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Unprecedented evaluation of macaúba (*Acrocomia aculeata*) oils from commercial sources: chemical profile and bioactivity

Carmen Torres GUEDES[1], Jaqueline Ferreira SILVA[1], Ana Paula Monteiro de MENDONÇA[1], Alisson de Lima FIGUEIREDO[1], Carolina Wolf Trentini SCHIPFER[1], Eloize da Silva ALVES[1], Oscar de Oliveira SANTOS JUNIOR[1], Benício Alves de ABREU FILHO[1], Monica Regina da Silva SCAPIM[1], Grasiele Scaramal MADRONA[1]

Abstract

The interest in macaúba (*Acrocomia aculeata*) oil is primarily driven by studies using experimental or non-commercial samples, while little is known about the quality and functionality of products available to consumers. This study provides an unprecedented evaluation of commercial macaúba oils, focusing on their fatty acid profile, acidity index, phenolic compounds, antioxidant capacity, carotenoid content, and antimicrobial potential. Gas chromatography analysis revealed a predominance of monounsaturated fatty acids, particularly oleic acid, with nutritional indices favorable to cardiovascular health. However, both samples exhibited linoleic acid levels at higher concentrations than those reported in the literature, raising concerns regarding raw material variability or possible adulteration. Despite relevant concentrations of carotenoids and moderate antimicrobial activity against *Escherichia coli* and *Staphylococcus aureus*, the oils presented a low phenolic content, limited antioxidant activity, and acidity values above acceptable limits, indicating quality deterioration. These findings highlight the importance of monitoring commercial macaúba oils to ensure authenticity, technological quality, and consumer safety, while reinforcing their potential as a sustainable alternative to conventional vegetable oils.

Keywords: antimicrobial activity; nutritional quality; gas chromatography; antioxidant activity.

Practical Application: Supports quality control, authenticity monitoring, and safer commercialization of oil.

1 INTRODUCTION

Due to the population growth over the last decade, there has been a significant increase in the demand for vegetable oils, primarily to meet energy needs and the requirements of the food sector. Currently, oil extraction revolves around crops such as palm, soybean, corn, and rapeseed. To meet this growing demand, deforestation of native vegetation has caused a substantial impact on greenhouse gas emissions, which is further intensified by intensive cultivation and post-harvest processing (Alcock et al., 2022).

Native to Latin America and widespread throughout Brazil, macaúba is recognized as an oilseed capable of providing high yields with products and by-products of a biodegradable and renewable nature. This palm stands out from other lipid sources, such as oil palm, as it can thrive in different Brazilian biomes due to its ability to survive in semi-arid, humid, and cooler regions (da Costa Lima Pires et al., 2023; Resende et al., 2020).

It is possible to extract oils from both the pulp and the kernel of macaúba. In the mesocarp, the oil presents an orange coloration due to the presence of carotenoids, and oleic acid predominates among its fatty acids (Oliveira et al., 2022). In the kernel, however, lauric acid dominates most of the lipid profile (da Silva et al., 2019). These among other characteristics have sparked interest in the valuable macaúba oil for applications in industrial sectors such as food, cosmetics, bioenergy, and sustainable development (Resende et al., 2020).

Recent interest in macaúba oil extraction has drawn the attention of researchers assessing its health effects. Studies using macaúba oil have yielded promising results, such as cytotoxic, antiproliferative, and antimigratory activity against triple-negative breast cancer cell lines (Aleixo et al., 2024), high antidiabetic activity through the reduction of blood glucose levels in rats compared with the control group (da Silva et al., 2019; Nunes et al., 2018), a neuroprotective effect by increasing reduced glutathione in rats that were fed the pulp oil (Jacobowski et al., 2021) as well as associations of macaúba oil with anti-inflammatory and antimutagenic effects (Costa et al., 2020).

Macaúba oil has been proven effective as a technological agent for improving the texture of margarine, mayonnaise (Silva et al., 2020) and cosmetic gels (Silva et al., 2023), with fatty acids being responsible for enhancing this characteristic. This oil has also shown promise for application in biodegradable chitosan films (Amaral et al., 2017).

