Original Article

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Exploring the potential of ucuúba (*Virola surinamensis*) seed fat

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Abstract: Ucuúba (*Virola surinamensis*) fat is an important income source for Amazonian communities. Local businesses typically process whole seeds for fat extraction; however, seed structural integrity may influence extraction efficiency and fat quality. This study evaluated the effect of seed shelling as a preprocessing strategy on lipid recovery from ucuúba seeds. Fat samples extracted by pressing from whole (WUF) and shelled seeds (SUF) were characterized in terms of fatty acid composition, quality parameters (smoke point, acid value, free fatty acids, peroxide value, slip melting point, saponification value, unsaponifiable matter, iodine value), total phenolic content (TPC), antioxidant activity measured using 2,2-diphenyl-1-picrylhydrazyl (DPPH) and 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) assays, and thermal behavior measured by differential scanning calorimetry (DSC). Shelling increased fat yield, with SUF reaching 52.05% compared with 47.65% for WUF, thereby reducing residual press cake generation. Both samples presented similar quality and showed a predominance of saturated fatty acids, including myristic (72% to 73%) and lauric (17% to 18%). The WUF sample showed a higher TPC than SUF (6.54 and 5.82 mg GAE g^{-1}, respectively), with correspondingly higher antioxidant activity, as determined by ABTS (4.26 μmol TE g^{-1}) and DPPH (12.25 μmol TE g^{-1}). Thermal analysis showed a distinct exothermic event during crystallization and a single endothermic peak upon melting. These results indicate that shelling enhances fat recovery but reduces phenolic content and antioxidant activity, potentially increasing operational costs. The compositional and thermal characteristics of ucuúba fat suggest its suitability for cosmetic and therapeutic applications within Amazonian bioeconomy value chains. © 2026 The Author(s). *Biofuels, Bioproducts and Biorefining* published by Society of Industrial Chemistry and John Wiley & Sons Ltd.

Key words: ucuúba fat; hydraulic pressing; saturated fatty acids; phenolic content; antioxidant activity; amazonian bioproducts

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Introduction

Ucuúba is an Amazonian tree from the genus *Virola*. *Virola surinamensis* (Rol.) Warb and *V. sebifera* Aubl are the most widespread species in the lower Amazon. The name 'ucuúba' derives from the Tupi language, meaning 'tree that produces fat', and the tree is also known as 'wild nutmeg' due to its resemblance to nutmeg – both belong to the Myristicaceae family.[1,2]

Products derived from ucuúba trees play a crucial role in the local economy and traditional practices. They are used to treat rheumatic pain, asthma, tumors, intestinal parasites, ulcers, and infections.[3,4] However, intensive exploitation of the tree for its wood during 1970s and 1980s resulted in significant damage, leading to its inclusion on the International Union for Conservation of Nature (IUCN) Red List of endangered species.[5] The responsible and sustainable use of ucuúba fruits as nontimber forest products represents an alternative to timber exploitation, supporting Amazonian bioeconomy initiatives that aim to enhance the livelihoods of local communities. Any valorization strategy for ucuúba fat should therefore be aligned with sustainable harvesting and conservation practices to avoid renewed pressure on natural populations.

The ucuúba fruit is ellipsoidal or elongated and contains a single seed, which constitutes approximately 40% of the fruit weight.[1] This seed is enclosed within a reddish or orange aril, a fleshy structure that surrounds the seed. The seed itself is primarily composed of kernel (82%) and a thin capsule-like shell (18%),[6] as presented in Fig. 1.

The lipid content of the seed can reach 76% (w/w).[1] It is characterized by highly saturated fat, which is considered to be uncommon due to its composition: myristic acid (C14:0) 71% to 77%, lauric acid (C12:0) 16% to 17%, and palmitic acid (C16:0) 2% to 6%,[7,8] with trimyristin (MMM) and dimyristyl-lauryl-glycerol (MMLa) as the major corresponding triglycerides.[9] Nevertheless, important differences have been observed in ucuúba fatty acid composition in some studies, primarily related to the predominance of C14:0 and C12:0 fatty acids.[10,11] These discrepancies may reflect not only environmental or genetic influences but also differences in analytical approaches.

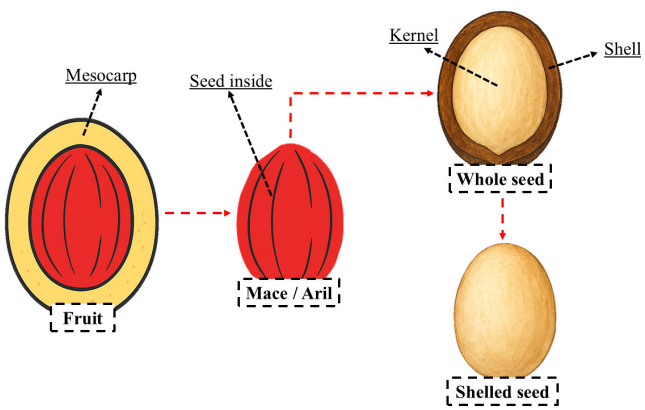


Figure 1. Parts of the fruit and seed of *Virola surinamensis*.

Due to the high saturated fatty acid (SFA) content, the lipid fraction of the seeds, mostly represented by ucuúba fat, has a high melting point, 39–45 °C, as noted by Serra *et al.*[12] Its stability and consistency, comparable to those of beef tallow, contribute to applications in high-melting-point products like soaps and candles.[13] Although it was historically used as fuel for lighting, the value and recognition of ucuúba have since evolved, and it is now appreciated in the cosmetic industry due to its skin-moisturizing properties.[14] Its unique fatty acid profile, combined with its stability, makes this fat especially suitable for cosmetics (body creams and soaps), where it enhances texture and hydration properties. The potential of ucuúba fat as a nano-structure lipid carrier (NLC) for onychomycosis treatment,[15] and as an alternative fuel source,[7] was investigated recently.

