

# NITROGEN CONCENTRATION, ACCUMULATION, EXPORTATION AND EFFICIENCY IN OIL PALM (*Elaeis guineensis* Jacq.) GROWN ON OXISOLS OF THE AMAZON

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## ABSTRACT

Oil palm (*Elaeis guineensis* Jacq.) is a vital economic resource in Brazil, originating from Africa. This study aimed to analyse nitrogen concentrations and dynamics within different plant components across varying ages of the Tenera hybrid (Dura x Pisifera) in Tailândia, Pará conducted on Oxisol, a dystrophic type characterised by low inherent chemical fertility and elevated acidity levels. The experiment spanned 2-8 years and employed a completely randomised design with four repetitions. Nitrogen levels increased consistently across all plant components with age, notably in the stem (42%) and leaflets (28%) by the eighth year. Nitrogen export was lower in the third year (7.84 g plant<sup>-1</sup>), while in the eighth year (410.10 g plant<sup>-1</sup>), there was a considerable increase. The immobilised nitrogen exceeded exports by 3.7 times, while recycled nitrogen surpassed removal by 3.8-35.0 times. Nitrogen use efficiency declined with age across various organs, with petioles showing the highest efficiency and the cabbage the lowest. This study provides insights into nitrogen dynamics in oil palm cultivation, highlighting age-dependent variations in nitrogen concentrations, accumulation, and utilisation efficiency across different plant parts.

**Keywords:** *arecaceae*, extraction, macronutrients, tropical forest, tropical soil.

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## INTRODUCTION

The African oil palm (*Elaeis guineensis* Jacq.) is an oil-producing palm tree native to Africa, which has been widely used as a source of energy and

food since ancient civilisations. Two types of oil are extracted from the fruit (pulp and kernel), with 72.0% used in the food industry, 14.0% in bioenergy, 9.2% in chemical production and 4.8% in other uses worldwide (Ministério da Agricultura, Pecuária e Abastecimento [MAPA], 2018).

The oil palm begins production in its third year and can be exploited for up to 30 years. It exhibits high productivity, yielding between 3-8 t of oil ha<sup>-1</sup> annually. Additionally, its year-round production presents an advantage, allowing for intensive and continuous labour (Müller & Andrade, 2010). The area of oil palm cultivation in Brazil in 2020 was around 188,502 ha, with Pará responsible for 93.45% (Instituto Brasileiro de Geografia e Estatística [IBGE], 2020). According to data from the Food and Agriculture Organization of the United Nations [FAO], 2020, oil palm fruit production in the country reached approximately 2,867,986 t in

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Oil palm cultivation not only offers profitability but also aligns with sustainable development criteria by rehabilitating degraded areas resulting from slash-and-burn agriculture practices in the Amazon. This approach demonstrates a strong socio-environmental character and receives support from national organisations (Center for International Forestry Research [CIFOR], 2015).

Understanding the growth, nutrient concentration, and exportation of nutrients in different plant parts at all stages is essential for designing efficient fertilisation programmes aimed at achieving high productivity. As dry matter production and nutrient accumulation in various oil palm organs vary with age, a better understanding of these characteristics would lead to improved fertilisation practices.

The indiscriminate use of fertilisers can lead producers to two situations. Firstly, excessive application results in fertiliser wastage, nutritional imbalances and increased production costs, as fertiliser expenses in an oil palm plantation account for approximately 60% of maintenance costs. Moreover, overuse can cause toxicity, damaging vascular tissue and hindering growth (Mohidin *et al.*, 2019). Secondly, applying fertilisers below the plant's real needs results in low crop productivity.

Nitrogen is a macronutrient of immense importance for plants, as it is involved in the formation of various carbon compounds, such as amino acids, proteins, nucleic acids and others, making it essential for plant growth and development (Taiz *et al.*, 2017). Nitrogen fertilisation contributes to the vegetative growth of plants. According to Bovi *et al.* (2002), the addition of nitrogen to peach palm trees promotes diameter growth, with maximum growth achieved at a dose of 400 kg ha<sup>-1</sup> yr<sup>-1</sup>.

In Brazil, oil palm plantations have incorporated the use of cover crops, such as *Pueraria phaseoloides*, between the rows of palm trees. This legume offers various benefits as ground cover, as it is capable of fixing atmospheric nitrogen

and converting it into a form that enhances soil fertility, thereby reducing the need for artificial fertilisers (Agreda *et al.*, 2024).

Considering these facts, the study aimed to determine the concentration and quantity of extracted nitrogen from various components of the oil palm as well as for each organ, as a function of age, the immobilised, recycled and exported amount of nitrogen in the form of harvested bunches, and the total nitrogen use efficiency.

## MATERIALS AND METHODS

### Environment of Study

The oil palms used in this study were of the commercial hybrid *Tenera (Dura x Pisifera)*, belonging to the Agropalma company, located in the Northeastern municipality of Tailândia (Pará). The geographical coordinates of this location are 2°00'S-4°00'S latitude and 50°00'W-48°00'W longitude. According to the Köppen climate classification, the region has an Am type climate (tropical rainy), with annual averages of 26.5°C for mean temperature, 2,400 mm of rainfall and 84% relative humidity.

The soil composition within the experimental area consists of Oxisol, characterised by inherently low chemical fertility, elevated acidity levels and a moderately textured structure (Rodrigues *et al.*, 2005; Santos, 2018). Four soil sub-samples were collected from the planting rows for each age of the oil palm at a depth of 30 cm. Soil analysis was conducted following the method described by Raij *et al.* (1987), and the results are presented in Table 1.