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[1]*Universidade Estadual de Maringá, Maringá, Paraná, Brazil.*
*Corresponding author: gsmadrona@uem.br
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The results of these studies are crucial for disseminating knowledge regarding the properties of macaúba oil, driving its consumption, and consolidating its position as a viable alternative to conventional oils. Although many studies have investigated macaúba oil, there are almost no reports on oils from fruits available on the market. Therefore, it is essential to monitor their quality to sustain consumer confidence in their active and technological properties. With this in mind, the present study aimed to evaluate the quality and fatty acid profile of two commercial macaúba oil samples, as well as to assess their antioxidant and antimicrobial effects and carotenoid content.

1.1 Relevance of the work

This study presents an integrated evaluation of the chemical quality and bioactivity of commercial macaúba oils, addressing gaps in the literature largely based on experimental samples. The results highlight nutritional and functional potential, while also revealing limitations in technological quality and product authenticity, reinforcing the need for monitoring and standardization to ensure consumer safety and sustainable valorization.

2 MATERIALS AND METHODS

2.1 Materials and reagents

Four different brands of macaúba oil were found in the Brazilian market, from which two were randomly selected and purchased. These were coded as OM1 and OM2, both packaged in amber polyethylene bottles and stored at room temperature (25°C).

2.2 Fatty acid composition

For the determination of the lipid profile, fatty acid methyl esters (FAMEs) were first prepared following the method proposed by Hartman and Lago (1973) modified by Maia and Rodriguez-Amaya (1993). Approximately 25.0 mg of lipids was weighed into a test tube, and 4.0 mL of 0.5 mol/L NaOH/MeOH was added. The test tube was then heated in a water bath (100°C) for 5 minutes and subsequently cooled. Next, 5.0 mL of esterification solution (NH_4Cl/H_2SO_4/MeOH) was added, and the heating and cooling process was repeated. Afterward, 4.0 mL of saturated NaCl solution and 2.0 mL of n-hexane were added to the tubes and vigorously shaken. Finally, the internal standard methyl tricosanoate (23:0, Sigma-Aldrich, Saint Louis, USA) was added, and after phase separation, the upper layer was collected and injected into the gas chromatography equipped with a flame ionization detector (GC-FID) (GC-Shimadzu-2010 Plus, São Paulo, Brazil).

FAMEs were separated using a fused silica capillary column CP-7420 (Select FAME, 100 m, 0.25 mm internal diameter, and 0.25 µm cyanopropyl/polysiloxane film thickness). Hydrogen (H_2) was used as the carrier gas at a flow rate of 1.2 mL/min, and nitrogen (N_2) was used as the make-up gas at a flow rate of 30 mL/min. The H_2 and synthetic air flow rates for the detector flame were set at 30 and 300 mL/min, respectively. A 1.0 µL volume was injected with a split ratio of 1:40. A temperature program initiated at 165°C for 18 min, followed by a 20 min ramp at a heating rate of 4°C/min. The detector temperature was set at 250°C, while the injector temperature was maintained at 230°C. Retention times and peak areas of the analytes were determined by integration using the Chromquest 5.0 software. Fatty acids were identified by comparing their retention times with known composition standards from the FAME Mix (C4–C24, Sigma-Aldrich, Saint Louis, USA). All procedures were performed in triplicate. The composition in FA was expressed in percentage of relative areas.

2.3 Nutritional quality of fatty acids

The determined fatty acid composition was used to estimate the contribution of commercial oils to human health through nutritional indicators that relate specific groups of fatty acids with recognized health effects (Equations 1 to 6), as indicated by Chen and Liu (2020) and by Ramos Filho et al. (2010).

$$\text{Polyunsaturated/Saturated (PUFA/SFA) ratio} = \Sigma\text{PUFA}/\Sigma\text{SFA} \quad (1)$$

$$\text{Omega-6/Omega-3 (n-6/n-3) ratio} = \Sigma n-6/\Sigma n-3 \quad (2)$$

$$\text{Health promotion index (HPI)} = \frac{MUFA+n-6+n-3}{[C12{:}0+(4\times C14{:}0)+C16{:}0]} \quad (3)$$

$$\text{Atherogenicity index (AI)} = [\text{C16: 0}]/\sum\text{UFA} \quad (4)$$

$$\text{Thrombogenic index (TI)} = \frac{(C14{:}0+C16{:}0+C18{:}0)}{[(0.5\times MUFA)+(0.5\times n-6)+(3\times n-3)+(\frac{n-3}{n-6})]} \quad (5)$$

$$\text{Hypocholesterolemic/hypercholesterolemic (H/H) ratio} = \frac{[(18{:}1n-9+\sum\text{PUFA})]}{[(C12{:}0+C14{:}0+C16{:}0)} \quad (6)$$

Where: UFA stands for unsaturated fatty acid.

