

EDAPHIC INFLUENCES ON ANTHOCYANIN COMPOSITION IN AÇAÍ (*EUTERPE OLERACEA* MART.) FROM PARÁ STATE, BRAZIL

INFLUÊNCIAS EDÁFICAS NA COMPOSIÇÃO DE ANTOCIANINAS EM AÇAÍ
(*EUTERPE OLERACEA* MART.) DO ESTADO DO PARÁ, BRASIL

INFLUENCIAS EDÁFICAS EN LA COMPOSICIÓN DE ANTOCIANINAS EN AÇAÍ
(*EUTERPE OLERACEA* MART.) DEL ESTADO DE PARÁ, BRASIL

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ABSTRACT

Anthocyanins are important phenolic compounds responsible for the antioxidant capacity and characteristic purple color of açaí. Despite their nutritional and economic importance, environmental factors influencing their accumulation in fruits remain insufficiently understood. This study evaluated the relationship between edaphic conditions and anthocyanin concentration in açaí fruits collected from different regions of Pará State, Brazil, including mainland municipalities, riverine islands, and the Marajó Archipelago. Anthocyanins were extracted under controlled light conditions and quantified by ultraviolet–visible spectrophotometry. Soil parameters, including pH, organic matter content, and electrical conductivity, were determined using standardized protocols. Statistical evaluation included analysis of variance followed by Tukey's test, principal component analysis, and multiple linear regression. Anthocyanin concentrations ranged from 43.97 ± 20.34 to $294.48 \pm 9.70 \mu\text{g mL}^{-1}$, showing significant

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differences among regions. Multivariate analysis indicated that soil pH, organic matter, and electrical conductivity were the main variables structuring the environmental variability of the dataset. Regression analysis suggested that these parameters collectively explain part of the observed variation in anthocyanin concentration. Overall, the results demonstrate that edaphic conditions influence anthocyanin accumulation indirectly by modulating plant physiological responses associated with environmental stress, contributing to understanding environmental determinants of açai chemical composition and supporting sustainable valorization of Amazonian bioresources.

Keywords: Total Anthocyanins. Purple Açai. Soil Quality. Geographical Variation. Amazon Bioeconomy. Environmental Factors.

RESUMO

As antocianinas são importantes compostos fenólicos responsáveis pela capacidade antioxidante e pela característica coloração roxa do açai. Apesar de sua importância nutricional e econômica, os fatores ambientais que influenciam sua acumulação nos frutos ainda são insuficientemente compreendidos. Este estudo avaliou a relação entre as condições edáficas e a concentração de antocianinas em frutos de açai coletados em diferentes regiões do Estado do Pará, Brasil, incluindo municípios continentais, ilhas ribeirinhas e o Arquipélago do Marajó. As antocianinas foram extraídas sob condições controladas de luminosidade e quantificadas por espectrofotometria no ultravioleta-visível. Os parâmetros do solo, incluindo pH, teor de matéria orgânica e condutividade elétrica, foram determinados utilizando protocolos padronizados. A avaliação estatística incluiu análise de variância seguida do teste de Tukey, análise de componentes principais e regressão linear múltipla. As concentrações de antocianinas variaram de $43,97 \pm 20,34$ a $294,48 \pm 9,70 \mu\text{g mL}^{-1}$, apresentando diferenças significativas entre as regiões. A análise multivariada indicou que o pH do solo, a matéria orgânica e a condutividade elétrica foram as principais variáveis responsáveis pela estruturação da variabilidade ambiental do conjunto de dados. A análise de regressão sugeriu que esses parâmetros explicam conjuntamente parte da variação observada na concentração de antocianinas. De modo geral, os resultados demonstram que as condições edáficas influenciam indiretamente a acumulação de antocianinas ao modularem respostas fisiológicas das plantas associadas ao estresse ambiental, contribuindo para a compreensão dos determinantes ambientais da composição química do açai e apoiando a valorização sustentável dos biorrecursos amazônicos.

Palavras-chave: Antocianinas Totais. Açai Roxo. Qualidade do Solo. Variação Geográfica. Bioeconomia Amazônica. Fatores Ambientais.

RESUMEN

Las antocianinas son importantes compuestos fenólicos responsables de la capacidad antioxidante y de la característica coloración púrpura del açai. Apesar de su importancia nutricional y económica, los factores ambientales que influyen en su acumulación en los frutos aún son insuficientemente comprendidos. Este estudio evaluó la relación entre las condiciones edáficas y la concentración de antocianinas en frutos de açai recolectados en diferentes regiones del Estado de Pará, Brasil, incluyendo municipios continentales, islas ribereñas y el Archipiélago de Marajó. Las antocianinas fueron extraídas bajo condiciones controladas de luminosidad y cuantificadas mediante espectrofotometría ultravioleta-visible. Los parámetros del suelo, incluyendo el pH, el

contenido de materia orgánica y la conductividad eléctrica, fueron determinados utilizando protocolos estandarizados. La evaluación estadística incluyó análisis de varianza seguido de la prueba de Tukey, análisis de componentes principales y regresión lineal múltiple. Las concentraciones de antocianinas variaron de $43,97 \pm 20,34$ a $294,48 \pm 9,70 \mu\text{g mL}^{-1}$, presentando diferencias significativas entre las regiones. El análisis multivariado indicó que el pH del suelo, la materia orgánica y la conductividad eléctrica fueron las principales variables responsables de estructurar la variabilidad ambiental del conjunto de datos. El análisis de regresión sugirió que estos parámetros explican conjuntamente parte de la variación observada en la concentración de antocianinas. En general, los resultados demuestran que las condiciones edáficas influyen indirectamente en la acumulación de antocianinas al modular las respuestas fisiológicas de las plantas asociadas al estrés ambiental, contribuyendo a la comprensión de los determinantes ambientales de la composición química del açai y apoyando la valorización sostenible de los biorrecursos amazónicos.

Palabras clave: Antocianinas Totales. Açai Morado. Calidad del Suelo. Variación Geográfica. Bioeconomía Amazónica. Factores Ambientales.



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INTRODUCTION

Açai (*Euterpe oleracea* Mart.) is a fruit native to northern Brazil and widely consumed throughout the Amazon region (Heck *et al.*, 2023). Its consumption dates back to Indigenous civilizations and it has long been considered an important dietary component for local populations (Oliveira *et al.*, 2021). Historically, açai has played a central role in the diet of communities in northern Brazil and is strongly associated with regional cultural traditions and socioeconomic activities, serving as a primary subsistence food for many families (Nogueira *et al.*, 2013).

