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Article

Baru Seed Extracted Oil (*Dipteryx alata* Vog.): Chemical Composition and Thermal and Oxidative Stability

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Baru seeds are commonly found in the Brazilian savanna and present potential to be used by the food industry due to their high content of fat. In this sense, this study aimed to determine the physicochemical properties, and chemical composition of baru seed oil. The thermal and oxidative stability, as well as the interfacial properties of the oil were also evaluated. The free fatty acid, peroxide, moisture, density, viscosity and the refractive index of the oil extracted from baru seeds were 0.08% oleic acid, 6.69 meq O_2 kg^{-1} of oil, 0.03%, 0.92 g cm^{-3}, 32.9 mPa s and 1.47, respectively. Since linoleic acid (L), oleic acid (O), palmitic acid (P) and linolenic acid (Ln) are the main fatty acids present in the oil, the most common predominant triacylglycerols in the oil are POO, POL, OOO, OOL, OLL and LLL. The oil extracted from baru seeds presented good thermal and oxidative stability. Moreover, the oil contains high contents of total phenolics and carotenoids. The reduction of oil-water dynamic interfacial tension was promoted by the presence of small molecules. Therefore, the oil extracted from baru seeds presents promising properties for processing in the food industry.

Keywords: rancimat, thermogravimetry, interfacial tension, carotenoids, phenolic compounds

Introduction

Brazil is home to a flora rich in oilseeds that have attractive sensory attributes, bioactive compounds and properties that can qualify them as an alternative source of oil production. *Dipteryx alata* Vog., also known as baru, is an oleaginous specie native to the Brazilian Cerrado biome, which belongs to the Fabaceae family. Baru seeds are a good source of energy (500-603 kcal 100 g^{-1}) to the human body, present a high protein content (23-30 g 100 g^{-1}), lipids (38-45 g 100 g^{-1}), fibers and minerals.[1-4] Moreover, the seeds present a phenolic content of 568.9 mg of gallic acid equivalents *per* gram (GAE 100 g^{-1}),[5] a significant content of phytate, tannins, carotenoids, and tocopherols.[2,6] Due to their nutraceutical profile, claims of health benefits arising from the consumption of baru seeds have been described in the literature.[7,8]

Dipteryx alata seeds provide an oil predominantly composed of unsaturated fatty acids, especially oleic and linoleic acids,[1,3,4,9] and compounds, such as tocopherols,[4,9] phytosterols and mono and sesquiterpenes.[9] The seeds are currently used in folk medicine due to their sweating properties, tonic, and menstrual regulator, as well as an anti-rheumatic agent.[10]

Regarding the industrial aspect, there is a consensus that one of the great challenges for the food industry is the introduction of new sources of edible oils that offer improved nutritional and functional characteristics. Furthermore, the high productivity and availability of this product in the Brazilian Cerrado region,[11] in addition to the high lipid content in the baru seeds, strongly indicate a potential for use of these oils by the food industry. Currently, the extraction/production/marketing of the oil from baru seeds is not of a very common occurence.[12,13] Therefore, in order to promote its consumption and application in the food industry, studies regarding the properties of this oil can be an interesting approach. Even though some properties and

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the influence of the extraction system on the fatty acid profile of baru oil are reported in the literature,[4,9,13-15] data regarding the characterization of this oil, such as the composition of triacylglycerols, oxidative and thermal stability, the content of bioactive compounds (phenolic compounds and carotenoids), and the interfacial properties of this product are scarce. In this sense, the information provided by this study can be relevant for the potential production and processing of the oil extracted from baru seeds by the food industry.

Experimental

Material

Crude oil extracted from seeds of *Dipteryx alata* Vog. was acquired from producers in the state of Goiás, Brazil. The oil from baru seeds was extracted by cold pressing at a temperature of 50 ± 5 °C, followed by filtration and storage in an amber bottle at room temperature. The oil was not refined for the following experiments. All the solvents and chemicals used for further analyses were of analytical grade.

Physicochemical characterization of baru oil

The chemical composition of the baru oil was evaluated in terms of free fatty acids composition, moisture, and peroxide contents. The density of the oil at a temperature of 25 °C and the refractive index at 40 °C were determined by using a 10 mL pycnometer and an ABBEMAT 200 automatic refractometer (Anton Paar, Graz, Austria), respectively. All experiments were done in triplicate, as described by the American Oil Chemistry Society (AOCS).

