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Research Article

Influence of Optimized Microwave Treatment on the Nutritional Parameters and Bioactive Compounds of Tucumã (*Astrocaryum aculeatum*) Nectar

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The tucumã-do-Amazonas (*Astrocaryum aculeatum*) is a fruit that is native to the Amazon region and known for its high content of β-carotene, phenolic compounds, and unsaturated fatty acids, making it a promising candidate for the development of functional products. However, conventional thermal methods can degrade heat-sensitive compounds. This study evaluated the application of microwave-assisted extraction in the production of tucumã nectar, aiming to maximize the retention of β-carotene and preserve the physicochemical and functional characteristics as well as the bioactive compounds of the product. Using a central composite rotational design, the optimal extraction conditions were 122.99 W for 63.28 s, which resulted in higher β-carotene retention (0.111 ± 0.003 mg/g). Microwave treatment also stood out for better preservation of volatile compounds such as β-(E)-ocimene and hexenal, as well as maintaining a suitable pH (6.52), light color ($\Delta E < 0.7$), and lipid profile, with oleic acid as the predominant fatty acid (82.93%). Compared to conventional heating, microwave heating showed lower thermal degradation and greater efficiency in preserving the bioactive compounds. It is concluded that this technology shows potential as an alternative for processing functional nectars derived from Amazonian fruits, preserving their bioactive compounds and functional properties.

Keywords: Amazonian fruits; emerging technology; experimental design; nectar

1. Introduction

The Amazon region is an ecosystem of great biological diversity and is home to a wide variety of native fruits, many of which are recognized for their nutritional, phytochemical, and bioactive compositions [1]. Among these fruits, species of the *Astrocaryum* genus, such as *Astrocaryum aculeatum* and *Astrocaryum vulgare*, stand out. The former is predominantly found in the states of Acre, Amazonas, Rondônia, and Roraima, while the latter occurs in Amapá, Pará, Tocantins, Maranhão, Piauí, and Goiás. The fruiting period of the tucumã-do-Amazonas (*A. aculeatum*) occurs between February and August, whereas the tucumã-do-Pará (*A. vulgare*) bears fruit between January and April, though in some regions, it can fruit throughout the year [2].

The tucumã-do-Amazonas (*A. aculeatum*), also regionally known as tucumã-arara, tucumã-piranga, tucum-açu, among others, belongs to the Arecaceae family. It is a palm tree that is native to the Amazon region, with an erect, columnar stem, usually solitary and occasionally cespitose, reaching up to 25 m in height and 40 cm in diameter. Its fruits are ellipsoid to globose, with a yellow epicarp, orange mesocarp, hard black endocarp, and homogeneous endosperm [3]. Widely consumed in northern Brazil, tucumã is

eaten fresh or processed into creams, ice creams, and, in the state of Amazonas, the traditional snack "x-caboquinho," made of French bread, curd cheese, fried banana, and tucumã pulp [4]. The fruit is valued for its nutritional and bioactive composition and is a potent antioxidant due to its high β-carotene content, which is beneficial for eye health [3, 5].

As an alternative use of this fruit, nectar represents a promising option to add value and broaden its consumption. It is a nonfermented beverage obtained by diluting the edible part of the fruit in potable water, to which sugars, plant extracts, and occasionally acids may be added, and is intended for direct consumption. Despite the presence of added sugars in its composition, nectar can still be considered a relatively healthy option compared to other ultraprocessed beverages, as it preserves some of the nutrients and bioactive compounds from the fruits [6, 7]. Although it has lower concentrations of vitamins and minerals compared to pure juice, nectar still represents a nutritious and economical alternative [6].

However, traditional food processing often involves conventional thermal methods, which can lead to the loss of nutritional quality due to low heat transfer rates and uneven heating. As an alternative, the use of microwaves has received attention for providing rapid volumetric heating, having lower energy consumption, and better preservation of desirable attributes [8, 9]. Microwave pasteurization, in particular, allows for the inactivation of pathogenic microorganisms while simultaneously retaining thermosensitive compounds and ensuring the final product quality [10].

Despite these advantages, studies exploring the application of microwaves in tucumã nectar processing, especially aiming at β-carotene retention, are still scarce. From this perspective, identifying the optimal extraction conditions requires a robust statistical approach. The design of experiment (DoE) methodology is widely used for process optimization, allowing systematic evaluation of variables such as temperature, time, and concentration. Experimental planning using matrices enables effective analysis of the influence of factors on the outcomes, ensuring greater precision, reproducibility, and sustainability in the processes [11, 12].

