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Elucidating the mechanisms of phosphorus accumulation and use efficiency in açaí palm plants at different cultivation ages

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The cultivation of the açaí palm (*Euterpe oleracea* Mart.) has experienced remarkable growth in the Amazon region. However, knowledge regarding the dynamics of phosphorus (P) in the vegetative and reproductive components of açaí plants across different growth stages remains limited. This study aimed to evaluate the dynamics of P accumulation, efficiency, and the rates of immobilization, recycling, and export in açaí palms cultivated on upland soils at varying plant ages in the Amazon. The experiment was conducted in Tomé-Açu, Pará, Brazil, using a completely randomized strip-plot design with four replicates and six treatments corresponding to planting ages (2–7 years). Data were analyzed using analysis of variance (F test, $p < 0.05$), followed by regression modeling where significant. The results revealed that P accumulation and efficiency varied across plant organs, with the highest demand observed during the productive phase, when total P requirements reached 106.5 g plant^{-1}. Maximum rates of P export, recycling, and immobilization were recorded at seven years of age, with immobilization accounting for up to 69.4 kg ha^{-1} of P. The stipe demonstrated the highest P use efficiency among the plant organs. Based on the findings, a recommended application of 200 kg ha^{-1} of P_2O_5 is suggested for fruit yields exceeding 25 t ha^{-1}. From a nutritional perspective, the daily P requirement for an adult (700–750 mg) can be met with the consumption of approximately 500 g of açaí pulp. These results contribute to the rational use of phosphate fertilizers, enabling improved yield of açaí palms in the unique soil and climatic conditions of the Amazon region.

Keywords *Euterpe oleracea* Mart., Nutritional diagnosis, Mineral nutrition, Phosphate nutrition, Palm tree

The açaí palm (*Euterpe oleracea* Mart.) is a native species of the Amazon with significant socio-economic importance for Brazil's northern region[1–3]. Its fruit, widely known as açaí, is valued across various industries, including food and cosmetics, due to its antioxidant properties and richness in vitamins[4]. The northern region accounts for approximately 95% of Brazil's açaí production, yielding 1,688,704 tons over 234,238 hectares, predominantly from floodplain plantations[5,6]. However, rising demand for açaí has led to the expansion of cultivation into upland areas, often characterized by soils with low natural fertility, such as Oxisols, which

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are particularly deficient in phosphorus (P)[7]. Consequently, improving the understanding of nutritional management, especially for P—a critical nutrient for Amazonian crops—has become increasingly necessary[8].

Recent advancements include the development of açaí cultivars adapted to upland conditions, enabling year-round production[9]. In this context, understanding P dynamics is fundamental for optimizing fertilization strategies. It is crucial to explore how P accumulates in vegetative and reproductive components of açaí plants over time, alongside its recycling, immobilization, and export rates. While previous studies have largely focused on fertilization management[10] and the identification of standard leaves for nutritional diagnosis[11], research on P dynamics has been limited to the seedling or early developmental stages in greenhouses and field settings[12,13]. This gap underscores the need for investigations that encompass the productive phase of the crop, as recommended by Viégas et al.[14], who emphasize the importance of precise nutritional monitoring to enhance crop yield.

As demonstrated in recent studies on magnesium dynamics in açaí[3], assessing the behavior of P throughout the plant's lifecycle is essential for developing effective fertilization strategies. This is especially relevant in regions dominated by low-fertility Oxisols, where high rates of phosphate fertilizers are required due to the predominance of iron and aluminum oxides, which enhance P uptake and reduce its availability to plants[15,16]. Consequently, understanding P dynamics not only ensures more efficient fertilizer use, but also promotes sustainable agricultural practices.

Phosphate fertilization has been shown to enhance the growth and yield of various palm species in the Amazon, including oil palm[17,18], coconut[19], and açaí[20,21]. Recommendations for P application in açaí cultivation are often based on soil availability and plant age[22], highlighting the importance of P in plant physiology. Phosphorus plays a pivotal role in membrane structure, coenzymes, nucleic acids, ATP synthesis, and root development[23,24]. For human nutrition, P is essential for energy production, protein synthesis, genetic material, and bone health, with a daily requirement of 700–750 mg for adults aged 19–50[25,26]. For many Amazonian communities, açaí serves as a critical dietary source of P, further emphasizing the importance of understanding P dynamics in açaí cultivation.

Despite its relevance, the dynamics of P immobilization, recycling, and export in tropical palms, including açaí, remain poorly understood. Addressing this knowledge gap is critical for improving P management in açaí cultivation under Amazonian conditions. This study hypothesizes that (i) the rate of P accumulation in different plant components increases throughout the açaí plant's lifecycle and (ii) this influences the efficiency of P use as well as the rates of immobilization, recycling, and export. By investigating these dynamics, this research provides valuable insights for advancing nutritional management and fertilization recommendations for açaí cultivation in the Amazon region. Therefore, the objective of this study was to evaluate the dynamics of P accumulation, efficiency, and the rates of immobilization, recycling, and export across vegetative and reproductive components of açaí palms at different growth stages.

Results

Total dry mass production

The total dry mass of *Euterpe oleracea* Mart. (açaí tree) exhibited a linear increase with plant age, with the value at 7 years (49.0 kg plant^{-1}) being nearly 50 times greater than at 2 years of age (1.59 kg plant^{-1}). This increase reflects the growth and development of both vegetative and reproductive components (Fig. 1).

