Received: 9 September 2024 | Revised: 25 November 2024 | Accepted: 9 December 2024

DOI: 10.1111/1541-4337.70097

Comprehensive REVIEWS in Food Science and Food Safety WILEY

COMPREHENSIVE REVIEW

Macauba (*Acrocomia* ssp.) fruits: A comprehensive review of nutritional and phytochemical profiles, health benefits, and sustainable oil production

Guilherme Dallarmi Sorita[1,2] | **Simone Palma Favaro**[2] | **Rossano Gambetta**[2] | **Alan Ambrosi**[1] | **Marco Di Luccio**[1]

[1]Laboratory of Membrane Processes (LABSEM), Department of Chemical and Food Engineering, Federal University of Santa Catarina (UFSC), Florianópolis, Santa Catarina, Brazil

[2]Brazilian Agricultural Research Corporation (EMBRAPA), Embrapa Agroenergia, Brasília, Federal District, Brazil

Correspondence
Guilherme Dallarmi Sorita, Laboratory of Membrane Processes (LABSEM), Department of Chemical and Food Engineering, Federal University of Santa Catarina (UFSC), Trindade, Santa Catarina, Brazi. Email: guilhermedallarmi@hotmail.com

Funding information
Conselho Nacional de Desenvolvimento Científico e Tecnológico, Grant/Award Numbers: 307576/2018-3, 420275/2018-5, 12/2020 MAI/DAI; Ministério da Agricultura, Pecuária e Abastecimento, Grant/Award Number: 21000.074917/2019-39; Coordenação de Aperfeiçoamento de Pessoal de Nível Superior

Abstract

Macauba is an underexplored palm with significant potential for food-grade vegetable oil production. Its fruits yield two distinct sources of oil, the pulp and the kernel, each with its unique composition, emerging as a potential vegetable oil source with high competitiveness with well-established conventional oil sources. Besides the oil, macauba fruits are rich in essential nutrients, including proteins, minerals, vitamins, dietary fiber, and phytochemicals, with outstanding health benefits. Macauba processing generates valuable co-products, including the epicarp, pulp and kernel cakes, and endocarp, which have considerable potential for enhancing the macauba production chain. This review explores the nutritional and phytochemical profile of macauba, its health benefits, and the potential for exploiting its co-products. Innovative extraction methods and a comprehensive strategy for producing multiple products from macauba co-products are also highlighted as opportunities to achieve sustainable development goals and a circular economy in macauba fruit processing.

KEYWORDS

Aqueous extraction, Bioactive compounds, Fatty acids, Macaw, Vegetable oil

1 | INTRODUCTION

Supply chains are facing unprecedented challenges due to a confluence of factors. Growing consumer demand, coupled with the impacts of climate change, natural disasters, global health crises such as the COVID-19 pandemic, and geopolitical conflicts like the Russia–Ukraine war, has created significant disruptions and exacerbated global and regional food security concerns. Multiple impacts related to the current tensions in the food supply chain increased the fertilizers and energy costs (Abay et al., 2023). Furthermore, with the high bioenergy demand (intensified by Russia–Ukraine war), conventional oil crops have been extensively driven to biofuel production. The rise in bioenergy demand has prompted efforts to diversify the energy matrix, implement renewable energy policies, address environmental concerns, and pursue opportunities in agricultural economics (Dahdouh et al., 2023; International Energy Agency, 2023; Sorita et al., 2023).

https://doi.org/10.1111/1541-4337.70097

The oil market is deeply dependent on oil palm (*Elaeis guineensis*), responsible for 40% of the total vegetable oil consumed globally (USDA, 2022). Despite the high productivity, oil palm cultivation has been associated with multiple negative impacts, including deforestation, habitat and biodiversity loss, forest fragmentation, disruption of food chains, air and water pollution, soil erosion, and hydrological changes due to alterations in precipitation (Ayompe et al., 2021), leading numerous oil-consumer companies to search for other sustainable alternatives.

Macauba, a general name that encompasses three main palm tree species of commercial interest (*Acrocomia aculeata, Acrocomia totai, and Acrocomia intumescens*), is widely distributed throughout tropical and subtropical regions of the Americas that has been highlighted as an important and competitive alternative to conventional oil crops, such as oil palm. Besides, in contrast with oil palm cultivation, macauba planting can be concentrated in areas occupied by degraded pastures, which plays an important role in ecological restoration (Pires et al., 2023). Projections show that macauba oil production (5–6.2 t ha^{-1}) can be similar to palm oil (2–8 t ha^{-1}). Macauba fruits provide two oil sources, from the pulp (macauba pulp oil—MPO) and from kernel (macauba kernel oil—MKO). Those oils have distinct fatty acid compositions that are suitable and desirable for many industrial applications. The pulp is rich in monounsaturated fatty acids (oleic acid, 70%) and carotenoids, and the kernel is rich in saturated fatty acids (lauric acid, 40.8%) (Colombo et al., 2018; Simiqueli et al., 2018). Besides the oils, macauba fruit could provide about 20 t ha^{-1} of biomasses, including rich protein cakes and lignocellulosic fractions.

The increasing global appeal for multipurpose plants with co-products used in the biobased industry motivates the consolidation of macauba as a prosperous vegetable oil source. Macauba processing could generate at least four main co-products: pulp and kernel cakes, epicarp (husk), and endocarp (shell), with multiple industrial purposes. The pulp and kernel cake co-products are rich in dietary fiber, carbohydrates, and proteins, respectively, which can be useful in food and feed formulations (Andrade et al., 2020; Gonçalves et al., 2020; Silva et al., 2021). Epicarp and endocarp are the non-edible co-products, mostly studied as biocoals, energy production, and materials for civil constructions (Ampese et al., 2021; Calvani et al., 2020; Costa et al., 2019; Vieira et al., 2021). Overall, those are the main drivers for the increasing interest on the development of the macauba value chain supported by scientific knowledge advances.

Brazil and Paraguay are leading the development of value chains based on *Acrocomia* fruits, and the first cultivated areas are in the establishment phase (Vargas-Carpintero et al., 2021). Attracted by its potential sustainable markets, some companies have begun to invest in the agricultural and industrial modules in Brazil. Among them, Soleum established a pilot macauba plantation in degraded areas, covering more than 700 ha, in Patos de Minas (State of Minas Gerais); Inocas (Innovative Oil and Carbon Solutions) already has planted 2400 ha and expects to expand to 30,000 ha by 2030 (Siamig, 2022). Recently (April/2023), the multinational ACELEN initiated an unprecedented and innovative macauba entrepreneurship to evolve the energy transition in Brazil envisaging the sustainable aviation fuel (Acelen BR, 2023), aiming to grow around 120,000 ha of macauba.

The potential of macauba to become a pillar of a robust global bioeconomy motivates this review, which aims to present a comprehensive analysis of the most relevant scientific reports and promote macauba, a rich yet underexplored palm, as an alternative source of conventional vegetable oils. This review examines the nutritional and phytochemical profiles of macauba and co-products, along with their biological activities. It also evaluates conventional and emerging methods of oil extraction from the pulp and kernel. The discussion extends to the potential use of macauba processing co-products as valuable feedstocks in a biorefinery system, emphasizing their significance within a bioeconomy framework. Finally, a biorefining approach is proposed to enhance profitability and minimize waste, positioning macauba as a high-value raw material for diverse industrial applications in-line with circular economy principles.

2 | *Acrocomia ssp.*: GENERAL ASPECTS

Macauba is a native palm to the tropics and subtropics, with occurrences in areas with high to medium precipitation and high solar irradiation in America, such as Mexico, Colombia, Argentina, Bolivia, Paraguay, Venezuela, Suriname, French Guiana, and the Antilles. Its remarkable resilience and resistance to water scarcity, easy adaptation to different climates, lower environmental impact, and versatility of uses make it a highly promising crop compared to palm oil, the world's main source of vegetable oil. Furthermore, macauba fits to integrated cultivation systems, such as the Crop-Livestock-Forest Integration, which renders low carbon emissions, representing a more sustainable alternative to conventional oilseed growing (Pires et al., 2023).