In recent decades, açai has gained international recognition as a functional food due to its potential health benefits. Its high antioxidant activity contributes to the neutralization of reactive species and the reduction of oxidative stress, processes associated with the prevention of cardiovascular, cancer-related, and neurodegenerative diseases (Mendes *et al.*, 2020). Antioxidant compounds present in the fruit protect essential cellular structures such as lipids, proteins, and nucleic acids, contributing to cellular stability and metabolic balance (Gomes *et al.*, 2022; Rigolon *et al.*, 2021).

These biological properties are closely related to the phytochemical composition of the fruit, particularly to anthocyanins (Oliveira *et al.*, 2021). Anthocyanins are natural pigments

belonging to the flavonoid class and are responsible for the characteristic purple coloration of açai fruits (Rigolon *et al.*, 2021). Among the main compounds identified in the fruit, cyanidin-3-glucoside and cyanidin-3-rutinoside are considered the predominant anthocyanins (Silva *et al.*, 2019). These compounds exhibit strong antioxidant and anti-inflammatory activities and play an important role in the neutralization of reactive oxygen species (Mendes *et al.*, 2020; Rigolon *et al.*, 2021; Lisboa *et al.*, 2022).

Due to these bioactive properties, açai has gained increasing commercial importance worldwide (Wang *et al.*, 2025). The state of Pará accounts for approximately 87.3% of Brazilian production, which has expanded substantially over recent decades, reaching approximately 1.9 million tons in 2022 (Oliveira, 2024). This expansion has been largely driven by scientific evidence demonstrating the fruit's nutritional and functional potential (Heck *et al.*, 2023).

Environmental conditions influence the synthesis of secondary metabolites in plants, including phenolic compounds such as anthocyanins. In the case of açai, the state of Pará offers favorable cultivation conditions, including a tropical climate and a wide diversity of soil types such as upland soils and floodplain environments (Queiroga *et al.*, 2023). Variations in soil properties, including pH, nutrient availability, and organic matter content, may influence plant physiological responses and consequently affect anthocyanin biosynthesis and accumulation in fruits (Embrapa, 2001).

Edaphic conditions are therefore important determinants of açai chemical composition. Soil characteristics influence nutrient availability, microbial activity, and root development, factors that regulate metabolic pathways involved in the synthesis of phenolic compounds (Embrapa, 2001; Oliveira *et al.*, 2017). Floodplain soils, which are periodically inundated, typically exhibit high fertility due to the accumulation of organic matter and essential nutrients such as potassium and magnesium (Queiroga *et al.*, 2023; Silva *et al.*, 2024). These conditions favor plant development and may stimulate secondary metabolic pathways associated with stress responses, potentially increasing anthocyanin biosynthesis.

Açai palms show high adaptability to environments characterized by elevated soil moisture and organic matter content, conditions typical of Amazonian floodplain ecosystems (Coutinho *et al.*, 2024; Coutinho *et al.*, 2017). The interaction between soil composition, hydrological dynamics, and plant physiology may therefore influence the accumulation of anthocyanins and other phenolic compounds in the fruit. However, despite the recognized importance of these environmental factors, the relationship between soil characteristics and

anthocyanin concentration in açai fruits remains insufficiently explored. Most available studies focus either on soil classification or anthocyanin quantification independently, without establishing a direct relationship between these variables.

Therefore, the present study investigates the influence of different soil conditions in the state of Pará on the anthocyanin composition of açai fruits. By evaluating the relationship between edaphic parameters and anthocyanin concentration, this research aims to contribute to a better understanding of the environmental determinants of açai chemical composition and to support the valorization of the fruit and its production chain.