Phosphorus concentrations

No significant differences ($p > 0.05$) were observed in P concentrations in the stipe, arrow, and leaflets across the different plant ages (Fig. 2a–c). Among these organs, the arrow exhibited the highest average P concentration.

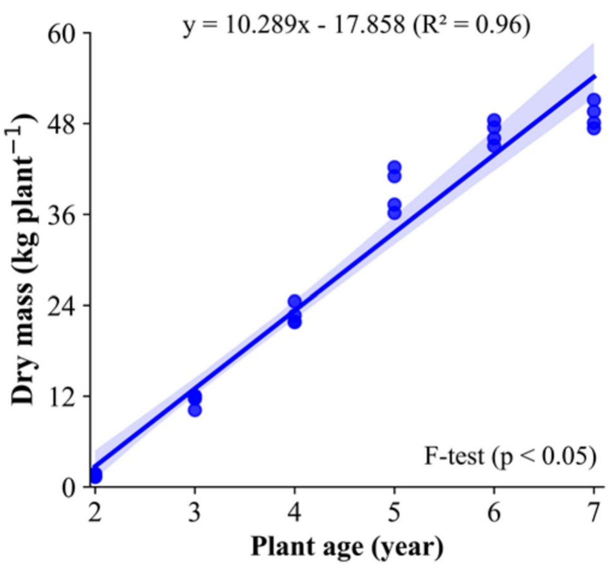

Fig. 1. Total dry mass of açaí trees at different ages (2–7 years).

In contrast, a linear increase in P concentration was observed in the petiole + rachis, meristem, empty bunches, and fruit with age, (Fig. 2d–g).

There was a greater percentage increase in P concentration in the petiole + rachis, with an increase of 88% at 7 years compared to 2 years of age (Fig. 2d). On the other hand, the highest P concentration recorded in the meristem at 7 years (2.15 g kg^{-1}), which is directly linked to the apical growth of the açaí palm (Fig. 2e). This is probably linked to the role of P in the formation of new cells and tissues. Furthermore, in the fruit, the percentage increase was less expressive, with 14% at 7 years compared to 4 years of age. This may indicate a lower demand for P in this organ compared to the others (Fig. 2g).

Variation in P concentration was minimal in the leaflets (9.62%, range 1.52–1.84 g kg^{-1}) and arrow (9.75%, range 2.09–2.54 g kg^{-1}), but greater in the stipe (40.89%, range 0.68–1.63 g kg^{-1}), showing nutrient fluctuations in vegetative parts over time (Table 1). It was observed that the highest average P concentration was in the arrow, which consists of the youngest leaf in formation, and followed by the leaflets. Thus, there is a greater direction of P in the essential components for the vegetative development and biomass production of the species (Table 1).

Phosphorus accumulation

Phosphorus accumulation in the canopy (arrows, leaflets, petiole + rachis, and meristem) and the stipe increased linearly, with notable values in the stipe beginning from the fourth year (> 10 g $plant^{-1}$) (Figs. 3a,b). A greater percentage increase in P accumulation was observed in the stipe at 7 years of age compared to 2 years of age (Fig. 3b). In the empty bunches and fruit, P accumulation followed a quadratic trend, peaking at 6.39 years (6.38 g $plant^{-1}$) (Fig. 3c).

