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Compositional Characterization, Quality Parameters, and Physicochemical and Bioactive Properties of Pequi (*Caryocar brasiliense*) Oils From Xingu and Cerrado in Mato Grosso, Brazil

Dhayna O. Sobral | Patrícia T. Souza | Gabriel S. L. Pereira | Sara Fraga | Maria E. O. Carvalho | Antonio J. A. Meirelles | Eduardo A. C. Batista | Klicia A. Sampaio | Guilherme J. Maximo

Laboratory of Extraction, Applied Thermodynamics and Equilibrium, Faculty of Food Engineering, Universidade Estadual de Campinas (UNICAMP), Campinas, São Paulo, Brazil

Correspondence: Guilherme J. Maximo (maximo@unicamp.br)

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ABSTRACT

Pequi (*Caryocar brasiliense*) is a native fruit widely distributed in Brazilian biomes, specially in Cerrado, known for its high oil yield and valuable bioactive composition. This study provides a comparative characterization of oils extracted from two varieties of pequi fruits from the Mato Grosso state, Brazil, the Xingu "giant pequi" and the common variety from Cerrado. The analyses included compositional and quality parameters characterization: fatty acid (FA) and triacylglycerol (TAG) profiles, lipid classes, acidity, moisture, volatile acids, and thermal behavior (melting and crystallization). The bioactive compounds content (carotenoids, tocopherols, and tocotrienols) and oil's antioxidant capacity were further evaluated. The Cerrado pequi oil exhibited a higher lipid content (60.15%) and predominance of monounsaturated FA, particularly oleic acid (64.03%), whereas Xingu oil showed a greater proportion of saturated FA (37.83%), mainly palmitic acid (35.81%). Both oils presented low acidity and moisture, confirming high oxidative quality. Xingu oil showed higher crystallization and melting temperatures (1.35°C and 20.88°C, respectively) associated with its greater content of di-saturated TAGs. The Cerrado oil, richer in unsaturated TAGs, displayed a wider melting range and lower transition temperatures, consistent with higher fluidity. The bioactive profile revealed elevated β/γ-tocopherol (7.48 mg kg^{-1}), β/γ-tocotrienol (1.80 mg kg^{-1}), and total carotenoid (37.43 mg 100 g^{-1}) contents in Xingu oil, while Cerrado oil contained higher α-tocopherol levels (7.39 mg kg^{-1}). Xingu oil also demonstrated superior antioxidant activity (IC_{50} = 65.58 μg mL^{-1}) compared to Cerrado oil (117.94 μg mL^{-1}), reflecting the synergistic action among tocopherols, tocotrienols, and carotenoids. These results highlight the influence of regional origin on the physicochemical and functional characteristics of *C. brasiliense* oils. Xingu oil, with its greater thermal and oxidative stability, shows potential for use in frying oils, margarines, and bakery shortenings, whereas Cerrado oil stands out for its nutritional quality and suitability in cosmetic and nutraceutical formulations.

1 | Introduction

The ongoing transformation of agrifood systems toward sustainability has been not only marked by the growing consumption and trade of vegetable oils (FAO 2024) but also by the increasing demand for oils with bioactive properties, high nutritional value, and sustainable origin (Correa et al. 2024). In this context, due to an exceptional socio-biodiversity, Brazil

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stands out as a strategic supplier of diverse lipid sources derived from native species such as andiroba (*Carapa guianensis*), buriti (*Mauritia flexuosa*), bacaba (*Oenocarpus bacaba*), açaí (*Euterpe oleracea*), and Brazil nut (*Bertholletia excelsa*). These oils have gained increasing prominence due to their distinctive chemical composition and functional potential, rich in unsaturated fatty acids, tocopherols, carotenoids, and phytosterols (Cornelio-Santiago et al. 2021; Lisboa et al. 2020; Fasciotti et al. 2020; Correa et al. 2024; Silva et al. 2025). This context underscores the relevance of sustainable extractive value chains in the Amazon and Cerrado biomes, aligning environmental preservation with economic and cultural benefits for local communities.

Among the highlighted species, pequi (*Caryocar* spp.), one of the most important Non-Timber Forest Product (NTFP) in Brazil (IBGE 2024), showed a remarkable relevance by its large lipid content and potential use for value-added applications. Pequi is the fruit from *Caryocar* genus, distributed throughout Central and South America, comprising 16 species, 12 of which are found in Brazil, with occurrences in the Cerrado, Amazon, Atlantic Forest, and Caatinga biomes (Miranda et al. 2019). Its primary product is the internal mesocarp (pulp), which has high oil and carotenoid content; the pulp is attached to a spiny endocarp surrounding the seed. The oil can be obtained from the pulp by aqueous extraction using boiling water, but also by mechanical processes (also called cold-pressing) using *expeller* or hydraulic presses, favoring quality and maintenance of bioactive thermolabile compounds (Nascimento-Silva et al. 2020, 2022). It is rich in unsaturated fatty acids, which account for approximately 60%–70% of its total composition, primarily oleic acid (C18:1, ~55%–60%), while saturated fatty acids represent 30%–40%, mainly palmitic acid (C16:0, ~35%) (Nascimento-Silva et al. 2020, 2022). This balanced composition contributes to the oil's desirable physicochemical behavior, combining fluidity with moderate oxidative stability. Its promising phytochemical profile, with a particular attention to its large carotenoids content, comparable to other oilseeds found in Brazilian biome, such as macauba (*Acrocomia aculeata*) and buriti (*Mauritia flexuosa*) (Silva et al. 2009; Colombo et al. 2018), as well as in red palm oil (Tan et al. 2021), has attracted attention from various industrial sectors due to its antioxidant, anti-inflammatory, aligned to its technological potential (Cicero et al. 2018; Nascimento-Silva et al. 2020; Carneiro et al. 2023).

The *Caryocar brasiliense* is the most popular species from the *Caryocar* genus in the Brazilian Cerrado region, and its composition is largely influenced by environmental, edaphoclimatic, and genetic factors (Geöcze et al. 2021). Alves et al. (2014) reported significant variations in pulp yield, lipid content, and mineral composition among *C. brasiliense* fruits collected from the states of Tocantins, Goiás, and Minas Gerais. *C. brasiliense* fruits from the Mato Grosso Cerrado are those with pulp yields exceeding 46%, according to Cordeiro et al. (2013), alongside high lipid and carotenoid contents, underscoring their agro-industrial potential. This variability reinforces not only the role of regional conditions on pequi's oil quality or technical viability for their exploitation but also the importance of region-specific investigations, especially considering Brazil's biome diversity.

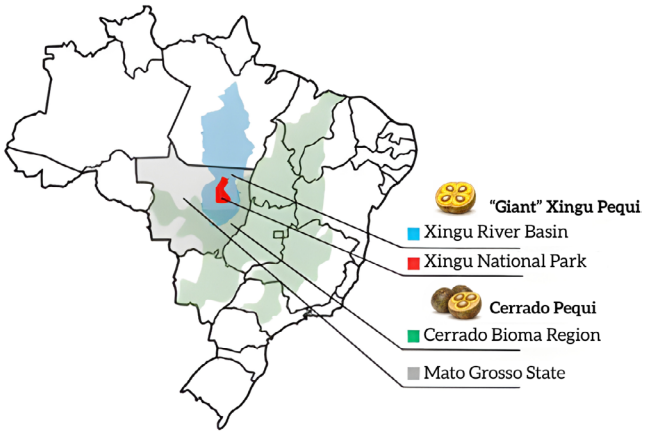


FIGURE 1 | Xingu and Cerrado regions and the Mato Grosso state (Brazil).