The harvesting and fat extraction of ucuúba seeds in Amazonian riverside communities remains predominantly artisanal. Seeds are typically heated near their fat melting point to improve pressing yield. Pressing is performed by an expeller or hydraulic press, depending on local resources (in this study, hydraulic pressing was specifically evaluated as a low-cost, energy-efficient option widely accessible to small-scale and community-based processing systems). Although shell removal is recommended, whole seeds are commonly processed,[6] making this a key technological variable that may influence product quality and production sustainability; however, systematic comparative studies remain limited. The shells contain valuable bioactive compounds,[16] highlighting the relevance of this decision within an integrated valorization perspective.

The aim of this study was therefore to comparatively evaluate how ucuúba processing (whole or shelled seeds) can influence the composition, quality, and thermal behavior of the recovered fat, while also considering the implications for the valorization of co-products within an integrated bioeconomy framework.

Material and methods

Samples

Ucuúba seeds (5 kg) were collected in the city of Breves, Ilha do Marajó, Brazil (1° 40′ 57″ S: 50° 28′ 51″ W), and donated by the company 100% Amazonia, located in Belém-PA, Brazil.

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Fat extraction

Fat samples were recovered from shelled and whole ucuúba seeds (SUF and WUF, respectively), using a Tecnal TE-098 hydraulic press (Piracicaba, Brazil). To produce the SUF, seeds were cracked manually and the shells were separated from the kernels. Prior to pressing, whole and shelled seeds were heated at 60 °C for 120 min in an air-circulating oven (Nova Etica, Piracicaba, Brazil), a common procedure employed industrially for the extraction of high melting-point fats.[17] Preheating improves the efficiency of the pressing process as the fat material is more fluid. The seed samples were pressed twice. The fat samples were purified, while still warm, by centrifugation using Daiki 80-2B centrifuge (São José dos Pinhais, Brazil) at 1968 × *g* for 10 min. The supernatant was collected using a micropipette and stored in an amber glass bottle under a nitrogen atmosphere at −20 °C. All assays were performed in triplicate for yield determination.

Shelling and pressing yields, and material balance

The shell yield was expressed as a percentage, calculated as the ratio of the shell mass (g) to seed mass (g). The shelling yield (X_s; g 100 g^{-1}) of the ucuúba seeds was calculated as the mass of shell (M_{shell}) relative to the total mass of raw material (M_{rm}). The pressing yield (X_p; g. 100 g^{-1}) was determined for shelled (SS) and unshelled seeds (US), as the mass of extracted fat (M_{fat}) relative to the corresponding seed mass (M_{ss} and M_{us}), using Eqn 1. The process mass balance was calculated with Eqn 2.

$$X_{p(SS)} = \frac{M_{fat}}{M_{ss}} \times 100 \text{ and } X_{p(US)} = \frac{M_{fat}}{M_{us}} \times 100 \quad (1)$$

$$M_{rm\ (SS\ or\ US)} = M_{fat} + M_{cake} + M_{lm} \quad (2)$$

where M_{rm} is the total mass of raw material for the SS or US samples (g); M_{fat} is the mass of fat recovered from pressing (g); M_{cake} is the mass of cake, remained after extraction (g); and M_{lm} is the mass of losses from the pressing process (g).

Proximate composition of ucuúba seed cake and seed shells

The proximate composition of the samples was analyzed in duplicate following official AOAC methods:[18] moisture (AOAC method no. 935.40) was determined by oven drying at 105 °C until constant weight; ash (932.03) was determined by incineration at 550 °C; protein (920.87) was determined by the micro-Kjeldahl method, calculated as nitrogen × 5.30; and lipids (920.85) were determined by Soxhlet extraction with hexane at its boiling point (~69 °C). Total carbohydrates were calculated by difference, subtracting moisture, protein, lipids, and ash from 100%. The energy value was calculated by summing the caloric contributions of protein and carbohydrates, each multiplied by 4, plus the contribution of lipids multiplied by 9.

Ucuúba fat quality assessment

The ucuúba fat samples were characterized in accordance with the American Oil Chemists Society (AOCS) official methods:[19] acid value (Cd 3d-63); peroxide value (Cd 8–53); saponification value with methanol (Cd 3c-91); calculated iodine value (Cd 1c-85); unsaponifiable matter (Ca-6b-53); smoke point (Cc 9a-48), and slip melting point (Cc 3b-92) were assessed. All analyses were performed in duplicate.

Fatty acids profile of the ucuúba fat

The fat samples were hydrolyzed and esterified to fatty acid methyl esters (FAMEs) as described by Hartman *et al.*[20] The FAMEs were determined on a gas chromatographer (GC-2014, Shimadzu, Kyoto, Japan) equipped with a flame ionization detector, a split-injection port, and 105 m long Restek capillary column (ID = 0.25 mm) coated with a 0.25 µm film of 10% cyanopropylphenyl and 90% biscyanopropylsiloxane. The injector and detector were at 260 °C. The oven was initially set at 140 °C for 5 min, and the temperature was increased by 2 °C min^{-1}. The fatty acids were identified by comparing the retention times with those of standards (Sigma, St Louis, USA). The quantification by area normalization was expressed as mass percentage. Class-GC10 software was used to acquire and process the gas chromatography data. This analysis was performed in duplicate.