Commercial exploitation and plantation of macauba are still in their early stages, as previously reported. Currently, the existing value chains rely on fruits gathered by smallholders' farmers from natural populations. The fruits are supplied to local small-scale oil extraction facilities, primarily driven to niche markets, or processed on-farm by local communities for own consumption and short-chain market (Pires et al., 2023; Vargas-Carpintero et al., 2021).

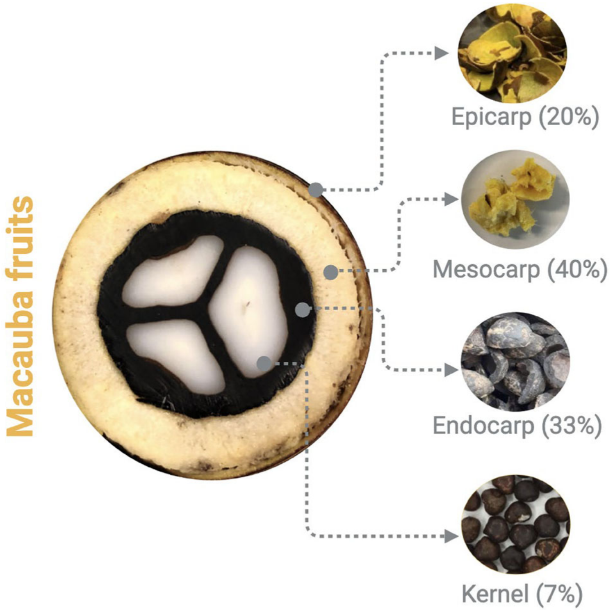

FIGURE 1 Macauba fruit fractions.

Macauba fruits are usually consumed fresh, and the pulp has sweet flavor and gummy texture. The kernel is also appreciated. At some places, the pulp is turned into flour. And both, fresh and dried pulp are ingredients for juices, ice-creams, and pastries, among others. The kernel oil is anecdotally claimed as a joint disease's relief (Oliveira et al., 2022).

Macauba shows a huge natural variability in its phenotype traits (Ciconini et al., 2013). For instance, the number of bunches is within three to seven plants per year, with total fruit yield between 320 and 1080 per plant. In a cultivation field, 1 ha could expect to have around 450 plants in a single production system and 320 plants in an integrated production. It means a total fruit yield in the range of 144.000–486.000 fruits ha^{-1} in a single production system or 102.400–345.000 fruits ha^{-1} in an integrated production.

The fruits are found in massive bunches weighing more than 25 kg (in natural conditions). The fruits (Figure 1) are a spherical drupe with diameter within 25–60 mm. They comprise the epicarp (husk), the mesocarp (pulp), the endocarp (shell), and the nut (kernel), corresponding to 20%, 40%, 33%, and 7% to the total mass of the fruit (Colombo et al., 2018; del Río et al., 2016).

3 | NUTRITIONAL PROFILES OF PULP AND KERNEL FRACTIONS

Macauba fruit is a source of valuable nutrients and bioactive compounds. Understanding the detailed composition, major and minor composition, the bioaccessibility of the nutrients, the functional properties, and the biological activities is paramount to introducing this fruit to a robust local and global market (Gonçalves et al., 2020).

Table 1 depicts the nutritional profile (macro- and micronutrients, pigments, vitamins, fatty acid, and amino acid profiles) of the macauba pulp and kernel. The nutritional profile varies significantly according to the genotype and the harvest place (Antoniassi et al., 2020). Tables S1 and S2 summarize the nutritional composition (macronutrients) and the fatty acid profile of pulp and kernel from different harvest places in South America, respectively.

The nutritional composition of macauba fruits is highly variable, influenced by factors such as genotype and harvest location, as depicted in Table S1. This variability can complicate the standardization of macauba-based products, making it challenging to achieve consistent quality and efficacy. Differences in genotypes variability, environmental conditions, soil types, and climate patterns also contribute to these inconsistencies, adding complexity to ensuring uniformity in product formulation and nutritional value (Al-Shammary et al., 2024; Madeira et al., 2024; Sant' Ana et al., 2024).

A comprehensive strategy should address this issue, focusing on genetic improvement and optimized agricultural practices. Genetic breeding programs can be used to select and propagate macauba trees with stable and desirable nutritional profiles, helping to reduce variability and enhance consistency; indeed, numerous recent studies have focused on identifying promising genotypes, paving the way for a pre-breeding process that combines multiple desirable traits (Ciconini et al., 2013; Madeira et al., 2024). Furthermore, in commercial cultivation areas, optimizing cultivation practices, such as controlled irrigation, fertilization, and soil management, can reduce environmental variability (Al-Shammary et al., 2024). By combining these genetic and agronomic approaches with standardized processing techniques to preserve nutrient integrity, macauba-based products can achieve greater consistency in quality and nutritional value. This integrated strategy will help overcome the current challenges of variability, supporting the development of reliable, high-quality macauba products that meet consumer expectations and industry standards. A more detailed analysis of each nutritional component will be addressed below.

3.1 | Lipids

Lipids are the most valuable component of macauba fruits, with their concentration ranging from 3.2% to 28.9% in the pulp and from 45 to 51.7 g 100 g^{-1} of fresh weight in the kernel, as reported in Table 1.

TABLE 1 Nutritional profile of macauba fractions (pulp and kernel).

Nutritional component	Pulp	Kernel
Macronutrients (g 100 g^{-1} fresh weight)		
Moisture content	5.98–61.7	5.0–12.9
Lipid	3.2–28.9	45–51.7
Carbohydrate	6.9–36.2	5.8–6.1
Protein	1.5–6.7	14.2–28.6
Dietary fiber	8.7–9.3	12.5–39.2
Ash	1.2–2.2	1.9–2.2
Micronutrients (mg 100 g^{-1} fresh weight)		
Nitrogen	0.7	3.6
Phosphorus	4.2	0.6
Potassium	5.4	9.3
Calcium	0.5	0.8
Magnesium	2.4	1.4
Copper	4.7	2.5
Iron	55.2	54.7
Manganese	27.5	5.8
Zinc	28.5	8.1
Pigments (μg 100 g^{-1} fresh weight)		
Xanthophylls	494	–
Carotenes	46	–
Carotenoids precursors	332	–
Flavonoids	1.4	–
Lycopene	0.2	–
Vitamins (μg 100 g^{-1} of oil)		
Vitamin A[a]	859	–
Vitamin C	5.2	–
Vitamin E	0.51	–
Fatty acids (%)		
Caproic acid (C6:0)	0.1–0.2	0.2–0.8
Caprylic acid (C8:0)	0.11–0.3	3.1–6.2
Capric acid (C10:0)	0.1–0.2	2.4–5
Lauric acid (C12:0)	0.1–1.3	24.6–41.9
Myristic acid (C14:0)	0.1–2.6	4.9–13.4
Palmitic acid (C16:0)	7.2–27.4	6–9.2
Palmitoleic (C16:1)	0.1–5	–
Margaric acid (C17:0)	0.05–0.07	–
Stearic acid (C18:0)	0.7–3.6	2.2–3.6
Oleic acid (C18:1)	29.1–72.7	20.5–36.3
Linoleic acid (C18:2)	2.4–35.0	3.1–3.8
Linolenic acid (C18:3)	0.04–7.1	–
Arachidic acid (C20:0)	0.1–1.3	–
Eicosenoic acid (C20:1)	0.1–0.3	–
Behenic acid (C22:0)	0.07–0.2	–
Essentials amino acids (g 100 g^{-1} of protein)		
Histidine	1.6	2.9
Isoleucine	4.1	2.9

(Continues)

TABLE 1 (Continued)

Nutritional component	Pulp	Kernel
Leucine	7.6	6.3
Lysine	3.3	4.9
Methionine	1.1	1.9
Phenylalanine	5.1	5.6
Threonine	4.9	2.8
Tryptophan	–	0.5
Valine	4.8	4.9
Nonessential amino acids (g 100 g^{-1} of protein)		
Alanine	9.2	3.8
Arginine	9.3	16.2
Aspartate	15.0	8.9
Cysteine	0.4	0.8
Glutamate	12.7	20.8
Glycine	6.3	4.6
Proline	4.8	3.7
Serine	5.7	4.9
Tyrosine	4.3	2.5
Pectin (g 100 g^{-1} of dried pulp cake mass)	33.3	–

[a] Retinol equivalent 100 g^{-1}.

