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Phosphorus in Oil Palm Cultivated in the Oriental Amazon

Ismael de Jesus Matos Viegas

Universidade Federal Rural da Amazônia, *Campus* Capanema, Pará, Brasil.
E-mail: matosviegas@hotmail.com

Magda do Nascimento Farias (Corresponding Author)

Universidade Federal Rural da Amazônia, *Campus* Capitão Poço, Pará, Brasil.
E-mail: magda.fariasagro@gmail.com

Eric Victor de Oliveira Ferreira

Universidade Federal Rural da Amazônia, *Campus* Capitão Poço, Pará, Brasil.
E-mail: ericsolos@yahoo.com.br

Henrique da Silva Barata

Universidade Federal Rural da Amazônia, *Campus* Belém, Pará, Brasil.
E-mail: henriquebarata2000@gmail.com

Heráclito Eugênio Oliveira da Conceição

Universidade Federal Rural da Amazônia, *Campus* Capitão Poço, Pará, Brasil.
E-mail: agroheraclito@yahoo.com.br

Jessivaldo Rodrigues Galvão

Universidade Federal Rural da Amazônia, *Campus* Belém, Pará, Brasil.
E-mail: jessigalvao50@gmail.com

Diocléa Almeida Seabra Silva

Universidade Federal Rural da Amazônia, *Campus* Capanema, Pará, Brasil.
E-mail: dioclea.seabra@ufra.edu.br

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Abstract

Amazon soils have a low phosphorus (P) availability and few studies have investigated nutrition of palm oil plantations. This study assessed the effects of P nutrition on oil palm organs according to plant age. The experiment was carried out under field conditions, at the enterprise Agropalma S/A, in the municipality of Tailândia, Pará State, Brazil. The experimental design used was completely randomized with four replications and comprised seven treatments: plants age (2, 3, 4, 5, 6, 7, and 8 years of planting). We evaluated P concentration, accumulation, and exportation in plant components (leaflets, petioles, stipe, rachis, palm heart, arrows, male inflorescences, peduncles, spikelets, and fruits). Palm heart (10.9 g kg^{-1}) and male inflorescence (3.8 g kg^{-1}) showed the highest P concentrations in the vegetative and reproductive organs, respectively. On the other hand, the largest P accumulations were observed in the stipe (159 g plant^{-1}) and fruits (59 g plant^{-1}), increasing from the 3rd year of age of the plants. Bunches exported the largest P amounts (81 g plant^{-1}), especially in older plants. The oil palm immobilizes (24 kg ha^{-1}) and recycles (23 kg ha^{-1}) a large amount of P, more than it exports (12 kg ha^{-1}) P.

Keywords: *Elaeis guineenses***,** oilseed**,** concentration**,** accumulation**,** nutritional diagnosis

1. Introduction

Oil palm (*Elaeis guineenses* Jacq.) is indigenous to Africa and an important source of vegetable oil widely used in the cosmetic and biodiesel industries (LEBID; HENKES, 2015). In economic terms, oil palm has a useful life of 25 years. Oil palm crops reach the maximum productive potential eight years after planting with an output of 25 t ha^{-1} year^{-1}, resulting in 4 to 6 t ha^{-1} year^{-1} of oil production (NABUN et al., 2017; CRUZ FILHO et al., 2019).

The Amazon region has the largest oil palm cultivated areas in Brazil, covering 38,912 ha, constituting the main matrix for palm oil production in the country (NAHUN et al., 2020). Despite favorable climatic conditions in this region (LOPES and GUILHERME, 2007), several factors still limit the crop full development, such as adequate nutrition, which lead to low average of oil palm yield (17 t ha^{-1}) (HOMMA and REBELLO, 2020).

In the Pará State (Brazil), Oxisols and Argisols predominate (GAMA et al., 2020) and these soils have high acidity, high aluminum (Al) saturation, and low fertility, requiring appropriate correction and fertilization to make crop production viable (FERNANDES et al., 2013). Phosphorus (P) is an essential nutrient for plant growth and functioning, ranked as the second most limiting nutrient to agricultural production (MOHIDIN et al., 2015). In tropical soils, P has low availability and is considered the most limiting factor for plant growth (TAN et al., 2010), as observed for oil palm crops in the Brazilian Amazon (RODRIGUES, 1993).

P is essential in practically all metabolic processes, namely photosynthesis, energy transfer, macromolecular biosynthesis, signal transduction, and respiration (KHAN et al., 2010; BUCHER et al., 2018). Thus, P absorption by oil palm is crucial for crop yield and dry matter (DM) accumulation in the plant (SHEN et al. 2011; NING et al., 2013). Oil palm has great and varied nutritional demands, depending on yield, genotype, spacing, palm age, soil type, soil conditions, and climate (WOITTIEZ et al., 2017). For a production of 17 t/ ha of bunches of fresh fruits, oil palm exports 25.5 kg of P_2O_5 (VIEGAS and BOTELHO, 2000). However, few studies have investigated P influence on oil palm nutrition, which is important for crop yield. This study assessed the effects of P nutrition on organs of oil palm trees according to the planting age.

2. Material and Methods

2.1 Study Site

The experiment was carried out under field conditions, at the enterprise Agropalma S/A, in the Northeast of Pará State, in the municipality of Tailândia (2° 56' 50" S and 48° 57' 12" W), Brazil. The climate in this region is Ami type (rainy tropical) (Köppen classification), with an average annual temperature 26.5 °C, annual precipitation 2,400 mm, and air relative humidity 84%. A gauge installed at Agropalma was used to monitor rainfall during the experimental period, which averaged 2,409 mm year^{-1} (Figure 1).