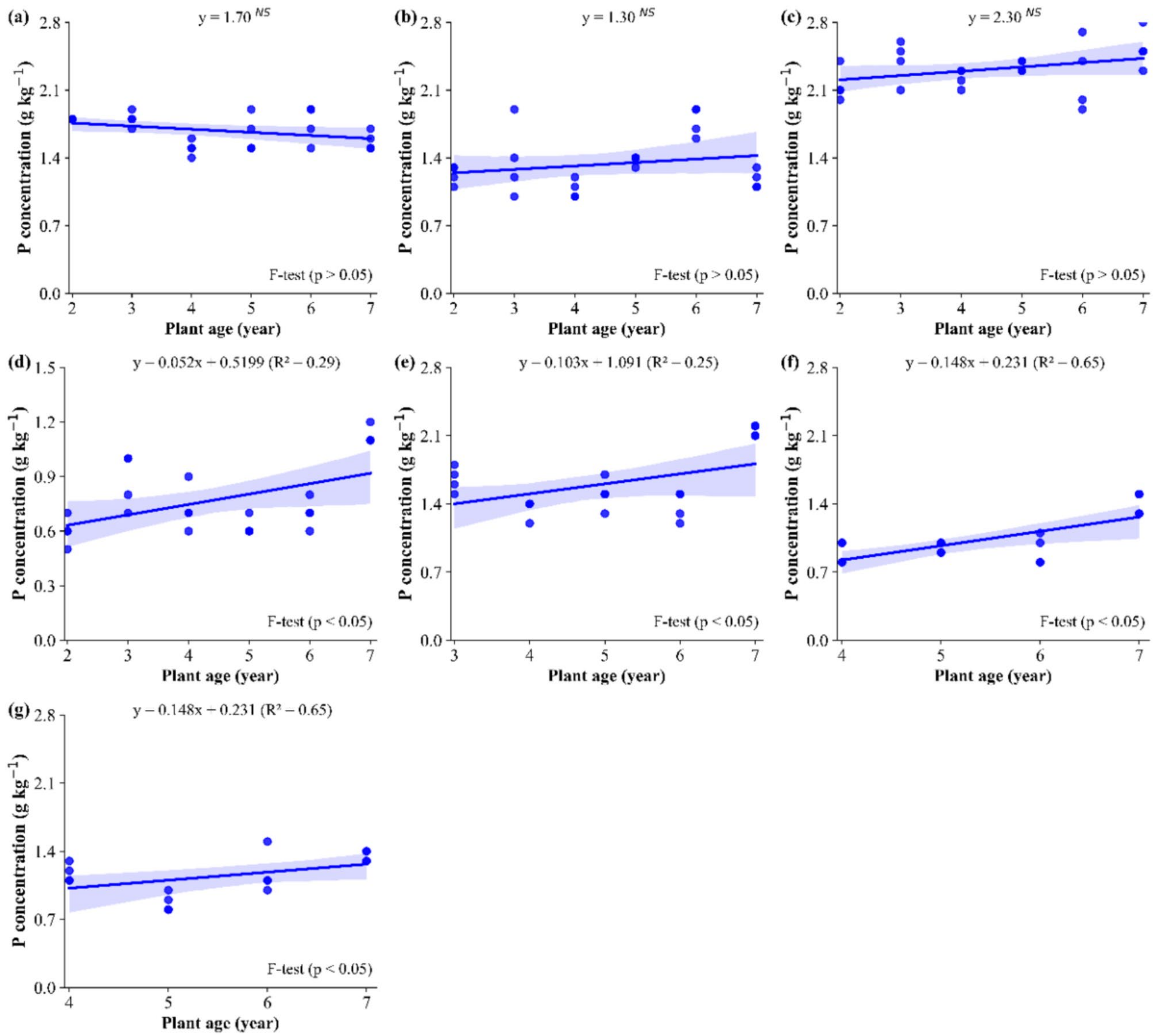

Fig. 2. P concentrations in the leaflets (**a**), stipe (**b**), arrow (**c**), petiole + rachis (**d**), meristem (**e**), empty bunches (**f**) and fruit (**g**) of açai trees at different ages (2–7 years).

Plant organ	Mean	Minimum	Maximum	Variance (%)
Stipe	1.16	0.68	1.63	40.88
Arrow	2.32	2.09	2.54	9.75
Leaflets	1.68	1.52	1.84	9.62
Petiolo + Rachis	0.78	0.57	0.98	26.15
Meristem	1.34	1.02	1.66	23.95
Empty bunches	1.04	0.81	1.28	22.66
Fruits	1.14	0.93	1.36	18.61

Table 1. Range of P concentrations (g kg^{-1}) in the vegetative and reproductive components of the açai tree.

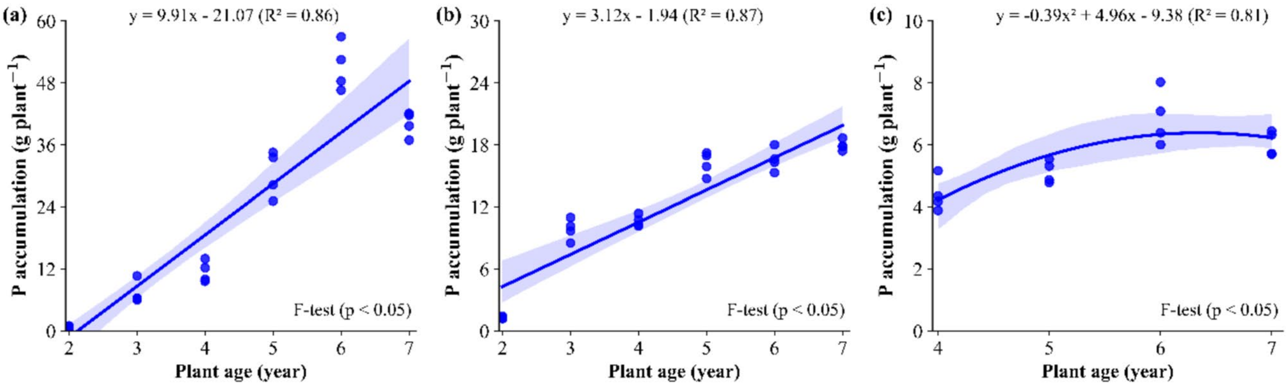

Fig. 3. P accumulation in the stipe (**a**), canopy (**b**) empty bunches + fruit (**c**) of açai trees at different ages (2–7 years).

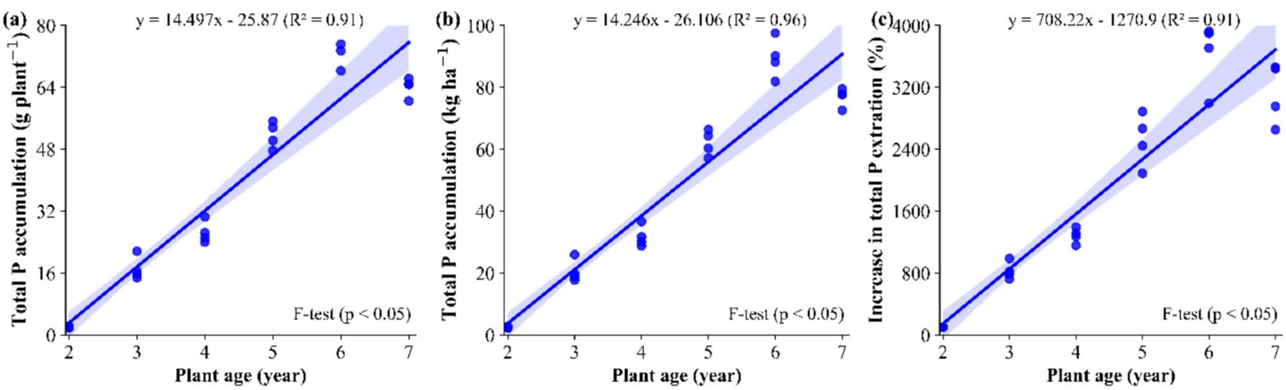

Fig. 4. Total accumulation of P in g $plant^{-1}$ (**a**) and in kg ha^{-1} (**b**) and total increment % (**c**) of P in the vegetative and reproductive parts of the açai tree at different ages (2–7 years).

