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Effect of Rates and Sources of Nitrogen on the O×G Hybrid (*Elaeis oleifera* × *Elaeis guineensis*) of Oil Palm at the Adult Stage

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Abstract

Although N is one of the two nutrients most required by oil palms and is determinant for crop growth and yield, more than half of the N applied can be lost to the environment, increasing production costs, decreasing its use efficiency, and causing air pollution through volatilization and greenhouse gas emissions. In addition, fertilization can account for up to 46% of total costs in *E. guineensis* cultivars and 39% in O×G interspecific hybrid cultivars in Colombia; therefore, selecting the right source and rate is considered crucial for agribusiness. In this regard, the objective of this study was to evaluate the effect rates and sources of nitrogen on the O×G interspecific hybrid of oil palm during the adult stage in terms of soil variables, nutrition, growth, FFB yield, N use efficiency, and N losses due to volatilization. Analysis of the results after five years of evaluation indicated that the use of PMCRU and PMCU did not promote significant effects on soil chemistry; however, it did have effects on nutrition, growth, FFBY, N use efficiency, and N losses due to volatilization in O×G hybrid oil palm in the productive stage according to the Tukey test at 5%. PMCRU allowed the biological optimum to be achieved with a rate of 134 kg ha^{-1} of N, while PMCU required the maximum rate of N evaluated (192 kg ha^{-1} of N). In addition, PMCRU was more efficient. In turn, the use of PMCRU can reduce N volatilization by between 92.3 and 88.9% for rates of 96 and 192 kg ha^{-1} of N, respectively. The use of PMCRU is a feasible alternative for the nutrition of the interspecific hybrid O×G during the adult stage in the Eastern Zone of Colombia, allowing higher yields to be achieved with lower rates of N and reducing N losses due to volatilization.

Keywords: fertilizers, crop nutrition, soil fertility, nutrient use efficiency, volatilization

1. Introduction

Nitrogen (N) is the nutrient most required by most plants (Epstein & Bloom, 2005), and because of this, its deficiency is the most common (Havlin et al., 2017), as between 1 and 5% of the dry biomass of the plant is made up of this element, which is an integral constituent of proteins, nucleic acids, chlorophyll, and secondary metabolites (Hawkesford et al., 2012). In oil palm crops, N is one of the two nutrients most required by oil palms and is determinant for crop growth and yield (Corley & Tinker, 2015; Arifin et al., 2022; Arias et al., 2023); hence the need to include it in fertilization plans in order to supply these requirements and help maintain soil fertility. However, more than half of the N applied can be lost to the environment (Lassaletta, 2014), resulting in losses of the element, increasing production costs, decreasing its use efficiency, and causing air pollution through volatilization and greenhouse gas emissions (Chaparro-Triana et al., 2020), in water through leaching (Wang et al., 2019) and/or in soil through denitrification (Alsina et al., 2013), a situation that has led to the implementation of practices and technologies aimed at increasing its use efficiency in recent years (Dobermann, 2005; Lassaletta et al., 2014; World Meteorological Organization, 2019).

The factors that determine the efficiency of N use by crops are the plant, the soil, the climate, and management. In terms of the plant, the most important factors are genetics, morphology, and the ability to absorb and use nutrients to transform them into biomass; soil, pH, organic matter (OM), texture, biology, cation exchange capacity, moisture, and processes that occur in the soil such as volatilization, greenhouse gas emissions, runoff, leaching, nitrification and denitrification, and N extraction by plants are the aspects that define N availability. Climate factors such as temperature, precipitation, relative humidity, and solar radiation, as well as management

practices such as nutrient supply through fertilizers, especially the rate, source, timing, and site of application, play an indispensable role in this process (Sadeghian et al., 2022).

Among the most common sources of nitrogen fertilizer in Colombian oil palm crop are urea, ammonium nitrate (mainly from chemical complex sources), and ammonium sulfate. Although these sources fulfill their function, they can be lost through volatilization, greenhouse gas emissions, leaching, and runoff due to their solubility and the reactions that can occur in the soil. However, controlled-release fertilizers (CRFs) are available on the market, which may contain soil bacteria inhibitors or mineral and/or polymer coatings that delay the release of N into the soil and aim to reduce N losses and N rates, as well as increase the efficiency of N use and, eventually, crop productivity (Havlin et al., 2017) (Figure 1). In this regard, the use of FLC in oil palm crop during the nursery stage promoted greater dry biomass production compared to conventional fertilizers (Murugan et al., 2020), a greater number of leaves, leaf area index, stem diameter, and palm height (Sukmawan et al., 2022), and greater weight, number, and productivity of fresh fruit bunches (FFB) in the productive stage (Nolberto et al., 2024). In turn, significant reductions in nutrient losses due to leaching of up to 15% have been reported (Bah et al., 2014).

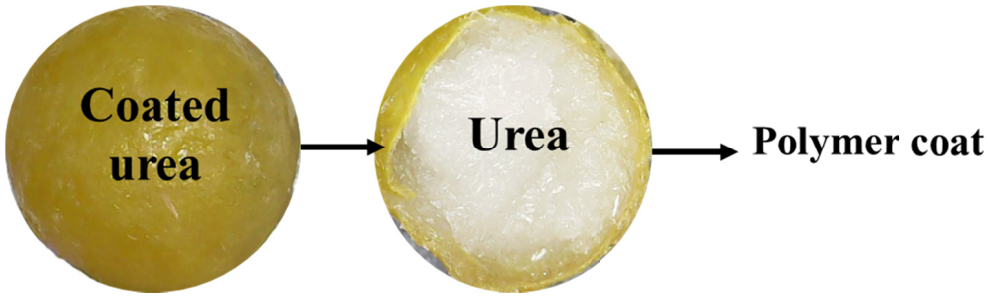


Figure 1. Representation of polymer-coated controlled-release urea

Source: Authors.

On the other hand, it should be noted that as fertilizer prices tend to increase, the profitability of the business is significantly affected. About it, in oil palm crop in Colombia, fertilization can account for up to 46% of total costs in *E. guineensis* cultivars and 39% in O×G interspecific hybrid cultivars (Mosquera-Montoya et al., 2023). Therefore, selecting the right source and rate is considered crucial for agribusiness. In addition, the labor required to carry out crop maintenance tasks, including fertilization, is often scarce, and strategies to mitigate this situation are needed by palm growers. Accordingly, the proper management and use of nutrients, especially N, should maximize the expected positive effects on crops, reduce production costs, and generate the least possible environmental impact, as otherwise this aspect compromises sustainability. In this regard, the objective of this study was to evaluate the effect rates and sources of nitrogen on the O×G interspecific hybrid of oil palm during the adult stage in terms of soil variables, nutrition, growth, fresh fruit bunch yield, N use efficiency, and N losses due to volatilization.

2. Method

2.1 Study Site and Duration

The study was conducted on Lot D4 of the La Cabaña plantation, located in the municipality of Cabuyaro, Meta, between 2018 and 2022, *i.e.*, during five years of crop production. The plantation is located at 200 meters above sea level, with an average temperature of 27 °C, relative humidity of 80%, and rainfall ranging between 2,500 and 2,700 mm $year^{-1}$ during the study period. The cultivar evaluated was an interspecific O×G hybrid (Coari × La Mé) with a planting density of 128 palms ha^{-1} in the adult stage (planted in 2008). The soil was classified as Inceptisol, characterized by low fertility (Table 1).