2.4 Antimicrobial activity

The antimicrobial activity of macaúba oils was tested against *Escherichia coli* and *Staphylococcus aureus*. The Minimum Inhibitory Concentration (MIC) and Minimum Bactericidal Concentration (MBC) were determined. First, the oils were diluted in different solvents (DMSO and Tween 1%) and subjected to ultrasound to improve solubilization. Bacterial strains were activated in culture broth and subsequently plated to obtain pure cultures. To determine the MIC, 96-well microplates were prepared with different concentrations of the oils and inoculated with bacterial suspensions. After incubation, the MIC was visually determined by the absence of bacterial growth and confirmed by the addition of resazurin. To determine the MBC, aliquots from the wells corresponding to the MIC were plated on agar to verify the absence of colonies, indicating bacterial death. Antimicrobial activity was also assessed using the disk diffusion method. For this, paper disks were impregnated with the oils and placed onto the surface of agar plates inoculated

with the bacteria. The formation of inhibition halos around the disks indicated antimicrobial activity (Wikler, 2006).

2.5 Determination of the acidity index

To evaluate the degradation state of the commercial macaúba oil, the acidity index was determined using the method described by the Instituto Adolfo Lutz (2008). This procedure consisted of adding 125 mL of an ether-alcohol solution (2:1) to 2 g of macaúba oil, followed by titration with 0.1 mol/L sodium hydroxide (NaOH) using phenolphthalein as an indicator until a pink coloration appeared. Results were expressed as acid percentages.

2.6 Bioactive compounds

The hydrophilic extracts of the oils were obtained according to Michels et al. (2016). For this purpose, 2.5 g of each oil was mixed with 5.0 mL of hexane and 5.0 mL of methanol/water (60:40, v/v) and transferred to centrifuge tubes. The mixture was vigorously vortexed for 2 minutes and centrifuged at 4000 rpm for 5 minutes. The hydrophilic fractions extracted with methanol/water (60:40, v/v) were used in the antioxidant and total phenolic compound assays.

2.6.1 Antioxidant activity

ABTS$^{\bullet+}$ assay: The antioxidant capacity of the oil was determined through its reducing potential against the cation radical of 2,2′-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS$^{\bullet+}$). The mixture of the ABTS$^{\bullet+}$ radical solution and the extract was vortexed and stored away from light. Readings were taken at 734 nm and compared with the Trolox standard curve. The results were expressed as μmol Trolox equivalents (TE)/100 g of sample (Re et al., 1999).

DPPH$^{\bullet}$ assay: The free radical DPPH$^{\bullet}$ assay was carried out following the methodology described by Thaipong et al. (2006) with modifications. A total of 150 μL of the sample was added to 2850 μL of the diluted 2,2-diphenyl-1-picrylhydrazyl (DPPH$^{\bullet}$) solution and vortexed. Readings were taken at 515 nm and compared with the Trolox standard curve, and the results were expressed as μmol Trolox equivalents (TE)/100 g of sample.

Ferric Reducing Antioxidant Power (FRAP) assay: The ferric reducing capacity of the sample was evaluated based on its reaction with a 2,4,6-tripyridyl-s-triazine (TPTZ) solution. Absorbance was measured at 595 nm, and the results were expressed as μmol Trolox equivalents (TE)/100 g of sample (Benzie & Strain, 1996).

The determination of total phenolic compounds was based on the method of Singleton and Rossi (1965), where readings were taken at 725 nm, and the total phenolic content was calculated using a gallic acid standard curve. The results were expressed as mg GAE/100 g.

Carotenoids were determined using the methodology adapted from (Rodriguez-Amaya & Kimura, 2004). Absorbance was measured in a spectrophotometer at 450 nm. The results were calculated considering the molar absorptivity coefficient in petroleum ether for β-carotene of 2,592 and expressed as μg of β-carotene per 100 g of oil.