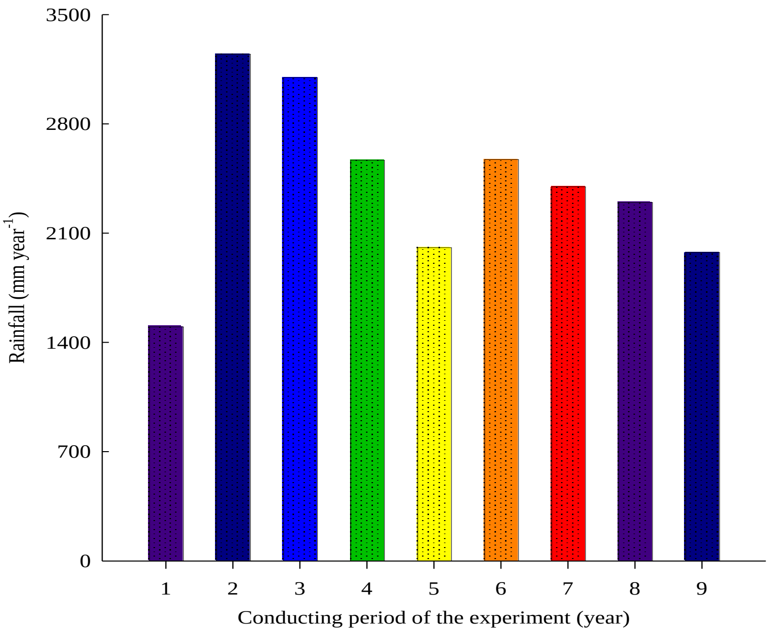

Figure 1. Rainfall in the area of enterprise Agropalma during the experimental period

The soil in the experimental site is classified as a dystrophic Yellow Oxisol, acidic, with low natural chemical fertility and medium texture (RODRIGUES et al., 2005; SANTOS et al., 2018). Soil samples (0-0.3 m) were taken during the plant collection period, composed of four simple samples each, collected between the planting lines for each age of the plants. Then, the samples were sent to the laboratory of the Soil Science Department of Luiz de Queiroz College of Agriculture for chemical characterization (Table 1). The physical analyses (Table 1) were carried out at the Agroforestry Research Center of the Eastern Amazon Embrapa.

Table 1. Chemical and physical characteristics of soil samples (0-30 cm) from plantations with different ages of oil palm plants

Features	Plants age (years)						
	2	3	4	5	6	7	8
pH ($CaCl_2$)	4.3	4.4	4.1	4.0	4.0	4.3	4.0
K* ($cmol_c\ dm^{-3}$)	0.07	0.06	0.05	0.07	0.05	0.05	0.06
Ca* ($cmol_c\ dm^{-3}$)	0.7	0.7	0.9	0.8	0.7	0.7	0.6
Mg* ($cmol_c\ dm^{-3}$)	0.4	0.2	0.2	0.3	0.3	0.3	0.3
Al ($cmol_c\ dm^{-3}$)	0.4	0.3	0.3	0.5	0.8	0.4	0.6
H+Al** ($cmol_c\ dm^{-3}$)	3.4	2.8	3.1	3.8	3.4	2.6	3.4
SB ($cmol_c\ dm^{-3}$)	1.17	0.96	1.15	1.17	1.05	1.05	0.96
P* ($mg\ dm^{-3}$)	4	6	5	6	6	6	8
V (%)	24	24	26	22	22	27	20
O.M*** ($g\ dm^{-3}$)	1.6	2.3	1.5	1.9	2.0	2.1	1.8
Coarse sand (%)	45	32	50	37	38	34	51
Fine sand (%)	28	30	19	31	21	32	23
Silt (%)	4	16	8	10	8	10	6
Clay (%)	23	22	23	22	33	24	20

*Extracted with ion Exchange resin. ** Method SMP. ***Colorimetric method.

The oil palm plants are from the commercial hybrid Tenera (Dura x Psífera), aged 2 to 8 years, grown in the 9 x 9 m spacing, in an equilateral triangle, totaling 143 plants/ ha. Table 2 shows information on plant age, yield, and fertilizers.

Table 2. Plants age, yield, and mineral fertilization of oil palm trees

Plant age	Yield	Mineral fertilization					
		N	P_2O_5	K_2O	Mg	S	H_3BO_3
(Years)	t ha^{-1}	---------------------- g/plant -----------------					
2	__	35	60	60	__	24	__
3	1.5	18	77**	154	__	__	__
4	7.0	56	115	300	60	45	__
5	9.0	97	336	240	60	45	__
6	15.0	135	470	335	77	58	__
7	19.0	135	470	335	102	58	50
8	20.0	160	384	324	68	52	60

** Application of 500 kg/ha of phosphine (rock phosphate).

The following criteria were used to select homogeneous plants: same plot, age, uniformity, development, nourishment, health, and with good yield. After plant identification, stem circumference and plant height were measured from the base of leaf 33, corresponding to the height of the ripe bunch to be harvested.

2.2 Study Experimental Design and Analysis of Variables

The experimental design used was completely randomized with four replications and comprised seven treatments: plant ages (2, 3, 4, 5, 6, 7, and 8 years of planting). Each plant corresponded to an experimental unit. The sampling process consisted of separating leaflets, petioles, rachis, palm heart, arrows, stipe, male inflorescences, peduncles, spikelets, and fruits in each plant. We obtained fresh matter (FM) and representative samples of each plant component.

Samples of the collected plant material were sent to the laboratory, where a sub-sample (SS) was removed, stored in a paper bag and dried in a forced air circulation oven (70 °C) until a constant mass was reached. Subsequently, we quantified the dry mass of sub-samples (DMSS) of the different vegetative organs collected. FM, SS, and DMSS data for each material were placed in the equation (DM = DMSS* FM / SS) to obtain the dry matter (DM) content of each plant part. P was determined after the plant tissue was ground through a Willey mill and by colorimetry using the vanado-immobilized ammonium method (MALAVOLTA et al., 1997).