Viscosity

The rheological properties of baru oil at 40 °C[16,17] was determined using a rotary rheometer (Brookfield, R/S plus SST 2000, Stoughton, USA) with a stainless steel concentric cylinder geometry (CC45 sensor). In order to determine the flow behavior, shear stress and absolute viscosity (Pa s), the measurements were determined by applying a continuous ramp at the shear rate from 0.01 to 200 s^{-1}. Newton's rheological model (equation 1) was adjusted to the experimental data.

$$\tau = \eta \dot{\gamma} \quad (1)$$

where τ is the shear stress (Pa), η is the absolute viscosity (Pa s), and $\dot{\gamma}$ is the shear rate (s^{-1}).

In order to evaluate the effect of the temperature on the viscosity of the oil, an oscillatory rheometer (Modular Advanced Rheometer System, Thermo Electron Corp., Karlsruhe, Germany) was equipped with a thermostatic bath (Phoenix II, Thermo Scientific, Karlsruhe, Germany), for temperature control. The baru oil was sheared at a constant shear rate of 100 s^{-1} over temperatures ranging from 20 to 70 °C.[18] The Arrhenius model (equation 2) was fitted to the experimental data obtained.

$$\eta = A \times e^{(Ea/RT)} \quad (2)$$

where A is the pre-exponential factor, Ea is the activation energy (kJ mol^{-1}), R is the gas constant (8.314 J mol^{-1} K^{-1}), and T is the absolute temperature (K).

Color

The color parameters of the oil were determined by using a colorimeter Color Quest XE (HunterLab, Reston, USA). The results were provided in the CIELAB system (Commission Internationale de I'Eclairage) for the D_{65} illuminant and a viewing angle of 10°. Regarding the color parameters, L* corresponds to the brightness, and a* and b*, red/green and yellow/blue coordinates, respectively. The hue angle (h*) and chroma (C*) parameters were calculated from data obtained for the parameters a* and b*.[19]

Determination of total phenolic compounds

The extraction of total phenolic compounds (TPC) from baru oil was performed following the methodology described by Parry *et al.*[20] Folin-Ciocalteau (Sigma-Aldrich, Saint Louis, USA) was used to determine the standard curve by using a UV-Vis spectrophotometer (PerkinElmer, Shelton, USA), according to Singleton *et al.*[21] After that, the absorbance was measured at 765 nm. The equation obtained from the gallic acid standard curve was used to determine the amount of phenolic compounds. The results were expressed as milligrams GAE 100 g^{-1} oil.

Determination of total carotenoids

The carotenoids content was determined based on the methodology described by Rodriguez-Amaya.[22] The quantification of carotenoids was performed by measuring the absorption at 450 nm in a UV-Vis Lambda 35 (PerkinElmer, Shelton, USA). After that, the oil was diluted in petroleum ether (Vetec, São Paulo, Brazil) and the content of carotenoids was calculated considering an absorptivity of 2592. The values were expressed as μg β-carotene *per* gram of oil (μg β-carotene g^{-1}).

Composition of fatty acids

The preparation of the methyl esters was carried out according to the methodology proposed by Hartman *et al.*[23] The experiment was carried out by using a gas chromatograph (Agilent 6850 series GC system, Santa Clara, USA) with a capillary column DB-23 (50% cyanopropyl-methyl polysiloxane, with dimensions of 60 m × 0.25 mm × 0.25 μm). The following operational conditions used were: oven temperature: 110 ºC-5 min, 110-215 ºC (5 ºC min^{-1}), 215 ºC-24 min; detector temperature: 280 °C; injector temperature: 250 °C; carrier gas: helium, 1:50 split injection ratio; injection volume: 1.00 mL min^{-1} and linear speed 24 cm s^{-1}. The fatty acids were identified by comparing their retention times of peaks with the respective commercial fatty acid standards. The quantitative composition was obtained by calculating the area of each peak. The results were expressed in percentage, according to the method established by AOCS Ce 2-66.