Table 1. Initial condition of the chemical properties of the evaluated soil

Property	Texture	pH	OM	P	Exchangeable cations					Al Sat.
					K	Ca	Mg	Na	Al	
			%	mg kg^{-1}	---------- $cmol_c$ kg^{-1} ----------					%
Result	Sandy loam	4.61	1.72	5	0.11	0.35	0.18	0.02	1.91	77

Note. OM: Organic matter; P: Phosphorus; CEC: Cation exchange capacity; K: Potassium; Ca: Calcium; Mg: Magnesium; Na: Sodium; Al: Aluminum; Al Sat.: Aluminum saturation.

2.2 Treatments

The treatments evaluated consisted of three rates (50, 75, and 100% of the recommended rate), two physical mixtures of fertilizers containing different sources of nitrogen: a physical mixture with controlled-release urea coated with polymer (PMCRU) (42% N) and physical mixture with conventional urea (PMCU) (46% N) both sources applied in two splits per year, and a control without fertilizer application (Table 2). In the case of the PMCRU source, a physical mixture type fertilizer, it contained, in addition to N, monoammonium phosphate (MAP-50% P_2O_5), potassium chloride (KCl-60% K_2O), kieserite (25% MgO and 20% S) and boron (B) (15% B) as sources of P, K, Mg and B, respectively. It should be noted that the only nutrients with controlled release were nitrogen and boron, in which case 94% of the N and 80% of the boron had this characteristic. For the PMCU source, also a physical mixture, the same fertilizer sources were used, matching the amounts of nutrients by using the same sources of phosphorus, potassium, magnesium, sulfur, and boron, so that the only difference was the source of N. All fertilizers were applied between March and April for the first split and between September and October for the second split, depending on the onset of rainfall for each period.

The 100% rate corresponded to the recommendation of Cenipalma, which considered the balance index for leaf leveling, total dry leaf mass, replacement of nutrients extracted by the FFB harvest, and expected FFB yield based on production estimates (Arias & Beltrán, 2014). In this regard, the average N rates for the years evaluated were 0, 0.75, 1.11, and 1.50 kg/palm or their equivalent of 0, 96, 144, and 192 kg ha^{-1}.

Table 2. Description of the treatments evaluated

Treatment	Fertilizer source	Recommended N rate (%)	Recommended N rate (kg ha^{-1})
1	Control (no fertilizer application)	0	0
2	Physical mixture with controlled-release urea (PMCRU)	50	96
3	Physical mixture with controlled-release urea (PMCRU)	75	144
4	Physical mixture with controlled-release urea (PMCRU)	100	192
5	Physical mixture with conventional urea (PMCU)	50	96
6	Physical mixture with conventional urea (PMCU)	75	144
7	Physical mixture with conventional urea (PMCU)	100	192

Note. PMCRU and PMCU sources were applied in two splits per year during five years of evaluation.

2.3 Experimental Design

The above treatments were established under a completely randomized block design in a factorial arrangement with one control (3 rates × 2 sources) with five blocks in which the slope of the land was considered as a blocking factor. Slope was quantified by using GPS equipment and the measurement results indicated a 2% slope across the terrain, in which the blocks were established in such a way that they were distributed throughout the area, establishing each block in areas where the topography was as homogeneous as possible. Each experimental unit consisted of eight rows of four palms each (32 palms), where the eight central palms were defined as the effective plot.

2.4 Response Variables and Analysis of Results

The response variables used to determine the effect of the treatments were soil chemistry (soil analysis), crop variables (nutrition, vegetative growth, and FFB yield), N use efficiency (partial productivity factor and agronomic efficiency), and variables related to N losses in the environment due to volatilization. The results were analyzed under the established experimental design using analysis of variance and mean separation by

Tukey's test at 5% with support of Rbio software (Bhering, 2017), which uses R software (2020) as the basis for data analysis.

2.4.1 Effect on Soil Chemistry (Soil Analysis)

About soil chemistry, sampling was carried out at a depth of 0 to 20 cm in the root zone of the oil palm. To this end, six (6) subsamples were taken from each effective palm in each treatment, in the form of a crown on the plate, and were then homogenized to form a composite sample. Finally, they were sent to the laboratory for chemical analysis (pH, OM, P, K, Ca, Mg, Al, and Al Sat.).

2.4.2 Effects on the Crop

(1) Nutrition (Leaf Analysis)

To evaluate the effect of the treatments on crop nutrition, the nutrient level in leaf 17 was analyzed according to the methodology proposed by Munévar-Martínez et al. (2016).

(2) Vegetative Growth (Vegetative Measurements)

The following variables were measured in the effective palms of each treatment with their respective replicates: leaf biomass of leaf 17 (LDB L17), total leaf dry biomass (TLDB), leaf area of leaf 17 (LA L17), total leaf area (TLA), and leaf area index (LAI), according to the methodology of Corley et al. (1971). To do this, leaf 17 of each palm was identified and cut, and measurements were made of the width and thickness of the petiole, as well as the length of the leaf. Finally, the total number of leaves on each palm was counted. Taking into account that the number of leaves per palm tree depends on factors such as the number of optimal bunches for harvesting (which will require more or fewer leaves to be cut by the operator to carry out the work), the average number of leaves for all treatments (38 leaves) was selected to estimate the variables of total leaf dry biomass and total leaf area, in order to isolate the effect of the operator from the effect of the treatments.

(3) Fresh Fruit Bunch Yield (FFBY)

For the yield variables, the weight and number of FFB harvested during the five years of evaluation was recorded to obtain the average number of bunches (ANB), average bunch weight (ABW), and fresh fruit bunch yield per hectare (FFBY).

(4) Nitrogen Use Efficiency (Partial Productivity Factor and Agronomic Efficiency)

For nitrogen use efficiency factors, the formulas suggested by Sarkar and Baishya (2017) (Equations 1 and 2) were used. For the partial productivity factor (PPF), the productivity of FFB (kg ha^{-1}) was divided by the rate of N (kg ha^{-1}) was applied. This factor allows us to estimate the amount of FFB produced (kg) per unit of N applied (kg), *i.e.*, how many kg of FFB are obtained per kg of N applied. Agronomic efficiency (AE) estimates the gain in FFB productivity (kg) per unit of N applied (kg), after subtracting the FFB yield obtained with the N supplied by the soil (Control without fertilizer).

$$\text{PPF (kg kg}^{-1}) = \frac{\text{FFBY obtained with N application}}{\text{N rate}} \quad (1)$$

$$\text{AE (kg kg}^{-1}) = \frac{\text{FFBY obtained with N - FFBY obtained without N}}{\text{N rate}} \quad (2)$$

(5) Determination of Nitrogen Losses to the Environment (Volatilization of Ammonia-NH_3)

To measure N losses in the form of ammonia gas (NH_3) through volatilization, the methodology proposed by Nömmik (1973) and modified by Cabezas et al. (1997) was used. This methodology consisted of installing a semi-open static chamber made from a 6″ (15.24 cm) high PVC pipe containing two 3 cm thick polyurethane foams located 15.4 cm apart and impregnated with 70 ml of solution 0.5N sulfuric acid (H_2SO_4) and 3% glycerin (v/v). The chamber also had an 8″ (20.32 cm) PVC cover that prevented the entry of water and foreign objects. The function of the foam located at the bottom was to capture the ammonia (NH_3), emitted in the area within the chamber, while the function of the upper foam was to prevent ammonia from entering the chamber from outside. The chamber was inserted into the ground at a depth of 5 cm (Figure 2).