### Experimental Design

The plants were grown at a spacing of 9 m in an equilateral triangular pattern, resulting in a density of 143 plants ha<sup>-1</sup>. The legume *P. phaseoloides* was used as ground cover throughout the plantation. The experiment was conducted using a completely randomised design with four replicates.

TABLE 1. CHEMICAL AND PHYSICAL SOIL CHARACTERISTICS (0 – 0.3 M) AT 2 TO 8 YEAR OIL PALM CULTIVATED PLOTS

Plant age (yr)	pH (CaCl <sub>2</sub> )	K*	Ca*	Mg*	Al	H+Al**	SB	P*	V	M.O***	Coarse sand	Fine sand	Silt	Clay
											----- cmol <sub>c</sub> dm <sup>-3</sup> -----			
2	4.3	0.007	0.07	0.04	0.04	0.34	0.117	4	24	1.6	450	280	40	230
3	4.4	0.006	0.07	0.02	0.03	0.28	0.960	6	24	2.3	320	300	16	220
4	4.1	0.005	0.09	0.02	0.03	0.31	0.115	5	24	1.5	500	190	80	230
5	4.0	0.007	0.08	0.03	0.05	0.38	0.117	6	22	1.9	370	310	10	220
6	4.0	0.005	0.07	0.03	0.08	0.34	0.105	6	22	2.0	380	210	80	330
7	4.3	0.005	0.07	0.03	0.04	0.26	0.105	6	27	2.1	340	320	10	240
8	4.0	0.006	0.06	0.03	0.06	0.34	0.96	8	20	1.8	510	230	60	200

Note: \* - Extracted with ion exchange resin; \*\* - SMP methods; \*\*\* - colorimetric methods.

## Statistical Analysis

Upon obtaining significant results from the analysis of variance, the Tukey test was employed for mean comparisons at a 5% significance level. After confirming the significance with the F test, the equations related to growth, nitrogen accumulation and exportation were analysed. To determine the most appropriate equations for explaining the results, both the F test and the coefficient of determination of the regressions were utilised. Nitrogen use efficiency was calculated by dividing the square of dry matter by the nitrogen accumulation (Siddiqi & Glass, 2008).

## Collection of Plant Component Samples

In selecting the palms, efforts were made to choose more homogeneous plants, which were within the same plot, representative of the age, uniform, well-developed, well-nourished, healthy and with good yield. The circumference of the stem base and the height of the plant were measured from the base of leaf 33, as recommended by Jacquemard (1979) and Surre (1979). Four palms were sampled for each age, and the following components were collected: Leaflets, petioles, rachises, cabbage, spear leaves, stems, male inflorescences (MI), peduncles, spikelets and fruits.

FronD sampling was carried out by analysing leaflets from all the fronds of the plant, in contrast to the standard method of focusing on the 17th frond, which is typically used to assess the nutritional status of mature palms.

Nitrogen determinations were conducted using the Kjeldahl method, as outlined by Sarruge and Haag (1974). The accumulated amounts of nitrogen in different components of the oil palm for each age were estimated by multiplying the nitrogen concentrations with the dry matter values of each component. The immobilised amounts of nitrogen were calculated by summing the accumulated nitrogen from the stem, the cabbage and spear leaves, as nutrient immobilisation primarily occurs in growing vegetative components. The recycled amounts were determined from leaflets, rachises, petioles and MI, as these vegetative components are eventually returned to the soil.

To determine the amount of nutrients exported from the agricultural area, it is important to consider the significant quantity of elements immobilised in the harvest product. Thus, the calculation of nitrogen removal includes the sum of nitrogen accumulated in the components of the bunch, including the fruit, peduncle and spikelet. This method is employed to accurately quantify the nutrient export that occurs during harvesting, reflecting the amount of nitrogen removed from the soil and the cultivated area.

To calculate the nitrogen accumulation for fruits, spikelets and peduncles (parts of the bunch), the number of bunches produced annually in two fertiliser experiments on the same plantation was considered. The content of these components was estimated by multiplying the concentration and dry matter weight by the number of bunches produced annually per plant: Six bunch in the third year, 15 bunches in the fourth and fifth year, 17 bunches in the sixth year, 20 bunches in the seventh year and 22 bunches in the eighth year.

MI were collected at the anthesis stage, along with fruits, spikelets and peduncles, starting from the third year of age. However, due to the high proportion of female plants in the current planting materials, the formation of MI is likely reduced, which may affect the accuracy of nitrogen estimates. Due to the absence of precise data on the number of MI produced annually under plantation conditions, the nitrogen content calculation was based on the work of Breure (1987). To estimate the nitrogen content in this component, the element concentration was calculated based on the multiplication of the dry matter weight by the number of inflorescences produced each year. Thus, in the third year, the number of MI was considered to be 2, 5 in the fourth and fifth, 8 in the sixth, 10 in the seventh and 11 in the eighth year.

## RESULTS AND DISCUSSION

### Nitrogen Concentration

The results showing nitrogen concentrations in the various components of oil palm, expressed as a percentage of dry matter, along with their ages and significant differences, are presented in *Table 2*.