The effects of the treatments were evaluated in terms of concentration, accumulation, and exportation of P in each plant organ. The accumulated quantities in the different oil palm components for each age were estimated from the P concentration in the plant tissue and dry mass values. The immobilized amounts of P were obtained by adding the accumulated stipe, palm heart, and arrows, while the recycled amounts were obtained from leaflets, rachis, petioles, and inflorescences. After carrying out P evaluations for each organ of the oil palm plant, the data were subjected to the analysis of variance (F test; $p< 0.05$) and adjustments were made to regression models using the Sisvar statistical software (FERREIRA, 2011).

3. Results

Plant age influenced P concentrations in different oil palm organs (Figure 2). In vegetative organs, palm heart showed the highest concentration (10.9 g kg^{-1}) in the eighth year, while rachis had the lowest value (0.2 g kg^{-1} P) in the second, third, and fourth years of life (Figure 2b). An increasing quadratic response was observed in P concentration in vegetative organs, petiole, palm heart, and arrows, at different plant ages (Figures 2a and 2b). On the other hand, P concentration in rachis and leaflets responded to the negative quadratic model for plant age (Figures 2a and 2b), while plant age did not influence P concentration in stipe (Figure 2a).

For reproductive plant organs, male inflorescence obtained the highest P concentration (3.8 g kg^{-1}) in the sixth year, while spikelets had the lowest concentration (0.4 g kg^{-1}) in the fourth year of age (Figures 2c and 2d). The P concentration showed a quadratic response increase in male inflorescence and fruits according to plant age. In peduncle and spikelets, P concentration reached its maximum value in the sixth and seventh years, respectively (Figures 2c and 2d).

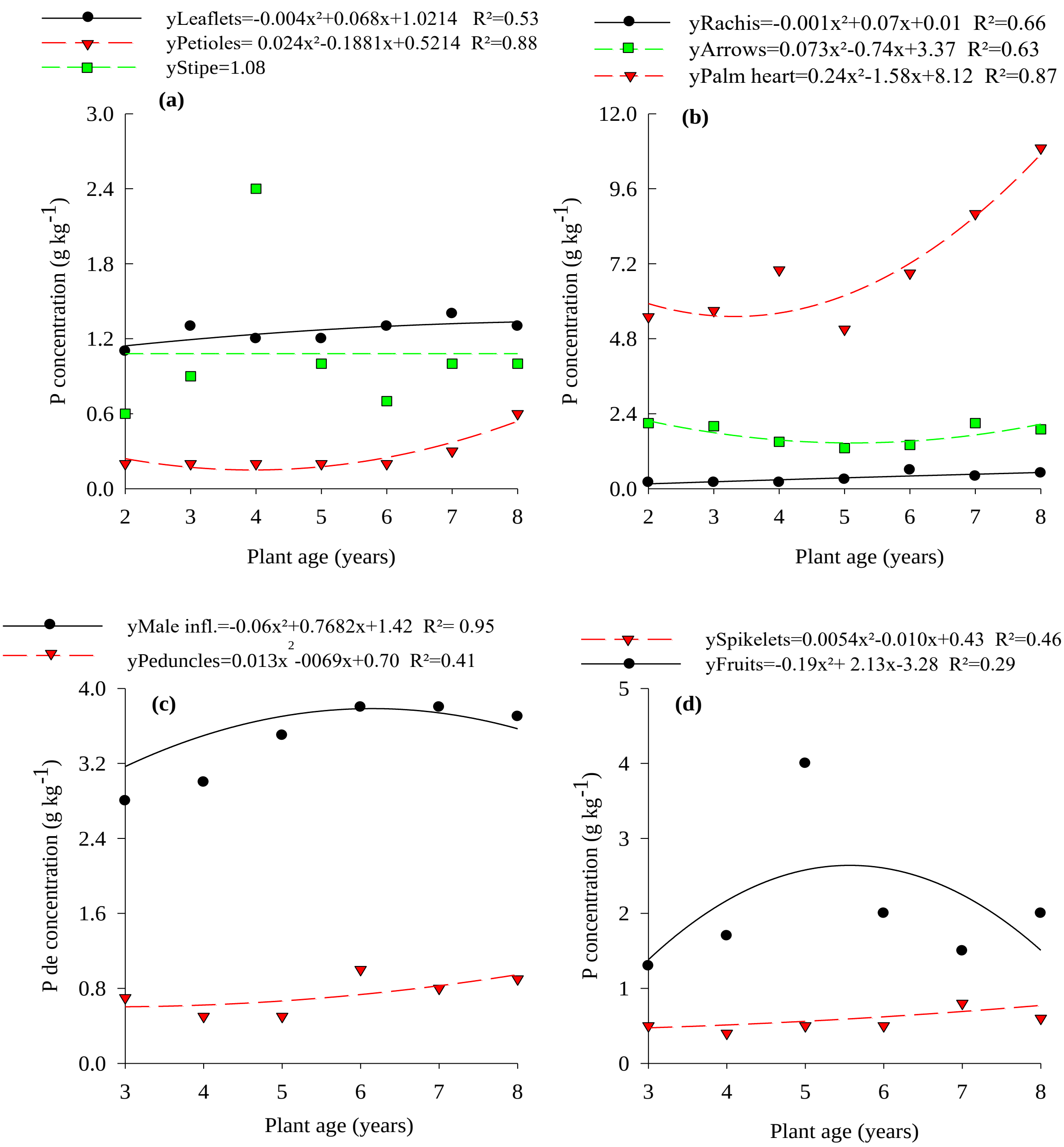

Figure 2. P concentration in leaflets, petioles, and stipe (a), in rachis, palm heart, and arrow (b), in male inflorescence and peduncle (c), and in spikelets and fruits (d), according to oil palm

All ages showed a variation in P concentrations in different organs of oil palm plants, mainly palm heart (114%), with 5.1-10.9 g kg^{-1} of P (Table 3). On the other hand, leaflets showed less variation (27%) in P concentrations (1.1-1.4 g kg^{-1}).