This study was aimed at optimizing the ideal microwave treatment conditions to maximize the β-carotene retention in tucumã nectar. In addition, the fatty acid and aromatic compound profiles of the nectar were characterized, providing a detailed overview of the product's bioactive composition. This research was aimed at contributing to the understanding of innovative technologies in the valorization of regional fruits and the development of products that may benefit human health.

2. Materials and Methods

2.1. Pulp Extraction and Nectar Production. The pulp of the tucumã fruit (*A. aculeatum*) was obtained in the municipality of Autazes, Amazonas, Brazil (03°34′47″S and 59°07′50″W), in August 2024. The pulp was stored at −80°C until nectar preparation, using a 3:7 ratio of pulp to mineral water [13]. The nectar was homogenized at 3000 rpm for 5 min and subjected to different thermal processes, such as conventional pasteurization and microwave heating (Figure S1). An untreated sample was kept as a control without any heat treatment until analysis.

2.2. Conventional Pasteurization. Tucumã nectar was subjected to conventional pasteurization using the HTLT method (85°C for 60 s). Samples were placed in a hot water bath at the target temperature, where they remained for 60 s under controlled conditions. As soon as the heat treatment was completed, the tubes were immediately immersed in a mixture of water and ice to stop the heating process and bring the nectar to room temperature [14].

2.3. Microwave Treatment. The samples were treated using a microwave oven (Electrolux, MTD30), in 50-mL Falcon tubes containing the beverage. In order to select and optimize the conditions for obtaining β-carotene-rich nectar, a central composite rotational design (CCRD) (2^2) was employed. The independent variables were microwave power (Watts) (x_1) and time (seconds) (x_2), with three central point repetitions, totaling 11 treatments (Table 1, see Section 3.1). After microwave exposure, the samples were immediately transferred to an ice bath until the nectar temperature dropped to approximately 10°C.

The response variable was defined as the β-carotene peak area (y), measured via HPLC-UV at λ max 450 nm. Optimization procedures were conducted using the Protimiza Experimental Design software (Protimiza Experimental Design, Brazil).

2.4. Determination of Bioactive Compounds

2.4.1. β-Carotene. Carotenoids were exhaustively extracted from the nectar using acetone, following the method of Rosso and Mercadante [15]. To 1.0 mL of tucumã nectar, 15 mL of acetone (1%) was added, and the mixture was left to stand for 2 h. The extracted β-carotene was transferred to a petroleum ether:ethyl ether solution (2:1 w/w). The upper phase consisted of the ether layer, and the carotenoid was dried using a rotary evaporator at < 37°C.

The determination of β-carotene was performed by high-performance liquid chromatography using a Shimadzu LC20AT system, equipped with an autosampler (10 μL), a reverse-phase Shim-pack VP-ODS column (150 × 4.6 mm, 5 μm), and a UV–Vis diode array detector (SPD-M20A). The chromatographic separation was carried out using a ternary gradient system composed of acetonitrile, ethyl acetate, and water. The solvent proportion gradually changed from 88:2:10 to 85:15:0 over 15 min, followed by a 30-min isocratic step. The analyses were performed at a constant flow rate of 1.0 mL/min and a column temperature of 29°C.

Spectral acquisition was carried out in the range of 200–600 nm, with detection performed at 450 nm. Identification was confirmed by comparing the chromatographic behavior and the UV–visible absorption spectrum with that of the β-carotene standard (Figure S2). Quantitative analysis was based on external standardization, using a calibration curve prepared in the range of 0.04–0.50 mg g^{-1} ($y = 3{,}000{,}000x - 110.346$; $R^2 = 0.9937$). Data processing

TABLE 1: Central composite rotational design applied for optimizing β-carotene retention in tucumã (*Astrocaryum aculeatum*) nectar.

Assay	Power (x_1) (W)	Time (x_2) (s)	(Y) Area of β-carotene	β-Carotene (mg/g)	Final temperature (°C)
1	−1 (210)	−1 (15)	131,421	0.081 ± 0.003	36.7 ± 0.85
2	1 (630)	−1 (15)	105,039	0.072 ± 0.005	48.2 ± 2.42
3	−1 (210)	1 (55)	185,326	0.099 ± 0.001	58.3 ± 1.87
4	1 (630)	1 (55)	122,004	0.077 ± 0.001	66.3 ± 4.9
5	−1.41 (122.99)	0 (35)	202,442	0.104 ± 0.003	47.4 ± 1.0
6	1.41 (717.09)	0 (35)	61,237	0.057 ± 0.004	85.2 ± 2.4
7	0 (420)	−1.41 (6.72)	129,021	0.080 ± 0.00	31.2 ± 1.89
8	0 (420)	1.41 (63.28)	163,491	0.091 ± 0.003	73.8 ± 2.86
9	0 (420)	0 (35)	122,428	0.078 ± 0.002	68.6 ± 2.76
10	0 (420)	0 (35)	134,367	0.082 ± 0.002	66.4 ± 2.42
11	0 (420)	0 (35)	129,349	0.080 ± 0.00	61.9 ± 1.9
Optimal condition	122.99	63.28	222,062	0.111 ± 0.003	53.6 ± 2
Untreated	—	—	108,234	0.073 ± 0.001	—
Conventional pasteurization heating (85°C/60 s)	—	—	96,439	0.069 ± 0.002	77.2 ± 2.4

and curve construction were performed using Microsoft Office Excel 2016 software (Microsoft Corp.).