Total phosphorus accumulation

A linear increase in total P accumulation and increment was observed, in g $plant^{-1}$ and kg ha^{-1}, with the highest values recorded at 7 years of plant age, with an average value of 76.9 kg ha^{-1} at that age (Fig. 4a,b). This indicates a growing P demand throughout the crop cycle, especially during the productive phase (5–7 years), for the formation of reproductive components, with nutrient extraction increasing by up to 4000% (Fig. 4c).

Phosphorus export

For the empty bunches, a quadratic response was observed, peaking at 6 years (3.07 kg ha^{-1}), 83.8% higher than that observed at 4 years of age (Fig. 5a). Phosphorus export in the fruit followed a linear trend, reaching approximately 5 kg ha^{-1} at 7 years, with a percentage increase of 39% compared to 4 years of age (Fig. 5b), accounting for about 40% of the total P exported (Fig. 5c).

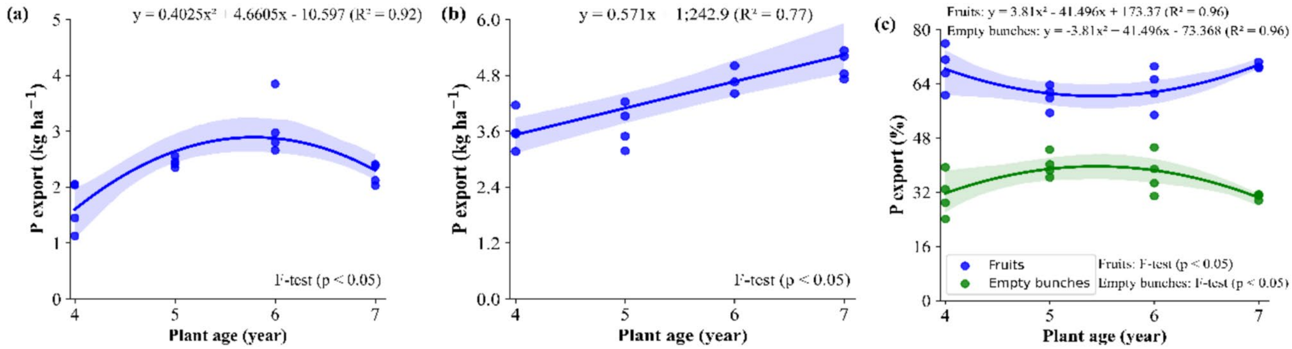

Fig. 5. P export (kg ha^{-1}) in the empty bunches (**a**) and fruit (**b**) and percentage P export in the empty bunches and fruit (**c**) of açai trees at different ages (2–7 years).

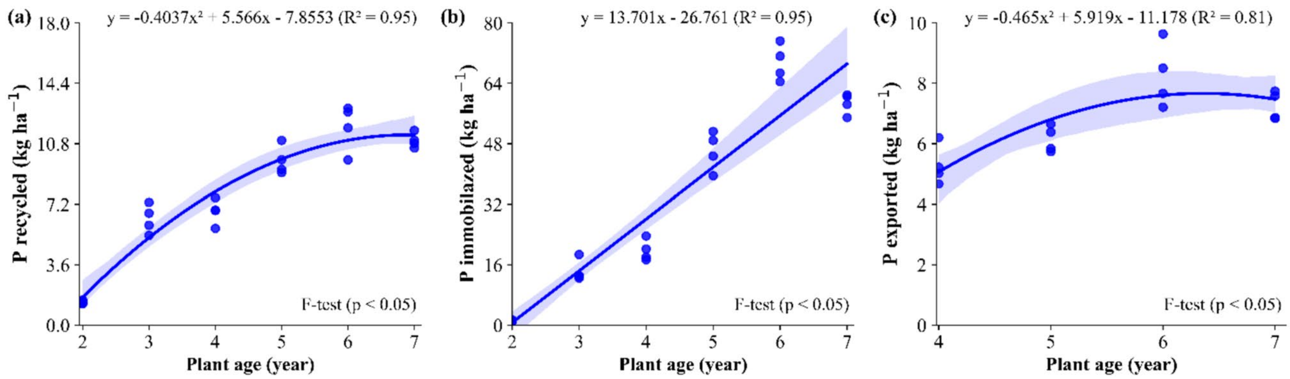

Fig. 6. Total P recycled (**a**), immobilized (**b**) and exported (**c**) in açai trees at different ages (2–7 years).

Phosphorus recycling, total export, immobilization and requirement

Total P recycling and export followed quadratic trends, peaking around 6 years (Fig. 6a–c). Total P export showed a smaller percentage increase among 7-year compared to 4-year, with a value of 37.5% (Fig. 6a–c). Phosphorus immobilization showed a linear increase with plant age, with an average value of 59 kg ha^{-1} at 7 years of age (Fig. 6b).

Both total and effective P requirements increased linearly with plant age, with values of 91.6 and 78.5 g plant^{-1}, respectively, indicating a greater need for P to support growth and fruit production over time (Fig. 7).