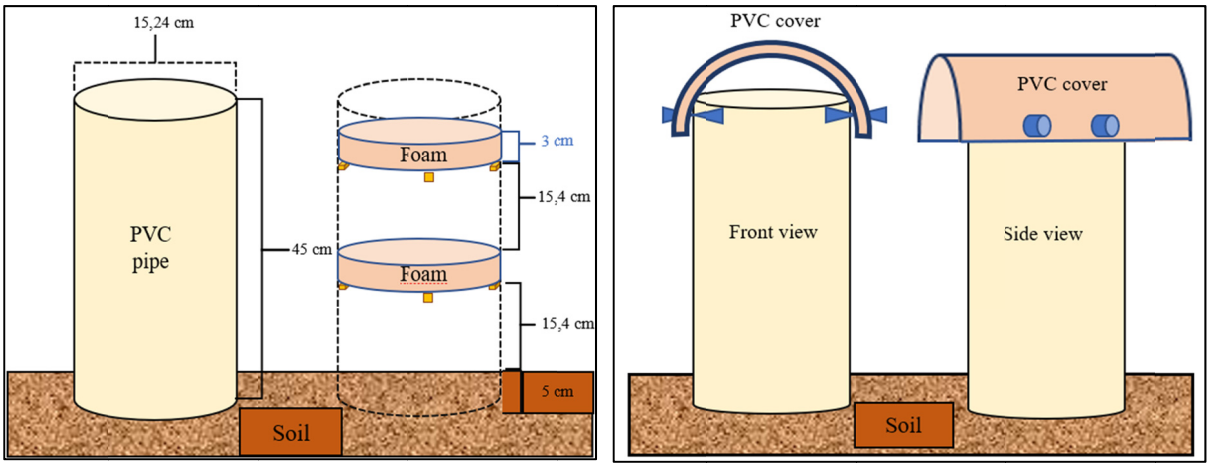


Figure 2. Representation of the components, measurements, and installation of the semi-open static chamber in the field

Subsequently, a chamber was placed in the fertilizer application area of one effective palm for each treatment and repetition. From the N sources evaluated, conventional urea and controlled-release urea granules were isolated and applied inside the chamber, prior to the placement of the foams, so that they would come into contact with the soil, which was confirmed to have optimal soil moisture conditions for fertilizer application (between 30 and 35%). In order to understand some of the environmental conditions under which these rates and sources of N were evaluated, soil moisture and daily and accumulated precipitation were recorded during the days evaluated.

The calculation of the N rates applied per chamber according to each treatment was performed considering the total amount applied per palm in one of the two splits of the year and the total application area estimated at 4 m^2. It should be noted that this variable was measured for treatments 1, 2, 4, 6, and 8, *i.e.*, for rates of 50% and 100% of the two N sources and the control. The treatment with 100% of the PMCRU rate applied once a year was not considered, as it was the only treatment with this single split condition. The rates applied inside the chamber corresponded to 1.70 and 3.40 g of N/chamber, respectively, for the evaluated rates of 50% and 100% of the recommended rate, *i.e.*, 4.05 and 8.10 g of controlled-release urea and 3.69 and 7.39 g of conventional urea, respectively. Once the chambers were installed and the fertilizers applied, ammonia volatilization was measured at 1, 2, 3, 8, and 23 days later. During each day of evaluation, the two foams in each chamber were replaced and a volume of water like the precipitation collected in containers near all chambers were added equally. Subsequently, the lower foam was taken to the laboratory, where the solution with the captured ammonia was extracted and measured using a spectrophotometer.

3. Results

3.1 Effect on Soil Chemistry (Soil Analysis)

Table 3 shows the results of the chemical analysis of the soil after five years of evaluation. In general, no statistical differences were detected by analysis of variance in response to N rates and sources according to ANOVA. On the other hand, statistically significant differences in soil fertility were observed in some properties were detected compared with the values found at baseline (prior to treatments application) (Table 3). In this regard, pH decreased by an average of 0.5 units and P increased by an average of 10.3 mg kg^{-1} after 5 years of evaluation according to Tukey's test at 5%. Besides, other descriptive results were observed in OM and Ca variables which showed an average decrease of 0.2%, and 0.6 $cmol_c$ kg^{-1}, respectively, without statistically significant differences.

Table 3. Soil chemical properties in response to nitrogen rates and sources before and after five years of evaluation

Treatments	pH	MO	P	K	Ca	Mg	Al	Sat. Al
		%	mg kg^{-1}	---------- $cmol_c$ kg^{-1} ----------				%
Initial condition (Baseline)	4.61 a	1.72	5 b	0.11	0.35	0.18	1.91	77
Control (no fertilizer application)	4.17 b	1.58	16 a	0.15	0.30	0.23	1.7	75
PMCRU (96 kg ha^{-1} of N)	4.12 b	1.60	15 a	0.13	0.34	0.29	1.8	72
PMCRU (144 kg ha^{-1} of N)	4.13 b	1.42	13 a	0.11	0.28	0.21	1.7	76
PMCRU (192 kg ha^{-1} of N)	4.07 b	1.49	12 a	0.12	0.2	0.19	1.8	74
PMCU (96 kg ha^{-1} of N)	4.11 b	1.54	13 a	0.12	0.25	0.30	2.1	77
PMCU (144 kg ha^{-1} of N)	4.07 b	1.51	16 a	0.11	0.19	0.30	1.9	80
PMCU (192 kg ha^{-1} of N)	4.13 b	1.42	15 a	0.12	0.29	0.24	2.0	80
Average	**4.18**	**1.54**	**13.13**	**0.12**	**0.28**	**0.24**	**1.86**	**76**
CV (%)	**2.7**	**29.8**	**46.3**	**36.5**	**67.2**	**62.2**	**22.4**	**12.8**
p-value	**< 0.001**	**0.29**	**0.01**	**0.26**	**0.82**	**0.23**	**0.80**	**0.46**

Note. OM: Organic matter; P: Phosphorus; CEC: Cation exchange capacity; K: Potassium; Ca: Calcium; Mg: Magnesium; Al: Aluminum; Al Sat.: Aluminum saturation. PMCRU: Physical mixture with controlled-release urea. PMCU: Physical mixture with conventional urea. Different letters within the columns indicate statistically significant differences according to the Tukey's test at 5%.

3.2 Effects on the Crop

3.2.1 Nutrition (Leaf Analysis)

In terms of oil palm nutrition (leaf analysis), effect was observed in five of the seven macronutrients evaluated (N, P, K, Ca, and S) (Table 4), although only for N rates, *i.e.*, both N sources and the interaction of the two factors (*rates x sources*) did not show statistically significant differences.