2.4.2. Volatile Compounds. The volatile compounds were extracted using the headspace-solid phase microextraction (HS-SPME) technique, with the adapted methodology of Aguiar [16]. For this, 1.0 mL of the sample was transferred to a 20-mL SPME vial and subjected to a water bath at 55°C under continuous stirring for 15 min. Then, a 65 μm polydimethylsiloxane/divinylbenzene (PDMS/DVB, Supelco) fiber was exposed for 10 min. After this period, the fiber was removed and inserted into the gas chromatograph (GC) coupled to a mass spectrometry (MS) detector (Shimadzu, CG2010/QP2010 Plus) for desorption for 15 s.

For the GC-MS analysis, a WM-5MS column (30 m × 0.25 mm × 0.25 μm) was used, with a programmed temperature range from 50°C to 310°C at a gradient of 2°C/min. Helium was used as the carrier gas at a flow rate of 1 mL/min. The injection mode was split with a ratio of 1:50, and the injector was set at 240°C. Mass spectra were obtained over a detection range of m/z 50–600. To determine the retention index, a homologous series of hydrocarbons (C8–C20) was injected. Retention indices were calculated using the Van der Dool–Kratz equation [17]. Constituents were identified based on comparison of the obtained spectra with those stored in the Wiley seventh edition library of the equipment and by comparing the calculated retention indices with those from the literature [18].

2.4.3. Fatty Acids. The methodology for obtaining fatty acids was adapted from Souza [19], with prior conversion of the lipids into fatty acid methyl esters (FAMEs). The chromatographic analyses were carried out using a GC-MS system (Shimadzu, GC-2010 coupled to QP-2010 Plus). Separation was achieved on a fused silica capillary column WM-5MS (30 m × 0.25 mm × 0.25 μm). The oven temperature program started at 80°C and was increased to 220°C at a heating rate of 5°C min^{-1}. The injector was maintained at 230°C and the detector at 240°C. Helium was used as the carrier gas at a linear velocity of 40 cm s^{-1}, with a split injection mode set at 1:50.

Fatty acids were identified based on a comparison between their retention times and those obtained from analytical standards, while quantification was performed by normalization of chromatographic peak areas. The reference standards (Sigma Supelco) included saturated and unsaturated fatty acids ranging from short- to long-chain compounds, such as C6:0 to C24:1, including mono-, di-, tri-, and polyunsaturated species.

2.5. Physicochemical Analyses. The physicochemical analyses included the determination of pH, lipid content, soluble solids, and titratable acidity. The pH was determined according to the protocols [20]. Lipid quantification followed the method of Bligh and Dyer [21], in which 3 mL of the sample was homogenized with chloroform, methanol, and distilled water (6 mL each), causing phase separation. The lower phase, containing the lipids, was evaporated in an oven at 105°C for 15–20 min and then desiccated and weighed on an analytical balance. The soluble solids content (°Brix) was determined using a digital refractometer with a range of 0%–93%, according to the Instituto Adolfo Lutz [20]. Titratable acidity was measured via volumetry using an acid–base indicator, also as recommended by the Instituto Adolfo Lutz [20]. The results obtained were compared with those of the control samples (untreated) and those subjected to conventional thermal treatment (heating).

2.6. Colorimetric Analysis. For the colorimetric analysis, the parameters $L*$ (lightness), $a*$ (green to red), and $b*$ (blue to yellow) were measured using a colorimeter (UltraScan

VIS, Hunter Lab). The color difference ($\Delta E*$) was calculated according to Equation (1). The variation in color parameters (Δ) was calculated as the difference between the value of the treated sample and that of the standard sample (pure nectar not subjected to thermal treatment):

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a*)^2 + (\Delta b^*)^2}. \quad (1)$$

2.7. Statistical Analyses. The data obtained were subjected to statistical analyses using Minitab software (Version 18). Initially, the normality of the data was assessed using the Shapiro–Wilk test. Once normality was confirmed, one-way analysis of variance (ANOVA) was performed, followed by Tukey's test, with a significance level of 5% ($p < 0.05$), in order to identify significant differences among the treatments.