2.7 Statistical analysis

All experiments were performed in triplicate. The data obtained were analyzed using analysis of variance (ANOVA), and differences between means were tested using the t-test at a 5% significance level ($p < .05$), with the SISVAR software version 5.8 (Ferreira, 2019).

3 RESULTS AND DISCUSSION

3.1 Fatty acids profile and nutritional quality of commercial Macaúba oils

The fatty acid profile (Table 1) of the two samples showed great similarity ($p < .05$), with a predominance of monounsaturated fatty acids, followed by polyunsaturated ones. Oleic acid (18:1n-9) was the major component in both samples (59.10 ± 2.48 and 61.00 ± 2.33%), followed by linoleic acid (18:2n-6) (17.10 ± 0.62 and 19.00 ± 0.82%, respectively) and palmitic acid (16:0) (6.30 ± 0.30 and 6.60 ± 0.24%). The other fatty acids identified accounted for less than 6% of the total fraction. Some specific differences were observed: palmitoleic acid (16:1n-7) was not detected in OM1, whereas lignoceric acid (24:0) was absent in OM2; a significant difference ($p < .05$) was also observed in the concentration of heneicosanoic acid (21:0) between the samples.

Table 1. Fatty acid composition (% area relative) and health indicators of commercial macaúba oils.

Fatty Acids (%)	OM1	OM2
16:0	6.30^{a} ± 0.30	6.60^{a} ± 0.24
16:1n-7	ND	0.50 ± 0.03
18:0	2.40^{a} ± 0.13	2.50^{a} ± 0.12
18:1n-9	59.10^{a} ± 2.48	61.00^{a} ± 2.33
18:1n-7	2.90^{a} ± 0.12	3.10^{a} ± 0.07
18:2n-6	17.10^{a} ± 0.62	19.00^{a} ± 0.82
18:3n-3	0.20^{a} ± 0.01	0.30^{a} ± 0.03
18:3n-6	4.50^{a} ± 0.20	5.10^{a} ± 0.28
20:0	0.70^{a} ± 0.02	0.70^{a} ± 0.07
21:00	5.70^{a} ± 0.21	1.20^{b} ± 0.04
24:0	1.10 ± 0.10	ND
ΣMUFA	62.01^{a} ± 2.57	64.60^{a} ± 2.41
ΣPUFA	21.80^{a} ± 0.83	24.40^{a} ± 1.12
ΣSFA	15.44^{a} ± 0.47	10.96^{b} ± 0.44
Nutritional Quality of Fatty Acids		
PUFA/SFA	1.42^{b} ± 0.02	2.23^{a} ± 0.03
n-6/n-3	3.88^{a} ± 0.14	3.78^{a} ± 0.07
HPI	9.89^{a} ± 0.39	9.98^{a} ± 0.10
IA	0.29^{a} ± 0.01	0.27^{a} ± 0.00
IT	0.20^{a} ± 0.00	0.20^{a} ± 0.00
H/H	12.92^{a} ± 0.52	12.99^{a} ± 0.13

Means followed by the same letters in the same row do not differ statistically according to the t-test at $p < .05$; OM1: Macaúba Oil brand 1; OM2: Macaúba Oil brand 2; SFA: Saturated fatty acids; MUFA: Monounsaturated fatty acids; PUFA: Polyunsaturated fatty acids; HPI: Health Promotion Index; AI: Atherogenicity Index; TI: Thrombogenicity Index; H/H: Hypocholesterolemic/Hypercholesterolemic Index; ND: Not detected.

In non-commercial macaúba oils, Sorita et al. (2024) reported oleic acid contents ranging from 67.22 to 75.19%, whereas Fonseca et al. (2021) observed a content of 68.76 ± 0.34%, higher than the values observed in the present study. Regarding linoleic acid, the commercial oils evaluated in this study exhibited concentrations higher than those reported by Fonseca et al. (2021) (9.03 ± 0.72), Sorita et al. (2024) (8.88 ± 0.07–12.17 ± 0.13%) and Aires et al. (2025) (8.77%).

It is noteworthy that the presence of high amounts of linoleic acid may indicate adulteration of specialty oils for economic reasons (Hirashima et al., 2013), since this fatty acid is abundant in soybean, sunflower, or corn oils. These oilseeds have low commercial value and are therefore regarded as potential adulterants (Aued-Pimentel et al., 2008).

