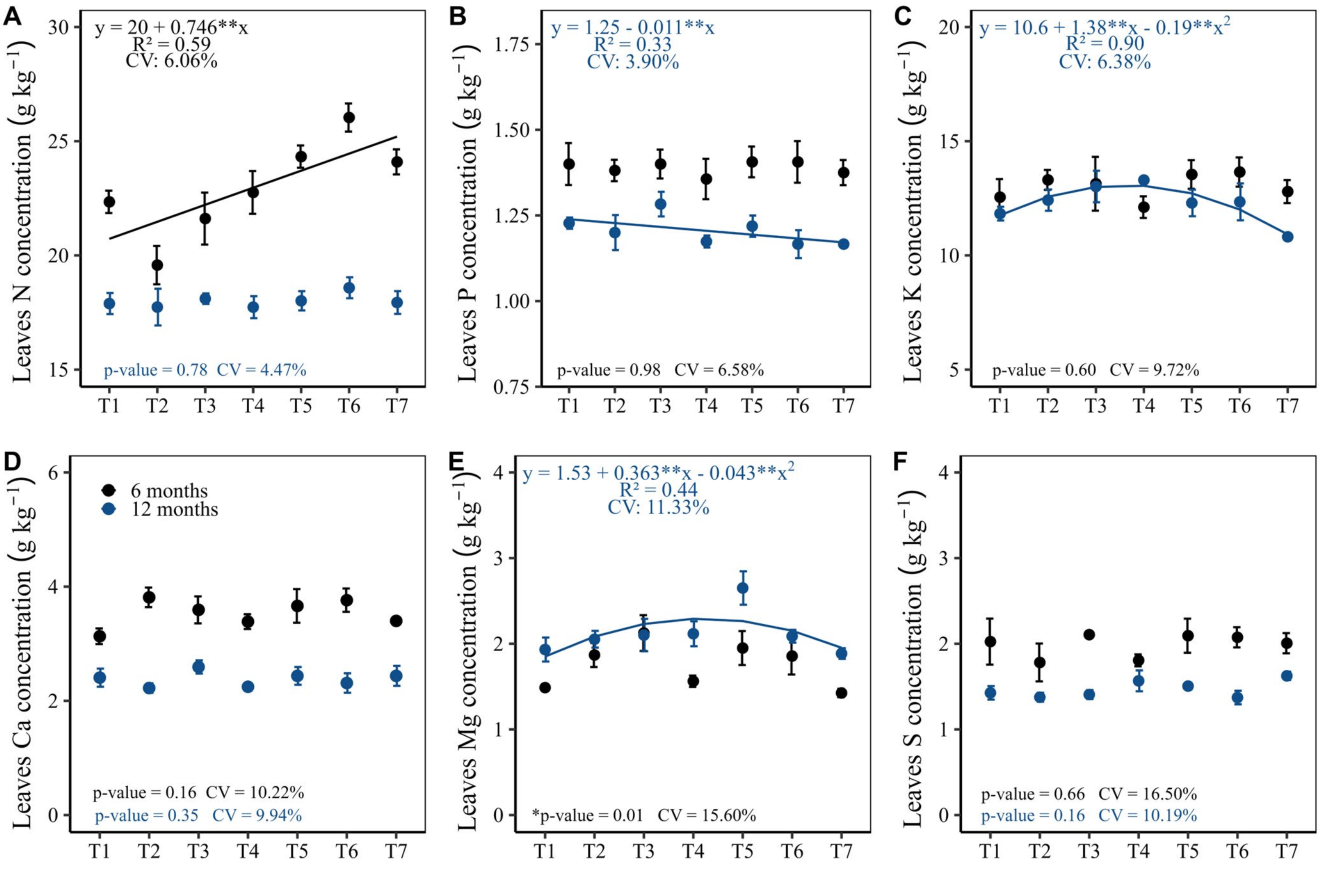

Figure 4: Influence of gypsum and lime rates on the concentrations of nitrogen - N (A), phosphorus - P (B), potassium - K (C), calcium - Ca (D), magnesium - Mg (E) and sulfur - S (F) in the leaf tissue of young plants of green dwarf coconut at two evaluation times. *- significant at $p \leq 0.05$, ** - significant at $p \leq 0.01$ by the F test; R^2 – coefficient of determination; CV – coefficient of variation. Vertical bars indicate standard error of means (n = 16).