Composition of triacylglycerol

The composition of triacylglycerols (TAGs) of baru oil were determined by the AOCS Ce 5-86 method. The experiment was performed by using a capillary phase chromatography (CGC Agilent 6850 Series GC System, Santa Clara, USA) with a capillary column DB-17HT (Agilent Catalog No. 122-1811 50% phenyl-methylpolysiloxane, with dimensions of 10 m × 0.25 mm × 0.15 μm). The operating conditions were as follows: column temperature: 250-350 °C at a rate of 5 °C min^{-1}; carrier gas: helium at a flow rate of 1.0 mL min^{-1}; injector temperature: 360 °C; detector temperature: 375 °C; injected volume: 1.0 μL; sample concentration: 10 mg mL^{-1} in tetrahydrofuran. For the qualitative determination, the area of each peak was calculated and compared with the peaks obtained for the standard fatty acids.

Determination of thermal stability

The reactions induced by heat in oils during its processing and storage is very important for industrial applications.[24] The thermogravimetric (TG) curve was obtained by using a thermogravimetric scale DTG-60H (Shimadzu, Kyoto, Japan) with the following parameters: air flow of 50 °C min^{-1}, temperature range from 25 to 700 °C, heating rate of 10 °C min^{-1}, crucible of alumina and mass of 3.50 mg ± 0.5. The first derivative of the TG curve (DTG) was plotted for better visualization of the measured thermal transitions.

The glass transition and degradation temperatures were determined by using a differential scanning calorimetry (DSC-60A, Shimadzu, Kyoto, Japan). For this experiment, approximately 2 mg of oil was hermetically sealed in an aluminum capsule. The experimental conditions were: temperature from 25 to 600 °C, synthetic air flow of 30 mL min^{-1} and a heating rate of 10 °C min^{-1}.

Determination of oxidative stability

The oxidative stability index was determined by a Rancimat (Biodiesel Rancimat 873, Metrohm AG, Herisau, Switzerland). Standard Rancimat tubes containing 2.50 ± 0.1 g of baru oil sample were heated to 100 °C with an air flow of 10 L h^{-1}. The gases released during the oxidation were transferred to a conductimetric cell containing 50 mL of distilled water, and the effects in the conductivity of the solution were plotted on a graph over time. Oxidative stability was determined by identifying the induction point (IP), which is defined as the time (in hours) corresponding to the inflection point of the curve.

Interfacial tension

Interfacial tension measurements between baru oil and water were determined by the pendant drop method with a PAT-1 tensiometer (Sinterface Technologies eK, Berlin, Germany), at 25 °C. An oil droplet (25 mm^2) was automatically formed at the tip of the curved capillary inserted in a quartz cuvette containing deionized water. The image of the drop was captured and digitized by a charge-coupled device (CCD) camera. The interfacial tension was calculated by analyzing the interfacial tension decay profile, which was monitored for 7200 s. The variation of the interfacial tension with time was adjusted to the Laplace equation, using the equipment software (Tensiometer Sinterface PAT 1 version 8.01). Interfacial tension data as a function of time were adjusted to the exponential equation (equation 3)[25] to obtain the equilibrium interfacial tension.

$$\gamma = \gamma_{eq} + B\exp(-C\sqrt{t}) \quad (3)$$

where γ is equilibrium interfacial tension (mN m^{-1}) at time t (s), γ_{eq} is the equilibrium interfacial tension (mN m^{-1}) and B (mN m^{-1}) and C ($s^{-1/2}$) are constants.

Statistical analysis

The experiments were carried out in three replications. The results obtained in the characterization of baru oil were expressed as mean ± standard deviation (SD).

Results and Discussion

Physicochemical characterization of baru oil

The physicochemical properties of baru seed oil obtained by cold pressing is presented in Table 1, mainly refer to its identity, quality and stability. The baru oil presents low acidity and a low content of free fatty acids. According to the Codex Alimentarius,[26] a reference for a good quality of edible vegetable oils, such as soybean and corn, the maximum acidity index value for unrefined cold-pressed oils is 4.0 mg KOH g^{-1} of oil. The low free fatty acids content in the oil indicates a good quality of the raw material, as well as for processing and storage conditions.[27]

Table 1. Physicochemical properties of baru seed oil (*Dipteryx alata* Vog.) extracted by cold pressing