P use efficiency

Quadratic adjustments were observed for P use efficiency (PUE) in the leaflets, petiole + rachis, meristem, empty bunches, and fruit, but with the highest mean value between 5 and 6 years of age (Fig. 8a,d–g). This variation is related to the oscillation in the need for this nutrient according to the crop stage. There was a percentage reduction of approximately 43% in PUE in the empty bunches at 7 years compared to 4 years (Figs. 8f). On the other hand, there was a similar percentage increase in PUE of the meristem and fruits (~ 4%) (Fig. 8e,g).

The PUE in stipe and arrow and total PUE exhibited linear behavior, with maximum efficiency at 7 years (Fig. 8b,c,h). In relation to these three variables, there was a high percentage increase during the period evaluated, indicating high biomass production with lower P accumulation.

Estimated P supply for açai trees at different ages

Estimates of P supply through phosphate fertilization based on soil P availability (mg dm^{-3}) and expected fruit yield (t ha^{-1}) revealed a rising requirement with increasing productivity expectations. Regardless of soil P availability, the need for P increased by 545%, 600%, and 667% for productivity levels exceeding 25 t ha^{-1} in soils with low, medium, and high P availability, respectively (Table 2).

Discussion

The results demonstrated significant variation in the dynamics of P within the vegetative and reproductive components of açaí tree. While no significant differences were observed in P concentrations within the stipe, arrow, and leaflets across plant ages, other organs exhibited a linear increase in P concentration with age. This trend likely reflects the rising nutrient demand associated with increased fruit production, which requires higher nutrient inputs for the formation of bunches and fruit[22]. Furthermore, the expansion of leaf area with plant age[27] likely contributes to the increased P demand, as this nutrient is vital for cell and tissue development[28].

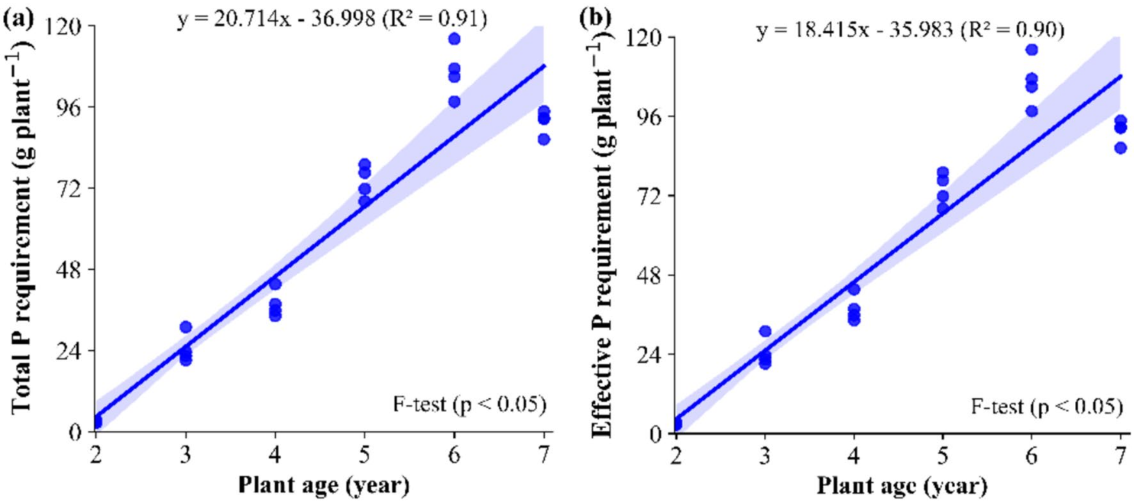

Fig. 7. Total (**a**) and effective (**b**) P requirements of açai trees at different ages (2–7 years).

The increased P concentration in the açaí tree is associated with plant growth and the productive phase, showing varying proportions among plant organs. Leaflets exhibited minimal fluctuations in P concentration (1.68 g kg^{-1}, Table 1), highlighting their metabolic stability. This value is higher than the critical threshold of 1.40 g kg^{-1} reported by Viégas et al.[14], but lower than the 1.86 g kg^{-1} found in specific açaí cultivars[29]. Similarly, Moreira et al.[30] observed 1.40 g kg^{-1} P in leaflets of açaí grown in agroforestry systems. The stability of P in leaflets aligns with findings in oil palm, where minimal variation in leaflet P concentrations has also been reported[8].

In contrast, the stipe exhibited greater fluctuations in P concentration (Table 1), likely due to nutrient translocation to support vegetative growth and fruit pulp production. Higher P concentrations in the arrow may be attributed to its younger tissues, which require P for critical physiological processes such as cell division, photosynthesis, and respiration[28,31].

The concentration of P in the fruit reached an average of 1.35 g kg^{-1} in 7-year-old trees, underscoring the açaí fruit's nutritional value for Amazonian populations. A diurnal intake of 500 g of açaí pulp nearly fulfills the day-to-day P requirement for adults (700–750 mg day^{-1}). In comparison, the meristem (palm heart) contains 2.15 g kg^{-1} P, providing enough P to meet three days of consumer demand. This highlights açaí's potential role in addressing P deficiencies, which can lead to anemia, muscle weakness, rickets, and bone pain[32]. Thus, understanding P dynamics in açaí is crucial for optimizing fertilization strategies and ensuring food security for Amazonian communities.