More recently, Silva et al. (2020) described a new variety of *C. brasiliense* in northern Mato Grosso, referred to as "giant pequi", cultivated in transitional areas between the Cerrado and Amazon biomes (Figure 1) including the Xingu Indigenous Territory (TIX). Mainly exploited by Indigenous communities, this variant exhibits larger fruit size when compared to *C. brasiliense* fruits from Cerrado, absence of spines in the endocarp, a pulp yield of 45.62%, and a composition rich in carotenoids and phenolic acids, with a lighter and more stable lipid profile. According to Silva et al. (2020) its botanical characteristics are probably attributed to shared crops and agricultural management. Making part of traditional agroecological systems, pequi cultivation or exploitation is managed through multistage and multispecies practices, being not only a genetic but also a cultural asset, important for the maintenance of indigenous and regional socio-biodiversity (Otero Sturlini et al. 2018; Smith and Fausto 2016). Initiatives such as the Xingu Women's Movement (MMX) and AMAFPA (*Associação de Mulheres da Agricultura Familiar do Portal da Amazônia*—Association of Women in Family Farming of the Amazon Gateway, free translation) have strengthened local economies through the valorization of this important NTFP and the productive and political empowerment of Indigenous women (Pereira 2021).

Therefore, the Xingu "giant pequi" attributes make it a promising candidate for large-scale applications in food, cosmetics, or pharmaceutical products. However, detailed characterization of the oil obtained from its pulp remains limited, particularly regarding complete lipid profile, tocols and carotenoids content, and antioxidant and thermophysical properties. The present study aims to provide a comprehensive characterization of the oil extracted from the "giant pequi" from the Xingu region and to perform a comparison with the common variety from the Mato Grosso state Cerrado region. This investigation integrates physicochemical, compositional, and quality analyses to identify attributes that influence the oil's technological performance and functional value. By combining regional productivity data with a green extraction approach, this study contributes to the valorization of high-yield native varieties and the development of natural ingredients for industrial applications within sustainable bioeconomic chains.

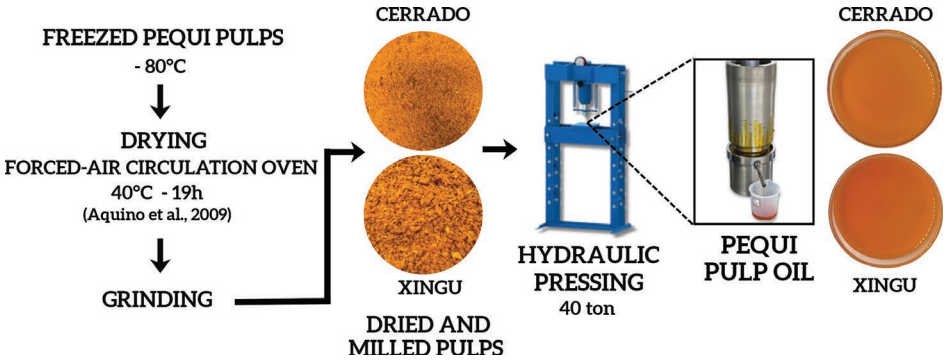


FIGURE 2 | Cold-press extraction process of pequi pulp oil: Raw material, equipment, and final products.

2 | Material and Methods

2.1 | Samples

For this study, frozen pulps of pequi fruits were used as raw materials. The samples correspond to the 2023/2024 harvest season, gently provided by the *Associação de Mulheres da Agricultura Familiar do Portal da Amazônia* (AMAFPA), located in Terra Nova do Norte, Mato Grosso state, Brazil (10°31′01″ S, 55°13′51″ W; altitude 250 m), near the transition zone between Mato Grosso state Cerrado biome and Xingu region. The two varieties were acquired from the same supplier, the Xingu "giant pequi" and the common variety from Mato Grosso state Cerrado, here called Cerrado pequi, which were stored in an ultra-freezer at −80°C throughout the analyses to preserve their physicochemical and bioactive properties.

2.2 | Oil Extraction and Characterization

To improve oil extraction yield efficiency, both samples underwent a pre-treatment adapted from Aquino et al. (2009), which involved drying the fruit pulp at 40°C for 19 h in a forced-air circulation oven (Marconi, MA03012, Brazil). The pequi pulps received already frozen and depulped from AMAFPA were thawed and homogenized before the drying process. The dried material was then ground using a bench-top blender and sieved to obtain a uniform particle size distribution. This procedure aimed to preserve sensitive bioactive compounds, such as carotenoids, reduce lipid oxidation, and standardize particle size to optimize extraction performance. The oil was subsequently extracted using a hydraulic press (Charlott, no. 5991, Brazil) operated at 25°C under a load of 40 tons-force, as defined and monitored by the equipment, and an extraction cell with an internal diameter of 5 cm. Figure 2 illustrates the extraction process, including images of the dried and homogenized raw material, the hydraulic press, and the obtained oils.

After extraction, oil's moisture content was determined according to the AOCS Official Method Ca 2e-84 (AOCS 2017), using a Karl Fischer titration system (model 870 KF Titrino Plus, Metrohm, Switzerland) coupled to a temperature-controlled oven (model 860 KF Thermoprep, Metrohm, Switzerland) maintained at 100°C. Nitrogen gas was employed to transport the released water vapor to the titration cell at a constant flow rate of 50 mL min^{-1}. The total lipid content of the oils was evaluated using the Bc 3-49 method (AOCS 2017), with the aid of an Ankom XT15 extractor (Ankom Technology, Macedon, NY, USA). Protein content was determined using a nitrogen and protein analyzer (DUMAS method) with a NDA 701 unit (Velp Scientifica, Italy), following AOAC (2019) Method 968.06. Ash content was quantified by incinerating the samples in a muffle furnace (model 3000 3P, EDG, Brazil) at 550°C, according to AOCS Method Ba 5a-49 (2017). Total carbohydrate content was estimated by difference, as defined in RDC No. 360 (Brasil 2003), subtracting the sum of moisture, ash, protein, and lipid contents from 100%. All analyses were made in triplicate.

2.3 | Fatty Acid (FA) Profile

The FA compositions of the oils were determined in triplicate by gas chromatography according to AOCS Official Method Ce 1-62 (AOCS 2017), using the following equipment conditions: Gas Chromatograph (Agilent, 7890B, USA) equipped with Flame Ionization Detector (FID) and capillary column (Agilent, DB-WAX, USA) with a length of 30 m, internal diameter of 0.25 mm, and film thickness of 0.25 μm. Helium was used as the carrier gas at a flow rate of 38 cm/s, and the column temperature was programmed from 140°C to 240°C, with an increase of 4°C/min and a 15-min hold. The injector and detector temperatures were set at 250°C, with an injection volume of 1 μL. The conversion of fatty acids into fatty acid methyl esters (FAME) was based on the methodology developed by Metcalfe et al. (1966), adapted from Hartman and Lago (1973). Peak identification was performed by comparing the retention times of fatty acid methyl ester standards (FAME mix C8—C24; Sigma Aldrich, USA).

2.4 | Triacylglycerol (TAG) Profile

The TAG profile was determined by the method described by Antoniosi Filho et al. (1995), which uses a regiospecific distribution of the FA in the sn-1, sn-2 and sn-3 glycerol backbone, considering that: the highly unsaturated fatty acid is preferentially acylated in the sn-2 position; among the remained FA, that with higher degree of unsaturation is preferentially acylated in the sn-3 position; if no difference in the degree of unsaturation is observed, the FA with the longer chain length is acylated at the sn-3 position (detailed explanation is found in the paper). The regiospecific distribution ensures more consistency in the determined TAG profile. Also, it is

considered that the main triacylglycerol represents the component with the highest concentration in the defined isomer with n carbons and double bonds (same molar mass), ignoring the set of TAGs with a composition below 0.5%. As required by the methodology, the content in tri-saturated TAGs were obtained in literature (Segall et al. 2006), set as close to 0.0%. Calculated TAG profile (for which standard deviation does not apply) was obtained by using an algorithm implemented in MATLAB software (Mathworks, Natick, MA), described elsewhere (Ceriani 2005).