Table 4. Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), and chlorine (Cl) in leaf 17 in response to nitrogen rates and sources after five years of evaluation

Treatments	N	P	K	Ca	Mg	S	Cl
	---------- % ----------						
Control (no fertilizer application)	1.89 b	0.13 b	0.50 c	0.70 a	0.22	0.13 b	0.70
PMCRU (96 kg ha^{-1} of N)	2.42 a	0.15 a	0.60 bc	0.63 ab	0.22	0.15 a	0.78
PMCRU (144 kg ha^{-1} of N)	2.46 a	0.15 a	0.64 ab	0.60 abc	0.19	0.15 a	0.74
PMCRU (192 kg ha^{-1} of N)	2.57 a	0.15 a	0.68 a	0.48 c	0.19	0.15 a	0.79
PMCU (96 kg ha^{-1} of N)	2.37 a	0.15 a	0.58 bc	0.60 abc	0.19	0.15 a	0.75
PMCU (144 kg ha^{-1} of N)	2.53 a	0.15 a	0.63 ab	0.52 bc	0.18	0.15 a	0.74
PMCU (192 kg ha^{-1} of N)	2.59 a	0.15 a	0.69 a	0.51 bc	0.18	0.15 a	0.80
Average	2.43	0.15	0.62	0.57	0.20	0.15	0.76
CV (%)	**5.8**	**3.9**	**11.9**	**11.4**	**18**	**6.2**	**11.4**
p-value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.43**	**<0.001**	**0.58**

Note. PMCRU: Physical mixture with controlled-release urea. PMCU: Physical mixture with conventional urea. Different letters within the columns indicate statistically significant differences according to the Tukey's test at 5%.

Regarding foliar N, the omission of N application (control) promoted a decrease in this nutrient in the leaf, as the concentration reached an average of 1.89, which showed significant differences using the Tukey test at 5% with the other treatments ($p \leq 0.001$). On the other hand, there were no significant differences between the rates and sources of N, with both sources showing very similar behavior, with increases in foliar N as the N rate increased, with values of 2.42, 2.46, and 2.57% N for rates of 96, 144, and 192 kg ha^{-1} of N, respectively in PMCRU and

2.37, 2.53, and 2.59% N for PMCU at the same rates. The response to the application of the 192 kg ha^{-1} of N with PMCRU applied in a single split promoted an average value of 2.54% (Table 4).

In foliar P and S, a similar response to that of foliar N was observed, in addition to a synergistic effect with respect to the control, since for both foliar concentrations the control presented a concentration of 0.13%, while in all other treatments it was 0.15% ($p \leq 0.001$). Based on the observations, foliar K also had a synergistic effect with N, since, in addition to foliar K decreasing when N was not applied (0.50% K) ($p \leq 0.001$), this condition also occurred when the N rate was 96 kg ha^{-1} of N (0.60 and 0.58% for PMCU and PMCRU, respectively). On the other hand, rates of 144 kg ha^{-1} of N and 192 kg ha^{-1} of N promoted K concentrations of 0.68% and 0.69% and 0.63% and 0.64% for PMCU and PMCRU, respectively, for each source and rate. On the other hand, foliar Ca showed an antagonistic effect, as the highest concentrations (0.70% Ca) occurred when fertilizer was not applied, and a decreasing trend was observed when the applied N rates were greater than 50% ($p \leq 0.001$). In this case, the highest rates of N promoted foliar Ca concentrations of 0.48 and 0.51% for PMCU and PMCRU, respectively.

Although Mg and Cl in leaves did not show a significant effect resulting from the application of N rates and sources, it should be noted that they showed different trends. In the case of foliar Mg, a tendency toward a decrease in foliar concentration was observed as the N rate increased. While foliar Mg in the control and the 50% PMCRU rate was 0.22%, in the 100% N rate it was 0.19 and 0.18 for PMCRU and PMCU, respectively. This was contrary to the case of foliar Cl, which also showed a synergistic trend, as the foliar Cl concentration in the control was 0.70%, while at the 192 kg ha^{-1} of N it was 0.79% and 0.80% for PMCRU and PMCU, respectively.

About micronutrients boron (B), iron (Fe), copper (Cu), zinc (Zn), and manganese (Mn), the rates and sources of N did not have statistically significant effects according to ANOVA in any of the cases. In general, micronutrients had the following concentration ranges at the foliar level (mg kg^{-1}): B between 19 and 23, Fe between 71 and 75, Cu between 6.7 and 7.7, Zn between 8.1 and 9.4, and Mn between 1035 and 1243 (Table 5).

Table 5. Boron (B), iron (Fe), copper (Cu), zinc (Zn), and manganese (Mn) in leaf 17 in response to nitrogen rates and sources after five years of evaluation

Treatments	**B**	**Fe**	**Cu**	**Zn**	**Mn**
	mg kg^{-1}				
Control (no fertilizer application)	21	71	6.9	9.2	1190
PMCRU (96 kg ha^{-1} of N)	19	71	6.7	8.1	1039
PMCRU (144 kg ha^{-1} of N)	20	73	7.3	8.3	1079
PMCRU (192 kg ha^{-1} of N)	21	71	7.2	8.9	1053
PMCU (96 kg ha^{-1} of N)	23	73	7.7	9.1	1243
PMCU (144 kg ha^{-1} of N)	23	75	6.9	8.8	1035
PMCU (192 kg ha^{-1} of N)	23	74	7.7	9.4	1143
Average	**21**	**73**	**7.1**	**8.8**	**1127**
CV (%)	**9.2**	**9.0**	**10.8**	**10.0**	**34.9**
p-value	**0.12**	**0.47**	**0.44**	**0.34**	**0.52**

Note. PMCRU: Physical mixture with controlled-release urea. PMCU: Physical mixture with conventional urea. Because no significant differences were found according to the ANOVA, the Tukey's test at 5% was not performed.

3.2.2 Vegetative Growth (Vegetative Measurements)

Table 6 shows the results of vegetative growth after five years of evaluation. In general, statistical differences were detected through analysis of variance in response to fertilizer rates and sources compared to the control for the variables LDB L17 and TLDB according to ANOVA.

Table 6. Leaf dry biomass of leaf 17 (LDB H17), total leaf dry biomass (TLDB), leaf area of leaf 17 (LA L17), total leaf area (TLA) and leaf area index (LAI) in response to nitrogen rates and sources after five years of evaluation

Treatments	**LDB L17**	**TLDB**	**LA L17**	**TLA**	**LAI**
	kg/leaf	kg/palm	m^2/leaf	m^2/palm	
Control (no fertilizer application)	3.0 b	114 b	9.9	376	4.8
PMCRU (96 kg ha^{-1} of N)	3.5 ab	132 ab	10.7	407	5.2
PMCRU (144 kg ha^{-1} of N)	3.6 a	135 a	10.6	403	5.1
PMCRU (192 kg ha^{-1} of N)	3.7 a	142 a	10.5	399	5.1
PMCU (96 kg ha^{-1} of N)	3.4 ab	131 ab	10.2	388	4.9
PMCU (144 kg ha^{-1} of N)	3.8 a	147 a	10.7	407	5.2
PMCU (192 kg ha^{-1} of N)	3.7 a	142 a	10.6	403	5.2
Average	**3.5**	**135**	**10.5**	**398**	**5.1**
CV (%)	**7.0**	**7.0**	**6.0**	**6.0**	**6.0**
p-value	**< 0.001**	**< 0.001**	**0.25**	**0.25**	**0.25**

Note. PMCRU: Physical mixture with controlled-release urea. PMCU: Physical mixture with conventional urea. Different letters within the columns indicate statistically significant differences according to the Tukey's test at 5%.