Parameter		Mean (standard deviation)	Reference value[a]
Acidity index / (mg KOH g^{-1} oil)		0.16 ± 0.00	4.0
Free fatty acid / (% oleic acid)		0.08 ± 0.01	–
Peroxide value / (meq O_2 kg^{-1} oil)		6.69 ± 0.29	15
Refractive index (40 °C)		1.47 ± 0.00	–
Specific density at 25 °C / (g cm^{-3})		0.92 ± 0.00	–
Moisture / %		0.03 ± 0.00	0.2
Viscosity / (mPa s)		32.9 ± 0.00	–
Color	L*	62.15 ± 0.01	–
	a*	–5.01 ± 0.00	–
	b*	32.45 ± 0.02	–
	C*	32.84 ± 0.02	–
	h* / degree	81.22 ± 0.00	–
Induction period / h		10.99 h ± 0.15	–

[a]Maximum limits according to the Codex Alimentarius Commission Regulation[26] for the specified and edible vegetable oil quality category. L*: lightness; a*: transition from green (– a*) to red (+ a*); b*: transition from blue (– b*) to yellow (+ b*); h*: hue angle (h*); c*: chroma.

The peroxide index, which is also often used as a quality parameter for oils, is used to quantify the concentrations of hydroperoxides formed during oxidation processes.[17] The baru oil presented a peroxide index of 6.69 mEq O_2 kg^{-1} oil, below the maximum of 15 mEq O_2 kg^{-1} oil, as recommended for specific cold-pressed and unrefined oils.[26] The value found can be attributed to the cold pressing extraction, since this method of extraction tends to make the oil more vulnerable to lipid oxidation due to the time of exposure to oxidizing environmental conditions.[28]

The baru oil presented a refractive index of 1.47, which can be due to its high content of unsaturated fatty acids. The results are in accordance to the refractive index reported in the literature. Fetzer *et al*.[14] reported a refractive index of 1.46-1.47 for the baru oil obtained by different extraction methods (conventional (Soxhlet), compressed propane and supercritical carbon dioxide (sCO_2)). Therefore, it is possible to affirm that the extraction method does not play a role in the refractive index of the oils. In general, the refractive index reported in the literature for predominantly unsaturated oils, such as the ones from chia seeds, beech, and Brazil nuts, is in the range of 1.45 to 1.48.[17,29,30] The density of the baru oil (0.92 g cm^{-3}) is similar to the ones found in the literature for liquid vegetable oils, such as oils from beech (0.92 g cm^{-3}), chia (0.93 g cm^{-3}), faveleira and Brazil nut (0.91 g cm^{-3}).[17,29-31] Regarding the moisture content, it was determined a moisture content of 0.03% for the baru oil. The values of moisture determined for the baru oil indicate that the oil has a moisture content below the maximum recommended by the Codex Alimentarius,[26] which is an indicative of good quality regarding this parameter, since the stability of oils is strongly dependent on their moisture content. In fact, a high moisture content can contribute to the hydrolysis of TAGs and, consequently, contribute to an increase of free fatty acid molecules in the oil,[29] which are significantly more susceptible to oxidative reactions.

Viscosity

The flow curve obtained for the baru oil shows a Newtonian behavior for the sample (Figure 1a), as expected for edible oils. The behavior of curve shows a direct proportionality between the shear stress and the shear rate. The viscosity at 40 °C is constant, regardless of the applied shear rate. At this temperature, the viscosity obtained for the baru oil was 32.9 mPa s, similar to ones found in the literature for the soybean (33.01 mPa s), sunflower (31.61 mPa s)[24] and Brazil nut oils (31.86 mPa s), and slightly lower than the viscosity obtained for buriti (35.77 mPa s) and macadamia oils (35.26 mPa s).[32]

The effect of the temperature on the viscosity of the baru oil is illustrated in Figure 1b. The viscosity of the oil ranged from 73.3 to 13.5 mPa s at temperatures from 20 to 70 °C, respectively. The viscosity of liquids tends to decrease with the increasing temperature due to the greater intermolecular spacing promoted by the thermal expansion. Pineli *et al*.[13] reported a viscosity of 76.8 mPa s at 20 °C for the refined baru oil obtained by mechanical extraction. In addition to the effect of temperature, variations in the fatty acid profile between the oils can also play a role in the viscosity of these products. In the study carried out by Pineli *et al*.,[13] the baru seed oil presented a higher amount of saturated fatty acids (SFAs) (18.15%). In general, saturated