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Table 3. Variation in P concentrations in different plant organs (leaflets, petioles, rachis, palm heart, arrows, stipes, male inflorescences, peduncles, spikelets, and fruits) of oil palm trees

Plants organs	P concentration (g kg^{-1})	Variation (%)
Leaflets	1.1-1.4	27
Petioles	0.2-0.6	67
Rachis	0.2-0.6	67
Palm heart	5.1-10.9	114
Arrows	1.3-2.1	62
Stipe	0.6-2.4	75
Male Inflorescences	2.8-3.8	36
Peduncles	5.0-1.0	80
Spikelets	0.4-0.8	50
Fruits	1.3-2.0	54

P accumulation in the crown (leaflets, petioles, rachis and arrows), stipe, bunches and male inflorescence shows a higher value in stipe (159 g $plant^{-1}$ of P), corresponding to 39% of the total plant in the eighth year. The lowest accumulation (0.89 g $plant^{-1}$) occurred in bunches in the third year, representing 3.2% of total plant (Figures 3a and 3b). P accumulation in all organs increased with plant age. Stipe and bunches displayed a quadratic behavior, while crown and male inflorescence had a linear response to plant ages. Thus, P accumulation occurred in the order: stipe> crown> bunches> male inflorescence (Figures 3a and 3b).

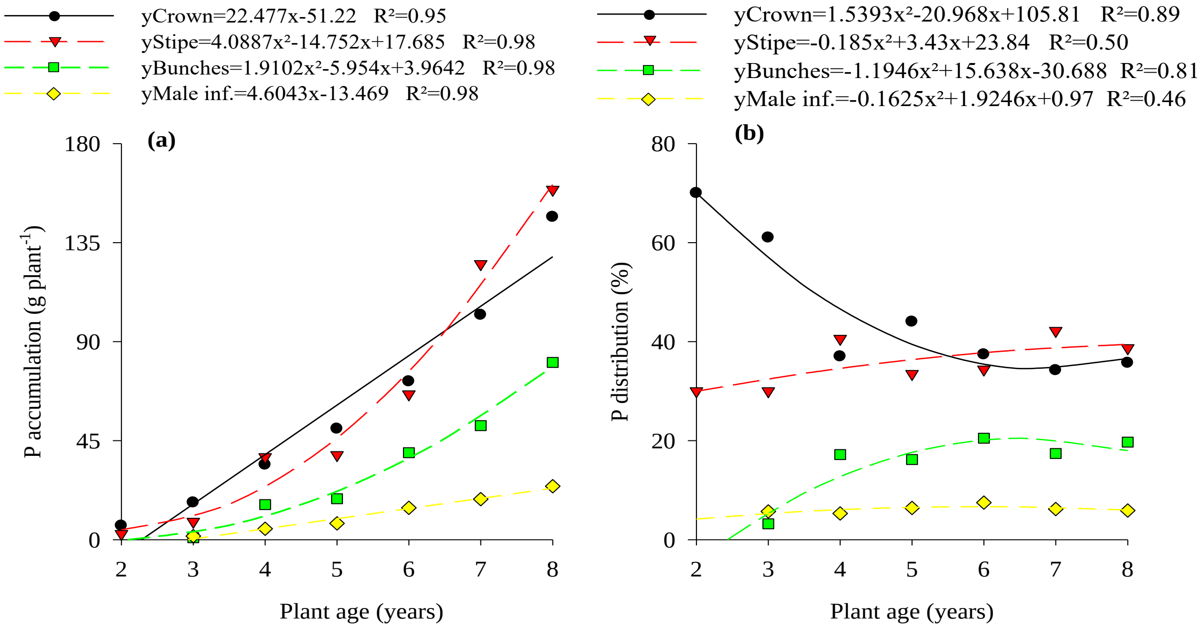

Figure 3. Accumulation (a) and percentage distribution (b) of P in crown, stipe, bunches, and male inflorescences, according to oil palm age

In the eighth year, P had an accumulation of 147 g plant^{-1} in crown, equivalent to 21 kg ha^{-1} of P (143 plants ha^{-1}). P accumulation in vegetative organs showed a maximum value in stipe (159 g plant^{-1}) and a minimum value in palm heart (0.46 g plant^{-1}) in the eighth and second years, respectively. Quadratic equations explained P accumulations in all organs, increasing over plant ages (Figures 4a and 4b).

For reproductive organs, fruits showed the highest P accumulation (59 g plant^{-1}), while peduncle had the smallest accumulation (1.3 g plant^{-1}) in the eighth and third years, respectively. The effects of this relationship were explained by the increases of quadratic equations according to plant ages (Figures 4c and 4d). The following increasing order of P accumulation was observed in oil palm plants: stipe> leaflets> fruits> petioles> male inflorescences> rachis> spikelets> arrows> palm heart = peduncles (Figure 4).