LDB L17 and TLDB ranged from 3.0 to 3.8 kg/leaf and 114 to 147 kg/palm for control treatment (without N application) and the 144 kg ha^{-1} of N PMCU rate, respectively. The sources and rates of N applied did not show statistical differences between them; however, there were differences between the PMCRU and PMCU fertilizer rates between 144 and 192 kg ha^{-1} of N and the control, while the 96 kg ha^{-1} of N rates for the two sources behaved as intermediate according to the Tukey test at 5%. On the other hand, the variables LA L17, TLA, and LAI did not show statistically significant differences after five years of evaluation. The values observed for these variables ranged from 9.9 to 10.9 m^2/leaf for LA L17, 376 to 414 m^2/palm for TLA, and 4.8 to 5.3 for LAI.

3.2.3 Fresh Fruit Bunch Yield (FFBY)

(1) FFBY Performance Over the Five Years

During the five years evaluated (2018-2022), the effect of N rates was only observed in the last two years (2021 and 2022) according to the Tukey test at 5%, unlike the N sources or the interaction between factors, which did not show statistically significant differences for the FFBY variable (Figure 3).

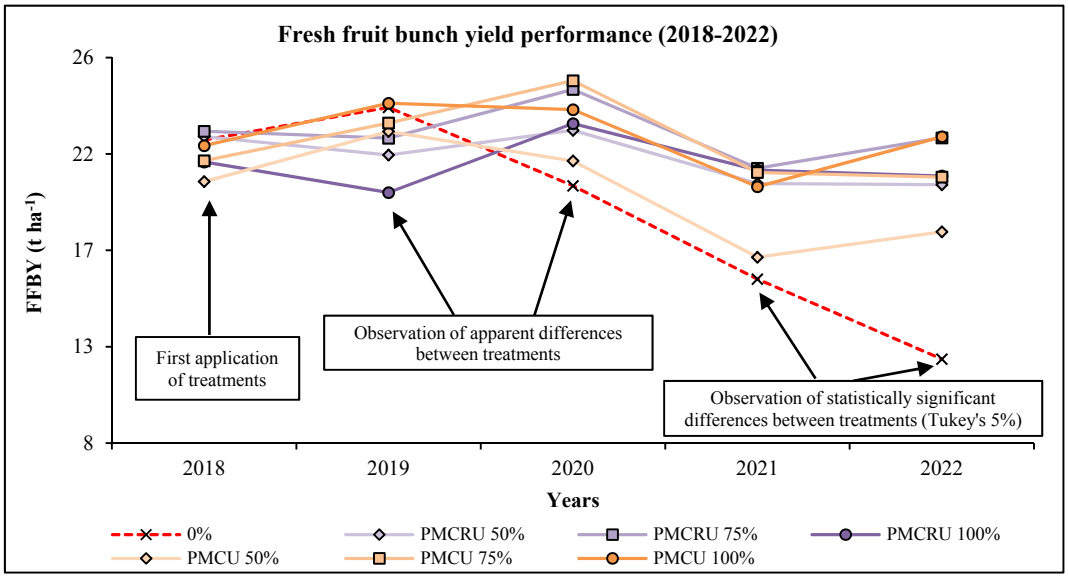


Figure 3. Fresh fruit bunch yield (FFBY) performance in response to nitrogen rates and sources during 2018 to 2022

Note. PMCRU: Physical mixture with controlled-release urea. PMCU: Physical mixture with conventional urea. The coefficients of variation (CV) were 13.2% (2018), 17.6% (2019), 10.9% (2020), 13.9% (2021, $p = 0.02$), and 17.4% (2022, $p \leq 0.001$).

In 2018, the year in which the first application of treatments was carried out, and which was considered the baseline, averages between 20.2 and 23.3 t ha^{-1} of FFB with descriptive differences of 3.1 t ha^{-1} of FFB, representing a difference of 13.3% with no significant effects between the rates and sources applied to each other or to the control. During 2019 and 2020, the descriptive differences between treatments increased to ranges between 19.7 and 23.9 t ha^{-1} of FFB in 2019 and between 20.0 and 25.4 t ha^{-1} of FFB in 2020, *i.e.*, differences of 17.6 and 21.3%, respectively, for each year. However, during these two years, there were no significant effects of the treatments either.

Statistically significant differences between treatments were detected until 2021 (four years after the start of the experiment). In this case, the 192 kg ha^{-1} rate from the PMCRU source (20.8 t ha^{-1} of FFB) and the 144 kg ha^{-1} rate from PMCU (20.6 t ha^{-1} of FFB) promoted higher FFB yields than the control (15.7 t ha^{-1} of FFB), representing a difference of up to 25.2% between the highest and lowest average (5.1 t ha^{-1} of FFB) ($p = 0.02$). In 2022, all treatments, except for the PMCU source at a rate of 96 kg ha^{-1}, showed statistically significant differences compared to the control. FFBY ranged from 11.9 t ha^{-1} of FFB (control) to 22.3 t ha^{-1} of FFB in PMCRU at 144 kg ha^{-1} and PMCU at 192 kg ha^{-1} rate in both cases), with a percentage difference between these treatments of 46.7%, or 10.7 t ha^{-1} of FFB ($p \leq 0.001$).

(2) Nitrogen Rate *vs.* Fresh Fruit Bunch Yield (FFBY)

It was observed that increasing N rates resulted in a positive and increasing increase up to rates between 75 and 100% for PMCRU and PMCU sources (144 and 192 kg ha^{-1} of N, respectively). Therefore, given the absence of interaction between the rate and N sources, the factors were analyzed separately for the last year of evaluation. For this analysis, the treatment of 100% of the PMCRU rate applied in a single split during the year was not considered, as it was the only treatment with this split condition, which did not allow for the estimation of the biological optimum. In this regard, considering the differential trend in the response of FFBY to N rates and sources, *i.e.*, linear for PMCU and quadratic for PMCRU, the rate that promoted the optimal biological was estimated for each case (Figure 4). For the PMCRU source, the rate that yielded the biological optimum was 134 kg ha^{-1} of N or 1.05 kg/palm; while for PMCU, which showed a linear trend, the maximum yield observed was obtained with 192 kg ha^{-1} of N or 1.50 kg/palm.