All plant components exhibited variations in nitrogen concentrations over the years, although the changes in petioles were not statistically significant. The statistical analysis revealed significant differences in the mean nitrogen concentrations of leaflets, rachis, cabbage, stem, MI, peduncles, spikelets and fruits. In the case of petioles, no statistically significant differences in nitrogen concentrations were observed between the years. Additionally, a decreasing trend in nitrogen concentration was observed in spear leaves over time.

Siang *et al.* (2022) obtained similar data with a decrease in nitrogen concentrations in the fronds as the age of the plants increased: 3 years (1.90%), 7 years (1.26%), 17 years (1.18%), and 20 years (0.99%). These results corroborated the findings of the present study, which revealed a significant variation in nutrient concentrations in the palms according to their age.

TABLE 2. NITROGEN CONCENTRATION ( $\text{g kg}^{-1}$ ) IN DIFFERENT COMPONENTS OF OIL PALM, AS A FUNCTION OF AGE

Plant age (yr)	Plant components									
	Leaflets	Petiole	Rachis	Cabbage	Spear leaves	Stem	MI	Peduncles	Spikelet	Fruits
	Nitrogen									
2	14.8b	4.6a	3.9c	29.3bc	16.7ab	7.8c	-	-	-	-
3	22.3a	4.6a	3.5d	31.6bc	18.0a	14.5ab	17.0b	6.0b	5.2d	10.6bc
4	23.8a	4.5a	4.5a	31.6bc	14.4bcd	17.1a	19.0a	5.8b	6.5ab	13.1a
5	22.5a	4.5a	4.4ab	35.9a	12.7cd	13.4ab	17.0b	6.4ab	6.1bc	9.6c
6	22.6a	4.8a	4.0bc	28.8c	12.0d	11.8b	16.8bc	6.8a	6.8a	10.4bc
7	23.0a	4.4a	4.4ab	33.1ab	15.4abc	11.6bc	15.5c	6.4ab	5.9c	10.4bc
8	22.6a	5.1a	4.5a	36.9a	14.8bcd	10.7bc	18.2ab	6.2ab	5.3d	10.8bc
<b>SD</b>	<b>2.8</b>	<b>0.2</b>	<b>0.4</b>	<b>2.8</b>	<b>1.9</b>	<b>2.7</b>	<b>1.1</b>	<b>0.3</b>	<b>0.6</b>	<b>1.1</b>

Note: Values with the same letters in the same column do not differ from each other at a 5% probability level by Tukey's test; MI - male inflorescences.

Ollagnier and Ochs (1981) observed a reduction in nitrogen content in the 17th frond with age, even in plants that received nitrogen fertilisation. They reported concentrations of 2.65% at 5-9 years, 2.50% at 10-15 years, 2.45% at 16-20 years and 2.35% at more than 20 years of age. Siang *et al.* (2022) also confirmed that nutrient concentrations among palms vary depending on factors such as palm age, nutrient element and tissue type. Moreover, the coefficient of variation of nitrogen concentrations for the entire palm can range from 5.70%-20.70%.

Among the crown components, the cabbage, leaflets and spear leaf showed the highest nitrogen concentrations, surpassing those found in the stem. In contrast, petioles and rachis had the lowest nitrogen concentrations. The decreasing sequence of nitrogen content was as follows: Cabbage > leaflets > MI > spear leaf > stem > fruits > peduncles > spikelet > petioles > rachis. The nitrogen concentration in all oil palm components for the corresponding years was higher than that reported by Ng *et al.* (1968), suggesting a better nutritional status of this element in Brazil.

In the study conducted in Malaysia, distinct analyses were conducted on the fruit components, specifically the mesocarp, fibre and kernel (Ng & Thamboo, 1967). Since the components of the bunch were not studied in the same manner in the study, the comparisons focus specifically on peduncles and spikelets.

The average nitrogen concentration in the peduncle in this study was 0.62% in the eighth year, which is similar to the 0.66% found in the city of Durian, Malaysia (Ng & Thamboo, 1967). However, the average nitrogen concentration in the spikelet was lower than that found in the three locations studied in Malaysia by Ng and Thamboo (1967): Durian, Serdang and Jerangau. Additionally, for MI, the average nitrogen concentration in the eighth year was similar to

that found at the Jerengau location and higher than that found in the other locations analysed in Malaysia.

Ng and Thamboo (1967) reported nitrogen concentrations in fruits (1.31%) and spikelets (0.52%) that are consistent with the results obtained in this study. On the other hand, Siang *et al.* (2022) reported equal concentrations for peduncles (0.84%) and spikelets (0.84%). However, the nitrogen concentration in the fruits was still higher. Although the current study did not separately analyse fruit components, it was observed that the descending order of nitrogen concentration in the bunch components was fruits > peduncles > spikelets.

The optimal nitrogen concentration in the 17th frond, as reported by Yadegari *et al.* (2020), ranges from 2.40%-2.80%. Nitrogen concentrations lower than 2.50% in young palms and lower than 2.30% in older palms indicate nitrogen deficiency, thereby suggesting the need for corrective measures (Uexküll & Fairhurst, 1991). However, the critical nitrogen level cannot be fixed as it depends on phosphorus concentrations, as mentioned by Rognon (1984). A nitrogen level of 2.50% may indicate deficiency if the phosphorus concentration is 0.17%, whereas a phosphorus concentration of 0.14% is associated with good nutrition when combined with the same nitrogen level. The interaction between nitrogen and phosphorus is fundamental for understanding plant nutrition, as an excess of phosphorus can create a scenario in which nitrogen becomes the limiting nutrient, even if its concentration is at adequate levels.