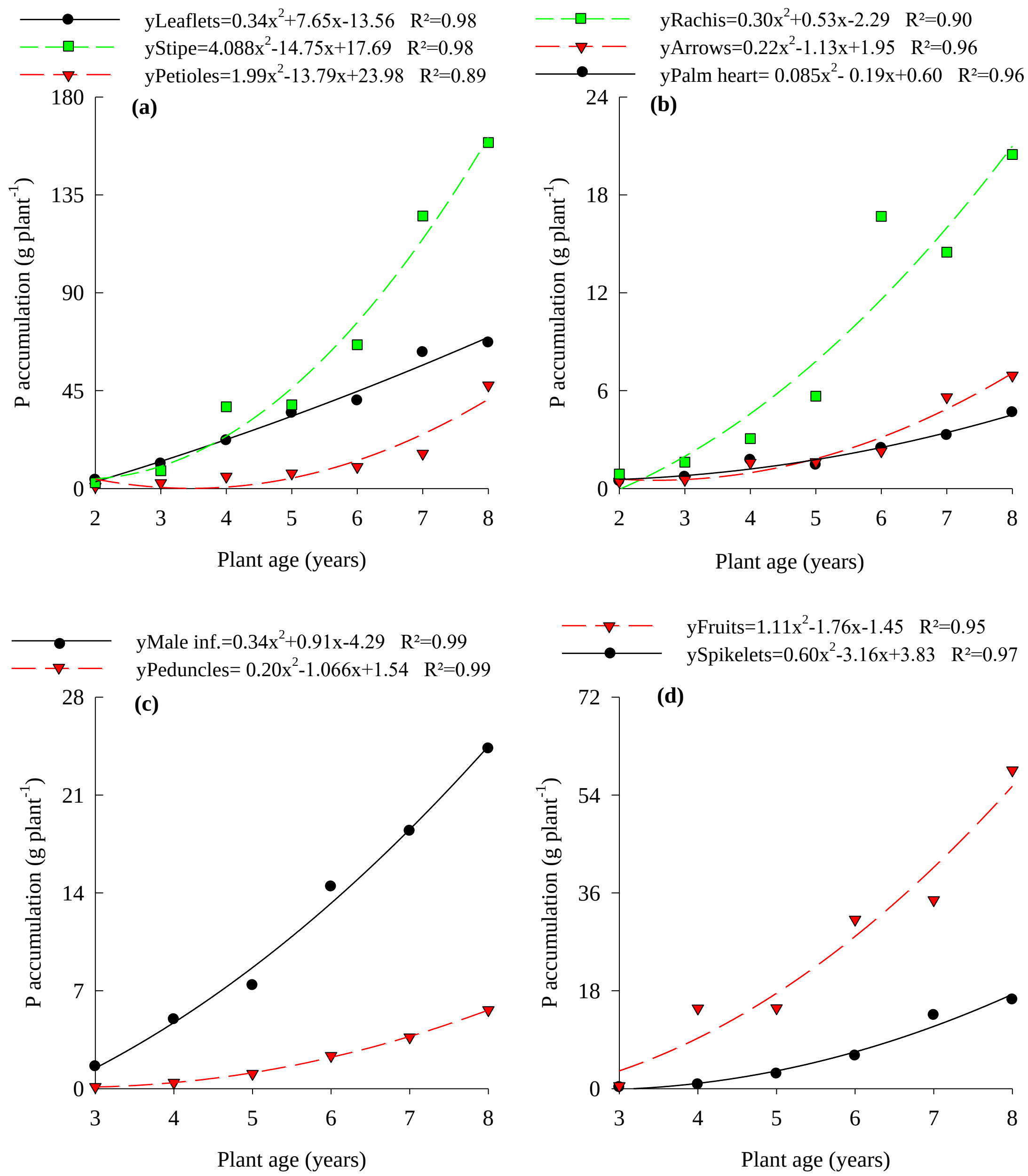

Figure 4. P accumulation in leaflets, petioles, and stipe (a), in rachis, palm heart, and arrows (b), in male inflorescences and peduncles (c), and in spikelets and fruits (d), according to oil palm ages

The highest total P accumulation was observed in the eighth year, reaching 411 g plant^{-1}, equivalent to 59 kg ha^{-1}, with an increasing quadratic response with plant ages (Figures 5a and 5b).

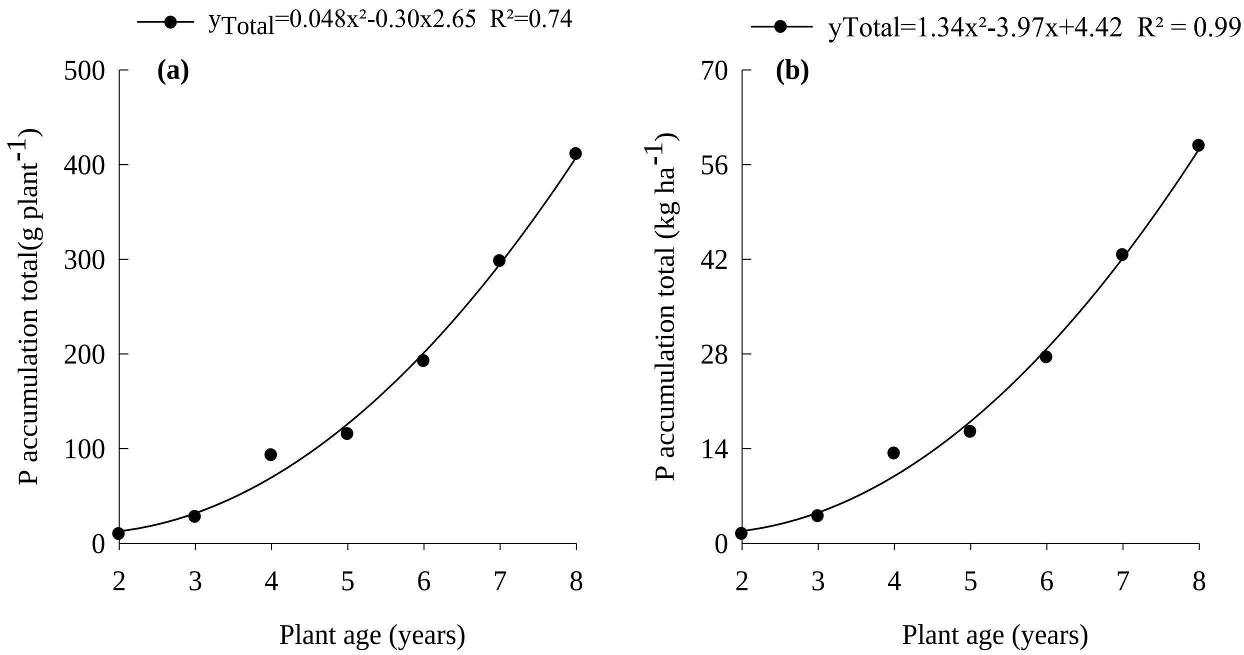

Figure 5. Total P accumulation per plant (a) and total P accumulation per area (b) in oil palm, according to plant age

The percentage increase in total P extraction in terms of oil palm age increased according to plant growth (Figure 6). The third year showed the lowest percentage increase (296%) in total P accumulation, while the eighth year had the maximum accumulation (4414%).