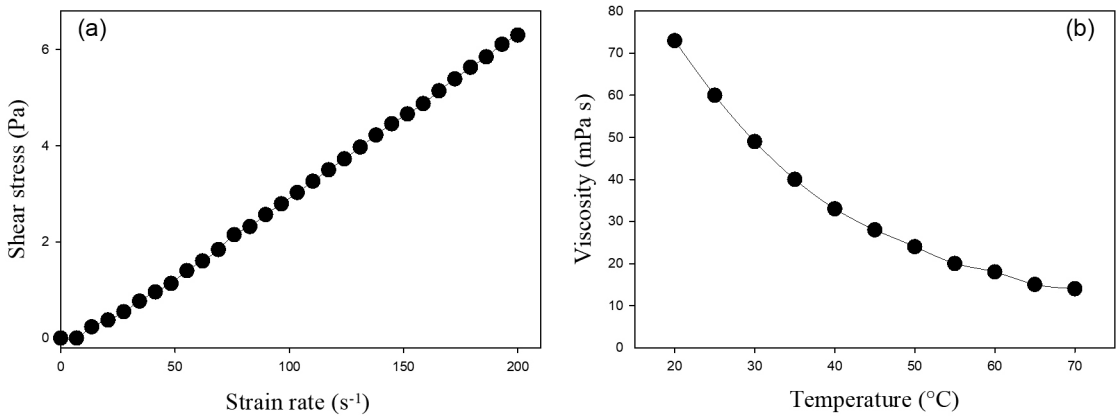

Figure 1. (a) Flow curve for baru oil at 40 °C, (b) effect of the temperature on the viscosity of baru oil.

oils present a higher viscosity compared to unsaturated oils,[18,28] since their chemical structure consists of stronger molecular interactions.

The values obtained for the activation energy and constant (A) of the baru oil were 28.4 kJ mol^{-1} and 0.62×10^{-6} Pa s, respectively. Kim *et al.*[18] reported activation energy values of 24.5 to 26.9 kJ mol^{-1} for hazelnut, corn, canola, soybean, grape seed, and sunflower oils. The activation energy values were similar to those obtained by Oliveira *et al.*[33] for buriti oil (30.2 kJ mol^{-1}), patuá oil (29.4 kJ mol^{-1}) and Brazil nut oil (28.7 kJ mol^{-1}). The activation energy indicates the sensitivity of the material to temperature changes.[34] In this sense, the effect of the temperature on the viscosity of the baru oil is similar to those obtained in the literature for different vegetable oils.

Color

The color of vegetable oils is related to the total content of pigments, such as the presence of carotenoids and chlorophyll.[35] Since there are no established color standards for oils, L*, a* and b* measurements can be used for color classification. The color parameters obtained for the baru oil were L* (62.15), a* (–5.01) and b* (32.45). The baru oil presented a negative a* parameter, attributed to the green color, in accordance with the data obtained for the chia, Brazil nuts, pumpkin seeds, beech and faveleira oils.[19,28-31,36] These values obtained for a* can be due to the presence of chlorophylls or other pigments extracted during oil pressing.[29] On the other hand, the amount of carotenoids present in the baru oil provide a yellowish color when compared to the oils extracted from chia, pumpkin seeds and Brazil nuts.[19,28,29,36] Therefore, in addition to being a parameter for consumer acceptance, color is also indicative of the composition of bioactive compounds present in the oil.[31]

The coordinates of the hue angle (h*) and chroma (C*) were also determined. The h* analytically describes the color through which the sample is perceived (blue, red, yellow, green), and the C* parameter corresponds to the intensity of the color. The h* of the baru oil (81.22°), close to 90°, indicates a tendency towards a yellow color, whereas the C* value of 32.84 indicates an intense or saturated color of the oil.