2.5 | Quality Parameters

2.5.1 | Fourier Transform Infrared Spectroscopy (FTIR)

FTIR analysis can provide a fingerprint of the oil, particularly important in case of adulteration or other chemical characterizations. Analysis was performed by using an Agilent Cary 630 spectrometer (USA), operated with Microlab software, and equipped with an Attenuated Total Reflectance (ATR—MicromATR Czitek, USA) accessory, employing a ZnSe crystal. Liquid and homogeneous samples were obtained by heating at 60°C, and a small film was deposited on the ZnSe crystal (also at 60°C). Spectra were recorded at multiple time points. Analysis was performed in the range of 4000–650 cm^{-1}, with resolution of 4 cm^{-1} in which 8 background scans and 8 sample scans were done for each spectrum, according to Souza et al. (2024). Spectra were acquired through transmittance, and data was subsequently analyzed using Origin 8.0 software (OriginLab Co., USA).

2.5.2 | Acid Value

The acid value, that indicates the triacylglycerols hydrolysis grade during fruit harvesting, storage and processing, allowing or avoiding consumption, according the Brazilian regulation for vegetable oils and fats (IN No. 87, Brasil 2021), was determined in triplicate in accordance with the AOCS Official Method Cd 3d-63 (AOCS 2017), using an automatic titrator (model 848 Titrino Plus, Metrohm, Switzerland) equipped with a LiCl electrode saturated in ethanol to detect the endpoint. To express the results as free fatty acids (FFA), the obtained acid value was divided by 1.99, which corresponds to the conversion factor for oleic acid, the predominant fatty acid in the samples.

2.5.3 | Partial Acylglycerols Content

Considering that potential TAG hydrolysis can lead to the formation of partial acylglycerols, responsible for oil's physicochemical properties changes, important for product formulation, total mono- (MAGs) and diacylglycerols (DAGs) were determined. Analysis was performed in triplicate by gas chromatography according to AOCS Official Method Cd 11-b-91 (AOCS 2017), which is based on the conversion of these glycerols into trimethylsilyl ether derivatives with N,N-bis(trimethylsilyl)trifluoroacetamide (BSTFA) (Sigma-Aldrich, USA). The gas chromatograph used was the same as described previously. Helium was used as the carrier gas at a flow rate of 5 cm^3/min, and the column temperature was programmed from 80°C to 380°C, with an increase of 10°C/min and a 1-min hold. The injector and detector temperatures were 320°C and 380°C, respectively, and the injection volume was 1 μL. The determination of mono- and diacylglycerols was carried out using the equations of the calibration curves obtained and the sum of the areas of the retention times. The content of triacylglycerols (TAGs) was obtained by 100% difference with respect to the levels of free fatty acids (FFA), mono- and diacylglycerols.

2.5.4 | Volatile Carboxylic Acid Profile

The carboxylic acid profile of the oils, related to oxidation phenomena, was determined in triplicate by ion chromatography (IC), according to the method described by Souza et al. (2017), using an ion chromatograph (Metrohm, 940 Professional IC Vario, Switzerland) equipped with a Metrosep organic acid 250-7.8 column (250 × 7.8 mm), and a pre-column with similar internal composition.

2.6 | Physicochemical and Bioactive Properties

2.6.1 | Melting and Crystallization Profile

The thermal behavior of the samples was analyzed in triplicate by differential scanning calorimetry, using the DSC 2920 calorimeter (TA Instruments, New Castle, USA) coupled with a cooling system using Nitrogen (Purity > 0.9999% m/m) as the purge gas and calibrated to standards indium (PerkinElmer, purity 0.99% m/m), naphthalene, cyclohexane, and n-decane (all Sigma-Aldrich, purity 0.99% m/m) adapted from AOCS Official Method Cj 1–94 (AOCS 2017; Pereira et al. 2019). The samples were weighed in aluminum crucibles (between 3 and 5 mg), with one empty and hermetically sealed used as reference. The analysis conditions were as follows: the samples were maintained at 70°C for 10 min, then cooled at a rate of 5°C/min to −60°C and held at this temperature for 30 min; after this cycle, the samples underwent a melting process from −60°C to 70°C at a rate of 5°C/min. The TA Universal Analysis 2000 software was used to obtain the thermal curves and to define the evaluation parameters: onset crystallization temperature (T_{onset}), crystallization and melting events (T_{peak}), final melting process (T_{offset}) as well as total crystallization (H_c) and melting enthalpies (H_m).

2.6.2 | Bioactive Composition: Total Carotenoids and Tocopherols/Tocotrienols Profile

Total carotenoid content was quantified in triplicate using a UV–visible spectrophotometer at 450 nm, following a method adapted from Rodriguez-Amaya (2001). The absorbance values were calculated using the absorption coefficient of β-carotene in acetone (2667), according to calibration curves constructed by using standard β-carotene (≥ 95%, HPLC, Sigma- Aldrich), and the results were expressed as β-carotene equivalents (μg of β-carotene per gram of oil). The quantification of tocols was carried out following the protocol described by Ansolin et al. (2017), employing

TABLE 1 | Centesimal composition (% mass) of pequi pulp, dried and *in natura* obtained in this work and from literature (*in natura*).

Compounds (g/100 g)[1]	This work				Literature (*in natura*)	
	Dry pulp		*In natura*		Cordeiro et al. (2013)[2] (Cerrado pequi)	Silva et al. (2020)[3] (Xingu pequi)
	Cerrado	Xingu	Cerrado	Xingu		
Moisture	5.91 ± 0.32^{b}	12.67 ± 0.21^{a}	45.90 ± 0.18^{b}	58.73 ± 0.10^{a}	46.80–50.62	47.56 ± 1.39
Lipid	60.15 ± 0.79^{a}	55.22 ± 0.53^{b}	32.54 ± 0.43^{a}	22.79 ± 0.26^{b}	27.06–32.40	15.95 ± 0.09
Protein	7.02 ± 0.24^{a}	5.95 ± 0.20^{b}	3.80 ± 0.12^{a}	2.46 ± 0.08^{b}	1.77–3.30	2.75 ± 0.09
Ash	1.73 ± 0.06^{a}	1.28 ± 0.02^{b}	0.94 ± 0.03^{a}	0.53 ± 0.01^{b}	0.46–0.57	0.26 ± 0.03
Carbohydrate	25.18 ± 0.33^{a}	24.88 ± 0.54^{a}	16.82 ± 0.58^{a}	15.49 ± 0.23^{b}	13.14–23.86	33.20 ± 0.43

[1]Values expressed as mean ± standard deviation ($n = 3$). Different letters (a and b, superscript) within the same row (in "Dry pulp" and "In natura" columns) indicate significant differences (between Cerrado and Xingu) at $p < 0.05$ (Tukey's test).
[2]Variation of the mean content of pequi pulps from four regions of Mato Grosso state.
[3]Composition of the municipality of Peixoto de Azevedo, Mato Grosso State, Brazil.

ultra-high performance liquid chromatography coupled with electrospray ionization and mass spectrometry (UHPLC/ESI/MS). The analyses were conducted using an Acquity SQD Single Quadrupole system (Waters, USA) equipped with a C18 reverse-phase column (UPLC Acquity BEH-C18, Waters, USA). The mobile phase consisted of a mixture of methanol:water:ammonium hydroxide (99:1:0.1, v/v/v) and isopropanol, delivered in gradient mode using a binary pump system. Instrument control and data acquisition were performed using MassLynx software (Waters, USA). Quantification was based on calibration curves constructed with external analytical standards (α, β/γ, δ-tocopherol and α, β/γ, δ-tocotrienol, ≥ 97%, HPLC, Supelco).