Source: Antoniassi et al. (2020), Bora and Rocha (2004), Coimbra and Jorge (2012), Favaro et al. (2017), Gonçalves et al. (2020), Lessa et al. (2022), Machado et al. (2015), Magalhães et al. (2020), Oliveira et al. (2014), Schex et al. (2018).

The oil from the pulp is composed mainly of monounsaturated fatty acids, such as oleic (70%), linoleic (2.4%), and palmitoleic (1.3%) (Antoniassi et al., 2020; Machado et al., 2015). The fruit's yellow-orange color is attributed to its high carotene content, which may enhance oil quality and offer potential human health benefits (Favaro et al., 2017; Schex et al., 2018). Kernel oil is rich in saturated fatty acids, mainly medium-chain fatty acids, lauric, and myristic, which account for 69.7% of the total oil composition. Oleic acid (26.9%) is predominant among monounsaturated fatty acids (del Río et al., 2016).

The pulp and kernel oils present a broad spectrum of physical and chemical characteristics depending on the harvest and post-harvest conditions, the evaluated accession, and the extraction method. For instance, the oils from pulp and kernel from Brazilian fruits, obtained by solvent extraction (hexane), presented similar density of 0.9 g cm^{-3} and refraction index of 1.5; acidity value of 0.87 and 0.05 mg KOH g^{-1}; viscosity of 29 and 27.9 mPa s; iodine index values of 189.3 and 193.7 g I_2 100 g^{-1}, respectively (Lescano et al., 2015). Additionally, the oils present high thermal stability, with melting point of −10 and 20°C, for pulp and kernel oils, respectively (del Río et al., 2016). Those characteristics indicate that this unexplored palm presents two important sources comparable with conventional vegetable oils, such as palm (*E. guineensis*) oil.

3.2 | Carbohydrates

Carbohydrates are the third major component in the pulp (6.9%–36.2%) and kernel (5.8%–6.1%) (Antoniassi et al., 2020; Machado et al., 2015), as presented in Table 1. Among the carbohydrates quantified in macauba pulp, starch is the main polysaccharide (12.6%), whereas glucose (3.64%–9.5%), fructose (3.93%), and sucrose (0.1%) are the prevalent monosaccharides (Antoniassi et al., 2020; Ramos et al., 2008a). Pectin was also quantified in macauba pulp by Gonçalves et al. (2021), achieving a value of 33.3 g 100 g^{-1} of dried pulp cake mass.

Other polysaccharides were also identified in macauba fruits. For instance, Silva et al. (2009) isolated and characterized the galactoglucomannan from the macauba mesocarp. The acid hydrolysis of this compound led to the identification of six oligosaccharides: (i) 3-*O*-*β*-D-galactopyranosyl-D-galactose, (ii) 4-*O*-*β*-D-galactopyranosyl-D-mannose, (iii) 4-*O*-*β*-D-mannopyranosyl-D-mannose, (iv) 4-*O*-*β*-D-mannopyranosyl-D-glucose, (v) 4-*O*-*α*-D-glucopyranosyl-D-glucose, and (vi) *O*-*β*-D-mannopyranosyl-(1 → 4)-*O*-*β*-D-mannopyranosyl-(1 → 4)-D-mannose. Another recent study by Denagbe et al. (2024) evaluated the aqueous extraction of glucomannan oligosaccharides and polysaccharides from macauba pulp. Structural characterization by NMR spectroscopy indicated that the extracted compounds are linear glucomannans composed β-(1–4) osidic bonds in a 3:1 general D-Manp/D-Glcp ratio. These carbohydrates displayed an acetyl group in the C2 position (D-Manp) with a substitution degree between 12% and 14%, presenting lower molecular weight and a 3-fold higher degree of acetylation. Those oligosaccharides presented promising emulsifying properties (stability > 6 months), useful for cosmetics and food industry applications.

3.3 | Fibers

Macauba pulp and kernels contain a good amount of dietary fiber (Table 1). The pulp and kernel had values ranging from 8.7 to 9.3 and 12.5 to 39.2 g 100 g^{-1}, respectively (Antoniassi et al., 2020; Ramos et al., 2008a). As reported in Section 3.1, the fiber concentration can also vary depending on the collection location. Table S1 shows that the fiber concentration in macauba fruits can range from 8.82% to 32.43% for pulp and 12.49% to 39.17% for the kernel (Coimbra & Jorge, 2011; Machado et al., 2015; Pereira et al., 2021). Fibers play an important role in the gastrointestinal microbiota, and low consumption of fibers can result in non-communicable chronic diseases, such as obesity and diabetes (Das et al., 2020). For this reason, the reported data indicate a substantial fiber content in macauba pulp and kernel. Given its high fiber content, macauba fruit has the potential to function as a prebiotic food that is beneficial for gut microbiota health (Andrade et al., 2020). In addition, the high fiber content in macauba pulp and kernel is paramount in promoting digestive health and managing hepatic steatosis. It helps to regulate blood sugar levels, improve lipid metabolism, and reduce liver fat accumulation. By incorporating macauba pulp into the diet, individuals can support the management of metabolic dysfunctions and enhance liver health (Zeng et al., 2024).

3.4 | Protein

Macauba pulp contains a poor amount of proteins (Table 1), with values of 1.5–6.7 g 100 g^{-1} of fresh pulp (Antoniassi et al., 2020; Ramos et al., 2008). However, it can vary according to the extrinsic factors (as mentioned previously for other nutrients), as reported in Table S1. Higher protein concentration values are observed in the kernel (14.2–28.6 g 100 g^{-1} of fresh kernel). The high protein content in the kernel enhances the overall nutritional value of macauba fruit because the different fractions of the macauba fruits synergize together to provide an optimal nutritional profile.

The nutritional quality of protein generally depends on its amino acid composition, particularly essential amino acids (Menegotto et al., 2019). The composition of the essential amino acids shows that the proteins from macauba pulp and kernel are of good quality. In the pulp, leucine (7.6), phenylalanine (5.1), threonine (4.9), and valine (4.8) (g 100 g^{-1}) are majoritarian, whereas in the kernel, leucine (6.3), phenylalanine (5.6), and lysine and valine (4.9) are the dominants (g 100 g^{-1}). Regarding the nonessential amino acids, aspartate (15), glutamate (12.7), arginine (9.3), and alanine (9.2) in the pulp, and glutamate (20.8), arginine (16.2), aspartate (8.9), and serine (4.9) (g 100 g^{-1}) in the kernel are predominant (Bora & Rocha, 2004).

Comprehending protein digestibility is essential for evaluating nutrient absorption and health benefits. A study by Hiane et al. (2006) examined the in vitro digestibility of native and heated globulin and glutelin from macauba kernels. The authors studied the heating effect because it can improve protein breakdown by altering its structure or inactivating protease inhibitors that reduce digestibility. They observed that both forms of globulin showed good digestibility compared to casein, whereas glutelin was less digestible in both conditions. Moreover, macauba globulin was more easily digested than proteins from legumes like soy and mesquite, which often contain protease inhibitors. The slight increase (nonsignificant) in digestibility after heating suggests that macauba proteins, free from such inhibitors, have promising absorption potential. The study underscores macauba kernel, particularly as a co-product of oil extraction, as a valuable and digestible protein source.

From a technological perspective, macauba pulp and kernel proteins extracted from cake byproducts (after oil removal) may be valuable nutrients in foods that can contribute to biorefinery industrial processing and contribute to enriched vegan foods from the nutritional point of view.