Triacylglycerol composition

The triacylglycerol (TAG) composition was estimated using the PrOleos platform software. The simulations were based on the 1,3-random-2-random distribution hypothesis, employing the equations proposed by Filho *et al.*,[21] which allow estimation of the molar percentage of TAGs in vegetable oil samples based on the concentration of the fatty acids present.

Total phenolic content and *in vitro* antioxidant activity

The phenolic fraction from the fat samples was obtained by exhaustive extraction from the ucuúba fats (WUF and SUF)

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using methanol, following Teixeira *et al.*[22] Total phenolic content (TPC) was then determined from the methanolic extracts, following the method described by Koşar *et al.*,[23] with samples analyzed at 725 nm using a microplate spectrophotometer (Agilent, Epoch-BioTek, Santa Clara, CA, USA) and reported as mg of gallic acid equivalent (GAE) per g of fat.

The antioxidant activity of the WUF and SUF was evaluated by two assays: a 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay, as described by Brand-Williams *et al.*,[24] and a 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) assay, as described by Re *et al.*,[25] with some modifications. For DPPH, measurements were taken at 517 nm. The methanolic extracts were brought to concentrations of 31.50 g L^{-1} (WUF) and 31.31 g L^{-1} (SUF). For ABTS, the reagent solution was mixed with potassium persulfate, and react for 16 h in the absence of light. The resulting solution was diluted to achieve an absorbance of near 0.7 at 734 nm. The methanolic extracts were diluted and adjusted to a concentration of 24 g L^{-1}, mixed with the ABTS solution, and after 30 min, the absorbance was measured at 734 nm.

The antioxidant activity was expressed as a percentage of DPPH or ABTS scavenging, calculated using Eqn (3), and as μmol of Trolox (6-hidroxi-2,5,7,8-tetrametilcroman-2-carboxilato) equivalent per g of extract (μmol TE g^{-1}). Ultrapure water was used as blank. For each sample, measurements were carried out on three technical replicates. All analyses were performed in triplicate.

$$AP = \left(1 - \left(\frac{Abs_{sample}}{Abs_{blank}}\right) \times 100\right) \quad (3)$$

Thermal analysis

Thermal analysis of fat samples was performed using a Q2000 differential scanning calorimeter (DSC) (TA Instruments, New Castle, DE, USA). Measurements were carried out in a nitrogen atmosphere using aluminium cells with a constant flow of 50 mL min^{-1}. Fat samples were melted and homogenized in a water bath at 50 °C. Then, 5 mg of each sample were deposited into an aluminium cell. The DSC analysis was conducted in three stages: first, the sample was heated from 25 °C to 80 °C at 10 °C min^{-1} and held for 10 min to reach thermal equilibrium. After this, the sample was cooled at 10 °C min^{-1} from 80 °C to −70 °C and held for 10 min to stabilize the sample. Then, the sample was heated again from −70 °C to 80 °C at a rate of (10 °C min^{-1}).[8] The analysis was performed in duplicate.

Statistical analysis

Data were expressed as means ± standard deviations. Graphs were created and statistical analysis conducted using OriginPro 2021 (OriginLab, Northampton, MA, USA). Differences between means were evaluated using Student's t-test at a 5% significance level ($P < 0.05$).

Results and discussion

Mass balance, extraction yield and proximal composition

Ucuúba fat (UF) samples were recovered from the whole (W) and shelled (S) ucuúba seeds, and the resulting fat materials were labeled as WUF and SUF, respectively. No differences in color or density were observed between WUF and SUF, and both samples behaved similarly during handling and pressing, although no instrumental measurements were performed. The (S) seeds appeared slightly easier to press and heated somewhat faster during preheating due to their lower mass. Table 1 summarizes the extraction mass balance (pressing from the heated seeds).

Reducing the shell content by 14% from the whole seeds, the corrected SUF yield was 44.6%, similar to that of the whole seeds sample (48%). The whole seeds, which include shells, produced a higher cake yield. From Table 1, although shell removal adds an extra step, pressing whole or shelled seeds gave comparable fat yields (after accounting for shell mass), while whole seeds yielded more cake for further processing and reduced losses. Pressing whole seeds, therefore, appears to be the most suitable approach. Whole seeds also contribute phenolics and other bioactive compounds from the shells, enriching both the fat and the cake.[26]

Table 1. Mass balance of ucuúba seed processing for fat extraction.

Seed	Shells (%)	Fat (%)	Cake (%)	Loss (%)
Whole	14.28 ± 0.92	47.65 ± 0.34^{b}	48.52 ± 2.26^{a}	3.83 ± 0.36^{b}
Shelled	N.A.	52.05 ± 1.04^{a}	41.17 ± 1.36^{b}	6.78 ± 1.08^{a}

Note: Data are expressed as means ± standard deviations ($n = 3$). Different superscript letters in the same line indicate significant differences ($P < 0.05$) between samples, as measured by a *t*-test.

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Table 2 presents the proximate composition (wet basis) of seed cakes from whole and shelled samples (WSC and SSC, respectively), obtained by hydraulic pressing, compared with the shells (SH). The cakes differed significantly in macronutrients ($P < 0.05$), particularly in lipids and total carbohydrate contents. The WSC sample showed higher lipid content (33.24%) than SSC (23.54%), indicating that pressing whole seeds retains more fat in the cake, consistent with Table 1. The WSC sample also had significantly lower carbohydrate content (43.32%) than SSC (53.20%), mainly due to its higher lipid and protein levels. Although shells are a source of fiber, their low proportion in WSC limits their effect on the total carbohydrate content. Protein content was similar in both cakes (~15%), whereas SH contained much lower levels (2.84%).