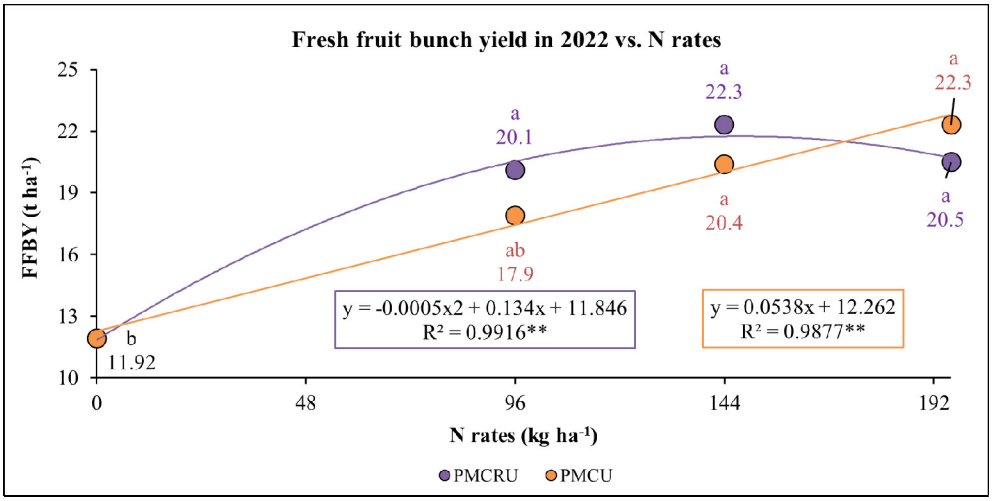


Figure 4. Fresh fruit bunch yield (FFBY) in response to nitrogen rates and sources during 2022

Note. PMCRU: Physical mixture with controlled-release urea. PMCU: Physical mixture with conventional urea. Different letters between trend lines indicate statistical differences according to Tukey's test at 5%. (CV = 17.4%; $p \leq 0.001$). **: Statistically significant at 1% by the F test at 5%.

(3) Nitrogen Use Efficiency (Partial Productivity Factor of and Agronomic Efficiency)

Figure 5 shows the partial productivity factor (PPF) values obtained using Equation 1 for the N rates evaluated. It should be noted that, for these variables, the nutrient use efficiency obtained by the 0 rate (control) is not estimated, since the applied N rate (which must go in the denominator of the calculation formula) does not allow these factors to be calculated mathematically because it is not possible to divide by 0.

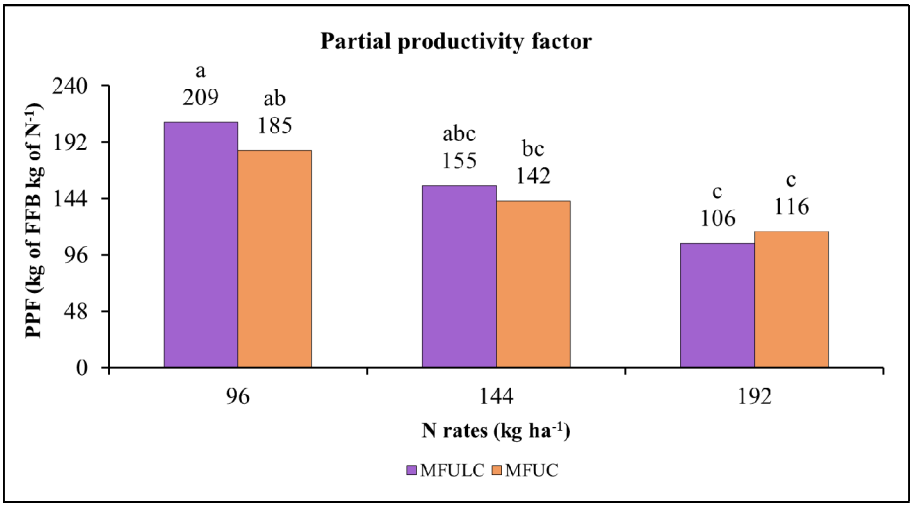


Figure 5. Partial productivity factor in response to nitrogen rates and sources during 2022 (CV = 17.9%)

Note. PMCRU: Physical mixture with controlled-release urea. PMCU: Physical mixture with conventional urea. Different letters between bars indicate statistical differences according to the Tukey's test at 5%.

In this regard, statistical differences were found between treatments according to the Tukey's test at 5%, in which case the 96 kg ha^{-1} of N rate for PMCRU promoted higher PPF values (209 kg of FFB kg^{-1} of N) than the 144 kg ha^{-1} N rate of PMCU (142 kg of FFB kg^{-1} of N) and for the 192 kg ha^{-1} of N rates for PMCRU and PMCU (106 and 116 kg of FFB kg^{-1} of N, respectively) ($p \leq 0.001$). Agronomic efficiency (AE) in N use also showed statistically significant differences between treatments, with differences between PMCRU at a rate of 96 kg ha^{-1} of N (85 kg of FFB kg^{-1} of N) and all other treatments, in which the lowest AE was 45 kg of FFB kg^{-1} of N in the PMCRU source at 192 kg ha^{-1} of N ($p = 0.026$) (Figure 6).

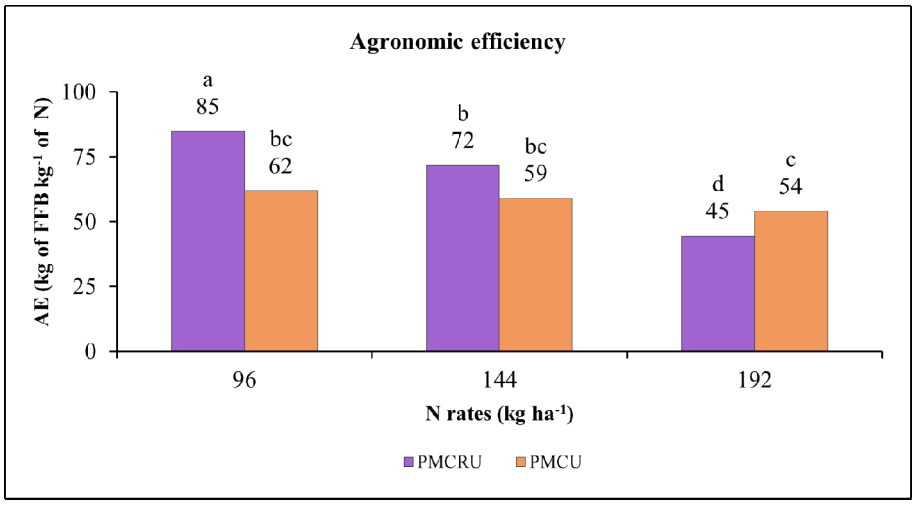


Figure 6. Agronomic efficiency in response to nitrogen rates and sources during 2022 (CV = 22.9%)

Note. PMCRU: Physical mixture with controlled-release urea. PMCU: Physical mixture with conventional urea. Different letters between bars indicate statistical differences according to the Tukey's test at 5%.

(4) Effects on Nitrogen Losses to the Environment (Ammonia Volatilization-NH_3)

Figure 7 shows the results of accumulated N volatilization during the days evaluated. In this case, there were statistically significant differences according to the Tukey test at 5% between N sources ($p \leq 0.001$). On the other hand, Table 7 shows the results of soil moisture and accumulated precipitation during the 23 days evaluated.