3. Results and Discussion

3.1. Optimization of Microwave Treatment for Maximization of β-Carotene Retention in Tucumã (A. aculeatum) Nectar. The CCRD results for the two variables studied in the optimization of β-carotene-rich nectar are presented in Table 1. The data analysis shows that both microwave power and heating time had significant effects on β-carotene content. High power levels, even at moderate times (Assay 6; 717.09 W, 35 s), resulted in lower β-carotene content (0.057 mg/g), likely due to thermal degradation caused by higher final temperatures (85.2°C). In contrast, very short times (Assay 7; 420 W, 6.72 s) led to partial extraction (0.080 mg/g), while longer times at moderate power (Assay 8; 420 W, 63.28 s) increased β-carotene content (0.091 mg/g) without reaching the high temperatures associated with the degradation observed in Assay 6. These results indicate that applied power directly influences the final temperature of the nectar, which in turn affects β-carotene yield due to the compound's heat sensitivity. This is consistent with the literature, which reports that elevated microwave temperatures can directly affect carotenoid levels [22].

At a 95% confidence level, both factors, x_1 and x_2, showed a significant influence on the β-carotene peak area ($p < 0.05$). The mathematical model obtained to describe the relationship between the variables and the response is represented by Equation (2):

$$Y_1 = 135{,}102.27 - 36{,}174.75\,x_1 + 14{,}952.24\,x_2. \quad (2)$$

Equation (2) demonstrates the relationship between microwave power (x_1), heating time (x_2), and the β-carotene peak area (Y_1). The negative coefficient for power indicates that increases in power reduce the β-carotene content, likely due to thermal degradation, while the positive coefficient for time suggests that longer heating periods favor extraction without causing significant degradation.

The statistical significance of the model was verified through ANOVA (Table 2), which assessed the contribution of each factor to the response, in addition to evaluating the p values. The model proved to be reliable, with a calculated F value higher than the tabulated F value, a highly significant regression ($p = 7.0 \times 10^{-4}$), and good predictive ability, explaining 83.73% of the data variability ($R^2 = 0.8373$). The analysis also showed no significant lack of fit ($p = 0.08782$), indicating that the model is adequate to describe the response within the studied range.

TABLE 2: Analysis of variance (ANOVA) results.

Variation source	SS	DF	MS	*F* value	*p* value
Regression	12,257,458,678	2	6,128,729,339	20.6	0.00070
Residuals	2,381,778,048	8	297,722,256		
Lack of fit	2,309,904,620	6	384,984,103	10.7	0.08782
Pure error	71,873,428.67	2	35,936,714		
Total	14,639,236,726	10			

Abbreviations: DF, degrees of freedom; MS, mean square; SS, sum of squares.

According to the response surface generated from Equation (2), the optimal conditions to maximize the β-carotene retention in the tucumã nectar were achieved with a low power level (122.99 W) and a maximum treatment time (63.28 s), as illustrated in Figure 1. This optimized condition was used to obtain the nectar for the subsequent steps of the study.

The optimal condition predicted by the model was experimentally tested in triplicate, resulting in a mean β-carotene peak area. This mean was compared to the value predicted by the model using the one-sample Student's t-test, and no statistically significant difference was observed ($p > 0.05$), thus validating the predictive model. Under the optimized conditions, the β-carotene content in the tucumã nectar was 0.111 ± 0.003 mg/g, which is significantly higher than in the pasteurized (0.069 ± 0.002 mg/g) and control nectars (0.073 ± 0.001 mg/g), as shown in Table 1 and Figure 2.

This result is consistent with the values reported in the literature for tucumã pulp [23, 24]. Comparing these experimental conditions with the control and pasteurized nectars, it can be observed that traditional treatments, even with similar heating times, do not achieve maximum β-carotene yield. The control maintains intermediate levels of this carotenoid, while conventional pasteurization causes a significant reduction due to thermal degradation.

It is important to note that, although the total heating time was similar between the conventional and microwave-assisted treatments, the latter provides more uniform volumetric heating. As described in Thostenson and Chou [25], microwave heating delivers energy directly to the material through an electromagnetic field, resulting in homogeneous heating throughout the sample with reduced thermal gradients. Therefore, even with similar heating times, microwave treatment tends to better preserve heat-sensitive compounds. This may explain the greater retention of β-carotene, as the compound is less exposed to localized overheating and thermal degradation compared to conventional heating.