3.5 | Minerals

The macauba is also an important source of minerals. Macauba pulp comprises higher levels of iron, zinc, and manganese, whereas iron, potassium, and zinc are the major minerals in the kernel (Table 1). Iron is the most available mineral, both in the pulp and kernel, whose content is 55.2 and 54.7 mg 100 g^{-1}, respectively (Machado et al., 2015).

Those compounds play a vital role in the functioning of the human organism, acting in diverse metabolic processes, biochemical reactions, and as cofactors of certain enzymes. Beyond knowing the total mineral content, understanding the bioavailability of each mineral is crucial for assessing its nutritional impact. The in vitro bioavailability of some minerals of the macauba pulp reached 57.6%, 20.3%, 15%, and 13.6%, respectively, to zinc, manganese, iron, and copper (Gonçalves et al., 2020).

3.6 | Vitamins

Vitamins are organic substances (micronutrients) that play various physiological and biological processes in the human body when consumed in small quantities. The consumption of those substances is highly necessary, and its deficiency is hitched with several health consequences (Tiozon et al., 2021). Vitamins A, C, and E are the main vitamins in macauba pulp (Montoya-Arroyo et al., 2021; Oliveira et al., 2014). For instance, vitamin A, that accounts for 859.4 of retinol equivalent 100 g^{-1} in the macauba pulp (Oliveira et al., 2014), is responsible for maintaining healthy vision, optimal growth and development, cellular integrity, and differentiation of epithelial cells, and it contributes to the functional immune system, human production of milk in lactating mothers, and acts as an antioxidant against cellular damage (Tiozon et al., 2021).

The vitamin E in fruits of macauba sampled in Costa Rica presented a range within 13.3–51.4 mg kg^{-1} in the pulp (Montoya-Arroyo et al., 2021). This vitamin also plays vital roles in the human body, such as in the antioxidant defense of cells against free radicals and, more specifically, in the avoidance of the oxidation of some fatty acids placed in the cell membranes, whose decay is related to development of dementia and atherosclerosis (Tiozon et al., 2021).

Macauba pulp also has significant quantities of vitamin C (52.1 mg 100 g^{-1}) (Montoya-Arroyo et al., 2021; Oliveira et al., 2014). Consuming this vitamin C-rich fruit contributes to various bodily functions, including antioxidant activity, collagen synthesis, carnitine and catecholamine production, tyrosine metabolism, peptide hormone synthesis, prevention of *N*-nitroso compound formation, and supporting nervous system function, iron absorption, and blood cell production (Tiozon et al., 2021).

4 | PHYTOCHEMICALS IN MACAUBA

Phytochemicals are minor bioactive compounds found in edible plants, such as vegetables, seeds, nuts, cereals, and other non-edible plant parts (like roots, leaves, and peel) that have been demonstrated to play a wide range of protective roles and health benefits, such as antioxidative, antiproliferative, anti-inflammatory, and anticancer effects to prevent chronic diseases, among them, aging, cardiovascular disease, and metabolic syndrome (Hu et al., 2023; Monteiro-Alfredo et al., 2021). Table 2 summarizes the phytochemicals identified in macauba fruits and their co-products. Macauba fruits are a valuable source of phytochemical molecules, such as phenolic compounds, carotenoids, tocopherols, and phytosterols. This section provides an overview of the primary phytochemicals investigated in macauba fruits and their derived co-products.

4.1 | Phenolic compounds

Macauba fruits and tree components exhibit a diverse phenolic profile, whose concentrations could be dependent of the accessions and edaphoclimatic conditions. The spectrophotometry assays for total phenolic compounds (TPC) were widely studied in macauba parts. The data regarding the phenolic quantification indicate a significant variation among different macauba fruit samples. For instance, the TPC value in the whole macauba pulp and in the kernel cake, from fruits collected in the State of Minas Gerais (Brazil), showed contents of 262.41 and 215.53 mg gallic acid equivalent (GAE) g^{-1}, respectively (Andrade et al., 2020). Oppositely, fruits from Mato Grosso do Sul, Brazil, exhibited significantly lower TPC values of 0.50 mg GAE g^{-1} (Correia et al., 2022). The same authors also evaluated the flavonol content, and the content was 0.32 mg of rutin equivalent, RE g^{-1}. Moreover, macauba pulp from Ceará, Brazil, exhibited a total phenolic content of 0.51 mg GAEs g^{-1} and a total flavonoid content of 0.37 RE g^{-1} (Oliveira et al., 2014).

As previously reported, macauba epicarp is an important co-product of macauba processing. This co-product has a high potential application due to the presence of bioactive compounds. For instance, phenolic compounds were extracted from macauba epicarp by ultrasound (frequency of 40 kHz) using a methanolic solution (50% v/v) at 25°C, and the TPC reported in the extracts ranged from 1.94 to 6.45 mg GAE g^{-1} (Gomes et al., 2021).

Chromatography assays for phenolic identification and quantification in macauba are currently in the beginning. Fonseca et al. (2021) extracted phenolic compounds from macauba pulp using ultrasound (40 kHz for 30 min at 25°C) with acetone/water/acetic acid solution (70:29.5:0.5 v/v/v). Twelve phenolic compounds were identified and quantified by HPLC/DAD, as depicted in Table 2: catechin, epicatechin, epicatechin gallate, epigallocatechin gallate, procyanidin B1, procyanidin B2, myricetin, kaempferol glucoside, caffeic acid, *trans*-caftaric, chlorogenic acid, and *cis*-resveratrol. Among them, flavonols were the predominant phenolic class, and the catechin (2318.6 mg 100 g^{-1}) and epicatechin gallate (657.1 mg 100 g^{-1}) were the most abundant ones.

Macauba leaves are also a potential source of phytochemical compounds, particularly phenolic compounds. Monteiro-Alfredo et al. (2020) studied the phenolic profile of macauba leaf extracts by two extraction techniques,

TABLE 2 Phytochemicals identified in macauba fruits and their co-products.

Fruit or plant part	Extraction method	Process conditions	Class of compounds	Identified compounds	Identification method	References
Pulp	Maceration	S: methanol acidified *T*: 75°C *t*: 30 min *f*: 40 kHz	Phenolic compounds	Catechin, epicatechin, epicatechin gallate, epigallocatechin gallate, procyanidin B1, procyanidin B2, myricetin, kaempferol glucoside, caffeic acid, *trans*-caftaric, chlorogenic acid, and *cis*-resveratrol	HPLC/DAD	Fonseca et al. (2021)
Pulp	Ultrasound	S: ice-cooled acetone *t*: 15 s	Carotenoids	Violaxanthin isomer, (all-*E*)-violaxanthin, (all-*E*)-neoxanthin, (all-*E*)-luteoxanthin, (all-*E*)-antheraxanthin, (13*Z*)-lutein, (13′*Z*)-lutein, (all-*E*)-lutein, (13*Z*)-zeaxanthin, (all-*E*)-zeaxanthin, (9*Z*)-lutein, phytoene 1, (9′*Z*)-lutein, (9*Z*)-zeaxanthin, phytoene 2, phytoene 3 + phytofluene 1, phytofluene 2, phytofluene 3, phytofluene 4, phytofluene 5, phytofluene 6, (13*Z*)-*β*-carotene, (all-*E*)-*β*-carotene, (9*Z*)-*β*-carotene	HPLC-DAD-APCI/ESI-MS^n	Schex et al. (2018)
Pulp oil	Mechanical pressing	–	Carotenoids and tocopherols	Tocopherol, *α*- and *β*-carotenoids, lutein, and lycopene	HPLC-DAD	Sant' Ana et al. (2023)
Kernel	Soxhlet	S: petroleum ether *T*: 40–60°C		*α*-, *β*-, and *δ*-tocopherol	HPLC-FL (fluorescence detection)	Coimbra and Jorge (2011)
Pulp	Mechanical pressing	–	Tocopherol and tocotrienol	*α*-Tocopherol and γ- and *α*-tocotrienols	UHPLC/MS	Prates-Valério et al. (2019)
Leaves	Maceration	S: methanol *T*: room temperature	Terpenoids	Totaiol, cylindrin, arboniol, isoarborinol, campesterol, daucosterol, and the carboxylic acid tridecanoic acid triterpene	LC-ESI-MS-MS	Souza et al. (2019)
Thorns	Maceration	S: sequential, hexane, chloroform, ethyl acetate, and methanol *T*: 35°C *t*: 36 h	Triterpene, steroids, and stilbene	*O*-Methyl-acrocol 1, *O*-methyl-lupeol 2, 3-oxo-arborinone 3, sitostenone 4, campesterol 5, sitosterol 6, stigmasterol 7, and piceatannol 8	HR-ESI-(+)-MS	Souza et al. (2017)

Note: S: solvent; *T*: temperature; *t*: time, *f*: frequency.
Abbreviation: LC, liquid chromatography.