Based on the findings of Uexküll and Fairhurst (1991), the nitrogen concentration in the fronds of the whole plant, except for the second year, is slightly below the lower limit, indicating a potential deficiency of this nutrient. It is important to emphasise that the levels measured in this study reflect the analysis of leaflets from all the fronds of

the plant. This approach differs from the common practice of focusing on the 17th frond, which is often associated with the nutritional status of mature palms. While the 9th frond is frequently used to assess young palms, our method provides a more comprehensive view of the plant's nutritional dynamics throughout its various growth stages. As a result, we offer a more complete analysis of the palms' nutritional requirements.

The nitrogen concentration range in different components of the oil palm, related to age, is presented in Table 3. The rachis showed the highest variations, while the petioles had the smallest variations. Such differences in nitrogen and other nutrient levels were expected, given the influence of several factors, including plant organs composed of different tissues, age, climate, element interactions, cultural management and so on (Li *et al.*, 2016; Pardon *et al.*, 2017; Siang *et al.*, 2002; Viégas *et al.*, 2021).

### Nitrogen Accumulation

It was found that the nitrogen accumulation in all components increased as the palm tree aged, with the stem and leaflets being the most prominent in the eighth year, with 1,723.47 and 1,144.40 g plant<sup>-1</sup>, corresponding to 42% and 28%, respectively. In general, the nitrogen accumulation sequence was as follows: Leaflets > petioles > fruits > rachis > spikelet > MI > spear leaf > peduncles > cabbage. Similarly, Manurung *et al.* (2023) observed that nitrogen accumulation was higher in leaves.

It was observed that the highest nitrogen accumulation in the leaflets occurred up until the fifth year (625.86 g plant<sup>-1</sup>), with significant increases noted each year. However, from the sixth year onwards (690.47 g plant<sup>-1</sup>), this dominance shifted to the stem. This highlights the role of the leaflets as a nitrogen storage organ during the first five years and the stem's increasing importance from the sixth year. The emergence of the stem as the primary site for nitrogen storage in the sixth year was notably later than for other nutrients, as shown by the significant rise in the nitrogen accumulation from 494.82-1,046.87 g plant<sup>-1</sup> and then to 1,723.47 g plant<sup>-1</sup> in the subsequent year. The increased nitrogen accumulation in the crown, combined with the delayed storage of this element in the stem, highlights an

important practice in oil palm plantations. Over time, the decline of the legume *P. phaseoloides* L. adds further significance to depositing cut leaves in the inter-rows, as this practice aids in nutrient supply.

Comparing the nitrogen accumulation obtained in Nigeria by Tinker and Smilde (1963), even for 22-year-old plants, it is evident that the nutrient accumulation in the current study was higher. In the leaflets and stems, the accumulation was up to 1.4 times greater, and in the rachis, it was 2.5 times higher. Only the cabbage accumulation was 2.5 times higher than in the Nigerian conditions. This remarkable superiority of the results obtained in the Amazon can be explained by the low yield and high heterogeneity of the sampled palms in Nigeria, including some potassium-deficient palms. Thus, the results obtained in Nigeria on dry matter production and nutrient accumulation must have been influenced by the strong water deficits, common in that country, which, as is known, condition the growth and production of oil palm.

The most comprehensive work on nutrient concentration and content in various organs of oil palm as a function of age was carried out in Malaysia by Ng *et al.* (1968), despite using only one plant for each age. Comparative results between the nitrogen contents determined in Brazil and Malaysia show notable differences. From the fifth year onwards, nitrogen content in the leaflets and rachis in Brazil was up to 1.4 and 1.9 times higher, respectively. In the stem, this superiority was observed only from the sixth year onwards. In Malaysia, the accumulated amounts of nitrogen in the fronds in all years were higher, while in the cabbage, this occurred only up to the fifth year and subsequently became equivalent.

Siang *et al.* (2022) observed in Malaysia that the sequence of nitrogen concentrations in the various components of the oil palm closely mirrors the findings of the present study. In both cases, nitrogen concentrations were highest in the cabbage, followed by the leaflets and the stem. Although the absolute concentrations vary between the studies, the relative order of nitrogen concentrations in the plant components remains consistent.

The comparison between the accumulated amount of nitrogen in the crown, stem, bunches and MI, which encompass all the studied components, is shown in Figure 1.

TABLE 3. RANGE OF VARIATION OF NITROGEN CONCENTRATIONS IN DIFFERENT COMPONENTS OF OIL PALM

Plant components									
Leaflets	Petioles	Rachis	Cabbage	Spear leaves	Stem	MI	Peduncles	Spikelet	Fruits
----- % -----									
1.48-2.38	0.45-0.51	0.35-0.45	2.93-3.59	1.20-1.80	0.78-1.71	1.55-1.90	0.60-0.68	0.52-0.68	0.96-1.31

Note: MI - male inflorescences.

The highest nitrogen accumulation was observed in the eighth year, with 4,098.50 g plant<sup>-1</sup>, which based on the density of 143 plants, corresponds to 586.08 kg ha<sup>-1</sup>. If nitrogen fertiliser such as urea were used for example, with 45% N, this amount of nitrogen would correspond to 1,300 kg ha<sup>-1</sup>. However, it should be noted that this demand for urea is mitigated by the nitrogen supply from *P. phaseoloides* L., and nutrient recycling from leaf deposition in the inter-rows of oil palm planting. Nevertheless, it is important to highlight that the return of nitrogen and other nutrients to the soil through recycling occurs in the long term and is not fully utilised, as only a part becomes available to the oil palm. These losses are due to leaching, consumption by microorganisms and absorption by *P. phaseoloides* L. (Pardon *et al.*, 2017).