From a biorefinery perspective, processing whole or shelled seeds should be evaluated in terms of overall biomass utilization. The use of whole seeds enables comprehensive biomass utilization, allowing simultaneous valorization of fat, phenolic compounds, and shell carbohydrates, while producing a larger press cake that can serve as a valuable source of lipids, proteins, and carbohydrates for subsequent industrial or functional applications. In contrast, shelled seeds yield higher purity fat, but the resulting cake is smaller and potentially less enriched in bioactive compounds.

Quality parameters of the fat samples

Table 3 shows the quality parameters of the ucuúba fat samples, with significant differences between samples ($P < 0.05$) for smoke point, acid index, and free fatty acid content (FFA).

The acid index for WUF (28.29 mg KOH g^{-1}) showed significantly higher values than SUF (23.63 mg KOH g^{-1}). Values ranging from 10 to 39 mg KOH g^{-1} of acid index for ucuúba fat were previously reported,[8,10–12] although they are significantly higher than the maximum limit of 4.0 mg KOH g^{-1} established by the Codex Alimentarius[27] for

Table 2. Proximate composition (wet basis) of ucuúba seed cake obtained by hydraulic pressing from shelled seed cake (SSC), whole seed cake (WSC), and seed shells (SH).

Components (g 100 g^{-1})†	SSC	WSC	SH
Moisture	5.21 ± 1.14[a]	5.16 ± 0.13[a]	10.45 ± 0.97
Ash	3.33 ± 0.41[a]	3.19 ± 0.23[a]	3.30 ± 0.84
Protein‡	14.72 ± 0.43[a]	15.09 ± 0.57[a]	2.84 ± 0.43
Fat	23.54 ± 1.02[b]	33.24 ± 2.71[a]	4.41 ± 4.35
Total carbohydrate content§	53.20 ± 1.64[a]	43.32 ± 2.78[b]	79.00 ± 4.56
Energetic value (kcal 100 g^{-1})¶	483.54 ± 11.41[b]	532.8 ± 26.91[a]	367.05 ± 43.22

Note: Different letters in the same row indicate significant differences between cake samples (SSC and WSC) as measured by a *t*-test ($P < 0.05$).
†Constituents expressed as mean ± standard deviation of two replicates (wet basis).
‡Protein content calculated using a conversion factor of 5.30.
§Total carbohydrates estimated by difference.
¶Energy value calculated using the factors 4 for crude protein, 4 for total carbohydrates, and 9 for total fats.

Table 3. Quality parameters of ucuúba fats from whole seeds (WUF) and shelled seeds (SUF).

Quality parameters	WUF	SUF
Smoke point (°C)	134.00 ± 1.00[b]	142.67 ± 2.52[a]
Acid value (mg KOH g^{-1})	28.29 ± 0.05[b]	23.63 ± 0.03[a]
FFA (% myristic acid basis)	11.50 ± 0.02[b]	9.61 ± 0.01[a]
Peroxide value (mEq O_2 kg^{-1})	1.11 ± 0.13[a]	1.52 ± 0.07[a]
Slip melting point (°C)	41.13 ± 0.65[a]	41.73 ± 0.25[a]
Saponification value (mg KOH g^{-1})	195.66 ± 0.56[a]	191.74 ± 2.15[a]
Unsaponifiable matter (%)	2.04 ± 0.36[a]	1.75 ± 0.38[a]
Iodine value (g I 100 g^{-1}, TAG basis)*	2.98 ± 0.39[a]	3.11 ± 0.36[a]

Note: Data are expressed as means ± standard deviations ($n = 2$). Different superscript letters in the same line indicate significant differences ($P < 0.05$) between samples, as measured by a *t*-test.
*Calculated from the fatty acid profile.

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cold-pressed oils and fats. These higher values result from greater triglyceride hydrolysis. Usually, hydrolytic rancidity in fats and oils from seeds is due to the presence of lipolytic enzymes in the seeds,[28] and due to the presence of water. Ucuúba trees usually grow near water streams and the seeds are often collected from water, contributing to hydrolytic processes. The lack of adequate post-harvest processing in local communities also promotes nonmicrobial deterioration of the fat, leading to a further increase in acidity. The low smoke points of the fat samples, 134 °C for WUF and 143 °C for SUF, are correlated with the high acidity of the fat samples.

Although these conditions limit the direct food use of ucuúba fat, they do not preclude industrial or oleochemical applications, as in cosmetics, soaps, candles, or structured lipids. As cultivation and handling of ucuúba fruits and seeds advance technically, reducing the acidity of the lipid fraction could expand its industrial applicability. This characterization therefore provides a baseline for understanding current fat quality and identifying potential upgrading pathways within Amazonian bioeconomy frameworks. Strategies to reduce hydrolytic degradation (such as lowering the moisture content of the seeds during harvest, preventing them from falling into flooded areas using physical barriers, or accelerating the collection process) could help to improve the quality of the oil both during processing and in the final product.

Peroxide values for the WUF and SUF samples showed no significant differences, with low values consistent with those previously reported for ucuúba fat.[8,10] These results can be attributed to the very low unsaturated fatty acid content and high saturated fatty acid content, which make ucuúba fat extremely stable against oxidative rancidity. These values are also below the upper limits permitted by Brazilian food regulations (ANVISA) and Codex Alimentarius (2019)[27] of 15 mEq O_2 kg^{-1} peroxide value for unrefined fats and oils.

The slip melting point values did not differ significantly between samples, and the high values reflect the high SFA concentration. These results are consistent with those of Serra *et al.*,[12] who reported a melting point at 39.3 °C for fat from *V. surinamensis* seeds.