For Mg concentration, the joint addition of gypsum and lime, at 12 months after application of the treatments, had a positive influence up to the treatment that received 2000 kg ha^{-1} lime + 500 kg ha^{-1} gypsum (T5), with an increase of 0.363 g Mg in leaf contents for each 1 kg gypsum added along with lime, as shown in the equation: $y=1.53 + 0.363 - 0.0432x^2$, and this is equivalent to an increase of 37.30% when comparing this treatment with the control treatment (Figure 4E). After the rate of 420 kg ha^{-1} gypsum, Mg concentration decreased by 0.043 g kg^{-1} for each 1 kg gypsum applied (Figure 4E).

The values found in the present study are justified by the high concentration of Ca^{+2}, which can remove Mg^{+} and K^{+} from the exchange sites. Thus, these cations are free in the solution and form ion pairs with the SO_4^{2-} provided by gypsum. Consequently, the mobility and movement of these cations to more subsurface layers of the soil are increased, which increases their absorption by plants (Pivetta et al., 2019).

The decrease of exchangeable aluminum content in the deeper layers, caused by the addition of gypsum and lime, reduces the competition for binding sites in the apoplast between Al^{+3} and Mg^{2+}, improves the activity of Mg^{2+} transporters and Mg^{2+}-permeable cation channels, and reduces the competition between Mg^{2+} and Al^{+3} in the ATP molecule (Fernandes, Souza, & Santos, 2018). Thus, gypsum and lime applied to the soil, in addition to reducing Al^{+3}, promote an increase in Mg content, which will be reflected in the leaf concentrations of these two nutrients, significantly reducing Al contents in the plant. Achieving optimal concentrations of Mg in leaf tissue is important for plant development, as Mg is a nutrient that constitutes the chlorophyll molecule, an enzymatic activator, and has the ability to migrate to various parts of the plant in the process of development, contributing to the formation of new plant tissues (Bayer, 2019).

Regarding the micronutrients present in the leaf tissue, Na concentrations were influenced by the treatments only in the analysis performed at 6 months after application of the treatments (Figure 5F), while for Mn, Zn, Na and Cl the changes in their concentrations in the leaf tissue were significant only at 12 months after application of the treatments (Figure 5D, 5E, 5F, and 5G).

Mn concentrations in the leaf tissue, at 12 months after application of the treatments, were quadratically influenced by the addition of gypsum and lime in the system (Figure 5D). The highest values were found in the control treatment and in the treatment with application of only gypsum (500 kg ha^{-1}), with values of 125.93 mg kg^{-1} and 93.43mg kg^{-1}, respectively.

Zn concentrations in the leaf tissue, at 12 months after application of the treatments, were quadratically influenced by the addition of gypsum and lime in the system (Figure 5E). The highest values were found in the control treatment and in the treatment with application of only gypsum (500 kg ha^{-1}), with values of 21.25 mg kg^{-1} and 20.25 mg kg^{-1}, respectively.