2.6.3 | Antioxidant Capacity by DPPH IC_{50}

The antioxidant capacity of the oil samples was evaluated in triplicate using the DPPH (2,2-diphenyl-1-picrylhydrazyl) free radical scavenging method, adapted from Espín et al. (2000), Valavanidis et al. (2004), and Silveira et al. (2018), with modifications. Reactions were prepared in 15 mL Falcon tubes, with a total volume of 6 mL and a final DPPH concentration of 100 μmol·L^{-1}, obtained by mixing 3 mL of a 200 μmol·L^{-1} DPPH solution with 3 mL of solvent. Oil samples were prepared by weighing approximately 2.4 g into Falcon tubes, followed by the addition of 8 mL of ethyl acetate to obtain an initial concentration of ~0.3 g·mL^{-1}. Samples were vortexed until fully dissolved. If undissolved material remained, the solution was centrifuged at 10,000 rpm for 5 min, and only the supernatant was used in the assay. Reaction mixtures were prepared by varying the sample volume (100–800 μL) and adjusting the final volume to 6 mL with the respective solvent, while maintaining the DPPH solution constant at 3 mL. A control sample containing DPPH and solvent (without the oil) and a blank with only the solvent were included in the assay. After incubation in the dark for 30 min at room temperature, the absorbance was measured at 515 nm using a UV–Vis spectrophotometer. The percentage of DPPH radical reduction was calculated relative to the control. A linear regression curve was constructed by plotting the percentage of DPPH reduction against the final sample concentration, and the IC_{50} (μg mL^{-1}), concentration required to reduce 50% of the DPPH radicals, was determined from the regression equation.

2.7 | Statistical Analysis

Data obtained from triplicate analyses were expressed as mean values ± standard deviation. Statistical comparisons among groups were performed using Tukey's test at 5% significance level, employing R software (version 4.1.1, R Foundation for Statistical Computing, Vienna).

3 | Results and Discussion

3.1 | Characterization of the Pulp and Extracted Oils

Before extraction, pequi pulps from Xingu and Cerrado were preceded by a standardized drying process, as detailed described in methodology, to improve extraction performance. After drying, notably, a significant difference in the residual moisture content of the samples was observed: 12.67% ± 0.20% for pequi from the Xingu and 5.91% ± 0.32% for pequi from the Cerrado of Mato Grosso. This difference may be attributed to the morphology of the Xingu pequi pulp, which exhibits a thicker and denser texture. Table 1 presents the chemical composition (as mean values ± standard deviation) of dried and *in natura* pequi pulps in this study (Cerrado and Xingu), along with values reported in the literature for the same study region and varieties (Cordeiro et al. 2013; Silva et al. 2020).

The moisture and lipid contents of the fresh pequi pulps from the Cerrado and Xingu regions exhibited statistically significant differences ($p < 0.05$), reflecting distinct compositional characteristics between the two populations. The Cerrado pulp displayed a moisture content of 45.90% ± 0.18% and a lipid content of 32.54% ± 0.43%, while the Xingu pulp showed higher moisture (58.73% ± 0.10%) and lower lipid content (22.79% ± 0.26%) (Table 1). These results highlight a compositional contrast that may influence oil yield and stability between the regional varieties. These findings align with the literature, which reports variations in the nutritional profiles of pequi based on geographic origin. Cordeiro et al. (2013) observed lipid contents ranging from ~46 to 51 g/100 g in pequi pulps from Mato Grosso, while Nascimento-Silva et al. (2020, 2022) reported values ranging from ~13.0 to 37.5 g/100 g for

fruits from various Cerrado regions. The lower lipid content in the Xingu pequi may be associated with the greater thickness of the pulp, which hindered uniform drying, or with genetic differences among populations, as observed by Silva et al. (2020), who highlighted morphological and compositional variations in novel pequi populations.

The elevated moisture content in Xingu pulp (58.73%) contrasts with the typical values for Cerrado (~46%–51%) reported by Cordeiro et al. (2013), suggesting that factors such as precipitation, soil type, and fruit maturation may influence water retention. This characteristic directly impacts drying efficiency, as the Xingu pequi required a longer processing time to reach 12.67% moisture (dry basis), compared to 5.91% in the Cerrado. The inverse relationship between moisture and lipid content is consistent with previous studies, such as those by Alves et al. (2014), who associated higher lipid levels with less hydrated pulps. Regarding other components, the Cerrado pequi exhibited a higher protein content (3.80% ± 0.12%) compared to the Xingu (2.46% ± 0.08%), a difference that may reflect variations in soil nutrient availability. This aligns with discussions by Cordeiro et al. (2013), who related the chemical composition of the pulp to edaphic parameters such as silt, phosphorus, and magnesium. The ash content, indicative of mineral levels, was also higher in the Cerrado (0.94% ± 0.03% vs. 0.53% ± 0.01%), supporting the hypothesis of soil influence on nutritional composition. In contrast, carbohydrates, calculated by difference, were similar between the regions (Cerrado: 16.82%; Xingu: 15.49%), consistent with the range of 15%–28.67% reported by Silva et al. (2020) for *Caryocar* spp. pulps.

From an industrial perspective, these compositional differences directly affect oil recovery and processing efficiency. The higher moisture content of the Xingu pulp increases the time and energy required for drying and can reduce oil yield due to limited solvent penetration and slower mass transfer (Pérez et al. 2019). Conversely, the Cerrado pulp, with its lower moisture and higher lipid content, favors more efficient extraction and reduced processing costs. Similar relationships between pre-drying conditions and extraction performance have been demonstrated in several oilseed matrices (Aquino et al. 2009; Rani et al. 2021). Moreover, excessive moisture during processing can promote lipid hydrolysis and accelerate lipid oxidative degradation, negatively affecting oil stability and shelf life (Mwaurah et al. 2020; Machado et al. 2023).

Therefore, the higher lipid content of Cerrado pulp (32.54%) suggests greater potential for oil extraction compared to Xingu pulp (22.79%), further supported by the yield after drying (60.15% vs. 53.43%). However, the high initial moisture content of Xingu pulp demands further optimization of the drying process to prevent oxidative losses, as highlighted by Borges et al. (2022) in studies on pequi oil. It is important to note that, despite, the presence of monounsaturated fatty acids (MUFA), such as oleic acid (~55% of lipids), as previously documented by Cordeiro et al. (2013) and Nascimento-Silva et al. (2020, 2022), underscores the nutritional and technological value of the oil, drying and other process stages strongly requires careful handling in order to preserve thermosensitive compounds such as carotenoids and polyphenols.

Table 2 presents the fatty acid composition and estimated triacylglycerol (TAG) profile of the extracted oils. Cerrado oil stood out for its higher MUFA content (64.51%), predominantly oleic acid (C18:1), whereas Xingu oil exhibited a higher proportion of saturated fatty acids (SFA, 37.83%), primarily palmitic acid (C16:0, 35.81% ± 0.00%). The high oleic acid content provides cardiovascular health benefits, such as reducing LDL cholesterol and modulating lipid profiles, aligning with studies that highlight pequi as a source of functional lipids (Nascimento-Silva et al. 2020). The higher SFA content observed in Xingu oil (Table 2), together with its relevant proportion of MUFAs, contributes to enhanced oxidative stability—a desirable attribute for thermal applications such as frying or baking, but also during storage and temperature variations (Xu et al. 2015; Ghaly and El-khamissi 2021; Saha et al. 2025). Therefore, the combination of saturated and monounsaturated fatty acids provides a balanced lipid profile, ensuring both nutritional quality and resistance to oxidation.

Both oils exhibited low polyunsaturated fatty acid (PUFA) levels (< 2.1%), which reduces the risk of rancidity but limits the supply of essential fatty acids, such as linoleic acid (C18:2). Beyond PUFA levels, previous studies also highlight pequi as a source of natural antioxidants, such as carotenoids (e.g., β-carotene) and phenolic compounds (Silva et al. 2020; Geöcze et al. 2021). These bioactive compounds, that will be further investigated in next sections, may mitigate oxidative susceptibility associated with MUFA or PUFA, thereby contributing to an extended shelf life of the oils.

It is interesting to highlight that, in this context, pequi oil has been found as a prominent food source with health benefits. Braga et al. (2022) demonstrated that pequi fruit extracts enhance antioxidant enzyme activity and reduce oxidative damage in human coronary artery endothelial cells, highlighting its cardioprotective action. More recently, Silva et al. (2023) reinforced these findings, showing that pequi oil exerts anti-inflammatory and antioxidant effects that may aid in the prevention of metabolic and cardiovascular disorders. Souto et al. (2025) and Assis et al. (2025) have demonstrated that native Brazilian oils such as pequi, buriti, and acuri enhance antioxidant capacity and provide favorable nutritional attributes when incorporated into food products.