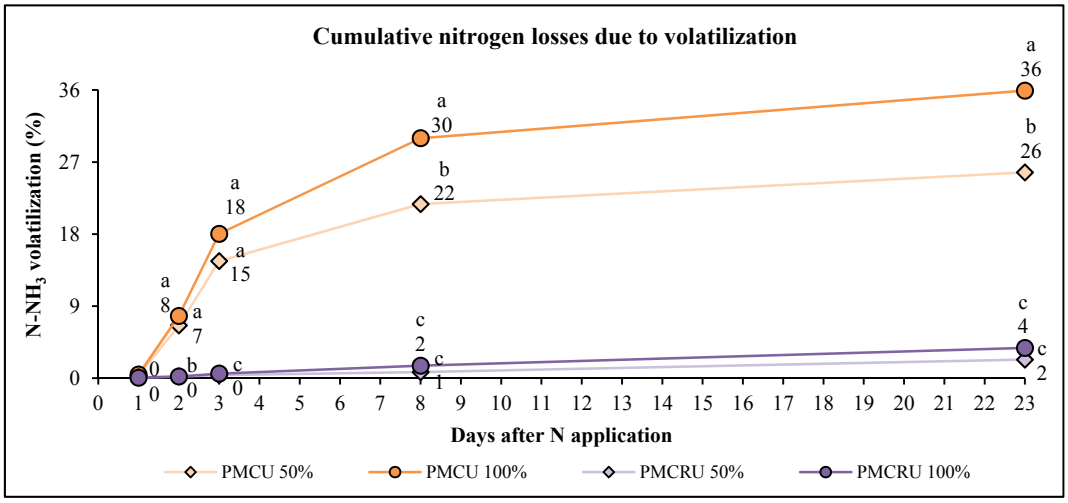


Figure 7. Cumulative nitrogen volatilization over 23 days in response to nitrogen application rates and sources (CV = 28.3%)

Note. PMCRU: Physical mixture with controlled-release urea. PMCU: Physical mixture with conventional urea. Different letters between trend lines indicate statistically significant differences according to Tukey's test at 5%.

Table 7. Soil moisture and accumulated precipitation during the 23 days evaluated

Day after N application	Soil moisture (%)	Accumulated precipitation (mm)
1	32	10
2	35	12
3	36	27
8	36	72
23	35	246

The highest values were found for the PMCU source of N, with losses of 26% and 36% of the total applied for rates of 96 and 192 kg ha^{-1} of N, respectively. It should be noted that the use of 192 kg ha^{-1} rate compared to 96 kg ha^{-1} rate, *i.e.*, twice the amount of N applied, does not necessarily result in twice the loss of N through volatilization. On the other hand, PMCRU showed losses of 2% and 4% for the same N rates. This indicates that, when using PMCRU, N volatilization can be reduced by between 92.3% and 88.9% for rates of 96 and 192 kg ha^{-1} of N, respectively.

4. Discussion

4.1 Effect on Soil Chemistry (Soil Analysis)

About soil acidity (pH), as it is an intrinsic characteristic of natural fertility over time due to climatic factors such as rainfall (Havlin et al., 2017; Sadeghian, 2022) and also to management factors such as the addition of fertilizers, especially in the area of the plate in the case of oil palm (Rey-Sandoval & Arias, 2024).

The previous fact can be verified by the result of the control treatment in which, even without the application of fertilizers, the soil tended to acidify over time and not due to the effect of the sources or rates of nitrogen as such. For its part, the decrease in OM content may be caused by its mineralization, which is accelerated by the temperature conditions and rainfall regimes of the study site and which functions as a reserve and supply of nutrients for the crop (Chiriac et al., 2025).

In the case of Ca, its decrease did not occur for other exchangeable cations such as K and Mg and even for P, may be due to the fact that the latter were applied to the soil during the five years of evaluation, which was not the case with Ca (a nutrient that is not generally included in fertilization plans). This not only allowed the P, K, and Mg required by the crop to be supplied over time, but also allowed soil reserves to be maintained, which is one of the main objectives of fertilization (Sadeghian, 2022). Properties such as P, K, and Mg showed increases compared to the baseline, mainly P, which prior to the application of the treatments had a value of 5 mg kg^{-1} and after five years this value was 14 mg kg^{-1}, representing an increase of 180%. K and Mg showed increases of 0.01 and 0.70 $cmol_c\ kg^{-1}$, *i.e.*, 9 and 38%, respectively. Al and Sat. Al remained very similar to the baseline, which was 1.9 $cmol_c\ kg^{-1}$ before and after the five years evaluated and 76% and 77%, respectively, for the same periods.

Although after five years of evaluation the pH and Ca of the soil decreased, there were no increases in Al and Sat. Al, properties that are closely related to soil acidification (Sadeghian, 2022). This could be explained by the increases in other exchangeable bases such as K and Mg which, having been supplied through fertilization, as well as P, allowed their reserves in the soil exchange complex to be maintained and increased, which prevented the increase in Al and, therefore, in Sat. Al.

4.2 Effects on the Crop

4.2.1 Nutrition (Leaf Analysis)

The decrease in foliar N after omitting its application for five years not only promoted significant differences with the sources and rates of N but was also interpreted or classified as deficient (< 2.06%) according to the sufficiency ranges recommended by Arias et al. (2023). This evidence indicates the depletion of this nutrient's reserves in the leaf tissue because of translocation from the reserve tissues (Corley & Tinker, 2015), since prior to the application of treatments, the crop generally had a leaf concentration of 2.46% of N. Although no differences were detected between the N rates and sources for this variable, the two sources showed very similar behavior with values of 2.4, 2.5, and 2.6% N for the rates of 96, 144 and 192 kg ha^{-1} of N, a result that shows that the foliar concentration of N follows the trend of increasing with the rates of this nutrient and, therefore, the N supply capacity of both fertilizer sources for the O×G hybrid oil palm.

The synergistic effect between the application of N and foliar P and S is because, as N had not been applied for five years, the concentration of P decreased even though this nutrient was applied in the same way for all treatments. Similar results were reported by Arifin et al. (2022), who evaluated different rates of N, P, and K and found a synergistic effect of N application on foliar P. The increase in foliar S resulting from N application may be due to an increase in protein synthesis and, subsequently, in photosynthesis. Foliar K response is since oil palm responds better to potassium fertilization when N levels are adequate (Arifin et al., 2022), which is not the case in the control and in the treatments where the N rate used was 96 kg ha^{-1} of N.

For foliar Ca, this can be explained by the base balance effect, whereby greater K absorption tends to decrease Ca and Mg because of the antagonism between these cations. This phenomenon occurs because there may be competition for absorption sites in the roots, in addition to a generalized effect on the difference in electrical potential across the plasmalemma, which affects the rate of cation uptake (Hawkesford, 2012). It should be noted that, although Cl did not show differences attributed to N rates and sources, for most crops Cl is considered a

micronutrient that is reported in leaf analysis results in ppm or mg kg^{-1}. In the case of oil palm, the absorption of this nutrient is higher due to its physiology and, therefore, the results shown in Table 4 indicate that the average was 0.74% or 7400 mg kg^{-1}, *i.e.*, it is reported as a macronutrient (in %) even with concentrations higher than other macronutrients such as P, K, Ca, Mg, and S.

4.2.2 Vegetative Growth (Vegetative Measurements)

When comparing the results obtained when using the highest N rates (144 and 192 kg ha^{-1}) with the lowest rates (96 and 0 kg ha^{-1} of N), decreases of 10.5% were observed in the case of the rate 144 kg ha^{-1} and up to 21.0% when this nutrient was not supplied through fertilization. The effect of N application is explained by the transformation of proteins synthesized from amino acids, which translates into greater leaf growth (Arias & Beltrán, 2014). The LDB L17 values promoted by the highest N rate were higher than those reported by Rosero et al. (2013) and Arias et al. (2023), who report an average of 3.3 and 3.5 kg/leaf for Coari × La Mé palms between 8 and 12 years old. Although LA L17, TLA, and LAI did not show statistically significant differences after five years of evaluation, a descriptive downward trend was identified for these variables when fertilization was not applied. The results differ from those reported by Arias et al. (2023) and Arifin et al. (2022), who indicate that they found an effect of N fertilization on leaf area.