EXPERIMENTAL

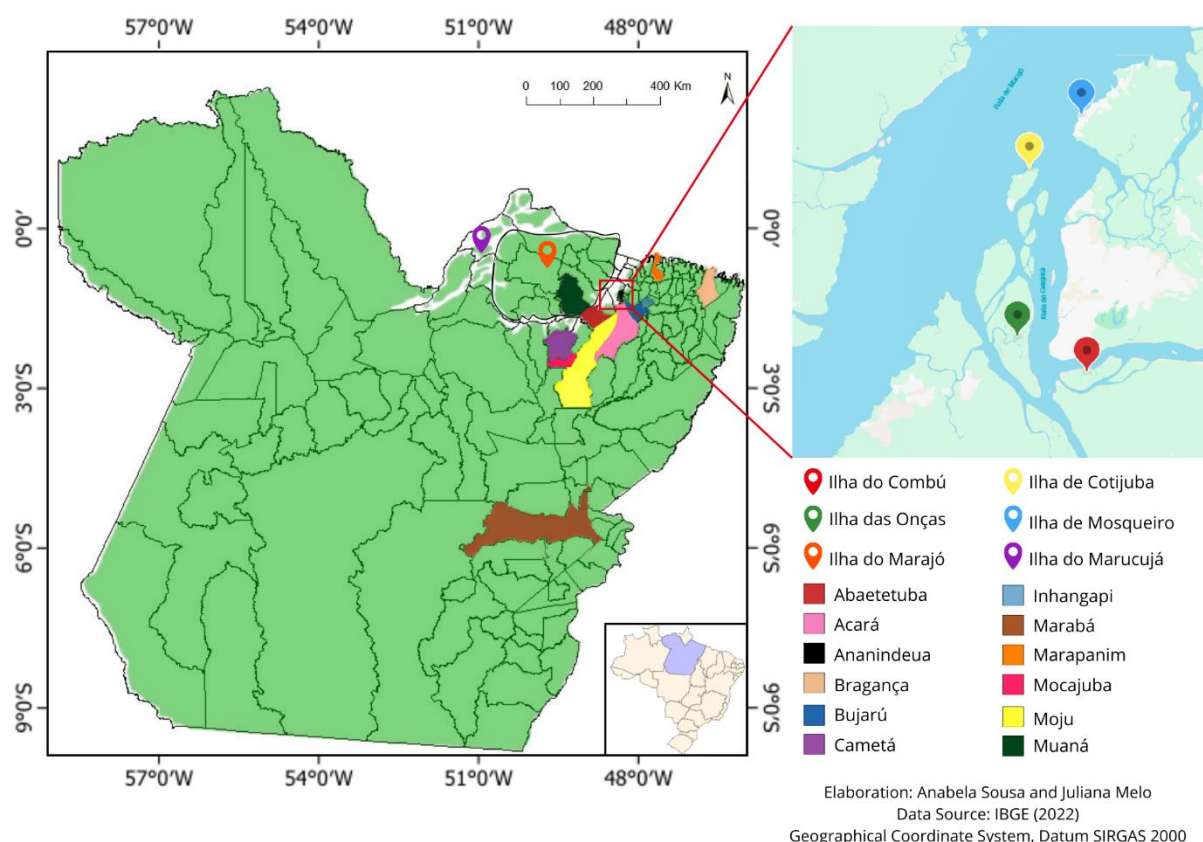
Sample Collection

A total of fifty açai (*Euterpe oleracea* Mart.) fruit samples (500 g each) were collected from different municipalities in the state of Pará, Brazil. The sampling sites included mainland municipalities and riverine islands, such as Combú, Onças, Cotijuba, Mosqueiro, Marajó, and Maracujá, as well as Abaetetuba, Acará, Ananindeua, Bragança, Bujarú, Cametá, Inhangapi, Marabá, Marapanim, Mocajuba, Moju, and Muaná. These locations were selected to represent the environmental and geographical diversity associated with açai cultivation in the region. The geographical distribution of the sampling sites is presented in Figure 1.

After collection, the fruits were transported to the laboratory and subjected to a sanitization procedure to remove surface impurities. The samples were then immersed in water at 45 °C for 20 min to facilitate pulp separation. The fruits were manually processed, and approximately 25 g of pulp from each sample were used for the extraction procedures.

Figure 1

Map of the origin of fruits collected from different regions of the state of Pará



Note. Created by the authors (2025).

Notably, the islands of Combú, Onças, Marajó, Cotijuba, Mosqueiro, and Maracujá, as well as the municipalities of Abaetetuba, Acará, Ananindeua, Bragança, Bujarú, Cametá, Inhangapi, Marabá, Marapanim, Mocajuba, Moju, and Muaná.

Anthocyanin Extraction

Anthocyanins were extracted from 25 g of açaí pulp using 50 mL of 70% ethanol acidified with concentrated hydrochloric acid until pH 2 was reached. The extraction was performed in 250 mL glass beakers protected from light with aluminum foil to minimize photodegradation of the pigments. The extracts were stored under refrigeration for 48 h to ensure efficient extraction.

After extraction, the samples were filtered and the liquid phase was collected. An aliquot of 10 mL of the filtrate was distributed into 2 mL centrifuge tubes and centrifuged at $6222 \times g$ for 15 min to remove suspended solids.

Preparation of Dilutions and Spectrophotometric Analysis

To prevent the photodegradation of the light-sensitive anthocyanins, all extraction and quantification procedures were strictly performed under low-light conditions, and any transparent vessels were wrapped in aluminum foil to ensure the integrity of the samples.

The centrifuged extract was transferred to a 10 mL volumetric flask. An aliquot of 1 mL of the concentrated extract was diluted to 10 mL using a solution composed of ethanol (analytical grade) and 1.5 mol L⁻¹ hydrochloric acid in a volumetric ratio of 85:15.

After homogenization, 1 mL of this solution was transferred to three separate 10 mL volumetric flasks and diluted again with the same ethanol–hydrochloric acid solution to obtain the final analytical dilution.

Absorbance measurements were carried out using a single-beam UV–Vis spectrophotometer (Shimadzu UV Mini 1240) equipped with a 1 cm quartz cuvette. Measurements were performed at 535 nm, maintaining absorbance values between 0.1 and 0.9 to ensure analytical reliability.

Anthocyanin concentrations were determined using a calibration curve obtained from standard solutions with known concentrations.

All extraction and analytical procedures were conducted under low-light conditions, and transparent containers were protected with aluminum foil to prevent photodegradation of anthocyanins.

Soil Analysis

Soil samples were collected at each sampling location at depths ranging from 0 to 20 cm. The analyses included determination of soil pH, organic matter content, and electrical conductivity.

Soil pH was determined by potentiometry in a soil-to-water suspension (1:2.5), following the methodology recommended by the Brazilian Agricultural Research Corporation (EMBRAPA) (Embrapa, 1998). Organic matter content was determined using the Walkley–Black method (Nelson and Sommers, 1996). Electrical conductivity was measured in a saturation extract using a digital conductivity meter (Rhoads, 1996). Soil temperature was measured in situ using digital sensors at a depth of 10 cm (Silveira *et al.*, 2019).

All chemical analyses were conducted according to standardized procedures widely used in soil chemistry.

Statistical Analysis

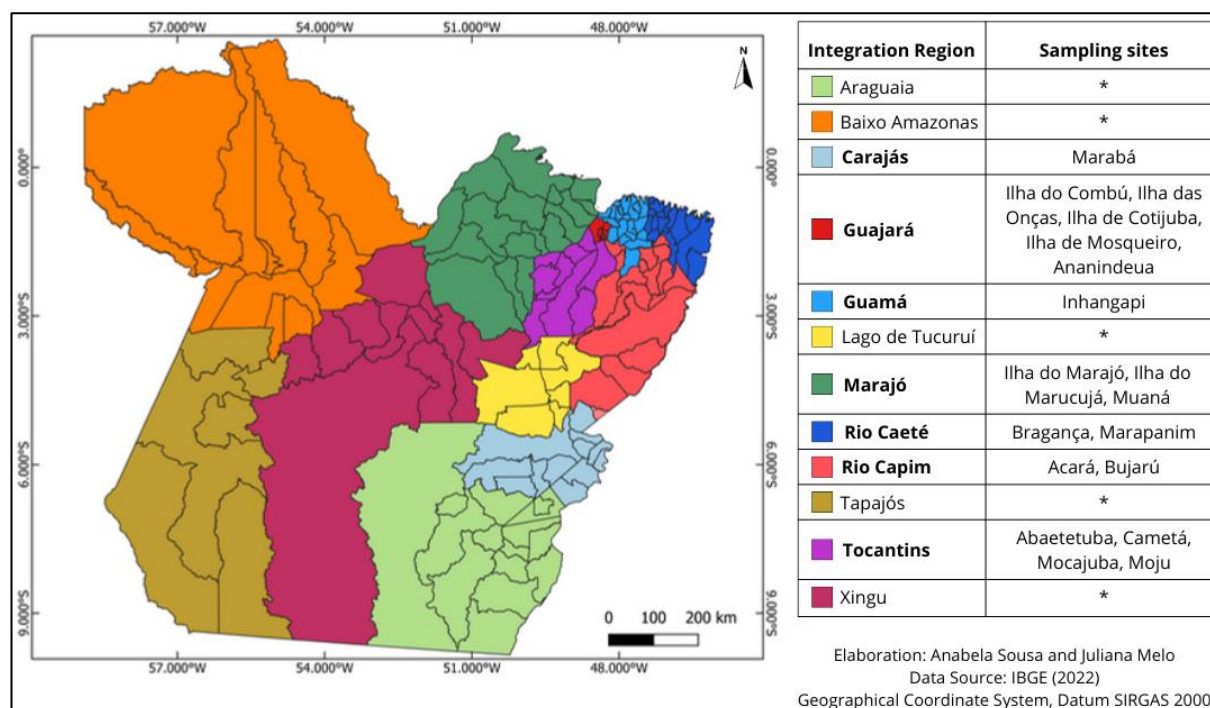
All experimental data were expressed as mean $\pm$ standard deviation of at least three replicates. Prior to statistical analysis, the assumptions of normality and homoscedasticity were verified. Differences among sampling regions were evaluated using one-way analysis of variance (ANOVA). When significant differences were detected, Tukey's honestly significant difference (HSD) test was applied for multiple comparisons at a significance level of $p < 0.05$.