The estimated TAG profile, calculated based on the experimentally determined FA distribution, revealed distinct compositions between the oils (Table 2). OOP (1,2-dioleoyl-3-palmitoyl-glycerol) was more prevalent in Cerrado oil (44.69%) compared to Xingu oil (41.79%), while POP (1,3-dipalmitoyl-2-oleoyl-glycerol) was higher in Xingu oil (32.04%) compared to Cerrado oil (23.84%). Additionally, the triolein (OOO) content was greater in Cerrado oil (21.00%) than in Xingu oil (13.67%), reinforcing the higher degree of unsaturation in the Cerrado sample. These main TAGs were also found by Segall et al. (2006) using electrospray and mass spectrometry for *C. brasiliense* oils from Minas Gerais state Cerrado region (6.0% OOO, 48.0% OOP, 47.0% POP), whose variation are due to a lower oleic acid and higher palmitic acid composition of this author's sample (44,28% palmitic acid, 48,71% oleic acid). This also reinforces how region, edaphic parameters and other variations can affect oil's composition and properties.

TABLE 2 | Experimentally determined FA profile and estimated TAG profile of pequi oils.

				Pequi oils from MT region (% w.w^{-1})	
Fatty acids[1]				**Cerrado**	**Xingu**
C12:0	L	Lauric acid		—	—
C14:0	M	Myristic acid		—	—
C16:0	P	Palmitic acid		30.33 ± 0.01^{b}	35.81 ± 0.00^{a}
C16:1	Po	Palmitoleic acid		0.48 ± 0.00^{b}	0.69 ± 0.04^{a}
C18:0	S	Stearic acid		2.06 ± 0.00^{a}	2.02 ± 0.00^{a}
C18:1	O	Oleic acid		64.03 ± 0.01^{a}	58.12 ± 0.00^{b}
C18:2	Li	Linoleic acid		1.75 ± 0.01^{b}	2.02 ± 0.02^{a}
C18:3	Ln	Linolenic acid		—	—
C20:0	A	Arachidic acid		—	—
C22:0	B	Behenic acid		—	—
Others[2]				1.35	1.34
SFA[3] (%)				32.39	37.83
MUFA (%)				64.51	58.81
PUFA (%)				1.75	2.02
TAG[4]	**CN**[5]	**UN**	**MM (g.mol^{-1})**	**Cerrado**	**Xingu**
OOP	55	2	859.4	44.69	41.79
POP	53	1	833.4	23.84	32.04
OOO	57	3	885.4	21.00	13.67
POLi	55	3	857.4	2.46	3.48
POS	55	1	861.4	2.90	3.26
OOS	57	2	887.4	2.72	2.12
OOLi	57	2	883.4	1.73	1.45
PLiP	53	2	831.3	0.66	2.18
Mono-unsaturated[6]				27.40	37.48
Di-unsaturated				47.41	43.91
Tri-unsaturated				25.19	18.60

[1]Values expressed as mean ± standard deviation ($n = 3$). Different letters (a and b, superscript) within the same row indicate significant differences (between Cerrado and Xingu) at $p < 0.05$ (Tukey's test).
[2]Other fatty acids not identified by analysis.
[3]MUFA = monounsaturated fatty acids, PUFA = polyunsaturated fatty acids and SFA = saturated fatty acids.
[4]TAG profiles were estimated; therefore, standard deviation does not apply to TAG values.
[5]CN (Carbon Number) and UN (Number of Unsaturation = double bonds).
[6]TAGs grouped according to the number of unsaturated acyl chains: mono-unsaturated (one unsaturated chain), di-unsaturated (two), and tri-unsaturated (three).

When grouped according to the number of unsaturated acyl chains, Cerrado oil exhibited 27.40% mono-, 47.41% di-, and 25.19% tri-unsaturated TAGs, while Xingu oil showed 37.48%, 43.91%, and 18.60%, respectively. These values highlight the slightly higher overall unsaturated characteristic of Cerrado oil, in line with its elevated MUFA content, whereas Xingu oil presented a greater share of mono-unsaturated TAGs linked to its higher SFA level.

This composition can affect oil's technological properties, as will be observed in the evaluation of the crystallization and melting profiles of the samples. Indeed, TAGs rich in oleic acid (e.g., OOP and OOO), most prominent in Cerrado oil, contribute to lower melting points and greater fluidity at ambient temperature, characteristics that enhance their technological suitability for liquid lipid formulations such as dressings, nutraceutical emulsions, or oleogel-based systems, that require oxidative stability and desirable texture (Fasciotti et al. 2020; Braga et al. 2022; Zhao et al. 2021; Correa et al. 2024). In contrast, a higher proportion of saturated fatty acids, as observed in Xingu oil, with a predominance of POP shows enhanced thermal and oxidative stability, imparting a firmer texture, making

TABLE 3 | Quality aspects, bioactive compounds (tocols and carotenoids) and antioxidant properties (DPPH) of pequi oils from Cerrado and Xingu.

Composition	Pequi oils from MT region[1]	
	Cerrado	Xingu
Total lipids (%)	99.04 ± 0.44[a]	98.46 ± 0.26[a]
MAG (% w/w)	1.43 ± 0.01[b]	2.38 ± 0.08[a]
DAG (% w/w)	2.69 ± 0.02[a]	2.77 ± 0.31[a]
TAG (% w/w)	95.04 ± 0.04[a]	94.86 ± 0.23[a]
Acid value (mg_{KOH}/kg)	1.36 ± 0.01[b]	2.09 ± 0.03[a]
FFA[2] (% w/w)	0.68	1.05
Moisture (%)	0.16 ± 0.02[b]	0.28 ± 0.01[a]
Volatile acids (mg/kg)		
Formic acid	6.54 ± 1.64[b]	13.64 ± 0.15[a]
Acetic acid	125.64 ± 5.3[a]	134.64 ± 6.8[a]
Propanoic acid	12.85 ± 0.20[a]	13.24 ± 0.38[a]
Total carotenoids (mg/100 g)	28.10 ± 0.49[b]	37.43 ± 1.70[a]
Tocopherols ($mg.kg^{-1}$)		
β/γ-tocopherol	4.16 ± 0.09[b]	7.48 ± 0.18[a]
α-tocopherol	7.39 ± 0.15[a]	4.72 ± 0.04[b]
β/γ-tocotrienol	0.81 ± 0.02[b]	1.80 ± 0.02[a]
α-tocotrienol	0.80 ± 0.02[b]	0.92 ± 0.03[a]
Antioxidant activity—DPPH (IC_{50} μg.ml^{-1})	117.94 ± 6.46[a]	65.58 ± 8.34[b]

[1]Values expressed as mean ± standard deviation ($n = 3$). Different letters (a and b, superscript) within the same row indicate significant differences at $p < 0.05$ (Tukey's test).
[2]FFA = acidity expressed as oleic acid content; Values expressed as mean ± standard deviation ($n = 3$).

it suitable for structured lipids, fat replacers, and semi-solid food applications such as shortenings, vegetable creams, or spreads (Xu et al. 2015; Guedes et al. 2017; Ghaly and El-khamissi 2021; Aragão and Maximo 2024).

3.2 | Quality Aspects

Table 3 presents the characterization of cold-pressed and crude pequi oils, focusing on their quality aspects. Statistically significant differences ($p < 0.05$) were observed between the Cerrado and Xingu samples. The total lipid content was slightly higher in the Cerrado oil (99.04% ± 0.44%) compared to the Xingu oil (98.46% ± 0.26%), whereas the latter exhibited a significantly higher acid value (2.09 ± 0.03 mg KOH/g) and free fatty acid (FFA) content (1.05%), which indicates a greater degree of TAG hydrolysis. The partial acylglycerol profile also supports these observations: DAG contents were higher than MAG contents in both samples, consistent with moderate hydrolytic activity but maintaining overall oil integrity. It is important to note that acylglycerol composition can also influence key physicochemical properties such as crystallization and emulsification behavior, which will be discussed later in this work.