The saponification index did not differ significantly between samples and was high (above 190 mg KOH g^{-1}), reflecting the high content of C14:0 and C12:0 fatty acids (see the next section). Feitosa *et al.*[10] reported a saponification value of 181 mg KOH g^{-1} for ucuúba fat extracted by pressing. These values are slightly lower than the saponification index of murumuru fat (228.3 mg KOH g^{-1}), which, like ucuúba fat, is rich in medium-chain SFA such as C12:0.[29]

The difference in unsaponifiable matter between samples was not significant, with higher values than those found in other Amazonian fats rich in lauric and myristic acids, such as tucumã kernel fat (0.47%) and murumuru fat (0.16%).[30] Unsaponifiable matter from SUF and WUF can be attributed to waxes, fat-soluble vitamins, phytosterols, pigments, resins, and phenolic compounds.[8,12,14,31]

Iodine values did not differ significantly between samples, consistent with the low unsaturated fatty acids (UFA) content (see the next section). These values were lower than those reported by Pereira *et al.*[32], who measured an iodine index value of 8.5 g I 100 g^{-1} for *V. surinamensis* fat with higher concentrations of monounsaturated (MUFA) and polyunsaturated fatty acids (PUFA) (4.21% and 0.89%, respectively), in comparison with those found in the present study as discussed below.

Fatty acids profile and triacylglycerols of ucuúba fat

Table 4 presents the fatty acid profiles of the WUF and SUF fat samples. Despite the overall similarity in the fatty acid profiles between the samples, significant differences were observed in the concentration of oleic acid (C18:1 *cis*-9) and the total polyunsaturated fatty acids (ΣPUFA). These variations can likely be attributed to the influence of the shell composition in the WUF sample, specifically in those molecules.

Saturated fatty acids were predominant in both samples (94% to 96%), with MUFAs and PUFAs present at low concentrations (0.5% to 3%). The main SFA is myristic acid (C14:0) (72% to 73%) followed by lauric (C12:0) (17% to 18%) and palmitic acids (C16:0) (3.6% to 3.9%). The high myristic acid content is unusual for most vegetable oils and fats; for instance, coconut, babassu, and cupuaçu oils contain 17% to 21%, 16%, and 0.60%, respectively.[33–35] The present results (Table 4) are consistent with those reported by Cordeiro *et al.*,[36] Takano *et al.*,[14] and others, indicating a higher concentration of C14:0 compared with C12:0, in contrast to the findings of Feitosa *et al.*[10] for *V. sebifera* and Holanda *et al.*[11] for *V. surinamensis*. These composition differences may be explained by the methods used for fatty acid identification. The results in Table 4 were based on retention times of analytical standards, whereas Feitosa *et al.*[10] used comparison with the mass spectra database of the National Institute of Standards and Technology (NIST), which could be further confirmed using standards. Agronomic, climatic, and genetic factors appear insufficient to account for such large differences. Kobelnik *et al.*[37] reported C12:0 concentrations similar to C14:0 using analytical standards for identification.

Oleic acid (C18:1) was the predominant MUFA in both samples, followed by myristoleic (C14:1) and palmitoleic acids (16:1), consistent with Pereira *et al.*[32] Takano *et al.*[14] also

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Table 4. Fatty acid profile of the ucuúba fat samples, from whole seeds (WUF) and shelled seeds (SUF).

Fatty acid	WUF (%)	SUF (%)
Capric acid (C10:0)	0.74 ± 0.20[a]	0.68 ± 0.20[a]
Lauric acid (C12:0)	17.55 ± 1.22[a]	17.43 ± 1.48[a]
Myristic acid (C14:0)	72.27 ± 2.19[a]	73.67 ± 0.96[a]
Myristoleic acid (C14:1)	0.63 ± 0.11[a]	0.56 ± 0.06[a]
Palmitic acid (C16:0)	3.64 ± 0.51[a]	3.91 ± 0.54[a]
Palmitoleic acid (C16:1)	0.11 ± 0.11[a]	0.15 ± 0.15[a]
Stearic acid (C18:0)	0.49 ± 0.02[a]	0.53 ± 0.07[a]
Oleic acid (C18:1 *cis*-9)	2.56 ± 0.16[b]	2.68 ± 0.15[a]
Linoleic acid (C18:2 *cis*-9,12)	0.41 ± 0.02[a]	0.41 ± 0.14[a]
Docosadienoic acid (C22:2)	1.44 ± 1.44	nd
Eicosenoic acid (C20:1)	0.09 ± 0.09	nd
ΣSFA	94.67 ± 1.30[a]	96.21 ± 0.10[a]
ΣMUFA	3.38 ± 0.03[a]	3.39 ± 0.24[a]
ΣPUFA	1.84 ± 1.44[a]	0.41 ± 0.14[b]
ΣUFA	5.22 ± 1.41[a]	3.79 ± 0.10[a]

Note: Data are expressed as means ± standard deviations ($n = 2$). Different superscript letters in the same line indicate significant differences ($P < 0.05$) between samples, as measured by a *t*-test. Abbreviations: MUFA, monounsaturated fatty acids; nd, not detected; PUFA, polyunsaturated fatty acids; SFA, saturated fatty acids; SUF, shelled ucuúba fat; UFA, unsaturated fatty acids; WUF, unshelled ucuúba fat.

Table 5. Triacylglycerol (TAG) composition of ucuúba fat extracted from whole (WUF) and shelled (SUF) seeds using hydraulic pressing.