Multivariate analysis was performed using principal component analysis (PCA) to investigate the relationships between edaphic variables and anthocyanin concentrations. Additionally, multiple linear regression was applied to evaluate the influence of soil parameters on anthocyanin content in the analyzed samples.

Statistical analyses were conducted using Minitab® statistical software (version 22.3.0).

RESULTS AND DISCUSSION

The Integration Regions of Pará (Figure 2) were created to group municipalities with similar characteristics, such as land use and economic dynamics, facilitating the planning and implementation of public policies in accordance with Decree No. 1,066 of 2008 (Doap, 2008).

Figure 2*Map of municipalities by integration regions*

Note. Created by the authors (2025).

The results presented in Table 1 reveal high spatial variability in anthocyanin concentration, particularly in Marajó and Cametá, which exhibited a wide total range and high dispersion, with extreme values approaching $500 \mu\text{g mL}^{-1}$. In contrast, the Rio Capim region showed higher and more homogeneous values, indicating greater production stability, while Guamá recorded the lowest concentrations, standing out as the region with the lowest anthocyanin accumulation. Additionally, Tocantins and Marajó displayed wide interquartile ranges, reflecting high internal heterogeneity, likely associated with edaphic variability and environmental and/or genetic factors. Overall, the data indicate that regions with greater stability exhibit lower dispersion, whereas areas with higher environmental heterogeneity tend to show wide variation in anthocyanin levels.

Table 1

Descriptive statistics of anthocyanin contents collected from different locations

Origin	Min.	Máx.	AT	M	MA	V	DP	EP	CV
Abaetetuba	221.54	421.30	199.76	226.54	289.79	12976.75	113.92	65.77	39.31
Acará	220.29	224.24	3.95	22.27	22.27	71.80	2.79	1.98	1.26
Ananindeua	30.35	57.60	27.25	43.97	43.57	371.39	19.27	13.63	43.82
Bragança	85.35	237.75	152.40	161.55	161.55	11612.73	107.76	76.20	66.70
Bujarú	276.08	299.62	23.54	297.96	252.90	126.48	11.25	5.62	3.84
Cametá	115.27	488.73	373.46	123.57	241.81	35207.95	187.64	76.60	77.60
Islands	232.15	269.00	36.85	241.48	249.07	251.74	15.87	7.10	6.37
Inhangapi	72.48	88.09	15.61	79.29	79.71	31.08	5.58	2.49	6.99
Marajó	53.23	478.31	425.08	113.46	220.44	32513.30	180.31	57.02	81.80
Ilha das Onças	273.63	339.47	65.84	254.30	299.46	521.45	22.84	8.07	7.63

Note. Created by the authors (2025).

Min. (Minimum), Max. (Maximum), TR (Total Range), M (Median), AM (Arithmetic Mean), V (Variance), SD (Standard Deviation), SE (Standard Error), CV (Coefficient of Variation).

The heterogeneity of soils in the state of Pará appears to exert a strong influence on the relationship with the anthocyanin content present in the analyzed samples, since the collection regions exhibit different soil types that favor distinct and heterogeneous conditions for analysis. Furthermore, a single locality may present different characteristics, resulting in distinct soils within the same area. Table 2 presents the soil types of the analyzed localities, as well as their general characteristics, according to previous studies (Embrapa, 2021; Embrapa, 2018; Ibge, 2022).

Table 2*Soil types and main edaphic characteristics of the studied locations in Pará, Brazil*

Location	Soil Type	Characteristics
Ilha do Combú	Gleysols	Floodplain soil, waterlogged, with high water saturation and organic matter.
Ilha das Onças	Gleysols, Spodosol	Waterlogged and poorly drained soils, common in floodplains and mangroves.
Ilha de Cotijuba	Spodosol, Gleysols	Sandy and moist soils, subject to flooding.
Ilha de Mosqueiro	Yellow Latosols, Spodosol	Well-drained soils in elevated areas and sandy soils in coastal regions.
Ilha do Marajó	Yellow Latosols, Plinthosol, Gleysols, Neossol	Predominantly floodplain soils, subject to seasonal flooding.
Ilha do Maracujá	Gleysols	Floodplain soil, frequently waterlogged, with high humidity.
Abaetetuba	Gleysols, Spodosol, Yellow Latosols	Riverside areas with waterlogged soils and well-drained upland zones.
Acará	Plinthosol, Gleysols, Yellow Latosols, Spodosol	Well-drained soils in upland areas and waterlogged soils in floodplains.
Ananindeua	Gleysols, Yellow Latosols	Well-drained soils in urban areas and waterlogged soils in riverside regions.
Bragança	Spodosol, Gleysols	Sandy and acidic soils in coastal areas and waterlogged floodplain soils.
Bujarú	Latosols, Spodosol, Yellow Latosols, Gleysols	Well-drained soils in gently rolling terrain and moist soils in floodplains.
Cametá	Latosols, Plinthosol, Gleysols, Spodosol	Waterlogged soils in floodplains and well-drained soils in upland areas.
Inhangapi	Yellow Argisols, Red-Yellow Argisols, Yellow Latosols, Gleysols, Neossol	Well-drained soils, common in flat and undulating terrain.
Marabá	Red-Yellow Podzol, Red-Yellow Latosols	Well-drained and dry soils with low natural fertility.
Marapanim	Yellow Latosols, Gleysols, Neossol	Flooded floodplain soils and sandy soils in coastal areas.
Mocajuba	Gleysols, Spodosol, Latosols	Waterlogged soils in riverside areas and well-drained soils in upland zones.
Moju	Latosols, Gleysols, Spodosol	Moist soils in floodplains and well-drained soils in gently rolling terrain.
Muaná	Gleysols, Plinthosol	Predominantly waterlogged soils, common in floodplain areas and natural fields.