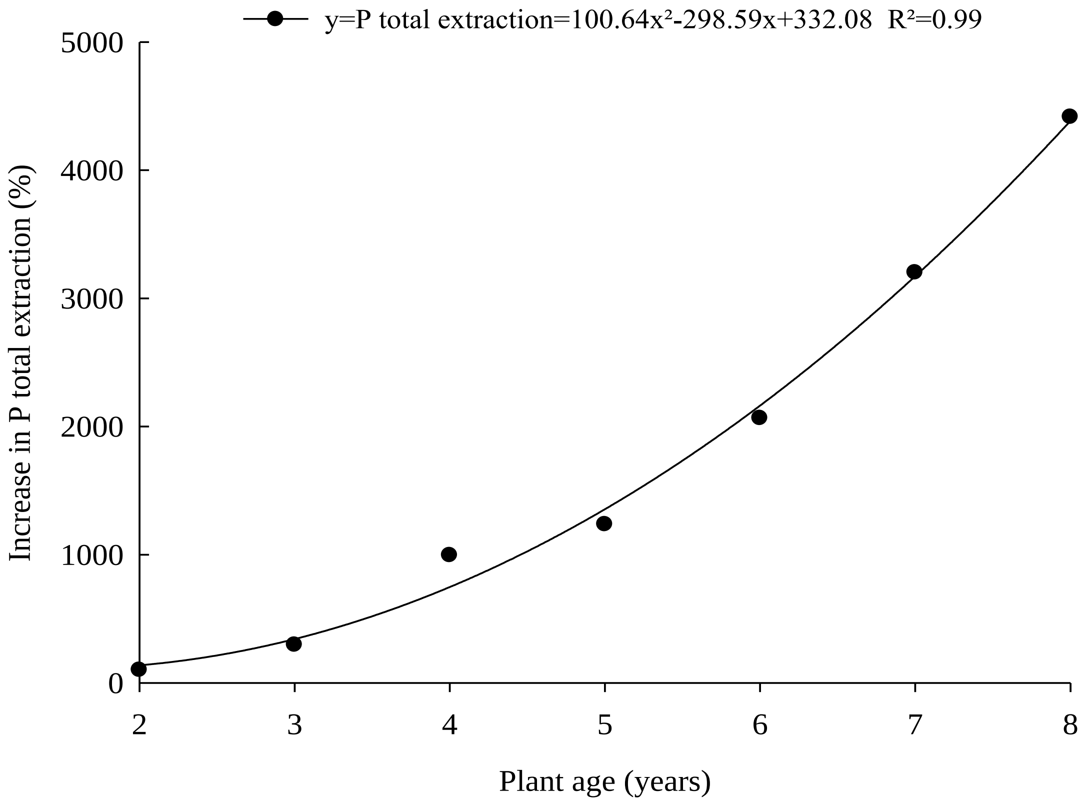

Figure 6. Percentage increase in total P extraction due to oil palm age

The highest P exports were observed for bunches (81 g plant^{-1}) in the eighth year and the lowest for fruits (0.5 g plant^{-1}) in the third year, corresponding, respectively, to 11.52 kg ha^{-1} and 0.07 kg ha^{-1} (Figures 7a and 7b). The P export showed a quadratic increase to plant age (Figure 7). The percentage variation in P export by peduncle occurred from 2.7 to 14.8%, from 4.8 to 28.5% in spikelets, and from 56.8 to 92.5% in fruits (Figure 7c).

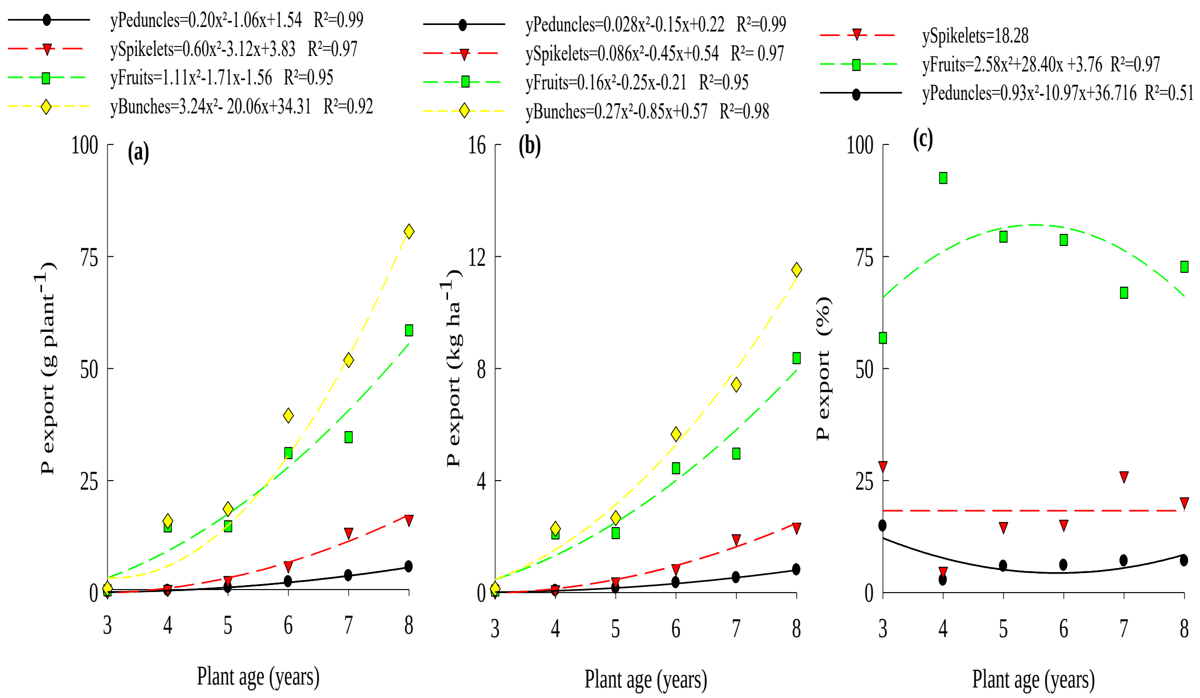

Figure 7. Export (a, b) and percentage distribution (c) of P in peduncles, spikelets, fruits, and bunches according to oil palm age

P amounts increased with plant growth and reached the maximum value of the amount extracted (59 kg ha^{-1}), immobilized (24 kg ha^{-1}), recycled (23 kg ha^{-1}), and exported (12 kg ha^{-1}) in the eighth year of age (Figure 8).