4.2.3 Fresh Fruit Bunch Yield (FFBY)

(1) FFBY Performance Over the Five Years

The above effect can be explained by the response in the average number of bunches (ANB), which was 7.6 bunches/palm for the control and 10.2 and 11.6 bunches for the PMCRU at 144 kg ha^{-1} and PMCU at 144 and 192 kg ha^{-1}, respectively, implying a significant difference between these treatments of 25.5 and 34.5%, *i.e.*, a difference of 4.0 and 2.6 bunches compared to the aforementioned treatments ($p = 0.03$). In addition to the above, the average bunch weight (ABW) also showed statistically significant differences between the control and the 144 kg ha^{-1} N rate with the PMCRU source ($p = 0.02$). These treatments promoted ABW of 17.8 and 13.6 kg, respectively, *i.e.*, a 23.6% difference for this variable. Although no differences were observed between N rate and sources, a tendency to obtain lower ANB and ABW was detected as the rate was reduced to 96 kg ha^{-1}. The results show the effect of N on the formation and growth of bunches in the O×G oil palm hybrid and, consequently, on FFBY, since after 4 and 5 years of omitting nutrient application, there were losses of between 25 and 48% in FFBY, respectively.

(2) Nitrogen Rate *vs.* Fresh Fruit Bunch Yield (FFBY)

Although there are no differences between the N sources, it would be more convenient to use PMCRU, as the same FFBY would be obtained with less N, which has an impact on both the costs associated with fertilization, mainly in terms of inputs, as well as a lower environmental impact and greater efficiency in the use of this nutrient. These results are similar to those reported by Arias et al. (2023) for the O×G hybrid in the adult stage in the Eastern Zone of Colombia, *i.e.*, in the same cultivar, stage, and zone in which the present study was evaluated. These authors found that the highest FFBY were obtained with the highest N rates, with increases of up to 87%.

(3) Nitrogen Use Efficiency (Partial Productivity Factor of and Agronomic Efficiency)

The PPF values were similar to those reported by Arias et al. (2023), who indicate that for the O×G (Coari × La Mé) hybrid aged 6 to 10 years, between 85 and 222 kg of FFB are produced per kg of N applied. The EA values, like those of PPF, were also like those reported by Arias et al. (2023), who report that, for similar study conditions, gains of between 40 and 86 kg of RFF per kg of N applied are obtained. The higher efficiencies observed for PPF and AE at lower N rates are because the response of FFBY relative to the control is striking even at levels of 96 kg ha^{-1} rate and at the lowest value in the denominator of the formula (N rate). It was to be expected that, at lower rates of the nutrient, the efficiency would be higher, which is explained by the law of diminishing returns, since at higher rates of the nutrient evaluated, the yield gain is lower (Rey-Sandoval et al., 2020; Sadeghian, 2022).

(4) Effects on Nitrogen Losses to the Environment (Ammonia Volatilization-NH_3)

It should be noted that on day 1, soil moisture was 32%, an adequate condition for fertilizer application, which was maintained throughout the evaluation period, ending at 35% on day 23 after N application. Meanwhile, the accumulated precipitation during this same period was 246 mm, an amount considered adequate for adult palms according to Álvarez et al. (2006), who suggest precipitation between 150 and 200 mm $month^{-1}$. The statistical differences mentioned above occurred from the second day evaluated onwards, as no N losses due to volatilization were recorded on day 1. The greatest losses occurred in the first 3 days evaluated for PMCU source at rates of 96

and 192 kg ha^{-1} of N, specifically on days 2 and 3 after N application, since of the total 36% and 26% volatilized at the end of the evaluation, on day 2 after application, 7% and 8% volatilized, respectively, and on day 3, 15% and 18% of the applied N volatilized. Between day 3 and day 8 after application, 22% and 30% of the total N was lost. From day 8 onwards, the percentage of volatilized N gradually decreased until reaching the lowest percentage on day 23, which can be explained by the reduction in the amount of N supplied by the fertilizer. According to the experimental conditions, the greater losses of N through volatilization in the first few days can be attributed to the rapid dissolution and hydrolysis of urea, processes that produce an increase in pH around the granule and facilitate the formation of NH_3 from ammonium (NH_4^+) produced by the first reaction of urea (Kiehl, 1989; Vitti et al., 2002).

The results found in this study are, in general, similar to those reported by Leal et al. (2007), González and Sadeghian (2012), González et al. (2015), and Sadeghian and González (2022) for various rates, sources, locations, and climates in the coffee-growing region of Colombia, and by Costa et al. (2003) for sugarcane plantations in Brazil, who reported that the first few days after the application of conventional urea are crucial during volatilization, as this is when the greatest losses due to this phenomenon occur, with N volatilization values between 21 and 36%.

The PMCRU source presented the lowest values of cumulative N volatilization. In this case, losses began on day 3 for the 192 kg ha^{-1} rate with 1% volatilization, increasing to 2% on day 8 for the 192 kg ha^{-1} rate and starting at 1% for the 96 kg ha^{-1} rate, and finally, 4% of the total N applied for 192 kg ha^{-1} rate and 2% for the 96 kg ha^{-1} rate on the last day of measurement (day 23). These lower losses resulting from the use of the PMCRU source are related to the polymer coating on this fertilizer, whose function is to delay and reduce the increase in pH because of urea hydrolysis, in addition to gradually releasing the N contained in the granule.

It should be noted that these losses occurred even under conditions of adequate soil moisture during the evaluation period (≥ 30%) because the behavior of precipitation with 246 mm in 23 days with relative adequate distribution, which is essential for the proper dissolution and subsequent absorption of nutrients by the plant. This is particularly relevant for the first few days after fertilizer application, when losses of 22% and 30% of the total applied were reached for PMCU at rates of 96 and 192 kg ha^{-1}, respectively.

Accordingly, N applications through PMCU under inadequate soil moisture and precipitation conditions could result in greater N losses in the form of ammonia. It is important that the observed response is It is derived from the interaction of precipitation and soil moisture factors that occurred during the evaluation, and considerable decreases or increases in these variables could lead to scenarios of greater or lesser volatilization.

5. Conclusions

Analysis of the results after five years of evaluation indicated that the use of PMCRU and PMCU did not promote significant effects on soil chemistry; however, it did have effects on nutrition, growth, FFBY, N use efficiency, and N losses due to volatilization in O×G hybrid oil palm in the productive stage according to the Tukey´s test at 5%.

In general, the use of PMCRU showed similar results to PMCU, with both fertilizer sources fulfilling their function of supplying N to the crop. However, PMCRU allowed the biological optimum to be achieved with a rate of 134 kg ha^{-1} of N, while PMCU required the maximum evaluated rate of N (192 kg ha^{-1} of N). In addition, PMCRU was more efficient. In turn, the use of PMCRU can reduce N volatilization by between 92.3 and 88.9% for rates of 96 and 192 kg ha^{-1} of N, respectively.

The use of PMCRU is a feasible alternative for the nutrition of the interspecific hybrid O×G during the adult stage in the Eastern Zone of Colombia, allowing higher yields to be achieved with lower doses of N and reducing N losses due to volatilization.

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