Source: Adapted from Embrapa, 2021; Embrapa, 2018; Ibge, 2022.

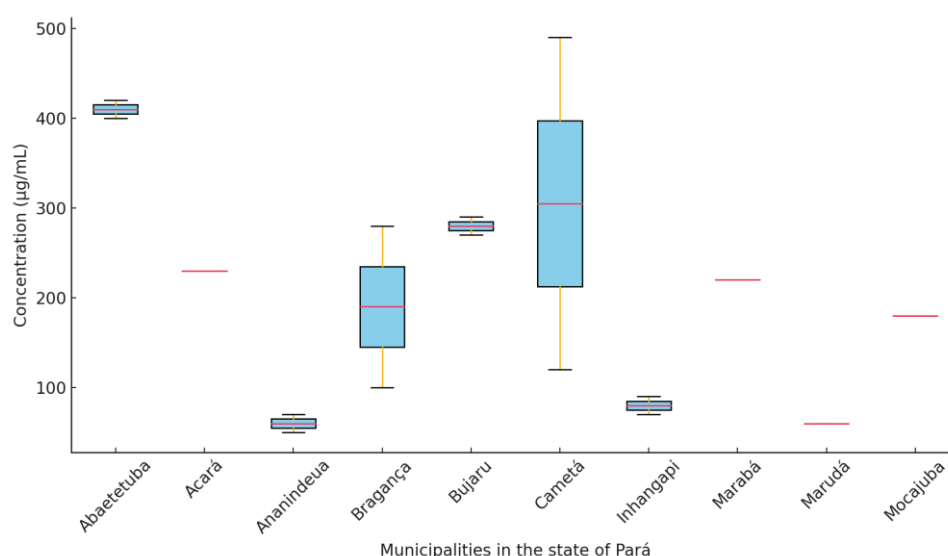
The results presented in Table 1 indicate a strong relationship between soil type and the environmental conditions of the studied locations. The predominance of Gleysols in various areas, such as Ilha do Combú, Marajó, and Abaetetuba, suggests a floodplain environment with high water saturation and organic matter conditions that may influence the concentration of anthocyanins in açaí. On the other hand, locations such as Marabá and Inhangapi, which have well-drained soils and are less prone to flooding, experience impacts on nutrient availability and possibly on the chemical composition of the fruits.

Regional Variability of Anthocyanin Concentration

Anthocyanin concentrations in *Euterpe oleracea* fruits showed considerable variability among the studied municipalities in Pará State. The boxplot distribution (Figure 3) illustrates the range and dispersion of the measured values, suggesting clear variations among sampling locations.

Figure 3

Variation in anthocyanin concentration in açai across different municipalities in Pará



Note. Created by the authors (2025).

Higher anthocyanin concentrations were observed in municipalities such as Cametá, Abaetetuba, and Bujarú, while lower values were found in Ananindeua and Inhangapi; however, these differences were not statistically significant ($p > 0.05$). Even so, the observed pattern suggests a possible association between environmental conditions and anthocyanin accumulation, with floodplain regions and higher soil moisture favoring the development of açai palms and the synthesis of secondary metabolites (Embrapa, 2021; Ibge, 2022).

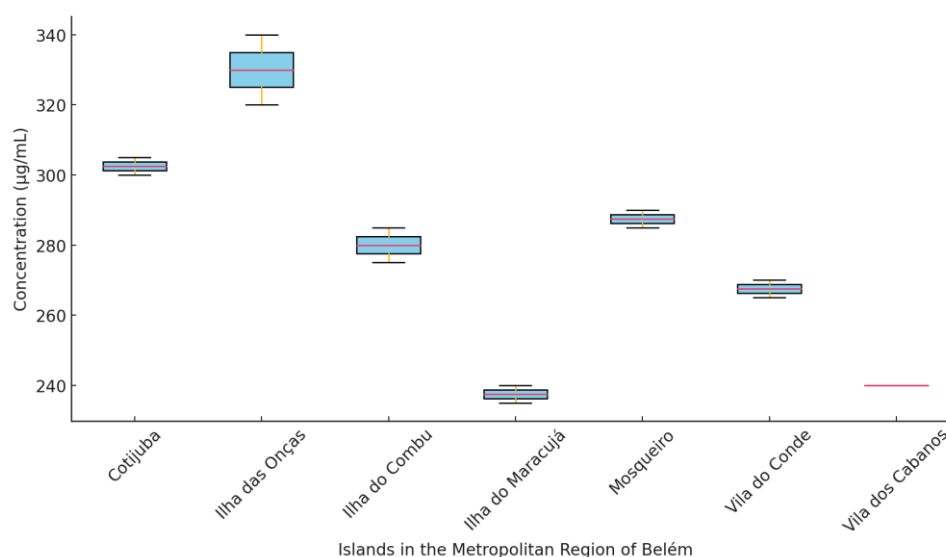
In contrast, areas with well-drained or drier soils showed lower concentrations, likely due to limitations in nutrient availability and effects on phenolic biosynthesis pathways. The variability observed in municipalities such as Cametá and Abaetetuba indicates heterogeneous environmental conditions, whereas Inhangapi and Ananindeua exhibited more homogeneous patterns, demonstrating that anthocyanin content in açai is not uniform across the state of Pará and appears to be influenced by local environmental factors.

Comparison Among Island Environments

The distribution of anthocyanin concentrations in fruits collected from different islands of the metropolitan region of Belém is shown in Figure 4. Although all islands presented relatively high anthocyanin levels, some variability was observed among sampling sites.

Figure 4

Variation in Anthocyanin Concentration in Different Islands of the Metropolitan Region of Belém



Note. Created by the authors (2025).

Ilha das Onças exhibited the highest average anthocyanin concentration, whereas Ilha do Maracujá presented the lowest values among the island environments analyzed. Intermediate concentrations were observed in Ilha do Combú, Cotijuba, and Mosqueiro.

The relatively narrow dispersion observed in most island samples suggests more homogeneous environmental conditions compared with inland municipalities. Floodplain soils typical of these islands are generally rich in organic matter and subject to periodic sediment deposition, conditions that favor nutrient availability and plant development (Embrapa, 2011; Embrapa, 2018; Ibge, 2022).