The linear increase in total P accumulation is consistent with biomass production trends as the plants age, culminating in approximately 49 kg $plant^{-1}$ of total dry mass at seven years (Fig. 1). This accumulation reflects P's role in fruit formation, similar to findings in other palms. For instance, Lins et al.[19] reported that phosphate fertilization significantly enhanced coconut fruit production, while Viégas et al.[33] demonstrated a positive effect of P on oil palm yield.

The increase in immobilized P corresponds to biomass accumulation driven by expanded leaf area and higher photosynthetic activity[23]. Proper management of phosphate fertilization is therefore essential to avoid P deficiencies that could limit açaí yield. Studies in other fruit crops have linked P limitation to reduced yield[34,35]. Exported P is closely tied to fruit production, which increases substantially after the plants reach five years. In oil palm, nutrient exports have also been shown to increase with fruit production[33].

Recycled P followed a quadratic trend, increasing with plant age due to phenological factors such as leaf area expansion and inflorescence emission during the reproductive phase. These components contribute to nutrient cycling in the soil, particularly during peak fruit production. Conversely, the reduced P export in empty bunches after six years may result from the translocation of P to the developing fruits. In oil palm, Viégas et al.[8] observed a decrease in fruit P export with increasing plant age, particularly after eight years of cultivation.

Total and effective P requirements increased linearly throughout the açaí tree's growth cycle, reflecting the nutrient's role in energy metabolism, genetic material synthesis, and plasma membrane formation. These demands are particularly high during the productive phase[23]. P also supports root system development, promoting aerial growth[36]. Similar patterns have been observed in oil palm, where P is critical for fruit formation and productivity[8,37].

Variations in P use efficiency (PUE) across plant ages correspond to increased crop production, particularly as the açaí tree approaches peak yield. Soil factors such as texture, organic matter content, moisture, and mineralogy also influence P absorption and translocation, thereby affecting PUE. Efficient nutrient use is crucial for sustainable fertilization practices, as it ensures nutrient recycling from decomposed vegetative material[18,38].

The study's P supply estimates indicate that higher P inputs are necessary for achieving greater açaí yields (Table 2). Although the producer applied 280 kg P_2O_5 per clump using the NPK formula (10-28-20) in the sixth and seventh years, this exceeds the recommended dose derived from this study for yields above 25 t ha^{-1}. Phosphorus dynamics in soils, particularly in low-fertility Oxisols and Argisols, must be considered, as these

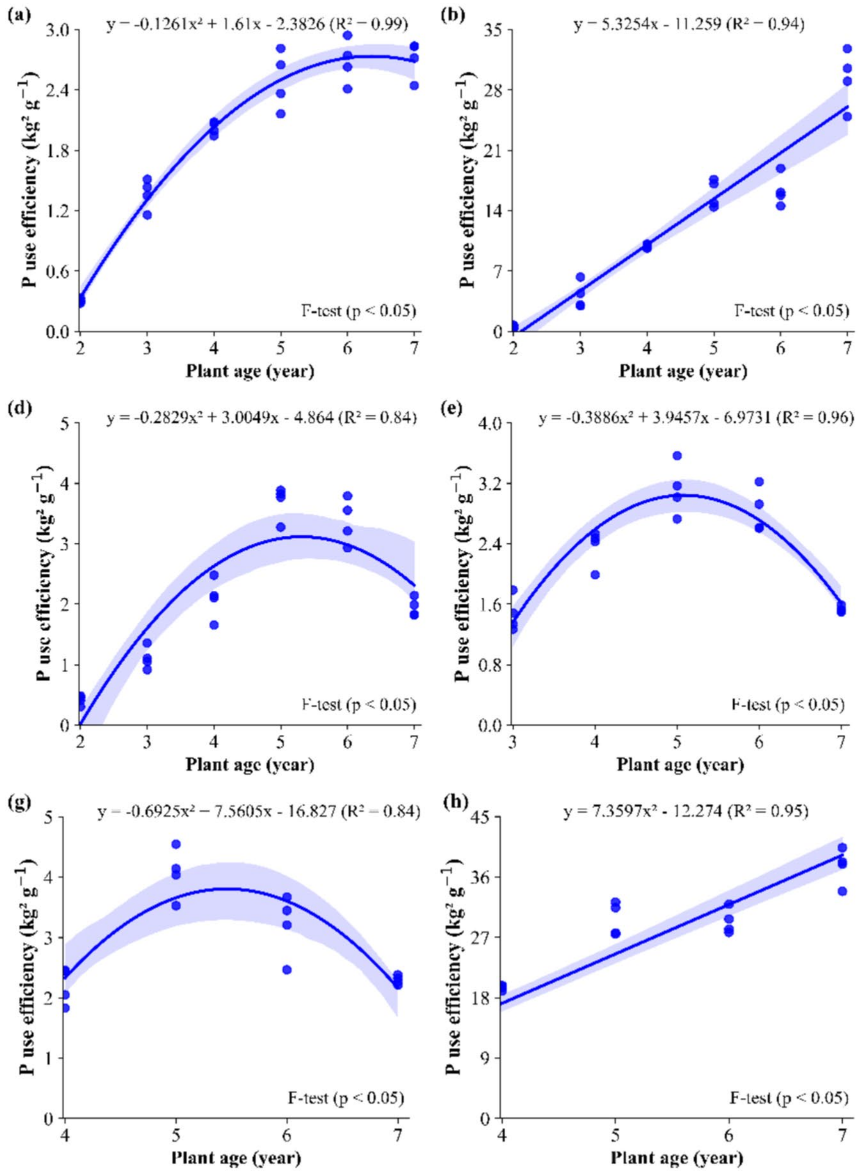

Fig. 8. P use efficiency in the leaflets (**a**), stipe (**b**), arrow (**c**), petiole + rachis (**d**), meristem (**e**), empty bunches (**f**), fruit (**g**) and total (**h**) of açai trees at different ages (2–7 years).

soils exhibit high P fixation due to iron oxides[39,40]. Effective fertilization management must account for soil mineralogy, texture, pH, organic matter content, and the cycling and immobilization of P within the plant[41–44].