It is important to emphasize that the concentration of linoleic acid may vary according to the maturation stage of the fruit, as observed by Oliveira et al. (2022) However, even in ripe fruits (360 days after anthesis), the authors reported values below 10%. Thus, although the linoleic acid content found in this study contradicts the literature, confirmation of adulteration remains uncertain, requiring additional labeling information and further detailed analyses.

The functional indices indicate a lipid profile favorable to cardiovascular health. The PUFA/SFA ratio represents an important aspect for health, particularly in reducing cardiovascular diseases. The recommended value for this ratio is above 0,4 (Preedy & Watson, 2020). In this study, the calculated values were 3.5 times (OM1) and 5.6 times (OM2) higher than the recommended value, highlighting the nutritional potential of commercial macaúba oils. The intake of polyunsaturated fatty acids (PUFAs) is associated with reduced low-density lipoprotein (LDL) concentrations and increased high-density lipoprotein (HDL) levels, whereas saturated fatty acids (SFAs) may have the opposite effect (Chen & Liu, 2020).

Greater precision regarding the influence of fatty acids on cardiovascular diseases can be obtained through the ratio of hypocholesterolemic fatty acids (C18:1 and PUFAs) to hypercholesterolemic fatty acids (C12:0, C14:0, and C16:0). High values of this index may indicate a lower risk of developing coronary artery disease (Silva et al., 2025). For commercial macaúba oils, the calculation showed that both samples promote cardiovascular health, comparable to other important vegetable oils such as rosehip oil (Wirkowska-Wojdyła et al., 2024), watermelon seed (Górska et al., 2023), cranberry, blackcurrant, and strawberry oils (Siol et al., 2025) and about six times more beneficial than marine fish oils (Fernandes et al., 2014).

Low Atherogenicity Index (AI) and Thrombogenicity Index (TI) values are desirable to validate the effect of macaúba oil on cardiovascular health. The calculation and interpretation of these indices are based on the concentrations of saturated fatty acids (SFA) and unsaturated fatty acids (UFA). AI is determined by the proportion of saturated fatty acids considered pro-atherogenic (C14:0, C16:0, and C18:0), while TI evaluates the lipid's potential for clot formation, considering the balance between saturated fatty acids with pro-thrombotic effects and unsaturated fatty acids with protective effects. Both commercial oils presented low AI and TI values (Table 1). When compared with other non-conventional carotenoid-rich fruits, such as mamacadela (AI ≤ 0.94 and TI ≤ 1.09) and cagaita (AI ≤ 0.80 and TI ≤ 1.04), commercial macaúba oil exhibits even lower indices, indicating a lipid profile potentially more favorable to cardiovascular health.

The Health Promotion Index (HPI) is considered a relevant dietary factor for the risk of cardiovascular diseases, with higher values being desirable. The commercial macaúba oils exhibited values consistent with high nutritional quality (9.89 ± 0.39 and 9.98 ± 0.10). When compared with dairy fats (0.16–0.68), these results suggest a more favorable lipid profile, reinforcing the potential of macaúba oil in promoting cardiovascular health.

Although the high levels of linoleic acid (a fatty acid of great nutritional importance) may suggest adulteration, its confirmation in commercial macaúba oils remains uncertain, since the present study did not apply specific methodologies for detecting added oils. Complementary analyses, such as determination of specific plant sterols, triglyceride profiling by chromatography, infrared spectroscopy (FTIR), nutclear magnetic resonance (NMR) spectroscopy, and DNA-based approaches, would be necessary to verify the authenticity of the oil (Srivastava et al., 2024). Incorporating these methods would allow for a more reliable interpretation of the nutritional and functional indices (PUFA/SFA, AI, TI, H/H, and HPI) and their potential effects on cardiovascular health.

3.2 Acidity index

The acidity index of the commercial macaúba oils was 11.19 ± 0.07 (OM1) and 13.54 ± 1.04 (OM2). It is well established that the acidity index indicates the quality status of macaúba oil by measuring the amount of free fatty acids (FFA) present in the sample, an important economic and technological parameter. FFAs are formed from the hydrolysis of ester bonds in lipids caused by the enzymatic action of lipase and microorganisms, a process accelerated by heat or moisture (Brito Mariano et al., 2011).