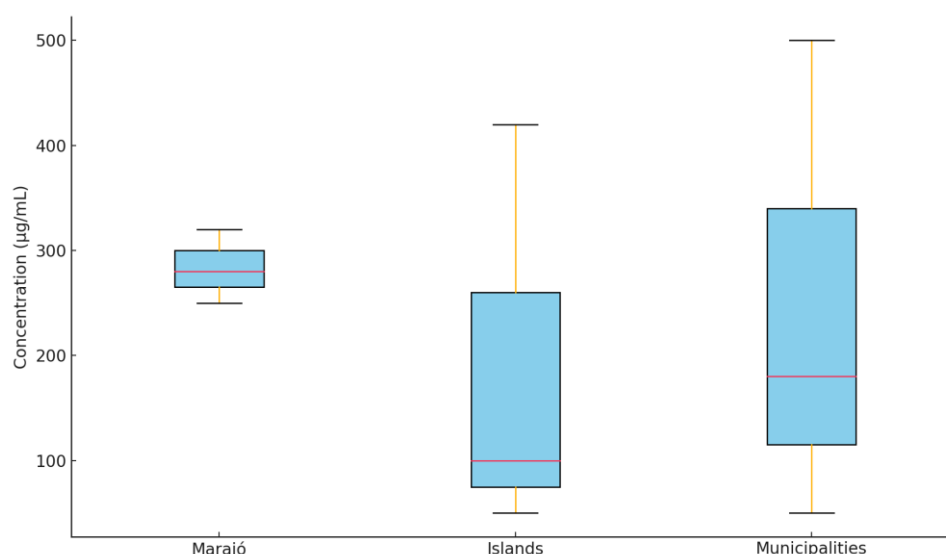
These characteristics may contribute to more stable anthocyanin accumulation in fruits harvested from island environments. Such regions may therefore represent promising locations for the production of açai with consistently high concentrations of bioactive compounds.

Regional Comparison of Anthocyanin Distribution

A broader comparison among the three main geographic groups analyzed municipalities, islands, and Marajó Island is presented in Figure 5. Although variability was observed among regions, no statistically significant differences were detected ($p > 0.05$).

Figure 5

Distribution of Anthocyanin Concentration in Açaí from Different Regions



Note. Created by the authors (2025).

Açaí fruits collected from island environments exhibited greater variability, with both low and high values anthocyanin concentrations, whereas municipalities showed greater variability. Samples from Marajó exhibited a narrower distribution, suggesting more homogeneous conditions. Marajó Island is characterized by a complex fluvio-marine environment influenced by both Amazon River discharge and Atlantic tidal dynamics (Lima *et al.*, 2005). These conditions generate a mosaic of floodplain and upland soils, which may contribute to the wide variation observed in anthocyanin concentrations.

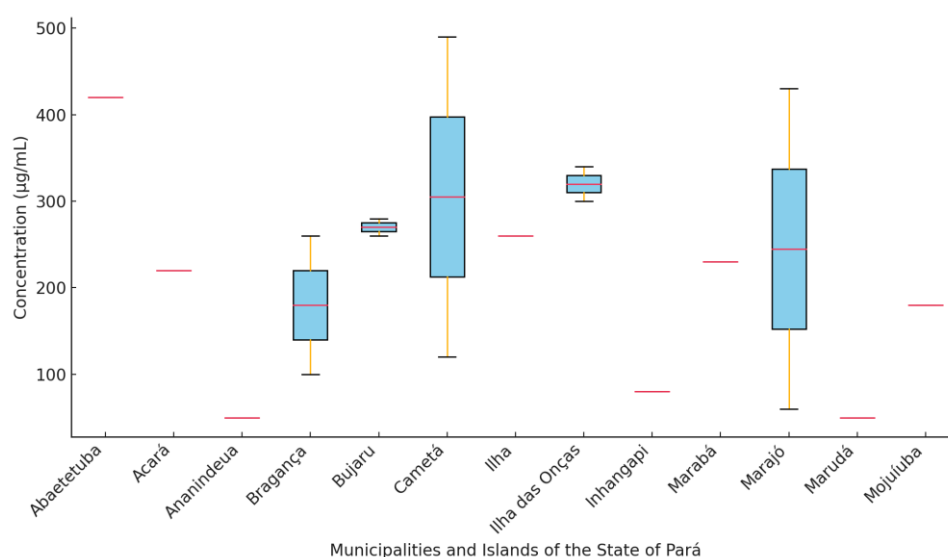
The more uniform distribution observed for island samples suggests that environmental conditions such as soil moisture and organic matter content may be more stable in these areas. Consequently, fruits from island environments may exhibit greater consistency in their anthocyanin content.

The distribution of anthocyanin concentrations ($\mu\text{g mL}^{-1}$) in açai collected from various locations is depicted in a boxplot in Figure 6. This shows notable differences in anthocyanin

concentrations among the various collect regions, and now compares municipalities, Marajó, Islands, and Ilha das Onças. To evaluate the overall variation among the collecting sites and to highlight the variations between the total locales, it is necessary to compare all the analyzed places directly and generally.

Figure 6

Anthocyanin Content from Different Locations



Note. Created by the authors (2025).

The X-axis represents the açai collection points in Pará, while the Y-axis shows the anthocyanin concentration in $\mu\text{g mL}^{-1}$.

The variations observed in anthocyanin concentration can be interpreted as a chemical response of *E. oleracea* to the environment. In floodplain areas and islands, such as Combú and Onças, water saturation in the soil reduces the availability of oxygen to the roots, which generates a metabolic imbalance in the plant. From a chemical point of view, this condition induces the formation of reactive oxygen species (ROS) or free radicals (Naing and Kim, 2021; Li *et al.*, 2023). When these unstable molecules accumulate, the plant enters a state of oxidative stress, signaling the need to produce defense compounds to avoid cell damage (Li *et al.*, 2023).