TAG code	WUF (wt%)*	SUF (wt%)*
CLaM	0.37 ± 0.01[b]	0.75 ± 0.01[a]
LaLaLa	0.44 ± 0.02[b]	0.69 ± 0.00[a]
CMM	0.85 ± 0.00[b]	1.42 ± 0.04[a]
MLaLa	6.01 ± 0.22[b]	7.84 ± 0.12[a]
PLaLa	0.35 ± 0.00[b]	0.36 ± 0.02[a]
MLaM	27.67 ± 0.49[b]	29.71 ± 0.92[a]
MMyLa	0.37 ± 0.01[b]	0.54 ± 0.03[a]
PLaM	3.19 ± 0.09[a]	2.71 ± 0.16[a]
MMM	37.53 ± 1.15[b]	42.48 ± 0.03[a]
MMyM	0.85 ± 0.00[a]	1.02 ± 0.05[a]
PMM	5.13 ± 0.38[b]	7.35 ± 0.35[a]
SLaM	0.41 ± 0.03[a]	0.42 ± 0.01[a]
MOLa	2.04 ± 0.00[a]	2.04 ± 0.07[a]
SMM	0.79 ± 0.02[a]	0.94 ± 0.09[a]
MLLa	0.44 ± 0.00[a]	0.43 ± 0.01[a]
MOM	3.86 ± 0.19[b]	4.70 ± 0.09[a]
MLM	0.82 ± 0.01[b]	0.87 ± 0.01[a]
POM	0.48 ± 0.10[a]	0.42 ± 0.09[a]
MPoM	0.80 ± 0.03[a]	0.52 ± 0.01[b]
PMP	0.40 ± 0.02[b]	0.47 ± 0.01[a]
MLnM	0.53 ± 0.02[b]	0.65 ± 0.04[a]
MLnLa	0.35 ± 0.02[a]	0.23 ± 0.02[b]
MDLa	2.62 ± 0.24	nd
MDM	5.16 ± 0.72	nd
PDM	0.44 ± 0.04	nd
MEM	0.46 ± 0.12	nd

Note: Data are expressed as means ± standard deviations ($n = 2$). Different superscript letters in the same line indicate significant differences ($P < 0.05$).
*TAG composition was estimated based on the 1,3-random-2-random distribution hypothesis using PrOleos software, disregarding values below 0.30%. nd, not detected. Fatty acid abbreviations: C, capric; La, lauric; M, myristic; My, myristoleic; P, palmitic; Po, palmitoleic; S, stearic; O, oleic; L, linoleic; D, docosadienoic; E, eicosenoic.

reported similar concentrations of myristoleic acid (C14:1) (0.65% to 1.5%) in *V. surinamensis* seeds from different regions of the Amazon.

Eicosenoic acid (C20:1) and docosadienoic acid (C22:2) were detected only in the sample obtained from whole seeds (WUF), at concentrations of 0.09% and 1.44%, respectively. The C20:1 content was lower than that reported by Takano *et al.*[14], with concentrations ranging from 0.28% to 0.34. Docosadienoic acid (C22:2) has not been previously reported in ucuúba fat and was detected only in WUF, suggesting a possible origin in the seed shell.

The especially high content of myristic acid (above 70%), which is rare in nature, is a distinctive feature of ucuúba seeds and may promote the formation of trimyristin (MMM), a valuable compound for the cosmetic industries with humectant properties. Nutmeg is the most common source of myristic acid; ucuúba may therefore represent a promising alternative.[38]

Table 5 shows the predicted TAG composition of the ucuúba fat from whole seeds (WUF) and shelled seeds (SUF), considering only fatty acids present at concentrations above 0.3%. The TAG profile was estimated using the model proposed by Filho *et al.*[21], based on the 1,3-random-2-random distribution hypothesis, which has shown high reliability, with a strong correlation ($r > 0.97$) between high-resolution gas chromatography (HRGC) data and the predicted values. This approach calculates the molar proportion of TAGs through simple combination equations, applying specific coefficients for each type of distribution. The calculations were performed using PrOleos software, which was applied successfully in previous scientific studies to estimate TAG profiles in vegetable fats.[39–42] The TAG

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Table 6. Total phenolics content (TPC) and antioxidant activity obtained by 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) and 2,2-diphenyl-1-picrylhydrazyl (DPPH) assays of ucuúba fats extracted from whole (WFU) and shelled seeds (SFU).

Sample	TPC	ABTS		DPPH	
	(mg GAE g^{-1})	(μmol TE g^{-1})	(% inhibition)	(μmol TE g^{-1})	(% inhibition)
WUF	6.54 ± 0.10[a]	4.26 ± 0.05[a]	77.03 ± 0.87[a]	12.25 ± 0.04[a]	81.24 ± 0.55[a]
SUF	5.82 ± 0.13[b]	3.86 ± 0.02[b]	70.96 ± 0.35[b]	11.52 ± 0.04[b]	80.09 ± 0.26[a]

Note: Data are expressed as means ± standard deviation ($n = 3$). Different superscript letters in the same column indicate significant differences ($P < 0.05$) between the samples, as measured by a *t*-test. The measurements were performed in triplicate.

composition was calculated using theoretical methods rather than being directly measured and should therefore be considered a predictive estimation.

The analysis revealed that the main TAGs in both samples contain myristic (M) and lauric (La) acids, and were mostly represented by MMM, MMLa, and MLaLa, which together accounted for over 75% of the total TAGs. These findings are consistent with the fatty acid profile (Table 4) characterized by high C14:0 and C12:0 acid content. These results (Table 5) agree with Saraiva *et al.*,[9] who, using matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF MS), identified MMM (40.5%) and MMLa (38.5%) as the predominant triacylglycerols in ucuúba butter (*V. sebifera*). Fasciotti *et al.*[43] also reported that, although ucuúba butter exhibits a mass spectrum generally like other Amazonian butters such as babassu, murumuru, and tucumã, it also shows two significantly abundant ions at m/z 712.5 and 740.6, likely corresponding to major triacylglycerol species. Indeed, ucuúba represents a sustainable alternative to nutmeg as a natural source of MMM,[38] with unique humectant properties, highly valued in cosmetic and oleochemical applications. The abundant MMM content highlights the industrial potential of this bioproduct. The differences in the main TAGs between the samples were statistically significant, indicating that the seed shell could potentially function as a structural barrier during extraction, possibly affecting the release of fatty acids, which might influence their concentration in TAG molecules.