(i) infusion (with water) and (ii) maceration (with ethanol and methanol). The aqueous medium (infusion) was more efficient in phenolic extraction, and six phenolic compounds were identified and quantified by liquid chromatography with photodiode array detector; four phenolic acids (gallic, vanillic, caffeic, and ferulic), and two flavonoids (rutin and quercetin). Gallic, ferulic, and vanillic acids were the most concentrated, with levels of 201.6, 197.9, and 182.4 mg g^{-1}, respectively, whereas quercetin was identified as the predominant flavonol at 88.7 mg g^{-1}.

The knowledge of phenolic compounds in macauba fruit co-products still needs to be perused. More studies should be carried out to explore the optimization of extraction techniques, identification, quantification, and the possible application of those valuable compounds. Co-products of macauba as raw materials for extracting valuable compounds could be an important strategy to add value and to transform the non-edible parts of the fruit into new ingredients for the food and pharmaceutical industries.

4.2 | Carotenoids

The most studied phytochemicals from macauba pulp are carotenoids, which are converted into vitamin A in the body. This conversion can contribute to a stronger immune response and reduced risk of degenerative diseases (Khalil et al., 2021). The literature presents a wide variation in carotenoid content in macauba pulp, with different studies reporting different concentration ranges. For instance, Ramos et al. (2008b) reported a β-carotene content of 49.0 µg g^{-1} fresh pulp, representing approximately 80% of the total carotenoids. Most of the carotenoid's molecules presented in the macauba fruit are concentrated in the pulp (140.88 µg g^{-1}), whereas a short amount is observed (1.25 µg g^{-1}) in the kernel (Munhoz et al., 2018). Besides that, the carotenoid content in macauba pulp is directly related to the post-harvest steps, and fruits storage at 23°C for 30 days presented an increase of 15% in carotenoid content (Tilahun et al., 2022).

In another study regarding the quantification and identification of carotenoids, macauba pulp from Guanacaste presented 8.72 µg g^{-1} as the total content of carotenoids, and 25 carotenoids were identified: violaxanthin isomer, (all-*E*)-violaxanthin, (all-*E*)-neoxanthin, (all-*E*)-luteoxanthin, (all-*E*)-antheraxanthin, (13*Z*)-lutein, (13′*Z*)-lutein, (all-*E*)-lutein, (13*Z*)-zeaxanthin, (all-*E*)-zeaxanthin, (9*Z*)-lutein, phytoene 1, (9′*Z*)-lutein, (9*Z*)-zeaxanthin, phytoene 2, phytoene 3 + phytofluene 1, phytofluene 2, phytofluene 3, phytofluene 4, phytofluene 5, phytofluene 6, (13*Z*)-β-carotene, (all-*E*)-β-carotene, and (9*Z*)-β-carotene. Among them, phytoene 2 (2.28 µg g^{-1} and (all-*E*)-violaxanthin (1.68 µg g^{-1}) were the majoritarian carotenoids identified (Schex et al., 2018). Additionally, the authors observed a correlation between fruit ripening and the accumulation of specific carotenoids, including phytoene, phytofluene, (all-*E*)-zeaxanthin, (all-*E*)-antheraxanthin, and (all-*E*)-violaxanthin, in the pulp.

Sant' Ana et al. (2024) investigated MPO, which is rich in carotenoids (β-carotene: 163.63, α-carotene: 21.03, lutein: 8.75, lycopene: 14.11 µg g^{-1}), for its effects on gut health in mice fed a high-fat (HF) diet. Although the study did not directly examine bioavailability of carotenoids, it focused on the impact on short-chain fatty acid (SCFA) production, colon structure, and gut microbiota, which are linked to the absorption and utilization of nutrients. Mice were divided into three groups: control, HF, and HF diets with 4% MPO (HFM). The HFM group showed higher butyric acid levels, increased goblet cells, thicker colon muscle layers, and higher microbiome diversity than the HF group. Additionally, MPO reduced harmful gut bacteria (Desulfobacterota phylum, Ruminococcaceae, Oscillospiraceae, Prevotellaceae, Bifidobacteriaceae family, *Faecalibacterium*, *Prevotella*, *Ruminococcus*, and *Enterorhabdus* genus). These results suggest that MPO rich in carotenoids may improve gut health and prevent dysbiosis, potentially enhancing the absorption and effectiveness of its bioactive compounds, thereby contributing to its health benefits.

4.3 | Tocopherol and tocotrienols

Macauba oils exhibit a high content of tocopherols. These compounds act as efficiently as an antioxidant, improving the quality of vegetable oils and preventing oxidation of PUFA, which is especially prone to oxidation (Azzi, 2019). The common tocopherol isomers observed in macauba oil (pulp and kernel) are α-, β-, γ-, and δ-, with quantities varying according to the fruit fraction (pulp or kernel), harvest place, and extraction technique. Fruits from the Southeast and Midwest of Brazil showed that the pulp (0.14, 0.003, 0.058, 0.008, and 0.21 mg g^{-1} for α-, β-, γ-, δ-, and total tocopherol content, respectively) has higher tocopherol content than the kernel (0.014, 0.0008, 0.008, and 0.023 mg g^{-1} for α-, β-, δ-, and total tocopherol content, respectively) (Coimbra & Jorge, 2011). Macauba pulp from Costa Rica presented lower tocopherol values than those from Brazil (0.02, 0.0003, 0.0002, and 0.02 for α-, β-, δ-, and total tocopherol content, respectively) (Montoya-Arroyo et al., 2021).

Tocotrienols, distinct from tocopherols by the number of methyl groups due to their position on the chroman ring and their biological activities (Azzi, 2019), have been identified in macauba palm oil. Recent studies reported the presence of tocotrienols in MPO. MPO from three different regions of Costa Rica presented values of γ- (0.0002–0.03 mg g^{-1}), β- (0.0003–0.002 mg g^{-1}), and δ- (0.0006–0.0012 mg g^{-1}) of tocotrienols isomers (Montoya-Arroyo et al., 2021).

4.4 | Phytosterol

Phytosterols, another class of phytochemicals identified in macauba fruit and leaves, exhibit a wide range of potential pharmacological and nutraceutical applications, including anti-inflammatory, antioxidant, and cholesterol-lowering properties. Additionally, phytosterols have shown promise in preventing diabetes, certain cancers, cardiovascular diseases, and skin conditions (Prasad et al., 2022).

Phytosterols were recently quantified in macauba pulp, kernel, and a 1:1 pulp–kernel blend using gas chromatography–mass spectrometry (GC–MS). Different extraction methods using ethanol extraction were employed to recover those compounds. The highest concentration of phytosterols was found in the kernel (0.86 mg g^{-1}), followed by the pulp + kernel blend (0.63 mg g^{-1}) and pulp (0.44 mg g^{-1}) by Soxhlet, whereas for ultrasound, the highest value was 0.73 mg g^{-1} (stigmasterol: 0.13, campesterol: 0.11, and β-sitosterol: 0.49 mg g^{-1}) at 70°C and a solvent-sample ratio of 12 mL g^{-1} (Rosa et al., 2020). Higher phytosterol content (1.88 mg g^{-1}) was observed by Trentini et al. (2017) using high-pressure propane (at 4 MPa and 60°C); among the phytosterols molecules quantified, β-sitosterol presented the highest concentration (1.50 mg g^{-1}), followed by campesterol (0.27 mg g^{-1}) and stigmasterol (0.12 mg g^{-1}).