Fatty acid composition

The fatty acid profile of the baru oil is presented in Table 2. For this sample, 17 fatty acids with chains ranging from 12 to 24 carbons were quantified and distributed in SFAs (15.96%), monounsaturated (MUFAs) and polyunsaturated (PUFAs) (84.04%) (Table 2). The predominant SFAs in the baru oil were palmitic acid (11.30%) and stearic acid (3.34%), while the most abundant unsaturated fatty acids were linoleic acid (49.00%) and oleic acid (30.43%). These results are not in accordance with the ones found in the literature.[4,14] Pineli *et al.*[13] found levels of oleic and linoleic acid of 37.48 and 39.40%, respectively, and did not detect the presence of linolenic acid in the baru oil. In the study carried out by Reis *et al.*,[37] it was reported a content of 46.71% of oleic acid and 29.34% of linoleic acid for the oil mechanically extracted from baru seeds. These differences can be explained by the fact that climatic conditions, soil type, genetics aspects, agricultural practices and raw material extraction conditions can influence the chemical composition of baru oil.[3]

The fatty acid profile of baru seed oil is similar to some commonly consumed vegetable oils reported in the literature, such as oils from soybean, sunflower and corn (50.5-57.8% linoleic acid, 20.6-28.3% oleic acid and 9.1-16.1% palmitic acid).[18] As for alternative sources of vegetable oils, it is reported in the literature a fatty acid profile for milk thistle oil (ca. 46% linoleic acid and ca. 30% oleic acid)[38] and grape seed oil (53.8% linoleic acid and 26.5 oleic acid).[39]

Table 2. Fatty acid composition of baru seed oil (*Dipteryx alata* Vog.)

Fatty acid / (% m/m)	
Lauric (C12:0)	0.10 ± 0.02
Miristic (C14:0)	0.12 ± 0.02
Pentadecanoic (C15:0)	0.02 ± 0.00
Palmitic (C16:0)	11.30 ± 0.01
Palmitoleic (C16:1)	0.17 ± 0.01
Margarian (C17:0)	0.10 ± 0.01
cis-10-Heptadecenoic (C17:1)	0.05 ± 0.01
Stearic (C18:0)	3.34 ± 0.02
Oleic (C18:1)	30.43 ± 0.04
t-Linoleic (C18:2)	0.25 ± 0.00
Linoleic C18:2)	49.00 ± 0.13
t-Linolenic(C18:3)	0.59 ± 0.01
Linolenic (C18:3)	3.30 ± 0.01
Araquic (C20:0)	0.47 ± 0.00
Eicosenoic (C20:1)	0.25 ± 0.01
Behenic (C22:0)	0.36 ± 0.00
Lignoceric (C24:0)	0.21 ± 0.01
Total saturated fatty acids (SFA)	15.96
Total monounsaturated fatty acids (MUFA)	30.90
Total polyunsaturated fatty acids (PUFA)	53.14

Data represent the mean ± standard deviation of triplicate determinations.

Composition of triacylglycerol

The composition of TAGs is shown in Table 3. The results show that the baru oil contains 14 main types of TAGs, composed of 16 and 18 carbon chains. The TAGs found predominantly contained linoleic (L), oleic (O) and palmitic (P) acids, compatible with the fatty acid profile of the oil. OLL (17.60%), PLL (15.16%), OOL (14.34%), POL (13.84%), LLL (13.56%), OOO (7.87%) and POO (7.12%) were the main TAGs in baru oil.

Table 3. Composition of TAGs s in baru oil

TAG	NC:IN	TAG quantity / %
PPS	50:0	0.23
POP	50:1	1.77
PLP	50:2	3.31
POS	52:1	0.75
POO	52:1	7.12
POL	52:3	13.84
PLL	52:4	15.16
PLLn	52:5	1.42
SOO	54:2	1.14
OOO	54:3	7.87
OOL	54:4	14.34
OLL	54:5	17.60
LLL	54:6	13.56
LLLn	54:7	1.89

TAG: triacylglycerol, NC: number of carbons, IN: degree of unsaturation, P: palmitic acid, S: stearic acid, O: oleic acid, L: linoleic acid, Ln: linolenic acid.

Total phenolic compounds (TPC)

Baru oil presented a TPC of 282.06 ± 5.51 mg GAE 100 g^{-1}. The extraction conditions, such as time, solvent, temperature and pressure can influence the content of bioactive compounds present in the oil.[40] In fact, Fetzer *et al.*[14] reported higher average levels of TPC, from 685 to 1386 mg GAE 100 g^{-1}, for the baru oil extracted by using compressed solvent technology, which indicates that the solvent used in the extraction played a role in the extraction of phenolic compounds. Moreover, the time required for the extraction and the mechanical pressing may have contributed to TPC degradation. Compared to other edible oils, baru oil presented a lower TPC when compared to jatoba seed oil (343 mg GAE 100 g^{-1}).[41] However, it contained higher TPC compared to other alternative sources oils: walnut, almond, hazelnut, peanut, and pistachio (7 to 32 mg GAE 100 g^{-1}),[42] faveleira oil (108.11 mg GAE 100 g^{-1}),[31] Majia pomelo oil (29.63-49.70 mg GAE 100 g^{-1}),[43] purslane oil (66.51-155.65 mg GAE 100 g^{-1}),[44] and perilla oil (75.7-130.4 mg GAE 100 g^{-1}).[45]