Total phenolic content and antioxidant activity

As Table 6 shows, the TPC values were higher for WUF than SUF. This could be due to co-extraction leaching, an expected behavior, as it is well known that seed shells of some seeds contain phenolic compounds in significant quantities, which may contribute to the higher phenolic content of the extracted samples.[16] However, these TPC values are modest in comparison with the findings of Holanda *et al.*,[11] who reported TPC as high as 76.25 mg GAE g^{-1} in ucuúba fat obtained by pressing. As phenolic compounds are generally minor constituents (<1.0%),[44,45] such a high value may not only reflect differences in raw material but also variations in extraction procedures, solvent systems, sample preparation, or analytical methodology. In particular, differences in co-extracted compounds and potential interferences in the Folin–Ciocâlteu assay could partially explain this discrepancy. The exceptionally high TPC value from Holanda *et al.*,[11] far exceeds the results from our samples and the typical TPC range for common oilseeds, generally between 0.1 and 4.0 mg GAE g^{-1}.[46]

Comparing results from Table 6 with data for typical fats or oils with high SFA content reveals large differences. For instance, babassu and coconut oils, both rich in C14:0 and C12:0, exhibited TPC of 0.915 mg GAE g^{-1} and 0.018 mg GAE g^{-1} respectively.[47,48] These values are much lower than those obtained for WUF and SUF, indicating that ucuúba is very rich in phenolic compounds, providing valuable bioactive and therapeutic properties, relevant for use in traditional medicine.[49]

The higher antioxidant activity of WUF in comparison with SUF (Table 6) may also be explained by the above. The ABTS results are within the range reported in Symoniuk *et al.*[50] for various pressed fats, oils, and their mixtures (from 3.9 to 12 μmol TE g^{-1}). Nevertheless, the ABTS results in Table 6 indicate higher antioxidant activity than in common oils with high content of SFA, such as palm oil (0.52 μmol TE g^{-1}) and nutmeg oil (58% ABTS inhibition).[51,52]

Significant oxidation inhibition was observed in the DPPH assay (80% to 81% at 31 mg mL^{-1}) of the fat methanolic extract, comparable to that from Amazonian buriti seed (78% at 100 mg mL^{-1}).[53] At a concentration of 333 mg mL^{-1}, Amazonian pracaxi oil extracted by different methods also showed a lower DPPH radical inhibition range (21.81% to 41.03%).[22] Analogously, DPPH values expressed in Trolox equivalents (11.52–12.25 μmol TE g^{-1}) were higher than other oils and fats with similar compositions, such as coconut oil (7.2 μmol TE g^{-1}) and cocoa butter (0.35 μmol TE g^{-1}), both rich in C12:0 and C14:0.[54] These high radical scavenging capacities are directly related to the presence of phenolic compounds such as flavonoids and coumarins, as well as

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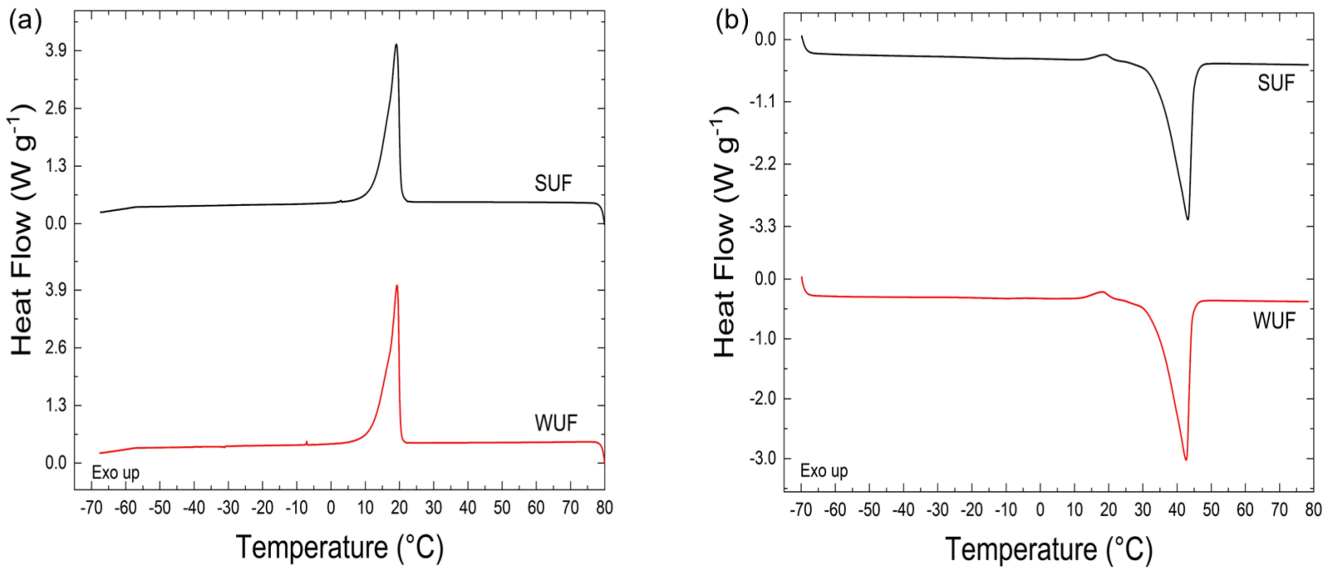


Figure 2. Crystallization (a) and melting (b) behavior by DSC for ucuúba fats extracted from shelled seeds (SUF) and unshelled seeds (WUF). DSC, differential scanning calorimetry.