Macauba leaves also contain phytosterols. Three phytosterols (campesterol, stigmasterol, β-sitosterol) and two triterpenoids (lupeol and lupeol acetate) were identified and quantified in methanolic (lupeol: 71.6, lupeol acetate: 55.1, stigmasterol: 34.7, β-sitosterol: 23.2, and campesterol: 18.9 mg g^{-1}) and ethanolic extracts (β-sitosterol: 60.1, lupeol acetate: 52.7, lupeol: 49.4, stigmasterol: 25.7, and campesterol: 21.0 mg g^{-1}) from extracts obtained from macauba leaves by GC–MS (Monteiro-Alfredo et al., 2020). Those findings showed that the recovery of phytosterols is highly dependent on the fruit fraction, extraction technique, and solvent employed.

5 | BIOLOGICAL ACTIVITIES OF MACAUBA AND ITS CO-PRODUCTS

Several studies have demonstrated the pharmacological and biological activities of the macauba fruits. The phytochemicals (presented in Section 4) are the main compounds responsible for the health benefits and the pharmacological activities, demonstrated by in vitro and in vivo trials. Table 3 summarizes the potential bioactivities and health benefits of macauba fruits and their co-products.

5.1 | Antioxidant capacity

Numerous studies have reported the antioxidant properties of the macauba oils and co-products (pulp cake, leaves, and epicarp), by in vitro assays (2,2-azinobis-(3-ethylbenzothiazoline-6-sulfonate)—ABTS; 2,2-diphenyl-1-picrylhydrazyl—DPPH; hydroxyl radical scavenging activity and β-carotene-linoleic acid assays). Moreover, in vivo studies have assessed the antioxidant effects of these materials by evaluating lipid peroxidation, lipid hydroperoxide levels, and H_2O_2-induced oxidative stress (Arena et al., 2018; Costa et al., 2020; Gomes et al., 2021; Monteiro-Alfredo et al., 2020).

Ethanol extracts of macauba epicarp, obtained through ultrasound-assisted extraction, exhibited significant antioxidant activity, as determined by ABTS and DPPH assays. The antioxidant capacity, expressed as Trolox equivalent antioxidant capacity (TEAC), ranged from 83.13 to 89.87 mg TEAC g^{-1} for ABTS and 97.98 to 102.57 mg TEAC g^{-1} for DPPH, which could be attributed to the high contents of phenolic compounds (1.94 and 6.45 mg GAE g^{-1}), as reported in Table 3 (Gomes et al., 2021).

MPO exhibited strong in vitro antioxidant capacity, inhibiting hydroxyl radical formation by 70.6% at 5 µg mL^{-1}. Notably, MPO demonstrated superior antioxidant activity compared to the synthetic benchmark, BHT, in the β-carotene-linoleic acid assay, with inhibition rates of 70.2% for MPO and 57.9% for BHT at the same concentration (5 µg mL^{-1}). These findings were confirmed by in vivo studies demonstrating a 67% reduction in lipid peroxidation, as assessed by the TBARS assay, in mice fed a diet supplemented with 20% MPO compared to the control group (Costa et al., 2020).

Oxidative stress is a critical factor contributing to reproductive disorders, including those induced by chemotherapeutic agents like cyclophosphamide (Arena et al., 2018). Given this, the antioxidant properties of MPO are particularly noteworthy. A recent study demonstrated the protective effects of MPO against cyclophosphamide-induced oxidative damage, as evidenced by a 50% reduction in lipid hydroperoxides when co-administered (200.6 nmol g^{-1}) with MPO (30 mg kg^{-1} day^{-1}) compared to the control treatment (cyclophosphamide without pulp oil: 401.0 nmol g^{-1}). This antioxidant activity is attributed to MPO's rich content of carotenoids and tocopherols, which effectively scavenge reactive oxygen species (ROS).

TABLE 3 Biological potential of macauba and their co-products.

Fruit part	Assay	Phytochemical	Bioactivity	In vitro/in vivo model or bacterial strains	Dose/administration method	Key findings	References
Pulp	In vitro and in vivo	Carotenoids	Antioxidant (AA) Anti-inflammatory (AI) Antimutagenic (AM)	In vivo: Animals: male and female Swiss mice 18–22 g (6 weeks) **Anti-inflammatory (AI)**: leukocyte migration into mice peritoneal cavity **Antimutagenic (AM)**: micronucleus test Mutagenic inducer: colchicine (0.5 mg kg^{-1}, intraperitoneally) Inflammatory inducer: thioglycolate 4% (500 μL) In vitro: **Antioxidant (AA)**: lipid peroxidation (TBARS), hydroxyl radical scavenging activity (HRSA) assay, and *β*-carotene/linoleic acid (B/A) system	Conventional food incorporated with MPO (5%, 10%, and 20% w/w) Supplementation time: 10 days Feeding: ad libitum	AA: TBARS: ~0.8 μmol MDA (malondialdehyde) mg^{-1} protein HRSA: 4–8.5 μmol MDA mg^{-1} protein B/A: 66.12%–91.74% AI: reduction of 68% in mononucleate infiltration AM: reduction of 67% of neutrophil migration	Costa et al. (2020)
Pulp	In vivo	Fatty acids and phenolic compounds	Anti-inflammatory (AI) Diuretic (D)	In vivo: Animals: male rats from the Wistar lineage (200–300 g) **Anti-inflammatory (AI)**: paw edema and pleurisy models Inflammatory inducer: intraplantar injection with carrageenan in the left paw (300 μg) or intrapleural cavity (200 μg)	Feeding: ad libitum Supplementation: An oral dose of macauba pulp oil (100–700 mg kg^{-1}) was administered to the animals before the assay	AI: reduction of 91% of the size of paw edema D: increase of 1 mL of urinary excretion 100 g^{-1} of body weight (b.w.)	Lescano et al. (2015)

(Continues)

TABLE 3 (Continued)

Fruit part	Assay	Phytochemical	Bioactivity	In vitro/in vivo model or bacterial strains	Dose/administration method	Key findings	References
Pulp	In vitro and in vivo	Fatty acids	Antidiabetic (AD) Antioxidant (AA) Cytotoxic (CT)	In vivo: Animals: adult male Wistar rats (150–300 g) Antidiabetic model: streptozotocin-induced *Diabetes mellitus* Diabetes inducer: intraperitoneal injection of streptozotocin (STZ) (65 mg kg^{-1}) In vitro: Cytotoxicity: LLC-PK1 cells (renal epithelial cells) Antioxidant (AA): B/A system and DPPH	Oral administration (3, 30, and 300 mg oil kg^{-1}) for 5 days	AD: reduction of ∼57% of blood glucose at 3 mg kg^{-1} AA: 102 µg mL^{-1} (DPPH) and 61 µg mL^{-1} (B/A system) CT: without CT at 5–500 µg mL^{-1}	Silva et al. (2019)
Pulp	In vivo	Carbohydrate (galactoglucomannans)	Immunoadjuvant (I)	In vivo: Animals: male Swiss mice (3 months old) Delayed-type hypersensitivity (DTH) responses model	Subcutaneously administration twice (100 µg oil + 100 µg ovalbumin in 100 µL of saline)	I: reduction of ∼75% of footpad thickness in mice	Silva et al. (2009)
Pulp	In vivo	Carotenoids and tocopherols	Antiadipogenic (AD) Anti-inflammatory (AI)	In vivo: Animals: black male mice C57Bl/6 (8 weeks old and 24 g) Antiadipogenic (AD): histomorphometric analysis of adipose and liver tissues Anti-inflammatory (AI): PPAR-γ, PPAR-α, NF-κB, and TLR-4 quantification from liver samples	Diet incorporated with MPO (40 g oil kg^{-1}) Supplementation time: 8 weeks	AD: MPO prevented adipogenesis AI: MPO reduced inflammatory infiltrate	Sant’ Ana et al. (2023)
Pulp	In vitro	Fatty acids	Anti-bacterial (AB)	*Bacterial strains*: *Escherichia coli* ATCC 25922, *Pseudomonas aeruginosa* ATCC 25853, *Staphylococcus aureus* ATCC 25923, *E. coli* 06, *P. aeruginosa* 24, and *S. aureus* 10 Fungal: *Candida albicans*—CA INCQS 40006, *Candida tropicalis*—CT INCQS 40042, and *Candida krusei*—CK INCQS 40095	–	Macauba pulp oil + fluconazole displayed a significant effect against *C. albicans* (IC_{50} = 15.54), *C. krusei* (IC_{50} = 78.58), and *C. tropicalis* (IC_{50} = 1588 µg mL^{-1})	Sampaio et al. (2023)