The acceptable amount of FFA in vegetable oil is 5%, a limit defined by both Brazilian and international regulations. However, industrial parameters are much stricter, as the industry sets the maximum acceptable FFA content in vegetable oils at no more than 3%, since higher levels may render subsequent processing unfeasible (Favaro et al., 2017). Both commercial macaúba oil samples analyzed exceeded the acceptable acidity limit (11.19 b ± 0.07 (OM1) and 13.54 a ± 1.04 (OM2) % oleic acid), which may be associated with the high degradation of the commercial oils. Although macaúba oil can present an acidity index of up to 30% oleic acid (Favaro et al., 2022), it is possible to obtain good-quality oil through proper process control and raw material quality. This is demonstrated by the works of Favaro et al. (2022) and Sorita et al. (2024) who reported acidity values below 5% oleic acid, the limit established by the Codex Alimentarius (2024).

The quality parameters of the final product are closely linked to the quality of the raw material. Because macaúba is a spiny palm, harvesting is carried out on the ground once the ripe

fruits detach from the bunch. Once in contact with the soil, the degradation process of the raw material is accelerated due to high humidity and exposure to adverse conditions such as rain and solar heating, which consequently increase the FFA content in the extracted oil. This effect is further aggravated by the number of days the fruits remain on the ground (del Río et al., 2016). An alternative for easier and safer harvesting is to invest in research aimed at genetic improvement to reduce or eliminate the spines on the trunk.

3.3 Bioactive compounds

Phenolic compounds and carotenoids, recognized for their antioxidant properties, have previously been quantified in the macaúba oil (Aires et al., 2025; Tilahun et al., 2022). Phenolics act in the modulation of reactive oxygen species, whose dysregulation is associated with the progression of chronic diseases, including cancer (Jayaprakasha et al., 2019; Kashyap et al., 2019). Carotenoids, in turn, exhibit provitamin A activity, which is important for the oxidative protection of LDL and HDL lipoproteins (Ramos et al., 2007), playing a relevant role in the prevention of cardiovascular disorders. Considering that most studies have focused on non-commercial matrices, evaluating macaúba oils available on the market is essential to validate their nutritional potential and increase consumer confidence. These results are summarized in Table 2.

The total phenolic content was low in both samples, with a statistically significant difference between them (Table 2), and was considerably lower than the values reported by Coimbra and Jorge (2011) (21 ± 2.0 mg GAE/100 g). Antioxidant activity was more effective against the $ABTS^{\bullet+}$ radical (90.2 ± 7.3 for OM1 and 186.98 ± 6.56 for OM2), while activity against the $DPPH^{\bullet}$ radical and ferric reducing capacity (FRAP) were very low. The result of OM2 against $ABTS^{\bullet+}$ is close to the findings of Cruz et al. (2020) for buriti oil, another Brazilian palm rich in carotenoids, which showed 220 μmol Trolox equivalents/100 g. The authors emphasized that the antioxidant activity of carotenoids is more effective in controlling singlet oxygen, while phenolic compounds perform optimally in scavenging free radicals.

Table 2. Quantification of bioactive compounds in commercial macaúba oil.

	OM1	OM2
Phenolic compounds (mg GAE/100g)	$3.60^{a} \pm 0.94$	$1.30^{b} \pm 0.09$
FRAP (μmol Trolox/100g)	$0.40^{a} \pm 0.00$	$0.20^{a} \pm 0.00$
$DPPH^{\bullet}$ (μmolTrolox/100g)	$15.53^{a} \pm 0.92$	$9.01^{b} \pm 0.55$
$ABTS^{\bullet+}$ (μmolTrolox/100g)	$90.20^{b} \pm 7.31^{b}$	$186.98^{a} \pm 6.56$
Carotenoids (μg de β -carotenoid/100g)	$2313.90^{a} \pm 54.90$	$2643.70^{a} \pm 250.0$

Means followed by the same letters in the same row do not differ statistically according to the t-test at $p < .05$; OM1: Macaúba Oil brand 1; OM2: Macaúba Oil brand 2.