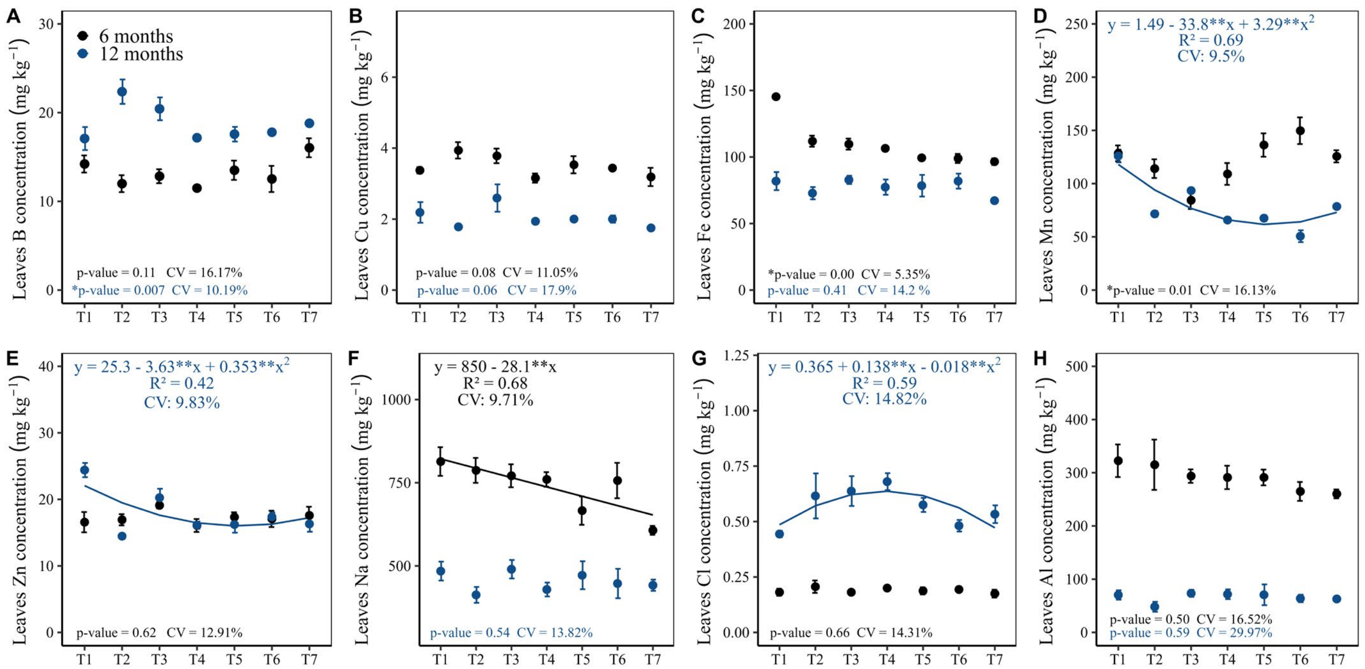

Figure 5: Influence of gypsum and lime rates on the concentrations of boron – B (A), copper – Cu (B), iron – Fe (C), manganese – Mn (D), zinc – Zn (E), sodium – Na (F), chlorine – Cl (G) and aluminum – Al (H) in the leaf tissue of young plants of green dwarf coconut at two evaluation times.*- significant at $p \leq 0.05$, ** - significant at $p \leq 0.01$ by the F test; R^2 – coefficient of determination; CV – coefficient of variation. Vertical bars indicate standard error of means (n = 16).

The results obtained for Mn and Zn showed the same behavior. The reduction in Mn and Zn concentrations in the plant tissue with the addition of gypsum and lime can be explained by the high pH, good drainage and aeration, which cause an effect contrary to the availability of Mn, even when the total amount of the element in the soil is large, possibly with low availability for absorption by plants. The availability of this element is higher in soils with poor drainage or in flooded soils (Novais et al., 2007). When the pH rises in the soil, the ionic form of cationic micronutrients is modified, resulting in oxyhydroxides, which have insoluble behavior, with a low capacity to supply ions necessary for plant growth (Malavolta, 2006). Therefore, the addition of gypsum and lime in Quartzipsamment had negative effects on Zn and Mn absorption by plants. Nevertheless, these results did not limit the development of the coconut plants analyzed in this study.

Na concentrations in the leaf tissue, at 6 months after application of the treatments, were influenced linearly by the addition of gypsum and lime in the system (Figure 5F). Na concentrations decreased with the addition of gypsum and lime in the system, which is evidenced by the decreasing linear model, represented by the equation y= 850-28.1x. The highest value was observed in the control treatment, 813.8 mg kg^{-1} Na in the plant tissue, and the lowest value was observed in the treatment that received 2000 kg ha^{-1} lime + 1000 kg ha^{-1} gypsum (T7), 679.7 mg kg^{-1}.

Combined application of gypsum and lime provides calcium for the soil solution in the surface and subsurface layers, which will facilitate the movement of SO_4^{2-} in the soil profile, and this sulfate will bind to Na, which undergoes leaching by the drainage water in the form of sodium sulfate (Costa et al., 2020). These results are relevant because soils with high Na contents have higher sodium saturation, which leads to salt stress environments, resulting in the chemical impediment of other nutrients. In addition, the Na^+ ion, at high concentrations, can replace K^+ in some functions in the plant, which can affect the internal ionic balance of plant tissue cells (Fernandes, Souza, & Santos, 2018).

At 12 months after application of the treatments, the addition of gypsum and lime positively influenced up to the treatment that received 2000 kg ha^{-1} lime + 300 kg ha^{-1} gypsum (T4), with an increase of 0.138 mg of Cl in leaf contents for each 1 kg gypsum added along with lime, as shown in the equation: $y= 0.365+0.138x-0.0175x^2$. This equates to an increase of 110.52% when comparing this treatment with the control treatment (Figure 5G). After the rate of 394 kg ha^{-1} gypsum, Cl concentration decreased by 0.0175 g kg^{-1} for each 1 kg gypsum applied (Figure 5G). Cl concentrations in plant tissues are justified by its availability in the soil solution, since it is an element that becomes more available to plants with the increase in pH, as found in the present study. Moreover, the addition of gypsum and lime in the system increased root development, thus promoting greater reach of fine roots to absorb this nutrient.

Gypsum and lime effects on root development

Regrading root development variables, statistical differences were obtained for fine root growth and for fine root width within the rhizotron at 12 months after application of the treatments (Figure 6). Significant values for fine root width were observed at 12 months after application of the treatments (Figure 6C), and the data were described by an increasing linear regression model, represented by the equation y=59.1+1.07.