The analysis showed that the crown was the dominant portion up to the fifth year, reaching 57%, but from the sixth year, this difference decreased, with the stem equalising. In Malaysia, Ng *et al.* (1968) found that the crown dominated the stem until the fifth year, after which the stem began to dominate and increased with age. The maximum nitrogen accumulation in fruits relative to the total plant was 11.8%, while in MI it was 2.9%.

The regression analysis showed that the accumulated amount of nitrogen in the vegetative components (stem, petioles, spikelet, peduncles, rachis, spear leaf and cabbage) can be calculated by ascending second-degree equations as a function of age (Figure 2a and 2b). This suggests that the relationship between plant age and the amount of nitrogen accumulated is complex and non-

linear. The quadratic pattern may reflect the initial rapid growth of these components, followed by a slowdown as the plant ages. This is consistent with plant physiology, where vegetative tissues often exhibit accelerated growth during early developmental stages (Mohidin *et al.*, 2015), followed by a more gradual increase or stabilisation as the plant matures.

In contrast, for the reproductive components (leaflets, fruits and MI), it can be calculated by ascending linear equations (Figure 2c). This indicates a more direct and proportional relationship between age and the amount of nitrogen. The simplicity of the linear pattern may reflect how these reproductive components assimilate nitrogen more uniformly throughout their development. This linearity may be attributed to the specific function of these components, which tends to require a constant amount of nutrients to support the reproductive process.

### Nitrogen Requirement

The present study reveals that the nitrogen nutritional requirement changes with the age of the crop, indicating an increase in nutritional demand as the oil palm crop matures. Additionally, nitrogen use efficiency promotes increased accumulation and, consequently, biomass gains, influencing nitrogen immobilisation, recycling and exportation (Figure 1) in oil palm agroecosystems. In this context, nitrogen use efficiency varies across the organs of oil palms, affecting accumulation in different plant organs and promoting greater biosynthesis of biomass.

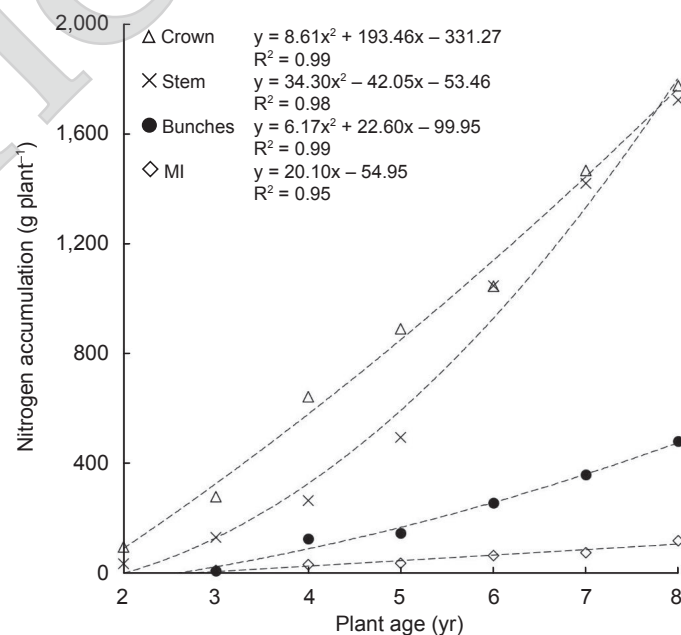


Figure 1. Nitrogen accumulation in the crown, stem, bunches and male inflorescences (MI) of oil palm as a function of age.

### Nitrogen Amount

Figure 3 displays the average results of comparing the immobilised (stem, cabbage and spear leaves), recycled (leaflets, rachis, petioles and MI), and exported (fruits, peduncles and spikelets) amounts of nitrogen. There was an increase in all categories with the age of the palm trees. Notably, until the fifth year, nitrogen recycling exceeded the immobilised amount. However, from the sixth year onwards, an equilibrium was observed. The immobilised amount in the eighth year was 3.7 times greater than the exported amount. Nevertheless, in the third year, this superiority reached 20 times. The recycled amount of nitrogen ranged from 3.8 to 35 times greater than the removed amount.

The comparison between the total extraction of macronutrients, based on dry matter production and nutrient concentration, in the present study and those obtained in Malaysia at corresponding ages is presented in Figure 4. It is evident that, in the study by Ng *et al.* (1968), the total accumulated nitrogen amount was significantly higher in the first three years, even without considering the extraction of nutrients from bunches and MI. However, from the fourth year onwards, the levels of accumulated nitrogen were higher in Brazil compared to Malaysia.