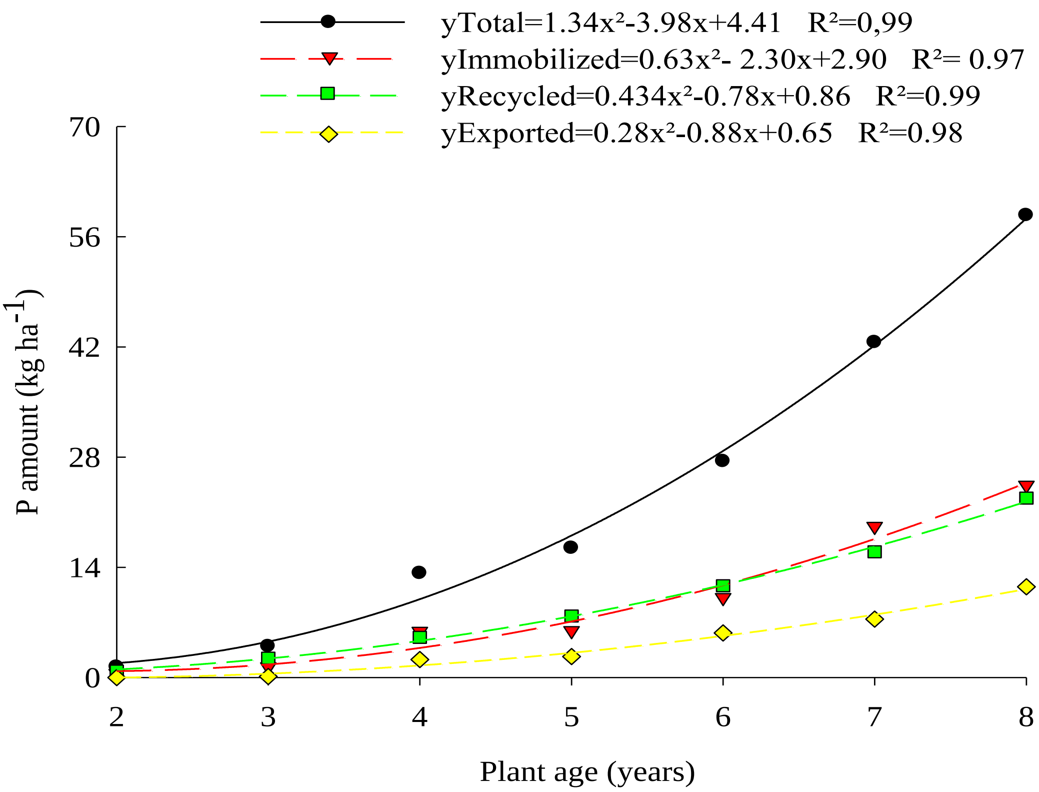

Figure 8. Amounts of P immobilized, recycled, exported, and total, according to oil palm age

4. Discussion

In general, older plants showed higher P concentrations in the organs (Figure 2), probably due to a more extensive root system, which provides a greater contact area with the soil. Thus, absorption of P applied as fertilizer (Table 2), a little mobile ion in the soil (NOVAIS et al., 2007), is entirely related to root length (BUCHER et al., 2018). In addition, higher P levels were applied to older plants (Table 2), which resulted in higher P concentrations in the soil (Table 1) and, consequently, greater absorption by older plants (Figures 2a and 2b). Matsumoto et al. (2008) analyzed oil palm in terms of age and observed higher P concentrations in leaflets (4.34 g kg^{-1}) and petioles (4.92 kg g^{-1}) in the third year. Bachy (1965) also found an increase in the P concentration in leaflets (leaf 17) according to oil palm age, corroborating our results. Haron et al. (2000) found that young oil palm plants absorbed between 10 and 20% of total P.

Levels of P in leaf 17 of the oil palm are considered appropriate of 1.5 g kg^{-1} (OCHS and OLIVIN, 1977), from 1.5 to 1.9 g kg^{-1} (UEXKULL and FAIRHURST, 1991), from 1.6 to 2.0 g kg^{-1} (MATOS et al., 2016), and from 1.5 to 1.8 g kg^{-1} (VELOSO et al., 2020). Lower P concentrations are observed in leaflets of oil palm trees of different ages (Figure 2a), which indicates P deficiency in the plants evaluated. The acidic soil pH (Table 1), due to lack of liming and high rainfall levels in the region (Figure 2), influences P absorption (MEURER, 2007). The P transport in the soil towards the roots occurs predominantly by diffusion; therefore, P supply in sandy soils is reduced (Table 2) due to lower water retention capacity (MEURER, 2007).

Possibly, the lowest P concentrations in reproductive organs of older plants (8 years of age) occurred due to the increase in the yield of bunches, varying from 1.5 to 20.0 t ha^{-1} (Table 2). The highest P concentration in the reproductive organs occurred in male inflorescence (Figure 2c). Ng et al. (1969) reported a high P concentration (3.2 g kg^{-1}) in male inflorescences, corroborating our results. Plant age and P availability in the soil influence P concentrations in plants (BATES, 1971; MARSCHNER, 2012). According to Mengel and Kirkby (1982), P mobility occurs in the phloem, translocated to younger tissues by root absorption or by its redistribution from older organs to growing regions.