Table 7. Crystallization and melting parameters of ucuúba fat extracted by hydraulic pressing from whole (WUF) and shelled (SUF) seeds.

Fat	Onset (°C)	Peak (°C)	ΔH (J g^{-1})
Crystallization			
WUF	20.17 ± 0.56	19.23 ± 0.34	99.64 ± 1.87
SUF	20.34 ± 0.24	19.08 ± 0.45	104.80 ± 3.54
Melting			
WUF	34.32 ± 0.08	42.64 ± 0.13	108.60 ± 1.65
SUF	34.80 ± 0.17	43.14 ± 0.04	113.60 ± 1.54

Note: Data are expressed as mean ± standard deviation ($n = 2$).

other secondary metabolites like steroids and terpenes, which have been detected in ucuúba fat.[36]

Thermal analysis

Figure 2 shows the crystallization and melting curves of WUF and SUF obtained by DSC analysis, and Table 7 summarizes the corresponding thermal event temperatures (onset, peak) and enthalpy values. The thermal profiles are similar, with minor variations, probably due to differences in crystallinity between the samples.

The presence of shells (WUF) may introduce impurities that disrupt the triglyceride organization and hinder nucleation, delaying crystallization. In contrast, the absence of shells in SUF results in greater purity; triglyceride organization is not disrupted by impurities, and this facilitates the crystallization process, resulting in more defined and stable crystals.[55] These differences reflect the impact of impurities and molecular organization on the thermal behavior of fats extracted from whole and shelled seeds.

The cooling curves (Fig. 2(a)) show that both samples exhibited well defined crystallization events, with onset at approximately 20 °C and a single peak for each fat sample. The SUF sample showed slightly higher energy release during crystallization (ΔH of 104.80 J g^{-1}). The single peak is attributed to the predominance of C14:0 and C12:0, which together account for over 90% of the total fatty acids (Table 4). Fats rich in SFA crystallize and melt at higher temperatures due to their linear structures, allowing better organization and efficient packing of triglycerides.

In contrast, Pardauil *et al.*[8] reported the formation of two peaks (a major peak at 16.5 °C and a minor peak at 11.4 °C) for ucuúba fat from *V. surinamensis* with 92.4% SFA. Similar behavior was observed for *V. bicuhyba* fat (with 85% SFA), consistent with other seeds from the same genus.[37] Differences in the peak number may reflect variations in the relative concentrations of the predominant fatty acids between samples.

The melting curves (Fig. 2(b)) showed a single endothermic transition at approximately 32 °C for both samples, with one peak in each case. The SUF exhibited a melting enthalpy of 113.60 J g^{-1}, indicating slightly higher thermal energy required for complete melting. Pereira *et al.*[32] similarly reported the formation of a single endothermic peak at 42 °C for ucuúba fat with 94.4% SFA.

In contrast, Pardauil *et al.*[8] observed different behavior for ucuúba fat with 92.4% SFA, identifying three main peaks. The first peak, at 21.5 °C, was attributed to the melting of medium-chain fatty acids such as lauric acid. This was followed by a

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notable increase in the released energy, which was interpreted as an exothermic event, likely related to a polymorphic change in the fat's structure. Two overlapping endothermic peaks at 30.8 °C and 37.2 °C were also observed, which could be associated with phase transition (melting) of triglycerides primarily composed of C14:0 and C16:0 chains.

Although the samples analyzed in this study were obtained from seeds collected at a single geographic location, which may limit broader extrapolation of the results, previous reports indicate that, despite regional variations, the relative predominance of the main fatty acids remains consistent across different Amazonian origins.[14] As industrial functionality is primarily governed by the overall compositional pattern rather than by minor quantitative differences, these findings may be considered representative of the characteristic lipid profile.

Conclusion

Shell removal slightly increased fat extraction by reducing press cake formation; however, the residual cake remains a valuable co-product for the recovery of high-value compounds, supporting an integrated ucuúba processing chain. As shelling had minimal impact on fat quality and introduces additional processing costs, fat recovery from whole seeds is suggested. The final decision should, however, depend on the intended application and specific functional requirements of the product.

The characterization of ucuúba fat showed a high acid index, strong resistance to primary oxidation, and a relatively high melting point, making it suitable for cosmetic applications such as soaps and candles, as well as for therapeutic uses due to its phenolic content (up to 6.54 mg GAE g^{-1}). The high C14:0 content contributes to thermal stability and indicates its potential as a viable and sustainable alternative to nutmeg, the common source of myristicin.

Overall, the significant phenolic content and antioxidant potential, together with its distinctive lipid composition and thermal behavior, reinforce the potential of ucuúba fruits as nontimber forest products. Decisions regarding shell removal should therefore be guided not only by economic and technical criteria, but also by strategies for sustainable sourcing, full biomass valorization, and the strengthening of Amazonian bioeconomy initiatives.

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Conflict of interest

The authors declare no conflict of interest.

Data availability statement

The article presents all data relevant to this study.

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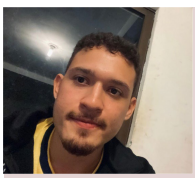
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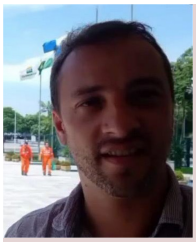
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