This difference can be attributed to the soil conditions in Malaysia during that period. Oil palm plantations in Malaysia are established on tropical Oxisols and Ultisols, which are characterised by high acidity, elevated aluminium

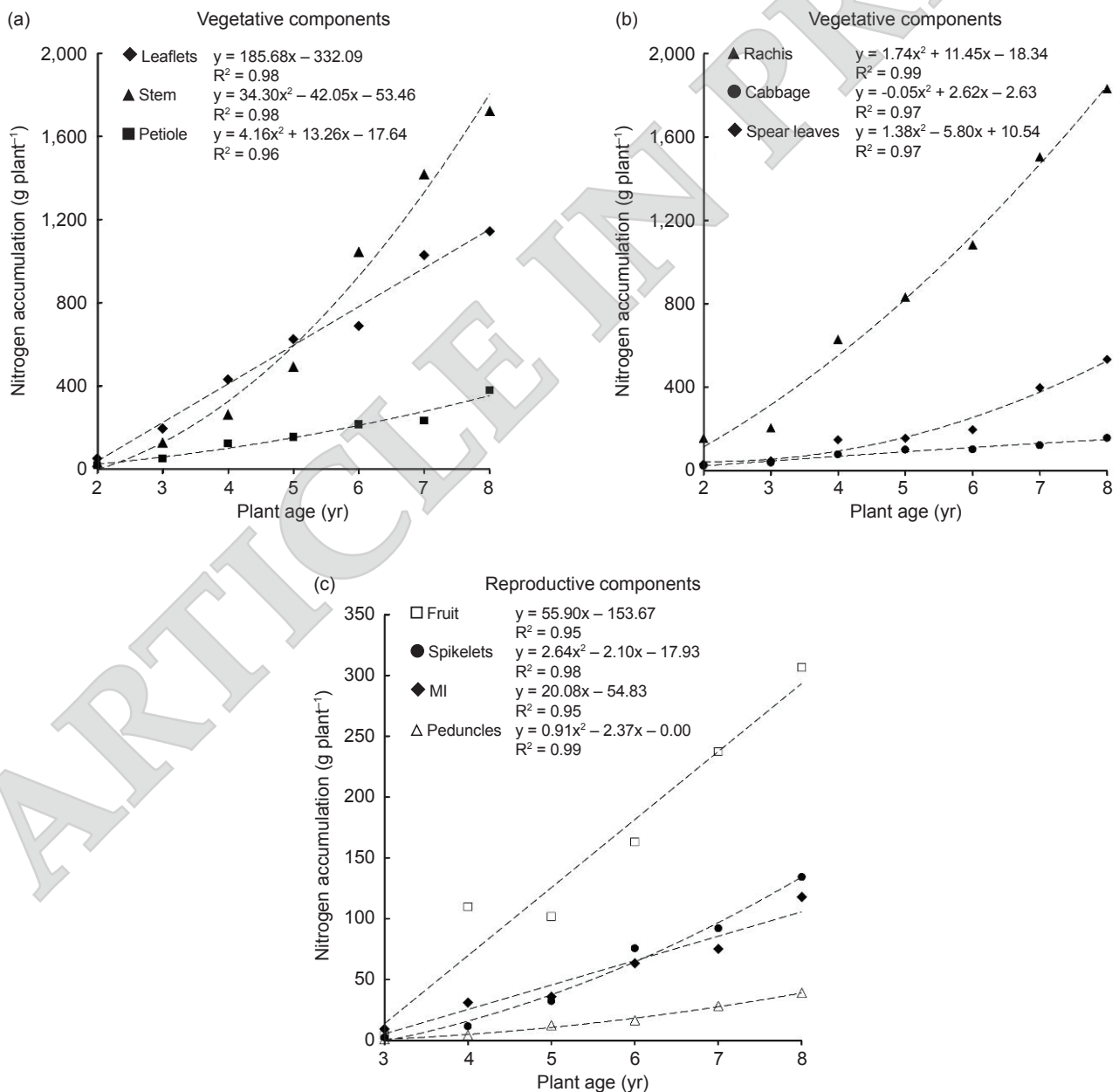


Figure 2. Regression equations of nitrogen accumulation in vegetative components and reproductive components of the oil palm as a function of age.

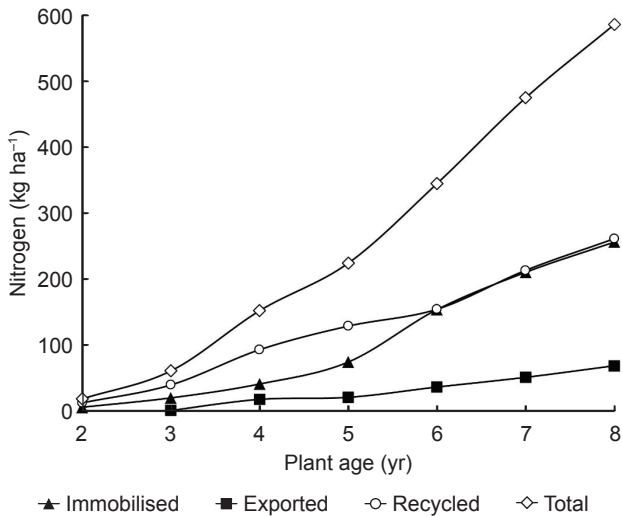


Figure 3. Immobilised, recycled and exported amounts of nitrogen in oil palm as a function of age.

saturation, and high capacity for phosphorus fixation due to intense rainfall (Mahmud *et al.*, 2022). These conditions make the soil less capable of sustaining high levels of oil palm production. The application of *P. phaseoloides*, a leguminous plant that enhances soil quality by fixing nitrogen and increasing soil fertility, contributed to the superior results observed from the fourth year in Brazil.