These findings are supported by the literature, which shows that microwave treatment can improve the preservation of β-carotene in foods [26]. They thus reinforce the

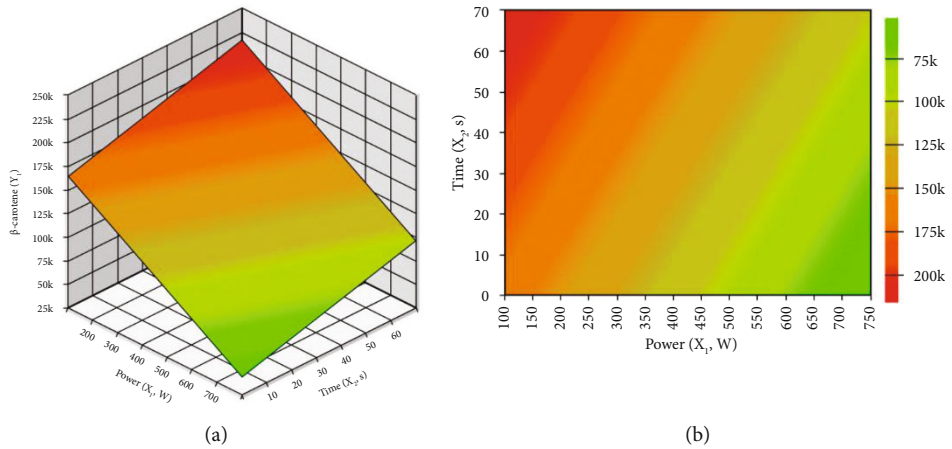


Figure 1: (a) Response surface and (b) contour plot for the optimization of β-carotene retention in tucumã (*Astrocaryum aculeatum*) nectar.

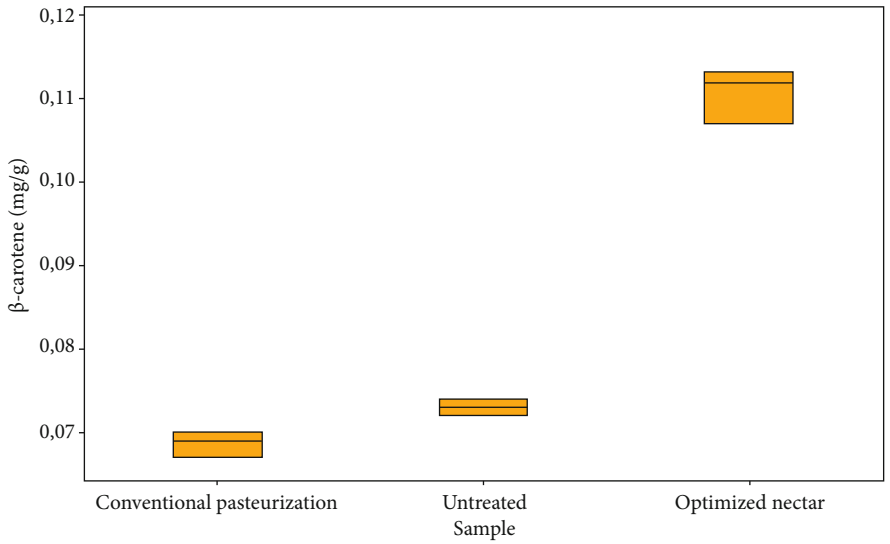


Figure 2: β-Carotene content in tucumã (*Astrocaryum aculeatum*) nectar.

potential of microwave technology as an efficient, sustainable, and promising approach for the valorization of products and by-products from the fruit industry, including nectars [27].

3.2. Characterization of Volatile Compounds. The HS-SPME/GC-MS technique has proven to be highly effective and advantageous for characterizing the volatile fraction of complex matrices, such as fruits, due to its high sensitivity and selectivity, and the absence of the need for solvents [28]. In the present study, it was possible to identify 52 volatile compounds in tucumã (*A. aculeatum*) nectar, corresponding to 85.2% of the compounds present in the untreated nectar, 82% in the conventionally pasteurized nectar, and 75.36% in the microwave-treated nectar, as shown in Table S1. The heating mode in the microwave treatment can explain the lower percentage of volatile compounds observed in the nectar. In microwaves, heating is considered volumetric, rapid, and intense [25], which can lead to the loss of highly volatile, low-molecular-weight compounds. In contrast, conventional pasteurization involves slower heating, resulting in less severe losses of volatile compounds, while the untreated nectar preserves the largest fraction of these compounds.