When compared with other studies that evaluated carotenoid content in macaúba oil, our results are 20 times higher than those reported by Tilahun et al. (2022) and lower than those reported by Sorita et al. (2024) (9,330 μg/100 g), and by Trentini et al. (2017) (356,050 ± 1,67 μg β-caroteno /100 g), indicating the potential of macaúba for carotenoid extraction. In addition to sample origin factors, the discrepancy between literature data and commercial oils may be attributed to the fact that carotenoids are natural antioxidant agents against lipid oxidation and may have acted against the oxidation reactions measured through the acidity index.

3.4 Antimicrobial activity

Macaúba oils were effective in inhibiting the growth of *E. coli* at a concentration of 1,000 μg/mL, while for *S. aureus,* the minimum inhibitory concentration was higher than 1,000 μg/mL (Table 3). Macaúba oil was not able to act as a bactericidal agent against either microorganism. The formation of inhibition halos (Table 3) indicates the antimicrobial effect of macaúba oils, with *S. aureus* being the most affected bacterium, likely due to its Gram-positive bacterium lacking an outer cell wall. This effect is associated with the oils' ability to affect bacterial cell wall structure, denature proteins, and disrupt the plasma membrane, thereby interrupting cellular metabolic processes and ultimately leading to cell death (Fonseca et al., 2022).

The literature reports some studies with macaúba oil, such as the formation of larger halos or inhibition zones described by Fonseca et al. (2022) who evaluated the antimicrobial activity of macaúba oil against *Escherichia coli* and the fungus *Candida albicans*, with diameters of 34 and 60 mm, respectively. The authors found no antimicrobial response against *S. aureus*. Sampaio et al. (2023) reported that macaúba seed oil alone showed no antibacterial effects against multidrug-resistant strains *E. coli* 06, *P. aeruginosa* 24, and *S. aureus* 10, nor antifungal effects against *Candida* species (*Candida albicans*, *Candida tropicalis*, and *Candida krusei*). However, when combined with the antibiotic norfloxacin, there was an increase in the antibacterial activity

Table 3. Antimicrobial activity by the diffusion technique of commercial Macaúba oils (OM1 and OM2).

Treatment	Concentration μl/disc	Escherichia *coli* (mm)	*Staphylococcus aureus* (mm)
OM1	20	9	12
OM2	20	8.5	13

Microrganism	OM1 CMI (μg/mL)	OM1 CMB (μg/mL)	OM2 CMI (μg/mL)	OM2 CMB (μg/mL)
E. coli (DMSO 1%)	1.000 ± 0.00	ND	1.000 ± 0.00	ND
E. coli (Tween 1%)	1.000 ± 0.00	ND	1.000 ± 0.00	ND
S.aureus (DMSO 1%)	> 1,000	ND	> 1,000	ND
S.aureus (Tween 1%)	> 1,000	ND	> 1,000	ND

The diameter (mm) of the inhibition zone is the mean of three independent experiments, including the diameter of the paper disk (5 mm).

against these microorganisms. Moreover, when combined with the antifungal fluconazole, it caused a significant inhibition of the growth of all three fungal strains studied, representing an alternative for developing cost-effective treatments for pathogenic diseases.

When it comes to active food packaging, oleic acid, which makes up most of the fatty acids in macaúba fruit (Table 2), is a fungistatic agent and can enhance the antimicrobial effect of chitosan films, for example. The chitosan–oil emulsion allows positively charged chitosan to interact with the negative charges of fatty acids, forming larger positively charged droplets that maintain or increase the antimicrobial activity of the film (Vargas et al., 2006; Vlacha et al., 2016). Therefore, the interactions between fatty acids and polymers may be considered for the development of active packaging using macaúba oil.

4 CONCLUSIONS

In conclusion, the results of this study demonstrate that commercial macaúba oils present a lipid profile characterized by the predominance of monounsaturated fatty acids and nutritional indices favorable to cardiovascular health, with little difference observed between OM1 and OM2. However, high levels of linoleic acid were found, which may indicate variations in the raw material or possible adulteration, whose confirmation requires additional analyses.

The oils showed antimicrobial potential against *E. coli* and *S. aureus* and relevant carotenoid content, with OM1 exhibiting higher levels of phenolic compounds and antioxidant activity (DPPH•). In addition, the high acidity indices highlight the compromised technological quality of the samples. These results underscore the necessity of monitoring the quality of macaúba oils available on the market, to ensure consumer confidence and to further explore their potential as a sustainable alternative to conventional oils.

AUTHORS' CONTRIBUTIONS

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