The use of *P. phaseoloides* may have improved soil conditions, facilitating better nutrient uptake and higher nitrogen levels in oil palm (Pipai *et al.*, 2023). Therefore, the incorporation of leguminous plants, such as *P. phaseoloides*, in oil palm plantations is recommended, as they improve soil fertility and increase nutrient use efficiency.

It is believed that the higher total nitrogen extraction in the early years of oil palm growth in Malaysia, even in the *Dura* variety, is due to better rainfall, soil fertility, fertilisation and cultural

management conditions. Conversely, the results obtained for total nitrogen extraction were much higher than those obtained in Nigeria by Tinker and Snilde (1963), even when excluding bunches and MI.

### Nitrogen Exportation

Regarding exportation, the highest was 480.10 g plant<sup>-1</sup> in the eighth year, while the lowest, as expected, was in the third year with only 7.84 g plant<sup>-1</sup>. Among the bunch components, fruits contributed the most to the exported amount of all macronutrients, followed by spikelets and lastly by peduncles.

The percentage contribution of nitrogen exportation by fruits, relative to other bunch components, ranged from 52.90%-87.20%, for spikelets from 9.3%-33.35%, and for peduncles from 3.50%-13.80%. The regression analysis for nitrogen exportation by bunches, as previously mentioned, followed an upward quadratic equation,  $y = 6.17x^2 + 22.60x - 99.95$ , with a coefficient of determination of 98.96% ( $R^2 = 0.99$ ), indicating a minimal error (Figure 1).

### Nitrogen Efficiency

Based on the data obtained from dry matter and nitrogen accumulation, nitrogen use efficiency was calculated. It was observed that nitrogen use efficiency increased with the age of the plant up to the eighth year (Figure 5), reflecting a growth trend throughout this period. However, it is important to emphasise that, as the study covered only up to the eighth year, there is no available data on efficiency beyond this period. Considering that the productive cycle of oil palm is approximately 30 years, the continuation of this trend suggests that nitrogen efficiency may continue to increase beyond the eighth year.

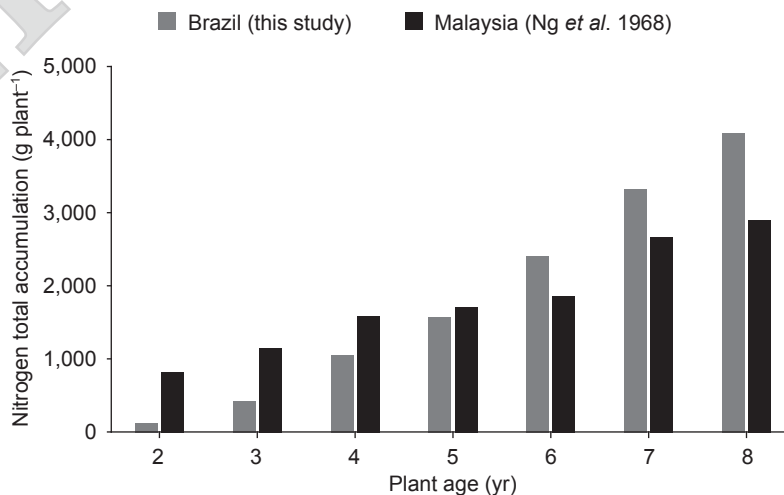


Figure 4. Total nitrogen accumulation in oil palm as a function of age, in Brazil and Malaysia.

The highest nitrogen use efficiency was found in the petiole ( $7.540 \text{ kg}^2 \text{ g}^{-1}$ ), while the lowest was found in the cabbage ( $0.008 \text{ kg}^2 \text{ g}^{-1}$ ), considering the average across all evaluation years. Among the different plant organs, nitrogen use efficiency varied, with the following descending order: Petiole > stem > rachis > spikelet > fruits > leaflet > peduncle > MI > spear leaves > cabbage. This means that, although nitrogen use efficiency improved with plant age, it varies significantly among different parts of the plant.

To achieve maximum nitrogen use efficiency, there was a linear response relative to the age of oil palms, with the highest increase observed in the eighth year of growth ( $38.40 \text{ kg}^2 \text{ g}^{-1}$ ). The findings from our study suggest that plant age modifies nitrogen use efficiency in oil palms (Figure 5 and 6), promoting an increase in efficiency with age

and altering the nutrient accumulation in different plant organs.

Nutrient use efficiency is characterised by a plant's ability to convert nutrients into biomass gains, that is, to reuse the nutrients, especially from senescent plant tissues (Prado, 2021). Under stress conditions, plants tend to decrease their ability to convert nutrients into biomass gains, consequently reducing their nutrient use efficiency (Prado & Silva, 2017) and redirecting metabolic energy towards defence mechanisms. However, under optimal conditions, plants convert their energy balance into biomass increment (Sardans *et al.*, 2012). In this scenario, oil palms demonstrate that their nitrogen use efficiency is influenced by age, indicating their ability to direct their energy balance towards dry mass biosynthesis, thereby increasing nitrogen use efficiency.