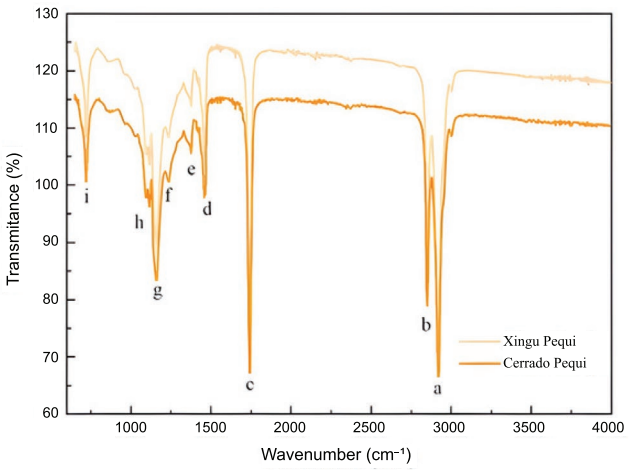


FIGURE 3 | FTIR spectra for the pequi oils obtained.

These findings suggest minor variations in post-harvest handling, storage conditions of the fruit, pulp's enzymatic activity, but also compositional and physiological differences in the fruits (Bustan et al. 2014; El Qarnifa et al. 2019). Indeed, Nascimento-Silva et al. (2020, 2022) reported that short-term storage at ambient temperature (~25°C) before processing can alter lipid and carotenoid contents in pequi fruits, reinforcing the importance of standardized post-harvest protocols to preserve oil quality and bioactive compounds. On the other hand, despite these findings, it is possible to observe that acid values for both oils are within the limits of the Brazilian legislation (IN No. 87/2021) for cold-pressed and unrefined vegetable oils (< 4.0 mg KOH/g), confirming their high quality for food purposes (Brasil 2021). Also, both oils were predominantly composed of triacylglycerols (TAG), representing over 94% of the lipid fraction, consistent with good extraction efficiency and low degradation, confirming their potential for food and cosmetic applications (Souza et al. 2024).

Regarding volatile carboxylic acids, statistically significant differences ($p < 0.05$) were observed for formic and acetic acids, which were higher in Xingu oil (13.64 ± 0.15 mg/kg and 134.64 ± 6.8 mg/kg, respectively) than in Cerrado oil (6.54 ± 1.64 mg/kg and 125.64 ± 5.3 mg/kg). Propanoic acid, however, showed no significant variation ($p > 0.05$). Results revealed distinct concentrations among the analytes for the Cerrado and Xingu samples. Volatile acids are end products of lipid oxidation and are directly associated with the oxidation level of such matrices (Souza et al. 2017). However, the volatile acid concentrations determined represent less than 2% of the total acidity index of the oils (1.5% for Pequi do Xingu and 2.1% for Pequi do Cerrado). This indicates that, despite the presence of volatile acids, most of the acid value determined in these pequi oils originates from free fatty acids, primarily formed through enzymatic or thermal hydrolysis, rather than from advanced oxidative processes. This result indicates minimal oxidative degradation, evidencing good preservation and extraction practices.

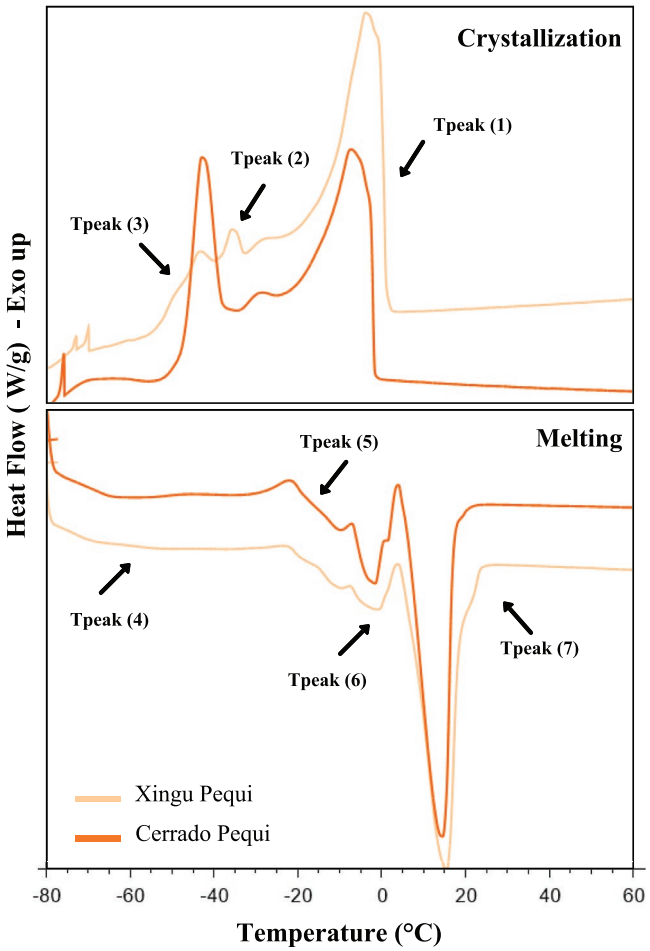


FIGURE 4 | DSC crystallization and melting thermograms of pequi oils from Cerrado and Xingu regions. Peak temperatures (T_{peak}) and other evaluated data are detailed in Table 4.

TABLE 4 | Crystallization and melting temperatures (°C) and enthalpy (J/g) of pequi oils from the MT region obtained by DSC (Figure 4).

	Pequi oils from MT region	
Parameter	**Cerrado**	**Xingu**
Crystallization		
T_{onset}	-1.55 ± 0.03^{b}	1.35 ± 0.13^{a}
$T_{peak\ 1}$ (Region 1)	-6.48 ± 0.06^{b}	-3.48 ± 0.17^{a}
$T_{peak\ 2}$ (Region 1)	-29.14 ± 0.25^{a}	-35.73 ± 0.21^{b}
$T_{peak\ 3}$ (Region 1)	-42.85 ± 0.19^{a}	-45.00 ± 1.31^{b}
ΔH_c	56.55 ± 1.32^{b}	62.29 ± 1.66^{a}
Melting		
$T_{peak\ 4}$ (Region 1)	-60.58 ± 0.71^{a}	-66.41 ± 0.86^{b}
$T_{peak\ 5}$ (Region 2)	-8.93 ± 0.13^{a}	-8.88 ± 0.75^{a}
$T_{peak\ 6}$ (Region 2)	0.72 ± 0.04^{a}	1.24 ± 0.34^{a}
$T_{peak\ 7}$ (Region 2)	17.11 ± 0.15^{b}	18.44 ± 0.36^{a}
T_{endset}	19.61 ± 0.09^{b}	20.88 ± 0.31^{a}
ΔH_m	59.00 ± 0.83^{b}	84.95 ± 1.00^{a}

Note: Values expressed as mean ± standard deviation ($n = 3$). Different letters (a and b, superscript) within the same row indicate significant differences at $p < 0.05$ (Tukey's test); ΔH values correspond to the total enthalpy of the crystallization or melting regions, obtained by integrating all peaks; Peak numbers correspond to equivalent thermal events observed in Figure 4.