Among these, β-(E)-ocimene, pyrazine, and (2E)-hexenal stood out as the major constituents. β-(E)-Ocimene was detected at high concentrations in all the analyzed samples: 58.5% in the untreated sample, 45.55% in the conventionally heated sample, and 39.99% in the microwave-treated formulation. This monoterpene is widely recognized for its role in the perception of floral and fruity notes and is considered a key aromatic marker of high sensory relevance [29]. β-(E)-Ocimene has been reported to exhibit anticonvulsant, antifungal, and antitumor activities and to contribute to pest resistance [30]. Monoterpenoids, in general, have been reported to act as antibacterial agents, disrupting microbial growth and interfering with their physiological activities [31]. Pyrazine, a nitrogen-containing heterocyclic compound, was identified at concentrations of 3.40% in the untreated sample, 6% in the conventionally heated

sample, and 4.50% in the microwave-treated sample. This compound is often associated with roasted, nutty and earthy notes and is considered a typical aromatic marker of thermally processed products such as roasted or heated items [32]. In addition to its sensory relevance, certain pyrazines have been reported to demonstrate antibacterial, antipyretic, anti-inflammatory, analgesic, anticancer, and antioxidant activities, suggesting potential health-related implications [33, 34]. (2E)-Hexenal, an unsaturated aldehyde, was also present in all three conditions, with contents of 4.29% in the untreated sample, 2.18% in the conventionally treated sample, and 4.10% in the microwave-treated formulation. This compound is well known for its contribution to green and herbaceous notes and is associated with the perception of freshness in exotic fruits [35]. Regarding its biological activity, it has been reported to exhibit antimicrobial and antifungal properties. Due to its ability to combat microbial infections, this volatile molecule is currently being studied as an ecological alternative to synthetic fungicides and for the control of postharvest decay of fresh produce [36, 37].

The presence of the volatile compounds listed in Table S1 in tropical fruits, especially in palm species, has already been reported in the literature. A relevant example is ethyl hexanoate, identified in all the samples analyzed in this study. This is a volatile ester that is widely associated with sweet and fruity notes and has been reported as the main volatile constituent of *A. vulgare*, with a content of 47.5% [38]. Additionally, heptenal and limonene have also been reported in fruits such as peach palm (*Bactris gasipaes*), with concentrations of 0.55% and 52.9%, respectively [27].

In the present study, limonene was not detected in the conventionally treated sample. Other relevant volatile compounds, such as α-pinene and (6Z)-nonenal, were also absent under this condition but were preserved in the untreated and microwave-treated samples. This suggests that conventional treatment (85°C/77.2°C) promotes more intense thermal degradation. Although microwave treatment resulted in a slightly lower total percentage of volatiles due to rapid and intense heating, it effectively preserved important thermosensitive compounds. Microwave heating, by promoting rapid and uniform heat distribution, helps preserve the functional and nutritional attributes [39], positioning it as a promising technique for the processing of products derived from Amazonian biodiversity.

3.3. Fatty Acids. The chromatographic analysis of the fatty acids present in the tucumã (*A. aculeatum*) nectar, as shown in Table 3, revealed that oleic acid (C18:1) is the main lipid component in both treated and untreated samples, accounting for 86.46% in the untreated sample, 84.63% in the conventionally treated sample, and 82.93% in the microwave-treated sample. Palmitic acid (C16:0) and stearic acid (C18:0) were also identified, with similar contents among the different processing methods. These results corroborate the similar lipid profiles in fresh tucumã samples [40–42]. Furthermore, the results also indicated the presence of these fatty acids in the oil of this fruit, reinforcing the stability of the lipid composition even after different processing methods [43].

The higher contents of palmitic and stearic acids observed in both microwave- and conventionally heated samples, compared to the untreated sample, can be attributed to the thermal effects of these processes. Microwave heating provides rapid and uniform volumetric heating, which may facilitate the release of lipids previously bound or complexed with proteins and carbohydrates, increasing the extractable fraction of these fatty acids. Additionally, partial loss of water and volatile compounds during heating can concentrate lipids, resulting in apparently higher levels of saturated fatty acids. Preferential degradation of polyunsaturated fatty acids may also contribute to the observed increase in the relative proportions of palmitic and stearic acids. These mechanisms are consistent with the reported effects of microwave heating in the literature, which can preserve certain bioactive and sensory compounds while promoting the inactivation of microorganisms and enzymes [8, 10].

It is important to highlight that the nectar produced using microwave treatment retains the characteristic fatty acid profile of the fruit, particularly regarding its high oleic acid content. The results indicate that microwave treatment preserves bioactive compounds, contributing to the maintenance of the functional value and nutritional profile of foods during processing [44]. The presence of these fatty acids in the processed nectar further supports the potential of tucumã as a regional source of functional compounds, with applications in both food and cosmetic formulations [45, 46].