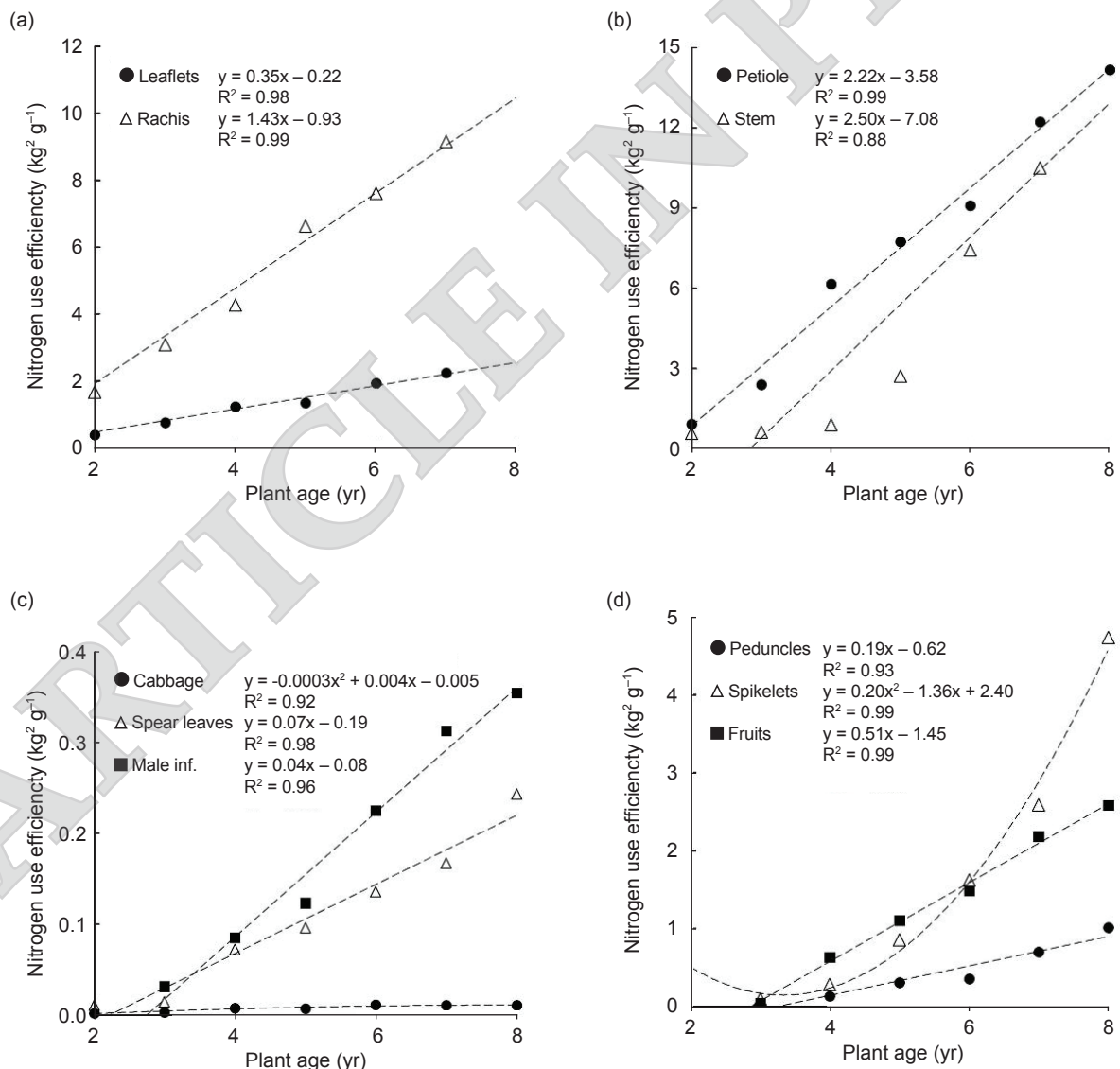


Figure 5. Nitrogen use efficiency in (a) leaflets, rachis, (b) petiole, stem, (c) cabbage, spear leaves, male inflorescence, and (d) peduncle, spikelet, fruits of oil palms as a function of crop age.

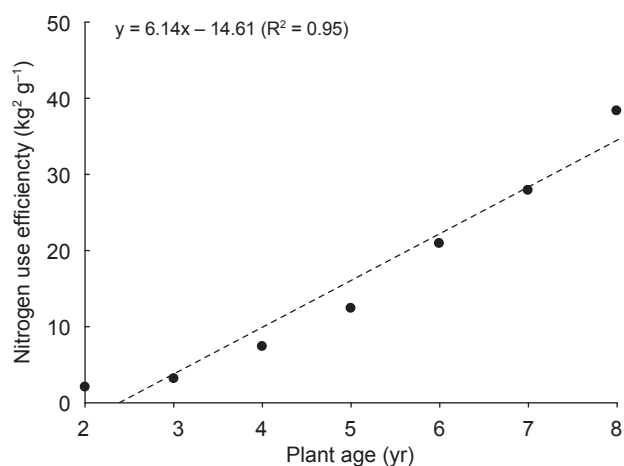


Figure 6. Total nitrogen use efficiency in oil palms as a function of crop age.

## CONCLUSION

The nitrogen concentration in different components increased with the age of the oil palm, with the highest values occurring in the cabbage. In contrast, the total nitrogen accumulation in the different components also increased with the age of the plant, with the stem showing the highest accumulated values. Conversely, the amount of exported nitrogen was lower than the recycled amount, becoming equal from the sixth year onwards, while the immobilised amount surpassed the exported amount in the eighth year. Nitrogen use efficiency was found to be influenced by the age of cultivation in different organs of the oil palm, showing a decreasing trend in the order of petiole > stem > rachis > spikelet > fruits > leaflet > peduncle > MI > spear leaves > cabbage.

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