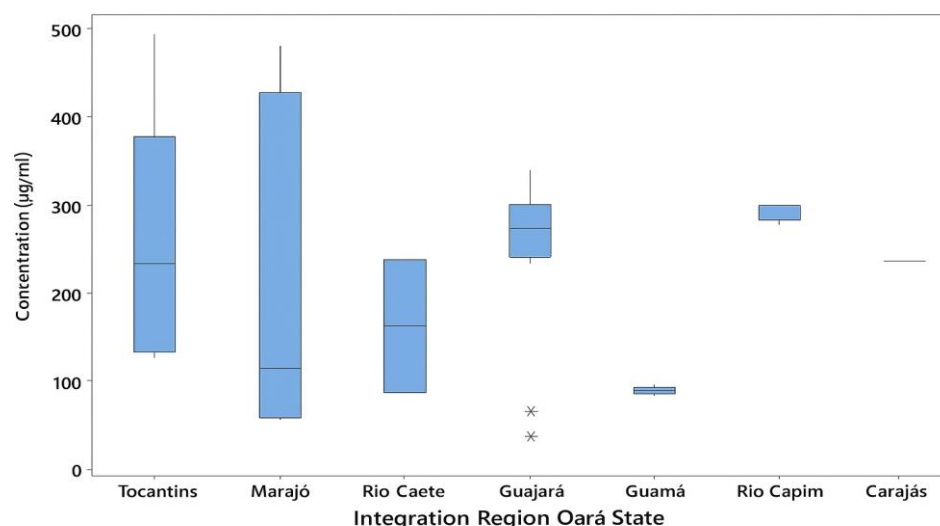
In this scenario, anthocyanin biosynthesis is intensified to act as an antioxidant protection mechanism (Zhou *et al.*, 2023). Since anthocyanins have a high capacity to neutralize free radicals, the plant increases their production when faced with adverse conditions, such as soil acidity or prolonged flooding (Wang *et al.*, 2023). Thus, the higher levels of anthocyanins found in places like Cametá and the island regions of Belém not only indicate the nutritional richness

of the fruit, but also serve as chemical markers that the plant has activated its secondary metabolism to adapt to and survive the stress caused by the soil.

Figure 7, a boxplot, presents the distribution of anthocyanin concentrations ($\mu\text{g mL}^{-1}$) across different integration regions of the state of Pará. The results of the statistical analysis (Kruskal–Wallis test) indicate significant differences between some regions, notably Guajará vs. Guamá and Guamá vs. Rio Capim ($p\text{-value} < 0.05$), suggesting that anthocyanin concentrations vary significantly between these locations.

Figure 7

Study of the integration regions of the State of Pará



Note. Created by the authors (2025).

(Tocantins, Marajó, Rio Caeté, Guajará, Guamá, Rio Capim, Carajás (X-axis) and on the Y-axis, the anthocyanin concentration (in $\mu\text{g mL}^{-1}$).

The Kruskal–Wallis test showed a significant difference between the integration regions of Guajará and Guamá, and Guamá and Rio Capim, with a $p\text{-value} < 0.05$. In terms of median, the results indicate that the Rio Capim integration region has the highest concentration ($\mu\text{g mL}^{-1}$), followed by Guajará and Tocantins. The Guamá integration region presented the lowest concentration.

Statistical Comparison of Physicochemical Parameters

The statistical comparison of physicochemical parameters among regions is presented in Table 3. Significant differences ($p < 0.05$) were observed for all evaluated variables, including anthocyanin concentration, soil pH, organic matter, electrical conductivity, and average temperature, highlighting the environmental heterogeneity of açai-producing regions in Pará State.

Anthocyanin concentrations ranged from $43.97 \mu\text{g mL}^{-1}$ in Ananindeua to $294.48 \mu\text{g mL}^{-1}$ in Bujarú, with higher values also observed in Abaetetuba, island environments, and Marajó. Conversely, Ananindeua and Inhangapi consistently exhibited the lowest concentrations. Soil pH varied from strongly acidic conditions (Inhangapi) to near-neutral values in Marajó and island regions, while organic matter content and electrical conductivity were markedly higher in these areas, reflecting floodplain environments influenced by sediment deposition (Embrapa, 2021; Ibge, 2022).

Table 3

Descriptive statistics and inferential comparison of physicochemical parameters and anthocyanin content in Euterpe oleracea fruits from different regions of Pará State

Region	Anthocyanins ($\mu\text{g mL}^{-1}$)	Soil pH	Organic Matter (g kg^{-1})	Electrical Conductivity (dS m^{-1})	Average Temperature ($^{\circ}\text{C}$)
Abaetetuba	289.46 ± 91.37^a	5.67 ± 0.85^e	45.37 ± 10.35^c	0.85 ± 0.30^c	28.80 ± 0.30^a
Acará	222.27 ± 2.05^b	4.52 ± 0.66^e	32.45 ± 7.05^c	0.35 ± 0.15^c	27.00 ± 0.10^c
Ananindeua	43.97 ± 20.34^h	4.63 ± 0.25^e	38.51 ± 8.11^d	0.55 ± 0.20^d	26.30 ± 0.05^d
Bragança	161.55 ± 80.21^c	5.80 ± 1.15^c	50.50 ± 12.05^b	1.10 ± 0.40^b	27.00 ± 1.00^c
Bujarú	294.48 ± 9.70^a	5.95 ± 0.10^b	33.38 ± 6.05^c	0.40 ± 0.15^c	28.40 ± 0.20^a
Cametá	210.43 ± 118.66^b	5.55 ± 0.30^e	44.31 ± 9.07^c	0.70 ± 0.30^c	27.60 ± 0.10^b
Inhangapi	79.49 ± 7.91^g	3.98 ± 0.55^f	28.28 ± 6.10^f	0.25 ± 0.10^f	27.30 ± 0.40^c
Islands	283.32 ± 43.54^a	6.02 ± 0.40^b	58.36 ± 15.04^a	1.80 ± 0.50^b	27.60 ± 0.08^b
Marajó	229.59 ± 103.83^b	6.20 ± 0.53^a	65.46 ± 18.07^a	2.50 ± 0.80^a	26.00 ± 0.30^c

Note. Created by the authors (2025).

Letters a–h indicate statistically distinct groups within each column (parameter). Values sharing the same letter do not differ statistically.

Despite the observed associations, edaphic variables should be interpreted as environmental modulators rather than direct determinants of anthocyanin biosynthesis. This interpretation is supported by the variability patterns observed across regions.

Island environments exhibited relatively high anthocyanin concentrations and lower dispersion, which can be attributed to waterlogged and poorly drained soils typical of floodplains and mangroves (Embrapa, 2018; Ibge, 2022). These soils, rich in organic matter and nutrients, provide favorable conditions for plant development and may contribute to more stable anthocyanin accumulation (Embrapa, 2001). Such stability suggests that these environments are promising for the production of açaí with consistent bioactive compound content.