Total carotenoids

The baru oil presented a carotenoid content of 10.8 ± 2.79 μg β-carotene g^{-1}. The results were similar to the ones found for the araticum oil (9.62 μg g^{-1}), and jatoba seed oil (10.65 μg g^{-1}), which are seeds also commonly found in the Brazilian Cerrado.[41,46] In general, when compared to the baru oil, lower levels of β-carotene were reported in the literature for the oils extracted from almonds (1.07 and 1.44 μg g^{-1}),[47] pumpkins oil (5.5 μg g^{-1}), rapeseeds oil (1.7 μg g^{-1}), olive oil (6.7 μg g^{-1}), and, < 1.0 μg g^{-1} for flaxseed, grape seed, corn, peanut, soybean and sunflower oils.[48] The carotenoid content in the oil depends on the seed maturation stage and the processing and storage conditions.[46] Carotenoids can play an antioxidant role in food matrices and play an important role in the coloring of oils. However, the oxidation of these molecules can result in the loss of their biological activity and the characteristic color of the oil.[49]

Thermal behavior

The baru oil thermograms were obtained to characterize the stages of decomposition and the thermal stability of the oil, as shown in Figure 2. The loss of mass *versus* the temperature curve shows a succession of degradation phenomena of the baru oil. The TG curve shows a negligible mass loss (< 2%) at a temperature below 235 ºC. DTG curves show three thermal decomposition events with peaks

at 349.62, 427.27, 521.15 °C. The first peak corresponds to the initial degradation of triglycerides, mainly PUFAs,[50] with a weight loss of 61%, whereas the mass loss of 21% is related to the decomposition of MUFAs. The third stage can be attributed to the degradation of SFAs and the volatilization of the polymerization products present in the oil.[17,50] Finally, the total decomposition of the oil occurs around 560 °C. Dweck *et al.*[51] also observed a thermal decomposition of commercial oils from soy, olive, sunflower and canola at approximately 200 °C and a combustion of the oils at 600 °C. Fetzer *et al.*[14] also reported three stages of degradation, the first at 250 °C with a loss of 2%, another loss of 18% at 300 °C, and one peak at 400 °C, with a mass loss of 80%. This behavior is probably due to the different proportions of PUFAs, MUFAs and SFAs present in the oils.

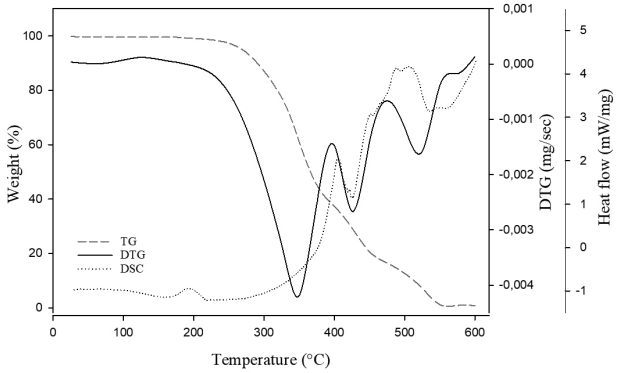

Figure 2. TG/DTG curves while heating the baru oil sample at a rate of 10 °C min^{-1}.

The exothermic peaks obtained by the DSC corroborate the TGA/DTG data, and are characteristic of lipid oxidation events as the temperature increases.[31] Exothermic behaviors evidenced in thermal analyses of oils are due to the high unsaturation of this material, which undergoes decomposition at high temperatures.[17]

Oxidative stability

The oxidative stability is defined as the time required for one or more oxidative parameters to suddenly increase, which causes unpleasant taste and odor, thus, reducing the quality of products. For this purpose, rancimat is a technique that allows continuous monitoring of oxidative processes in oils and fats. Data in the literature regarding the use of rancimat to determine the oxidative stability of baru oil are nonexistent.