The FTIR spectra of both Cerrado and Xingu pequi oils (Figure 3) exhibited the characteristic absorption bands of triacylglycerols, as summarized in Table S1. Strong bands near 2920 cm^{-1} and 2850 cm^{-1} correspond to the asymmetric and symmetric stretching of CH_2 groups, confirming the presence of long aliphatic chains typical of fatty acids. The intense band at 1743 cm^{-1} is attributed to the C═O stretching of ester groups, indicating a predominance of intact triacylglycerols with no evident hydrolysis, since no shift toward lower wavenumbers (around 1710 cm^{-1}) was detected. Additional bands at 1457 and 1375 cm^{-1} (CH_2 and CH_3 bending vibrations), and at 1234, 1116, and 1093 cm^{-1} (C—O stretching of ester groups), further support the structural integrity of the lipid matrix. The band at 721 cm^{-1}, assigned to CH_2 rocking and cis-olefinic bending, reflects both the length of methylene sequences and the degree of unsaturation. These spectral features are consistent with the fatty acid composition determined by gas chromatography, which showed high proportions of oleic and palmitic acids. Moreover, the absence of new or broad bands around 3400 cm^{-1} (hydroxyl groups) and 1710 cm^{-1} (free fatty acids) indicates that the oils are well preserved, with no evidence of oxidative or hydrolytic degradation. Slight variations in band intensity and frequency between the samples are attributed to differences in chain length and unsaturation degree of the acyl groups. This agreement between FTIR and chromatographic profiles, also highlighted by Souza et al. (2024) for vegetable oils, confirms the chemical quality and authenticity of the analyzed oils (Guillén and Cabo 1997; Guillén et al. 2003; Quiñones-Islas et al. 2013; Aktar and Adal 2019; Ioannidi et al. 2023).

3.3 | Physicochemical and Bioactive Properties

3.3.1 | Thermal Behavior of Pequi Oils (Melting and Crystallization)

Figure 4 shows the DSC crystallization and melting thermograms of pequi oils from the Cerrado and Xingu regions. The numbered peaks in Figure indicate the equivalent thermal events in both samples, while the corresponding peak temperatures and enthalpy values are summarized in Table 4. During crystallization, both oils exhibited a main crystallization region extending from approximately −45°C to 0°C, within which three exothermic peaks were identified for each sample. For Cerrado oil, the crystallization started (T_{onset}) at 1.35°C ± 0.13°C, whereas for Xingu oil this value was found at −1.55°C ± 0.03°C. The total crystallization enthalpy (ΔH_c) was 56.55 J/g for Cerrado oil and 62.29 J/g for Xingu oil. These enthalpy values correspond to the total enthalpy of the crystallization regions, obtained by summation of the area of all crystallization peaks. The higher enthalpy and the narrower crystallization range of the Xingu oil indicate greater crystalline order and packing efficiency, which can be attributed to its higher content of SFA and, therefore, higher content of di-saturated TAGs such as POP and POS. In contrast, the Cerrado oil, richer in unsaturated or di-unsaturated TAGs (OOP and OOO) due to its

predominance in oleic acid (64.03%), exhibited broader and less intense peaks, suggesting a more heterogeneous crystallization process typical of oils with a higher proportion of liquid fractions at low temperatures (Segall et al. 2006; Pereira et al. 2019).

Regarding melting behavior, two main endothermic regions were identified in both oils. The first region, extending from approximately −60°C to −20°C, contained low-intensity peaks corresponding to the melting of the lesser ordered and polyunsaturated TAGs (e.g., OOLi and POLi). The second region, between 0°C and 20°C, exhibited multiple overlapping peaks associated with the melting of mono- and di-saturated TAGs such as OOP, POP, and POS. Between melting regions, a recrystallization phenomenon (exothermic event) can also be observed, which is a characteristic behavior of TAGs molecules during heating, particularly due to polymorphism (Pereira et al. 2019). This profile was also observed in other fats and oils from Amazonian fats such as Bacuri and Cupuassu (Pereira et al. 2019; Souza et al. 2024; Aragão and Maximo 2024), which are also rich in di-saturated TAGs such as POP or SOS. The Xingu oil presented final melting temperature (T_{endset}) at 20.88°C ± 0.31°C, while the Cerrado oil exhibited final transitions at 19.61°C ± 0.09°C. The total melting enthalpy ΔH_m reached 59.00 ± 0.83 J/g for Cerrado oil and 84.95 ± 1.00 J/g for Xingu oil. The higher melting enthalpy and melting temperatures observed for Xingu oil reflect its greater degree of saturation (37.83% SFA) and the predominance of structured di-saturated TAGs such as POP (32.04%), which promote the formation of a more stable crystalline lattice. This structural rigidity enhances thermal and oxidative stability, making the Xingu oil more suitable for applications requiring high-temperature resistance, such as frying or margarine production. Additionally, this higher crystallinity and, therefore, molecular organization can be modulated to optimize texture and stability in formulated products, reinforcing Xingu oil potential for technological applications (Guedes et al. 2017). Conversely, the Cerrado oil, with its higher monounsaturated fatty acid content (64.51% MUFA) and abundance of unsaturated TAGs (OOO and OOP), exhibited lower enthalpy transitions and a wider melting range, consistent with greater fluidity at ambient temperature, an advantage for liquid oil applications in dressings, encapsulated nutraceuticals, and cosmetic formulations (O'Brien 2009; Pereira et al. 2019; Aragão and Maximo 2024).

Mono- and diacylglycerols (MAGs and DAGs), as well as free fatty acids (FFAs), exert complementary influences on the thermal behavior of oils. Both oils exhibited similar DAG contents, while Xingu oil contained higher levels of MAGs (2.38% ± 0.08%) and FFAs (1.05%). Although these values are low, they reflect subtle compositional differences likely associated with the oils' distinct fatty acid and triacylglycerol profiles (Table 2). According to Guedes et al. (2017), mono- and diacylglycerols act as modulators of the crystalline phase, influencing the nucleation process and, consequently, the formation, stability, and size of fat crystals. The authors demonstrated that these compounds promote molecular rearrangements within the lipid matrix, directly affecting crystal morphology and polymorphism in the oil. Crystallization processes can also be hindered or favored, as described in studies on vegetable oils (Nicholson et al. 2021; Oliveira et al. 2014). These minor compounds can also interact with triacylglycerols (TAGs), promoting rearrangements in the crystalline network, altering the stability of the polymorphic forms (α, β′, and β) sometimes retarding or accelerating some transitions, which can be interesting or negative depending on the demanded application. This behavior reflects the significant influence of these components on modulating the physical properties of oils, as evidenced in previous studies on vegetable oils and fats (Segall et al. 2006; O'Brien 2009).

3.3.2 | Bioactive Compounds

Table 3 presents the contents of bioactive compounds, including tocopherols, tocotrienols, and total carotenoids, as well as the antioxidant activity (DPPH) for both pequi oils. Statistical analysis revealed significant differences ($p < 0.05$) among all evaluated bioactive compounds and antioxidant activities between the Cerrado and Xingu pequi oils. Both oils exhibited significant amounts of total carotenoids, with the Xingu oil (37.43 ± 1.70 mg/100 g) showing higher levels when compared to the Cerrado oil (28.10 ± 0.493 mg/100 g). This difference in concentration may be attributed to factors such as botanical variety, cultivation conditions, and the maturity stage of the fruits at harvest. Previous studies have identified pequi oil as a valuable natural source of carotenoids, particularly β-carotene, which is primarily responsible for the intense yellow-orange color of the pulp and contributes significantly to its antioxidant capacity (Geöcze et al. 2021; Braga et al. 2022; Silva et al. 2011). Reported concentrations of total carotenoids in pequi pulp range from 15.5 to 27.0 mg/100 g, depending on the region of origin and fruit maturation stage (Ribeiro et al. 2014; Cordeiro et al. 2013; Lima et al. 2007). In oil extracted from pequi, carotenoid contents vary according to the extraction method: values between 29.61 and 42.66 mg/100 g have been reported for solvent-based extractions, while 24.96 mg/100 g and 26.87 mg/100 g were observed for mechanical pressing and cooking-based extraction, respectively—methods where thermal degradation may reduce the retention of these sensitive compounds (Rodriguez-Amaya 2001). Additionally, Cordeiro et al. (2013) reported an average β-carotene content of 21.55 mg/100 g in fruits collected in Mato Grosso, further highlighting the regional influence on the bioactive profile of pequi fruits and their derived oils.