In contrast, regions such as Marajó and Cametá showed high dispersion and wide concentration ranges, with extreme values approaching $500 \mu\text{g mL}^{-1}$. This variability reflects the marked edaphic heterogeneity of these regions, which include a mosaic of soil types such as Latosols, Gleysols, and Neossols (Embrapa, 2001; Silveira *et al.*, 2019). The coexistence of floodplain and upland environments, combined with seasonal flooding dynamics, contributes to spatial variability in nutrient availability and plant physiological responses.

Conversely, locations such as Bujarú and Acará exhibited low variability and more homogeneous anthocyanin concentrations, indicating more stable edaphic conditions (Embrapa, 2001; Santos *et al.*, 1999). In these areas, the predominance of relatively uniform soil types supports consistent plant growth conditions, resulting in lower dispersion of the measured values. In contrast, Ananindeua and Inhangapi presented low anthocyanin concentrations, which may be associated with well-drained and less favorable soils (e.g., Latosols, Argisols, and Neossols) that limit nutrient availability and reduce secondary metabolite accumulation (Usda, 2014).

The coefficient of variation further supports this interpretation, with regions such as Marajó and Cametá showing high dispersion, while Acará and Bujarú exhibited low variability, indicating more stable production conditions (Oliveira *et al.*, 2021; Coutinho *et al.*, 2024; Santos *et al.*, 1999).

From a physiological perspective, the observed variability can be explained by plant responses to environmental stress. Flooded or poorly aerated soils can induce oxidative stress through the accumulation of reactive oxygen species (ROS) (Naing and Kim, 2021; Li *et al.*, 2023). In response, plants activate antioxidant defense mechanisms, including the phenylpropanoid pathway, leading to increased anthocyanin biosynthesis (Zhou *et al.*, 2023; Wang *et al.*, 2025).

However, this response depends on the balance between stress intensity and resource availability. Moderate environmental stress may stimulate anthocyanin production, whereas excessive stress or nutrient limitation may reduce metabolic capacity. This dynamic helps explain both the high concentrations and the large variability observed in heterogeneous environments.

Overall, the results demonstrate that anthocyanin accumulation in *Euterpe oleracea* is governed by a physiological stress-response framework, in which soil acidity, organic matter, and ionic composition influence oxidative signaling and secondary metabolism. Thus, edaphic conditions act as indirect modulators of anthocyanin biosynthesis rather than direct controlling factors.

Finally, the spatial variability observed indicates that regions with more homogeneous environmental conditions tend to exhibit lower dispersion and greater production stability, whereas heterogeneous regions show wider variation in anthocyanin content. These findings are relevant for guiding crop management strategies and selecting production areas aimed at optimizing the nutritional and functional quality of açai.

Multivariate and Regression Analysis

Principal component analysis (PCA) provided an integrated overview of the relationships among anthocyanin concentration and edaphic variables. The first two principal components explained most of the variance in the dataset and enabled the differentiation of regions according to their environmental characteristics. PC1 was primarily associated with soil pH, organic matter, and electrical conductivity, indicating that these variables represent the main edaphic gradient influencing the samples. In contrast, PC2 was mainly related to temperature and secondary variation in anthocyanin concentration, reflecting additional environmental influences.

The PCA results highlight a clear structuring of the dataset driven by soil-related parameters, reinforcing the role of edaphic conditions in shaping anthocyanin variability across regions.

Multiple linear regression analysis further supported these findings by revealing significant associations between anthocyanin concentration and key soil variables, particularly pH, organic matter content, and electrical conductivity. However, the dispersion observed in the observed versus fitted values indicates that these variables explain only part of the total variability in anthocyanin accumulation.

This partial explanatory power suggests that anthocyanin biosynthesis in *Euterpe oleracea* is regulated by a complex interaction of environmental and physiological factors. While edaphic conditions define an important baseline, additional variables—such as microclimatic conditions, genetic variability, and plant stress responses—likely contribute to the observed patterns.

Overall, the combined multivariate and regression analyses reinforce the interpretation that edaphic factors act as key modulators, but not sole determinants, of anthocyanin accumulation, supporting a physiological framework based on plant responses to environmental heterogeneity.

Influence of Edaphic Conditions on Anthocyanin Accumulation

The variability observed in anthocyanin concentration may be interpreted as a physiological response of *Euterpe oleracea* to environmental conditions. Floodplain environments, common in Amazonian regions, are characterized by water-saturated soils with limited oxygen availability, which may induce oxidative stress in plant tissues and promote the formation of reactive oxygen species (ROS) (Naing and Kim, 2021; Li *et al.*, 2023).

In response to such conditions, plants may activate defense mechanisms involving the synthesis of antioxidant compounds. Anthocyanins, as part of the flavonoid class, have been associated with the neutralization of ROS and the protection of cellular structures against oxidative damage (Zhou *et al.*, 2023; Wang *et al.*, 2025).

Thus, environmental stress associated with edaphic conditions may contribute to the activation of the phenylpropanoid pathway, potentially enhancing anthocyanin biosynthesis. This mechanism may help explain the higher concentrations observed in some floodplain environments.

However, it is important to consider that excessive stress or nutrient limitation may negatively affect plant metabolic capacity, potentially reducing anthocyanin production. Therefore, the variability observed among regions likely reflects a balance between environmental stress and resource availability, rather than a direct effect of individual edaphic factors.

Physiological Interpretation

Taken together, the statistical analyses suggest that anthocyanin accumulation in açai fruits may be better explained within a physiological stress-response framework. Soil acidity, organic matter availability, and ionic composition may influence oxidative stress signaling, potentially modulating metabolic pathways involved in phenolic compound biosynthesis.

In this context, edaphic conditions should be interpreted as indirect modulators of secondary metabolism rather than direct determinants of anthocyanin production. This interpretation is consistent with the multivariate and regression analyses, which indicate that these variables contribute to, but do not fully explain, the observed variability.

CONCLUSIONS

The results suggest that edaphic conditions are associated with the variability of anthocyanin concentrations in *Euterpe oleracea* fruits from Pará State. Regions characterized by higher organic matter content and greater ionic availability tended to exhibit higher anthocyanin levels, although this relationship was not strictly deterministic.

Multivariate and regression analyses indicate that these variables act primarily as indirect environmental modulators rather than direct determinants of anthocyanin biosynthesis, supporting a physiological framework driven by plant responses to environmental conditions.

Overall, the findings highlight the role of environmental heterogeneity in shaping the chemical composition of açai and provide relevant insights for the sustainable management and valorization of Amazonian bioresources.

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