The induction period of oxidation processes determined by this technique for the baru oil was 10.99 h. Comparing this result with other oils is challenging due to different analysis conditions such as air flow, temperature, sample quantity and equipment used.[17] The baru oil presented an oxidative stability comparable to oils extracted from Brazil nut (14.85 h)[19] and faveleira (9.67 h)[31] both at a temperature of 100 °C. Differences in this period can be also related to the degree of saturation and the presence of antioxidants in the oil.

Dynamic interfacial tension

Droplet tensiometry is a simple and reliable technique capable of providing additional information on the quality and processing of oils.[52] The decay of the interfacial tension between baru oil and water shown in Figure 3 confirms the complexity of its composition by the surface activity between both compounds. The equilibrium interfacial tension obtained for the baru-water oil system was 10.63 ± 0.37 mN m^{-1} and implies the presence of surface-active molecules naturally present in the oil from the raw material or from chemical reactions that occurred during its processing,[52] such as phenolic compounds, phospholipids, tocopherols, free fatty acids, and others. These compounds are able to migrate to the interface more easily than triacylglycerolic structures.[53] The variation in the interfacial tension observed over time is the result of the diffusion and reorganization of surface-active molecules present in the baru oil at the oil-water interface, until the dynamic equilibrium is reached. Comparing these results with different sources of oil/water interfacial tension, lower values for this parameter were observed for babassu oil (11.70-12.15 mN m^{-1}),[54] peanut oil (10 mN m^{-1}), pepper oil (9.89 mN m^{-1}) and olive oil (13.15 mN m^{-1}).[53] The interfacial tension are usually higher in refined oils, corroborating the results reported for different source of oils, such as: safflower oil, sunflower oil, rapeseed oil and soybean oil (30.26 a 40.31 mN m^{-1}).[53] The refining of vegetable oils results in higher interfacial tension, precisely

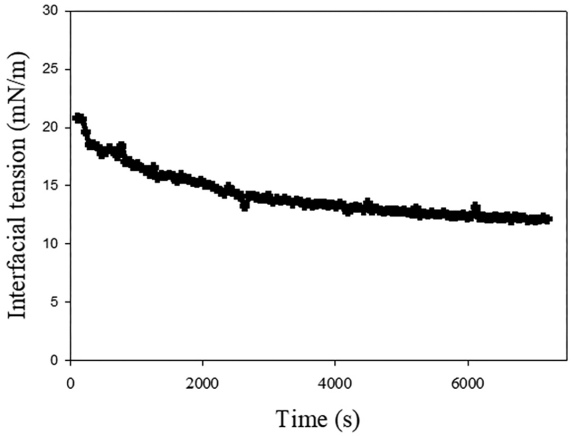

Figure 3. Dynamic interfacial tension for baru oil/water as a function of time.

because of the removal of smaller compounds with high interfacial activity.[54]

Conclusions

The physicochemical properties (free fatty acid, peroxide, moisture, density, viscosity at 40 °C and the refractive index) of the baru oil show that the sample presents good quality parameters, in accordance with the data found in the literature. The oil presented in its composition unsaturated fatty acids considered essential to the human body, such as omegas 3 (linolenic), 6 (linoleic) and 9 (oleic). Even though the baru oil is highly unsaturated, it presents good thermal and oxidative stability, which can be attributed to the levels of natural antioxidants (phenolic and carotenoid compounds) present in its composition. Information about thermo-oxidative stability, interfacial properties and composition of the baru oil can be useful for the development of new products and also for the application of this product in the food, cosmetic and pharmaceutical industries.

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Author Contributions

Linamarys Aparecida O. Paulo was responsible for methodology, investigation, validation, writing - original draft, visualization; Raquel N. Fernandes for methodology, validation, writing - review and editing; Kelly M. B. Gandra for methodology, resources, writing - review and editing; Valéria Paula R. Minim for methodology, resources, writing - review and editing; Luis A. Minim for methodology, resources, writing - review and editing; Renato Grimaldi for methodology, resources, writing-review and editing; Márcia Cristina T. R. Vidigal for conceptualization**,** funding acquisition**,** methodology, writing - review and editing, resources, project administration.

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