Fine root growth was significantly affected at 12 months after application of the treatments (Figure 6B), being described by a quadratic regression model represented by the equation $y= 59.1-9.55x+ 1.77x^2$, with coefficient of determination equal to 85%.

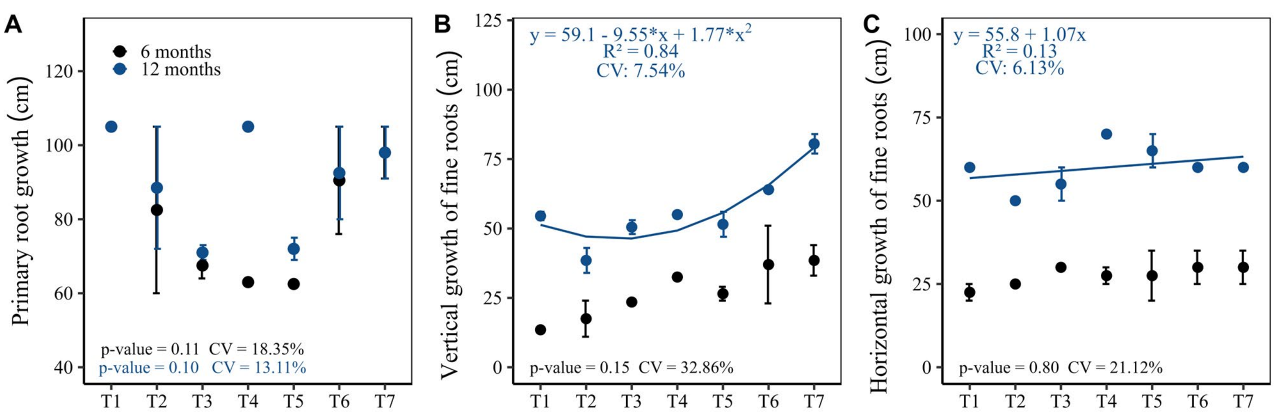

Figure 6: Influence of lime and gypsum rates on taproot length (cm), fine root length (cm), and fine root width (cm) in rhizotron analysis of young plants of green dwarf coconut at two evaluation times. *- significant at $p \leq 0.05$, ** - significant at $p \leq 0.01$ by the F test; R^2 – coefficient of determination; CV – coefficient of variation. Vertical bars indicate standard error of means (n = 5).

Plants that showed the highest development of fine roots were those that received 2000 kg ha^{-1} lime + 1000 kg ha^{-1} gypsum (T7). In addition, the treatment that received 2000 kg ha^{-1} lime + 500 kg ha^{-1} gypsum (T5) also had significant results, which is consistent with other results found in the present study, because with this rate there were increments in nutrient absorption. This behavior can be explained by the better condition of the soil, considering the pH variation from 5.5 to 5 in the 0-5 and 5-10 cm layers and the average value of 4.5 in the more subsurface layers, and by the reduction in aluminum saturation to 0% in the most superficial layers and aluminum saturation ranging from 20 to 30% in the subsurface layers.

Thus, it was possible to observe better root development, elongation of roots, and greater volume of soil occupied by fine roots. Higher concentration of roots increases the surface area for water and nutrient absorption, increasing the capacity to translocate solutes to the shoots. Improving soil conditions in the subsurface layers can increase and/or stabilize crop yields, especially in regions with irregular rainfall distribution, such as the Amazon region, which is also characterized by Ca-deficient soils in the subsurface, often in association with Al toxicity (Haneklaus et al., 2020). The reduction in aluminum saturation highlights the effect of gypsum on the soil, which enabled the ionic bonding of sulfate with exchangeable aluminum, forming a compound that is non-toxic to plants (Minato et al., 2023). Therefore, it can be inferred that the increase in root growth of young coconut plants will provide better development of adult plants, influencing the nutrient content in the aerial part of the plant, consequently in its productivity and fruit quality.

Conclusions

The rate of 2000 kg ha^{-1} lime + 500 kg ha^{-1} gypsum was efficient in to reduce total acidity, aluminum saturation and exchangeable aluminum and increase sulfur and base saturation, in addition to influencing N, Mg and K contents in leaf tissues and improving root development in coconut trees grown in Quartzipsamment of the North region. This behavior can be observed within 12- month after applying the treatments.

Author Contribution

Conceptual Idea: Lins, P. M. P.; Silva Júnior, M. L.; Methodology design: Silva Júnior, M. L; Gomes, M. S; Lins, P. M. P.; Data collection: Gomes, M. S.; Moraes, A. R. A.; Data analysis and interpretation: Gomes, M. S.; Gomes, M. F.; and writing and editing: Gomes, M. S.; Moraes, A. R. A.; Gomes, M. F.; Araújo, S. R.

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