(Continues)

TABLE 3 (Continued)

Fruit part	Assay	Phytochemical	Bioactivity	In vitro/in vivo model or bacterial strains	Dose/administration method	Key findings	References
Pulp–kernel	In vivo	Fatty acids and phenolic compounds	Chemopreventive activity (CA)	In vivo: Animals: male Swiss mice (*Mus musculus*) (39 g) Chemotherapeutic inducer: cyclophosphamide (100 mg kg^{-1}) via intraperitoneal	Supplementation: filtered water ad libitum of a commercial diet Oral gavage supplemented with 3, 15, or 30 mg oil kg^{-1}	CA: cell damage reduction of 88.2% (for MKO) and 90.0% (for MPO)	Magosso et al. (2016)
Kernel	In vivo	Medium-chain fatty acids of kernel oil	Anti-hypoglycemic (AH)	In vivo: Animals: male albino Wistar rats (150–170 g) Diabetes inducer: intraperitoneal injection of streptozotocin (STZ) (35 mg kg^{-1})	Supplementation: standard diet supplemented with 40 or 160 g oil kg^{-1} of diet Supplementation time: 28 days	AH: reduction of 50% of the glycaemia at both concentrations	Nunes et al. (2018)
Epicarp	In vitro	Phenolic compounds	Antioxidant (AA)	In vitro: DPPH (1,1-diphenyl-2-picrylhydrazyl) and ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid))	–	AA: 83.13–89.87 mg TEAC g^{-1} (ABTS) and 97.98–102.57 mg TEAC g^{-1} (DPPH)	Gomes et al. (2021)
Root	In vivo	Fatty acids	Anti-hypoglycemic (AH)	In vivo: Animals: adult, healthy mice CD1 (25–30 g) and Wistar rats (150–160 g) Diabetes inducer: alloxan-induced (70 mg kg^{-1} body weight), injected into the caudal	Administration: via stomach tube under anesthesia Dosage: 5, 10, 20, and 50 mg kg^{-1}	AH: reduction of blood sugar of 56.1%	Perez C et al. (1997)
Leaves	In vivo	Phenolic compounds	Anti-hypoglycemic (AH)	In vivo: Animals: male 12-week-old Wistar and non-obese Type 2 diabetic Goto–Kakizaki (GK) rats	Diet: water and food (standard diet) ad libitum Dose: 200 mg of extract kg^{-1} (b.w.) added in the daily water of the animals Supplementation time: 28 days	AH: decreased hypoglycemia by 30%–40%	Monteiro-Alfredo et al. (2021)
Leaves	In vitro	Phenolic compounds	Anticancer (AC)	In vitro: Cells: Ca Ski, MCF-7, and MCF-10 cells	–	AC: 6.25 mg mL^{-1} (IC_{50}) (Ca Ski)	Souza et al. (2019)

(Continues)

TABLE 3 (Continued)

Fruit part	Assay	Phytochemical	Bioactivity	In vitro/in vivo model or bacterial strains	Dose/administration method	Key findings	References
Leaves	In vitro and in vivo	Phenolic compounds	Antioxidant (AA) Toxicity (TX)	In vitro: Antioxidant: DPPH (1,1-diphenyl-2-picrylhydrazyl) and ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)) and *fibroblast cell line* derived from a green monkey (*Cercopithecus aethiops*) kidney (Cos-7) In vivo: Toxicity: Nematode *Caenorhabditis elegans* *Induced oxidation by Juglone*	–	AA (IC_{50}): 117.10 (DPPH) and 47.4 (ABTS) μg mL^{-1} AA: cell viability > 80% at 750 and 1000 μg mL^{-1} TX: no toxic for concentrations lower than 1500 μg mL^{-1} (*C. elegans* survival rate >90%)	Monteiro-Alfredo et al. (2020)
Leaves	In vitro and in vivo	Phenolic compounds	Antioxidant (AA) Anticancer (AC) Cytotoxicity (CT)	In vitro: Cells: Human chronic myeloid leukemia (K562) and breast cancer (MCF-7) In vivo: C57Bl/6 mice In vivo cardiotoxicity with Dox Evaluation: dosage of MDA levels in liver, heart, kidney, and brain	Diet: ad libitum *fed* Supplementation with leaves extracts: 2000 mg kg^{-1}	In vitro: Cytotoxic effect of approximately 73% on K562 cells and approximately 76% on MCF-7 cells at 500 μg mL^{-1} CT: no cytotoxicity was observed in mice AC: mice treated with aqueous extract showed reduction of the weight of 23%, 46%, and 49% of heart, kidney, and brain compared with the control	Monteiro-Alfredo et al. (2023)
Thorns	In vitro	Phenolic compounds	Anticancer (AC) Anti-bacterial (AB) Anti-parasitic (AP)	In vitro: Anticancer: human tumor lines U251 (glioma); MCF-7 (breast); 786-0 (kidney); NCI-H40 (lung); OVCAR-3 (ovary); HT29 (colon); K562 (leukemia) Anti-bacterial: *S. aureus* ATCC 25923, *E. coli* ATCC 25922, *P. aeruginosa* ATCC 27853, *Bacillus subtilis* ATCC 6623, and *C. albicans* ATCC 10231. Anti-parasitic: *L. amazonensis* and *Trypanosoma cruzi*	–	Ethyl acetate extracts: AC (IC_{50}): 10.4 μg mL^{-1} (breast cancer, MCF-7), 77.3 μg mL^{-1} (glioma, U251), and 92.2 μg mL^{-1} (colon, HT29) AB: *Staphylococcus aureus*: 50 μg mL^{-1} (MIC) AP: *Trypanosoma cruzi*: 15.5 μg mL^{-1} (EC_{50}) Hexane extracts: AC (IC_{50}): 91.9 μg mL^{-1} (breast cancer), 141.4 μg mL^{-1} (glioma), 241.6 μg mL^{-1} (colon), 133.4 μg mL^{-1} (ovary)	Souza et al. (2017)

Abbreviations: MKO, macauba kernel oil; MPO, macauba pulp oil; TEAC, Trolox equivalent antioxidant capacity.

The antioxidant protection was associated with the high levels of carotenoids and the presence of tocopherols in the oil (as expressed in Table 3), mediated by scavenging oxidants such as superoxide, resulting in a decrease in ROS (Arena et al., 2018).

5.2 | Anti-inflammatory activity

Inflammation is characterized by a natural protective physiological response of the body against any tissue injury (wound, cuts, burns, radiation, irritants, and physical or chemical stress), microbial infection (i.e., bacterial, viral, and fungal), and autoimmune disorders. Recently, the use of phytochemicals from plants or byproducts, such as polyphenols, flavonoids, flavones, terpenoids, alkaloids, and essential oils, has gained remarkable recognition due to its promising anti-inflammatory properties (Hussain et al., 2022).