These compositional variations are not only of nutritional interest but also directly influence the technological performance and industrial applicability of pequi oil. Oils with higher carotenoid concentrations exhibit greater oxidative stability due to the radical-scavenging capacity of β-carotene and other pigments, which delay lipid oxidation and color degradation during storage and processing (Geöcze et al. 2021; Braga et al. 2022). These properties also enhance their potential use as natural antioxidants or colorants in functional foods, cosmetic emulsions, and nutraceutical formulations (Ribeiro et al. 2014; Fasciotti et al. 2020; Correa et al. 2024). Therefore, understanding how regional and processing factors modulate the carotenoid profile is essential for tailoring pequi oil to specific industrial purposes.

Both pequi oils also revealed significant levels of tocopherol and tocotrienol. The main identified components were β/γ-tocopherol, α-tocopherol, β/γ-tocotrienol, and α-tocotrienol. Xingu oil stood out for its higher β/γ-tocopherol content (7.48 ± 0.18 mg/kg), while Cerrado oil showed a higher concentration of α-tocopherol

(7.39 ± 0.15 mg/kg). This result is noteworthy as α-tocopherol is the most biologically active form of vitamin E in the human body and is directly associated with protecting cellular membranes against oxidative damage. Conversely, β/γ-tocopherol exhibits synergistic action with other antioxidants, such as carotenoids and phenolic compounds, enhancing the oxidative stability of the oil (Souza et al. 2024; Shahidi and de Camargo 2016). Regarding tocotrienols, Xingu oil exhibited a higher content of β/γ-tocotrienol (1.80 ± 0.02 mg kg^{-1}) compared to Cerrado oil (0.81 ± 0.02 mg kg^{-1}). These compounds have been associated with additional health benefits, such as neuroprotective, anti-inflammatory, and hypocholesterolemic effects, as well as an important role in lipid protection within food systems (Braga et al. 2022; Silva et al. 2023; Souza et al. 2024).

These compositional profiles indicate distinct antioxidant strategies between the two regional varieties: while the Cerrado oil's higher α-tocopherol content provides superior biological vitamin E activity, the Xingu oil's higher levels of β/γ-tocopherol and tocotrienols enhance synergistic antioxidant effects and oxidative stability. Similar health and technological benefits were reported in previous studies (Souza et al. 2024; Pereira et al. 2019) for cold-pressed oils of Amazonian origin, such as pracaxi and murumuru, whose high levels of tocols were related to greater oxidative resistance and higher nutritional value of the oil. The balanced presence of different tocol isoforms in the evaluated oils also suggests potential technological advantages, as these compounds can enhance product stability during processing and storage. Furthermore, the cold-press extraction method contributes to the preservation of these compounds, as highlighted by Silva et al. (2020), who demonstrated that oils extracted without solvents and at low temperatures retain higher levels of tocopherols and other bioactive compounds.

Considering a main property associated with the presence of these bioactive compounds, oils' antioxidant activity was assessed via the DPPH assay. Results revealed the greater Xingu oil's antioxidant activity, which had a lower IC_{50} value (65.58 ± 8.34 μg mL^{-1}) compared to the Cerrado oil (IC_{50} = 117.94 ± 6.46 μg mL^{-1}). This result indicates a stronger ability of the Xingu oil to neutralize the stable DPPH radical, which agrees with its slightly superior bioactive profile. In this case, the superior level of total carotenoids and higher content of β/γ-tocopherol and tocotrienols found in Xingu oil seems to play a more significant role for the antioxidant performance of the product, probably due to a synergistic contribution of the compounds when compared to the higher concentration in α-tocopherol found in the Cerrado oil. According to Nascimento-Silva et al. (2020, 2022), the combined presence of tocopherols, tocotrienols, and carotenoids is key to enhancing the oxidative stability of vegetable oils and supports their functional and nutraceutical benefits. This antioxidant synergy is also extensively discussed by Correa et al. (2024), who emphasize the relevance of tocopherols and carotenoids as major contributors to the antioxidant activity and stability of oils from Brazilian tropical fruits. In addition to carotenoids, phenolic compounds naturally present in pequi pulp significantly contribute to its antioxidant capacity. According to Silva et al. (2011), the synergistic interaction between carotenoids and phenolics enhances protection against reactive oxygen species, amplifying the antioxidant efficacy of the lipid matrix. This bioactive composition, characteristic of Cerrado fruits, is particularly valued in natural health-oriented products, reinforcing the growing interest in pequi oil for nutraceutical and cosmetic formulations.

It is important to highlight that the antioxidant efficiency of these oils is directly associated with the preservation of bioactive compounds during oils' extraction. The cold-pressing technique used in this study (hydraulic press) avoids the use of organic solvents and excessive heat, favoring the retention of thermosensitive compounds such as carotenoids and tocopherols (Silva et al. 2020; Pereira et al. 2019). Similar findings have been reported in studies on native Amazonian oils, where low damage extraction methods proved essential for maintaining the functional profile of the oils, positively influencing their antioxidant potential, nutritional value, and industrial applications (Fasciotti et al. 2020).

4 | Conclusions

This study provided a comprehensive comparison between pequi oils extracted from fruits of the Xingu and Cerrado regions, whose botanical and origin differences markedly influenced their physicochemical, structural, and functional characteristics. Cerrado fruits exhibited a higher lipid content (60.15%) and predominance of monounsaturated fatty acids, particularly oleic acid (64.03% ± 0.01%), higher presence of tri-unsaturated TAG, together with higher levels of α-tocopherol (7.39 ± 0.15 mg kg^{-1}). In contrast, Xingu "giant" pequi oil presented a higher proportion of saturated fatty acids (37.83%), di-saturated TAGs, and a balanced presence of tocopherols, tocotrienols, and carotenoids with greater levels of β/γ-tocopherol (7.48 ± 0.18 mg kg^{-1}) and β/γ-tocotrienol (1.80 ± 0.02 mg kg^{-1}). This profile contributes to oils with higher solid fraction, oxidative stability, enhanced thermal resistance and notable antioxidant activity (IC_{50} of 65.58 ± 8.34 μg mL^{-1}).

These compositional traits highlight Cerrado pequi oil's advantages for industrial exploitation due to its higher oil yield and superior biological vitamin E activity, supporting its application in nutraceutical, cosmetic, and functional liquid lipid formulations. On the other hand, combined with its morphological advantages—spineless endocarp and thicker pulp—favoring its agro-industrial exploitation, Xingu "giant pequi" provides an oil that can be used in formulations demanding structural consistency and stability, such as margarines, creams, frying oils, bakery shortenings, and fillings.

Notedly, the use of cold-press extraction proved effective in preserving thermosensitive compounds, ensuring high bioactive retention, low lipid hydrolysis, and contributing to the stability and shelf-life of the final products. Altogether, the compositional and technological attributes of these oils emphasize their versatility and potential as functional lipid sources for food, nutraceutical, and cosmetic applications, particularly in the case of Xingu oil, emerging as an especially attractive alternative to other commercial oils such as palm oil or palm olein. In addition, the study underscores the importance of promoting sustainable production chains based on Brazilian socio-biodiversity, strengthening regional

economies while fostering the conservation and valorization of native species.

Author Contributions

D.O.S. worked on data validation, formal analysis, investigation, writing of original draft, reviewing and editing, conceptualization, methodology, and data curation. M.E.O.C., G.S.L.P., S.F., P.T.S. worked on data curation, formal analysis, conceptualization, methodology, and writing of original draft. K.A.S. worked on conceptualization, methodology definition, and supervision. E.A.C.B. worked on conceptualization, methodology definition, supervision, and funding/resources acquisition. A.J.A.M. worked on conceptualization, methodology definition, and supervision. G.J.M. worked on data visualization, supervision, project administration, funding/resources acquisition, reviewing, and editing of the manuscript.

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Ethics Statement

No humans or animals were used in the research for this paper.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Assignment of FTIR spectra of pequi oils (Ioannidi et al. 2023; Aktar and Adal 2019; Quiñones-Islas et al. 2013; Guillén et al. 2003; Guillén and Cabo 1997).