Nutrient uptake in plants is further modulated by their health, climatic conditions, and management practices[45,46]. Tailoring phosphate fertilization to meet the plant's age-specific nutritional demands is crucial for maintaining agricultural sustainability. This study confirms that P dynamics in the açaí tree are closely linked to plant age and the functional roles of different organs during vegetative and reproductive stages, with total P accumulation peaking at seven years.

Conclusions

This study demonstrated that P accumulation in açaí palms increased progressively with plant age, reaching approximately 80 kg ha^{-1} at 7 years. The stipe exhibited the highest P use efficiency, reflecting its role in nutrient storage and biomass production. The effective P requirement peaked at 6 years, coinciding with the productive phase when nutrient demand for fruit formation and vegetative growth is most intense.

The recommendation of 200 kg ha^{-1} of P_2O_5 was derived from the observed P accumulation, export, and efficiency values, ensuring that nutrient replacement is aligned with the crop's demands. Although the study did not include a dose–response trial, the nutrient accumulation method provided reliable estimates of P requirements to sustain fruit yields exceeding 25 t ha^{-1}, supporting more efficient and targeted fertilization practices.

	Availability of P (mg dm^{-3})*		
	Low	Medium	High
Yield	< 5	6–10	> 10
t ha^{-1}	kg ha^{-1} de P_2O_5		
< 5	33.07	30.07	27.07
6–9	61.92	58.92	55.92
10–13	90.78	87.78	84.78
14–17	119.63	116.63	113.63
18–21	148.48	145.48	142.48
22–25	177.34	174.34	171.34
> 25	213.41	210.41	207.41

Table 2.. Recommended P supply (kg ha^{-1}) via fertilization based on soil P availability (mg dm^{-3}) and expected fruit yield (t ha^{-1}) of açai trees *The table shows the recommended amount of P (kg ha^{-1}) for different levels of P availability in the soil; low (< 5 mg dm^{-3}), medium (6–10 mg dm^{-3}) and high (> 10 mg dm^{-3}). The recommendations were calculated based on the average efficiency of P use in the soil and the export of P by the fruit, taking into account the efficiency of phosphate fertilizers.

	Plant age (years)					
Properties*	2	3	4	5	6	7
pH (H_2O)	4.9	5.7	4.9	4.7	5.4	4.9
K (mg dm^{-3})	18.0	24.0	20.0	24.0	43.0	27.0
P (mg dm^{-3})	6.0	39.0	14.0	6.0	34.0	6.0
Ca ($cmol_c$ dm^{-3})	1.0	3.4	1.5	2.2	3.3	1.2
Mg ($cmol_c$ dm^{-3})	0.6	1.5	0.4	0.6	1.3	0.6
Al ($cmol_c$ dm^{-3})	0.4	0.1	0.3	0.4	0.1	0.5
H + Al ($cmol_c$ dm^{-3})	2.9	3.2	3.5	3.2	2.9	3.7
S (mg dm^{-3})	2.0	1.8	3.0	1.5	2.0	2.0
B (mg dm^{-3})	0.6	0.6	0.6	0.6	0.6	0.8
Cu (mg dm^{-3})	2.4	2.3	1.4	1.8	1.6	2.2
Fe (mg dm^{-3})	43.0	54.0	32.0	54.0	45.0	22.0
Mn (mg dm^{-3})	23.0	13.0	22.0	25.0	34.0	19.0
Zn (mg dm^{-3})	3.4	2.8	2.3	3.4	1.8	2.3
M.O. (g kg^{-1})	1.8	2.2	1.8	2.9	2.4	2.2

Table 3. Chemical properties of the soil (0.0–0.2 m) in the experimental area of açai tree (2–7 years old). *P was determined using metavanadate colorimetry and azomethine-H with a Mehlich 1 extractor. K was determined using flame photometry. The nutrients Ca, Mg, S, Cu, Fe, Mn and Zn by atomic absorption spectrophotometry and B in hot water. MO (soil organic matter) was determined using the sodium dichromate method. Al was determined by the KCl method and H + Al by calcium acetate at pH = 7.0

These findings offer valuable insights for improving P management in açaí cultivation, particularly in nutrient-poor Amazonian soils. By aligning fertilization strategies with the crop's actual P demands, it is possible to optimize yield potential, enhance P use efficiency, and promote more sustainable agricultural practices in the region.

Methods

Characterization of the experimental area

The experiment was conducted in agroforestry systems with *Euterpe oleracea* Mart. (açaí palm) plantations aged 2 to 7 years, located in the municipality of Tomé-Açu, Pará, Brazil (02° 31′ 28″ S, 48° 22′ 36″ W, altitude 42 m). The region's climate is classified as Ami according to the Köppen classification, with an average temperature of 26.4 °C and an annual rainfall of approximately 2300 mm[47]. The predominant soil in the study area, as per the Brazilian Soil Classification System[48], belongs to the Latossolos class, equivalent to Oxisols[49]. The chemical properties of the soil (Table 3) were determined from a composite sample collected with a Dutch auger at a depth of 0.0–0.2 m. The soil had a sandy-clay texture and was prepared prior to planting by applying 2 t ha^{-1} of dolomitic limestone to correct acidity, following the base saturation method.