Variation of P concentrations was higher in palm heart (Table 3). Viegas et al. (2020) evaluated Cl in oil palm and observed greater variation in P concentrations in palm heart of plants. According to the authors, these variations alter plant metabolism and, consequently, the absorption rates of nutrients. Due to the beginning of the vegetative development, production is still relatively low (6 to 8 t ha^{-1} $year^{-1}$ of bunches) and increases gradually when the plants reach 8 years of age, reaching a maximum yield of 20 to 30 t ha^{-1} $year^{-1}$ of bunches.

The increase in P accumulation in plants from 2 to 8 years of age (Figure 3) was probably influenced by DM production from different organs, as reported by Viegas et al. (2001). Approximately 45 to 50% of DM production is allocated to the growth of male inflorescences and bunches in productive oil palm plants (CORLEY et al., 1971). Vegetative and reproductive growth are limited at source and competition occurs between different collectors, despite the priority to vegetative growth (CORLEY and TINKER, 2016).

The crown, the second largest component in P accumulation (Figure 3), influences nutrient cycling, as deposition of its organs on the soil between crop rows provides a nutrient return (VIEGAS et al., 2001). The decomposition of oil palm leaves allows distribution of P (63%), N (43%), K (76%), and Mg (60%) during 24 months of planting (KEE and CHEW, 1997). The cycled P quantity (21 kg ha^{-1}) (Figure 3) is close to half of the recommended P amount (47 kg ha^{-1}) for oil palm cultivation at 8 years of age in Pará State (FRANZINI et al., 2020), considering the yield observed at this age (Table 2). P was added via fertilization of 384 g $plant^{-1}$ of P_2O_5, in the form of phosphine, to the eight-year-old oil palm (Table 2), which also contributed to P accumulation in the plants. Tajudin et al. (2020) state that the addition of fertilizers twice a year favors P accumulation in oil palm, especially in the young phase, which requires more P. According to Chan and Goh (1978), stores substantial amounts of nutrients in plants; nevertheless, rachis is not commonly used as a reference for P accumulation in palm oil. In addition, the legume *Pueraria phaseoloides* is commonly cultivated between oil palm rows in the region and this cover plant can cycle 18 kg ha^{-1} of P at 2 years of age (PEREZ, 1997).

Fruits accumulated greater P amounts among the reproductive organs (Figure 4). This shows the importance of P in fruit formation with a direct influence on crop yield (Table 2), with harvesting and fertilization assuming relevance in P replacement in the soil (Table 1). According to the source-drain relationship, leaves act as a carbohydrate source for other plant compartments that preferentially accumulate P, such as roots and fruits (NOVAIS et al., 2007). For Fairhurst and Härdter (2003), nutritional differences in plant age groups can be explained because nutrients are mostly allocated for DM production of leaves in young palms, while a redistribution of nutrients occurs for bunches in adult palms.

There was greater total P accumulation (59 kg ha^{-1}) in the eighth year (Figure 5). Due to P concentration in the soil (Table 1), 55 kg ha^{-1} of P_2O_5 were applied via phosphine in the eighth year (Table 2), which is the P amount close to the total extracted by plants at this age (Figure 5b); however, below recommended for the conditions in Pará State (FRANZINI et al., 2020). P is the macronutrient least extracted by oil palm (VIEGAS and BOTELHO, 2000) and in the weathered tropical soils, there is a drain of P (NOVAIS et al., 2007). According to Ker (1995), applications of large amounts of P fertilizers are required to provide P sources to weathered soils, which can adsorb the equivalent of 9.200 kg ha^{-1} of P_2O_5 on the surface layer (0-20 cm) (KER, 1995). The clay fraction defines the soil as a source or as drain of P, that is, in a highly weathered soil there is a predominance of P drain (NOVAIS et al., 2007). However, the soil in our study has medium texture (Table 1).

There was a higher percentage in total P extraction with increased plant age (Figure 6). In addition, oil palm showed a significant increase in P absorption from the second year after planting (NG, 1977). This shows that good nutrition at a young age is essential to provide an early start of crop growth and reach desired yields (RODRIGUES, 1993). Thus, adequate nutrition is crucial to prevent P from becoming a limiting factor for crop production, especially in Amazonian soils, which are weathered with high adsorption to Fe and Al oxides causing low P availability (NOVAIS et al., 2007), a limiting factor for plant growth (FITA et al., 2011). However, application of rock phosphate could gradually make P more available in the soil and reduce intensity of P losses due to unavailability reactions (RESENDE et al., 2006). Rock phosphate was the P source used in this study.

In the eighth year, bunches exported greater P amounts (Figure 7). Werkhoven (1965) states that oil palm bunches accumulate and export approximately half of the total P. Tampubolon et al. (1990) studied oil palm cultivated in an Oxisol in Indonesia and observed that P fixation requires application of levels initially higher than the plant needs, since the crop exports only 20 kg ha^{-1} $year^{-1}$. The amount of P immobilized was high, 1.7 to 10 times greater than P exported (Figure 8). Tinker and Smilde (1963) conducted a study in Nigeria and reported that the amounts of P immobilized in oil palm were higher for stipe, leaves, bunches, and roots. P, Ca and Mg are extracted in smaller amounts than N and K by oil palm plants (WERKHOVEN, 1965). Although the oil palm crop extracted and exported smaller P amounts (NG et al., 1968; VIEGAS and BOTELHO, 2000), P is the nutrient that mostly limits growth and yield of oil palm in the Brazilian Amazon (PACHECO et al., 1985; RODRIGUES, 1993).

5. Conclusion

The highest P concentration is found in the palm heart organ in the apical meristem, which commands plant growth and is responsible for the formation of leaves and inflorescences, as well as in the male inflorescence reproductive organ.

The P accumulation increases with the age of plants, with greater accumulation in fruits and stipe components, which can function as P stock.

Oil palm exports greater amount of P through bunches and P exports increase with plant age.

The amount of immobilized and recycled P is greater than that exported by oil palm, which is desirable, as it reduces P removal through bunches.

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