3.4. Physicochemical Analyses. The analysis of the physicochemical parameters of the tucumã nectar (Table 4) revealed statistically significant differences among treatments for both pH and lipid content. The microwave treatment resulted in a significantly higher pH value (6.52 ± 0.01) when compared to the untreated nectar (6.29 ± 0.06), suggesting that this method contributes to greater product stability. Similar findings were reported for the tucumã fruit [47, 48]. Although foods with a pH above 4.5 are considered low-acid and therefore more susceptible to microbial growth, conventional heating methods, while effective in microbial inactivation, may compromise nutritional value. In this regard, microwave technology has been reported to efficiently inactivate microorganisms and enzymes while preserving the food's bioactive and nutritional compounds. In our study, the treatment preserved the bioactive and nutritional compounds [49].

Regarding lipid content, the conventional treatment presented the highest value (13.94 ± 0.00), followed by the microwave-treated sample (11.43 ± 0.00), which, although lower, still represents a significant amount. However, both values are considerably lower than those found, which were 47% [50] and 32% [51], in fresh tucumã fruits. This discrepancy may be related to the type of sample (nectar vs. whole fruit), preparation methods, fruit seasonality, origin, and harvesting period.

TABLE 3: Fatty acids found in tucumã (*Astrocaryum aculeatum*) nectar.

Peak	Compounds	Symbology	Type	% MW treatment[a]	% Conventional pasteurization	% Untreated
1	Palmitic acid	C16:0	Saturated	8.52	8.50	6.77
2	Oleic acid	C18:1	Unsaturated	82.93	84.63	86.46
3	Stearic acid	C18:0	Saturated	8.55	6.87	6.78

[a]Microwave treatment.

TABLE 4: Physicochemical properties of tucumã (*Astrocaryum aculeatum*) nectar.

Experiment	pH	Lipids**	Soluble solids***	Titratable acidity**
MW treatment*	6.52 ± 0.01^{a}	11.43 ± 0.00^{a}	13.8 ± 0.52^{a}	0.29 ± 0.11^{a}
Conventional treatment	6.50 ± 0.02^{a}	13.94 ± 0.00^{b}	13.4 ± 0.91^{a}	0.27 ± 0.00^{a}
Untreated	6.29 ± 0.06^{b}	13.00 ± 0.00^{c}	12.7 ± 0.00^{a}	0.27 ± 0.20^{a}

Note: Asterisk (∗) denotes microwave treatment. Double asterisks (∗∗) denote values expressed as percentages. Triple asterisks (∗∗∗) denote values expressed in °Brix. Values represent means of triplicates ± standard deviation. Means in the same column followed by different letters are significantly different according to Tukey's test ($p < 0.05$), followed by ANOVA.

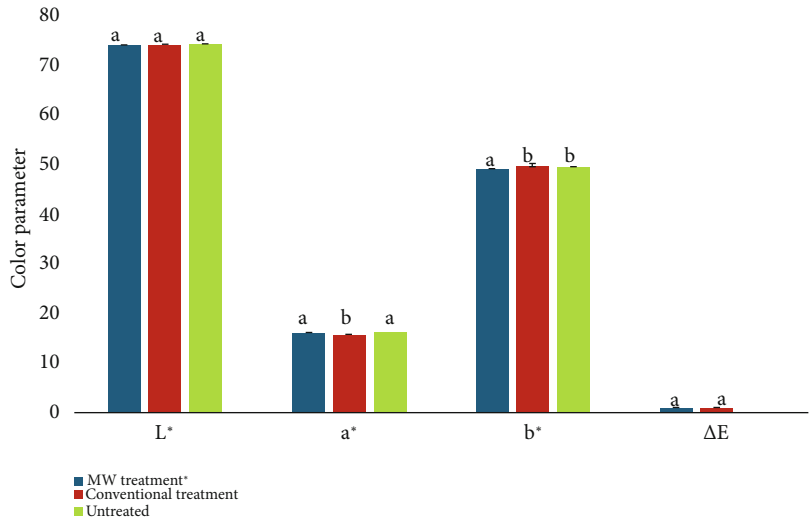


FIGURE 3: Color parameters ($L*, a*, b*$) and total color difference (ΔE) of tucumã (*Astrocaryum aculeatum*) nectar. Microwave treatment*; $L*$ = luminosity; $a*$ = red – green chromaticity; $b*$ = yellow – blue chromaticity; $\Delta E*$ = represents the distance between three colors in the $L*, a*, b*$ space. Values represent means of triplicates ± standard deviation. Means of the same treatment followed by different letters are significantly different according to Tukey's test ($p < 0.05$), followed by ANOVA.