The açaí palms were planted at 5 × 5 m spacing (400 plants ha^{-1}), intercropped with black pepper (*Piper nigrum* L.), cacao (*Theobroma cacao* L.) and cupuaçu tree (*Theobroma grandiflorum* (Willd. ex Spreng.) K.

Schum.). During planting, 5 L of decomposed bovine manure and 600 g of NPK fertilizer (10:28:20) were applied per planting hole, distributed over three applications. Subsequent manure and NPK applications were adjusted annually, increasing proportionally with plant age. From the fifth year onwards, 100 g of borax per clump was also applied annually. In the first year after planting, 20 L of tanned cattle manure and a further 500 g per clump of the 10-28-20 formula were applied; in the second year, 30 L of tanned cattle manure and a further 1 kg per clump of the same formula; in the third year, 40 L of tanned cattle manure and 1.2 kg per clump of the same formula; in the fourth year, 60 L of tanned cattle manure plus 1.5 kg of the same formula; in the fifth year, 70 L of tanned cattle manure plus 2 kg of the same formula; in the sixth and seventh years, 2.5 kg of the same formula. From the fifth year onwards, 100 g of borax per clump was applied.

Experimental design

The experiment followed a completely randomized strip-plot (split-block) design with four replicates. The treatments consisted of açaí plants at different ages (2–7 years), with each experimental plot comprising one randomly selected palm. Border plants were excluded to minimize edge effects.

Collection of vegetative and reproductive samples and determination of dry mass

Palm trees were selected based on uniformity, ensuring they were well-nourished (no visible deficiency symptoms), healthy (free of pests or diseases), and well-developed. Four palms per age group were sampled, focusing on the most developed plant in each clump. Samples collected annually included leaflets, stipe, arrow, petiole, and rachis. Additional components, such as the meristem (third year onward), empty bunches, and fruit (fourth year onward), were also sampled. The collected material was separated, dried in a forced-air oven at 70 ºC until a constant weight was achieved, and weighed to determine dry mass.

Determining the concentration and accumulation of P

Dried plant material was ground using a Willey knife mill, and P concentrations were determined through nitro-perchloric digestion, followed by spectrophotometric analysis using the ammonium molybdate and ammonium vanadate colorimetric method. The P accumulation in each organ was calculated as the product of dry mass and nutrient concentration. Total P accumulation was obtained by summing the P contents across all plant components.

Determining P immobilization, export, recycling, requirement and efficiency

The amount of P immobilized in the crop was calculated as the sum of P accumulated in the stipe, arrow, and meristem. Recycled P was determined from the accumulation in petioles, rachis, leaflets, and inflorescences, while exported P was calculated as the sum of P in fruit and empty bunches. Variation in P concentration in each organ across plant ages was also analyzed based on arithmetic means and standard deviations.

The total P requirement (g plant^{-1}) was estimated using Eq. (1):

$$P_{\text{requirement}} = \frac{\text{Accumulation of P}}{\text{phosphate fertilizer efficiency}} \times 100 \tag{1}$$

An average phosphate fertilizer efficiency of 30% was assumed for Amazonian soils[50]. Effective P requirement was further calculated using Eq. (2)[51]:

$$\text{Effective P requirement} = \frac{\sum \text{total accumulation-} \sum \text{recycled}}{\text{phosphate fertilizer efficiency}} \times 100 \tag{2}$$

P use efficiency (kg^2 g^{-1}) was calculated for each organ and the total plant as the square of dry mass divided by P accumulation[52].

Estimating P supply to the açai tree

The estimation of P supply considered both soil P availability and plant P use efficiency. Soil P concentrations (mg dm^{-3}) were converted to kg ha^{-1} using a conversion factor (1 mg dm^{-3} = 2 kg ha^{-1}). The average P export by fruits across cultivation years was used for these calculations. Phosphate fertilizer efficiency was set at 30%[50]. Adjustments were made to the recommended P dose by subtracting the available P in the soil from the calculated fertilizer requirement, as shown in Eq. (3):

$$Psupply\left(kgha^{-1}\right) = ((3.15 \times Expectedyield) \times 2.29 \times Efc) - (AvailabilityofP_2O_2 \times 2) \tag{3}$$

where: 3.15 is the average amount of P exported per ton of açaí fruit (kg t^{-1}), obtained in our study; 2.29 is the conversion factor for P to P_2O_5; 2 is the conversion factor for P_2O_5 from mg dm^{-3} to kg ha^{-1} and Efc is the efficiency of phosphate fertilization, which we considered to be 30% (0.3).

Statistical analysis

The data were subjected to the Shapiro–Wilk normality test ($p > 0.05$)[53] and Levene's test for homogeneity of variances ($p > 0.05$)[54]. Analysis of variance was performed using the F test ($p < 0.05$), and significant results were further analyzed using linear regression models based on plant age. All analyses were conducted using the Sisvar software version 5.7[55] (https://des.ufla.br/~danielff/sisvar.html).

Research involving plants

The experimental research was carried out in accordance with the relevant institutional, National and international guidelines and legislation and, still, does not involve an endangered species. The seedlings of *Euterpe oleracea, Piper nigrum, Theobroma cacao* and *Theobroma grandiflorum* were commercially purchased, and the identification of these species was presented in accordance with Brazilian legislation.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Competing interests

The authors declare no competing interests.

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