Total soluble solids and titratable acidity did not show statistically significant differences among the treatments. Soluble solids include water-soluble substances such as water-soluble vitamins, certain organic acids, and primarily simple sugars. These compounds are influenced by factors such as soil conditions and the fruit's ripening stage. In the present study, the adjusted mean soluble solid value in untreated tucumã nectar was 12.7°Brix, close to what was observed in the microwave-treated sample (13.8°Brix). These values are higher than those reported for tucumã pulp (1.60–5.13°Brix), which can be attributed to differences in the analyzed matrix (nectar vs. pulp) and the ripening stage [48]. The higher soluble solid content observed in thermally treated nectars compared to the untreated sample can be explained by water evaporation during heating, which concentrates sugars and other soluble compounds. In addition, the breakdown or degradation of pectic substances into smaller soluble molecules as a result of heating also contributes to the increase in soluble solids [52].

Regarding titratable acidity, the results confirm the low titratable acidity of tucumã nectar, even in the samples not treated by microwave. These levels are in agreement with previously reported titratable acidity values for tucumã fruit, which ranged from 0.16% to 1.80% [53, 54]. Similar results were also observed in tucumã peel, for which a pH of 6.01, titratable acidity of 1.05%, and a °Brix of 13.04 are reported, reinforcing both the low acidity and the significant concentration of soluble solids present in the species [55]. Although tucumã is not specifically listed in the Codex Alimentarius [56], reference values for tropical fruits from the same

region—such as pineapple, starfruit, cajá, mango, and cupuaçu—indicate a minimum soluble solid content of 7.5°Brix for fruit nectars. The Codex does not establish specific minimum values for pH or titratable acidity; however, the values observed in tucumã nectar are consistent with those reported for tropical fruit nectars, which typically present low acidity and pH values above 4.5.

3.5. Colorimetric Analysis. The evaluation of the color of the tucumã nectar revealed subtle yet statistically significant variations in some of the analyzed parameters (Figure 3). Similar values were reported for fresh tucumã fruits and tucumã oil [57, 58]. The $L^{\boxtimes}$ value, which represents lightness, showed little variation among the treatments, which remained high (above 73), indicating that the nectar has a light and homogeneous color, regardless of the processing method.

Regarding the $a^{\boxtimes}$ parameter, which represents the tone between red and green, a significant difference was observed between the conventional treatment (15.51 ± 0.18) and the others, with the microwave treatment (15.98 ± 0.11) and untreated sample (15.90 ± 0.02) showing higher values. This suggests that conventional treatment may lead to a slight reduction in the intensity of the reddish color of the nectar, possibly due to the degradation of heat-sensitive pigments, such as carotenoids. These observed color changes may be caused by heat-induced damage to pigments, as well as oxygen reactions, which primarily reduce the fruit's brightness [59].

For the $b^{\boxtimes}$ parameter, the values were higher in the samples subjected to conventional treatment and in the untreated samples, indicating an influence of the processing methods on the preservation of the fruit's yellow pigments. The total color variation (ΔE) was higher in the microwave-treated (0.59 ± 0.11) and conventionally treated (0.70 ± 0.15) samples, suggesting a slight visual change in color compared to the untreated sample, which had a ΔE equal to zero. These findings reinforce that thermal treatment, while effective in other aspects, may lead to perceptible changes in the final product's appearance. However, the observed values remain low, indicating that these alterations do not significantly affect the nectar's visual acceptability.

4. Conclusion

The study demonstrated that microwave treatment is a viable alternative for producing tucumã nectar while also helping to preserve β-carotene and other bioactive compounds such as unsaturated fatty acids and aromatic volatiles. The optimized conditions (low power and longer processing time) minimized thermal degradation, preserving the color and nutritional characteristics. Additionally, microwave-assisted processing demonstrated potential advantages over conventional pasteurization in terms of energy efficiency and processing time, with potential for industrial-scale application, although further studies are required to fully evaluate its overall sustainability. The results highlight the value of tucumã nectar as a nutrient-rich product and support the development of functional products from Amazonian biodiversity. By combining an innovative processing technology with the preservation of bioactive compounds, this study contributes to the use of native fruit nectars while maintaining their functional properties.

Data Availability Statement

The data that supports the findings of this study are available in the supporting information of this article.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Sara de Souza Comapa: conceptualization, investigation, data curation, formal analysis, writing—original draft. Bruna Ribeiro de Lima: conceptualization, data curation, supervision, review, editing, and validation. Sigrid Nara Ruiz: statistical analysis and data interpretation. Jaime Paiva Lopes Aguiar: visualization and validation. Francisca das Chagas do Amaral Souza: conceptualization, writing, review, editing, and validation.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. *(Supporting Information)* The supporting information includes Figure S1, showing nectar derived from the fruit of *Astrocaryum aculeatum*; Figure S2, presenting the chromatogram of β-carotene content in microwave-treated tucumã (*Astrocaryum aculeatum*) nectar compared to the reference standard; and Table S1, listing the volatile compounds identified in tucumã nectar.

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