MPO, rich in those compounds, exemplifies this potential. The administration of 25 and 50 µL of MPO for 10 days significantly reduced (67%) the neutrophil migration to the peritoneal cavity and reduced mononucleate infiltration (68%) in the inflammatory site in mice in comparison to the control group. The anti-inflammatory properties were directly related to the phytochemicals present in the MPO pulp, which is possibly mediated by phenolic compounds (Costa et al., 2020).

Additionally, MPO-encapsulated and non-encapsulated forms exhibited anti-inflammatory activity in models of pleurisy and paw edema induced by carrageenan. Regarding pleurisy, the administration of microencapsulated oil at concentrations of 300 and 700 mg kg^{-1} markedly inhibited leukocyte migration (91% and 81%, respectively). Related to plasmatic extravasation, the doses at 300 and 700 mg kg^{-1} inhibited 98% and 100%, showing a significant result. The non-encapsulated pulp oil administration at 300 mg kg^{-1} showed paw edema inhibition of 67% after 2 h, and after 4 h, there was no edema induction (Lescano et al., 2015).

The health benefits promoted by the macauba pulp and kernel oil resulted in a patent of an active ingredient (composed of a mixture of fatty acids having between 6 and 28 carbon atoms), being useful as a nutritional supplement, cosmetic–therapeutic formulations, and in pharmaceutical compositions for preventing and treating oxidative stress and inflammation (Canavaciolo Gonzales et al., 2013).

In this context, to fully elucidate the mechanisms underlying the anti-inflammatory effects of macauba oil, further investigations are essential to identify specific bioactive compounds and develop strategies for preserving their bioactivity in potential products.

5.3 | Antidiabetic

There is an increasingly interest in finding alternative therapies for Type 2 diabetic patients, because commercially synthetic drugs are reported to cause various side effects (Sorita et al., 2022 and Sorita et al. 2020). Macauba oils, both MPO and MKO, have also been studied for their antidiabetic potential. The hypoglycemic effect of the oil extracted from macauba pulp and kernel oils was studied in experimental models of streptozotocin (STZ)-induced diabetes rats by Silva et al. (2019), Nunes et al. (2018), and Nunes et al. (2020), respectively. The findings suggest that macauba oils are therapeutic in combating diabetes and related metabolic disorders.

Another study by Silva et al. (2019) showed that oral administration of MPO (3 g g^{-1}) to diabetic rats resulted in a rapid decrease in blood glucose levels within 21 days from the beginning of the treatment compared with untreated diabetic rats. This positive result was associated with reducing oxidative stress and lipid peroxidation due to the oil's highest oleic acid and β-carotene concentrations.

Diabetic-induced rats fed with low and high doses of MKO (0.04 and 0.16 g oil g^{-1} of diet) for 28 days decreased by 50% the glycemia compared to control rats. In this study, beyond hypoglycemic effect, it was observed that the rats fed with MKO had lower deposition of medium-chain fatty acid, the most relevant in MKO, in epididymal adipose tissue of the diabetic rats (Nunes et al., 2018).

These findings suggest that MPO and MKO are potential natural treatments for diabetes. The hypoglycemic effects of macauba oils and their ability to reduce oxidative stress and lipid peroxidation suggest their potential to improve blood glucose control and overall metabolic health. The reduced medium-chain fatty acid deposition in adipose tissue further underscores MKO's potential to prevent diabetes-related complications, enhancing the overall therapeutic profile of both macauba oils.

5.4 | Anti-tumor properties

Extracts of the different parts of fruits and co-products, including pulp and kernel oils (Magosso et al., 2016), leaves (Souza et al., 2019), and thorns (Souza et al., 2017), exhibit anticancer properties. These extracts exhibit potential in inhibiting the proliferation of cancer cells, including those associated with breast, glioma, colon, HPV, intestinal, and ovarian cancers, suggesting potential for the development of novel anticancer therapies.

In a corresponding study, Costa et al. (2020) evaluated in mice the antimutagenic properties of MPO by micronucleus test. MPO was added to the diet (5%–20%) for 10 days and then exposed to colchicine, a DNA damage inducer. Diets supplemented with MPO exhibited lower micronucleus frequency (45%) in all concentrations, compared to the control. The authors correlated the antimutagenic effects with fatty acid profile and antioxidant compounds, such as phenolic and carotenoids.

Terpenoids (totaiol, cylindrin, arboniol, isoarborinol, campesterol, daucosterol, and the carboxylic acid tridecanoic acid triterpene) isolated from macauba leaves presented antiproliferative effects against cancer cell lineages Ca Ski (HPV-modified human cancer cell), with an $IC_{50} \leq 6.25$ mg mL^{-1} (Souza et al., 2019).

Ethyl acetate extracts from macauba thorns also showed efficacy against many tumor cell lines. The extract demonstrated notable anticancer activity, with 50% inhibition of cell growth (GI_{50}) achieved at concentrations of 10.4 µg mL^{-1} for breast cancer cells (MCF-7), 77.3 µg mL^{-1} for glioma cells (U251), and 92.2 µg mL^{-1} for colon cancer cells (HT29). Additionally, the extract reduced cell viability at the IC_{50} concentrations in HPV-infected cervical human carcinomas: 39.8 µg mL^{-1} for HPV 16 (SiHa) and 12.0 µg mL^{-1} for HPV 18 (HeLa), as well as in human intestinal tumors (Caco-2) at 40.0 µg mL^{-1}. Hexane extracts also present efficacy against ovary cancer (3) with GI_{50} of 133.4 µg mL^{-1} (Souza et al., 2017).

Triple-negative breast cancer (TNBC) is an aggressive subtype representing 8%–13% of all breast cancers. Unlike other types, TNBC lacks estrogen, progesterone receptors, and HER2 (human epidermal growth factor receptor 2) overexpression, limiting treatment options and increasing the risk of recurrence, particularly in younger women and breast cancer associated 1 mutation carriers (Adrada et al., 2023). A recent study by Aleixo et al. (2024) developed polymeric micelles loaded with MPO to address this unmet clinical need. These nanoparticles demonstrated potent cytotoxicity and antimetastatic effects against TNBC cells after 48 and 72 h, whereas no toxicity was observed on non-tumor cells. The tested concentrations (386 and 96.5 µg mL^{-1}) significantly inhibited MDA-MB-231 (TNBC cells) cell migration. At 48 h, the difference between the treatment and control groups was approximately 40%. The observed reduction in cell viability, proliferation, and migration suggests that polymeric micelles loaded with MPO could be a promising therapeutic strategy for TNBC and warrants further in vivo evaluation.

5.5 | Other bioactivities

Extracts from distinct parts of macauba were evaluated against several other biological activities, such as immunoadjuvant, diuretic, bacteriostatic, and antiprotozoal effects.

Galactoglucomannan, a carbohydrate extracted from macauba pulp using an aqueous solution, presented high immunoadjuvant activity and delayed hypersensitivity responses in mice after ovalbumin-induced allergic inflammation. After 72 h of galactoglucomannan injection (100 µg), approximately 75% of the increment in the right footpad thickness of mice was reduced (Silva et al., 2009).

Male rats fed a diet supplemented with 5 g of pulp oil increased the urine concentration of 1 mL of urinary excretion 100 g^{-1} of body mass (compared with the control treatment) after 8 h showing potential diuretic effects due to its bioactive compounds, such as carotenoids, tocopherol, vitamin C, and others (Lescano et al., 2015).

Ethyl acetate extracts from macauba thorns exhibited bacteriostatic and protozoan effects against *Staphylococcus aureus* (with minimum inhibitory concentration of 50 µg mL^{-1}) and *Trypanosoma cruzi* (EC_{50} 15.5 µg mL^{-1}), respectively. The same extract was purified, obtaining an isolated compound called piceatannol 8, which presented activity against the leishmaniosis protozoan (IC_{50} of 58.4 µg mL^{-1}) (Souza et al., 2017).

6 | CONVENTIONAL AND NEW TRENDS FOR OIL RECOVERY

The primary products from macauba fruits are the pulp and kernel oil due to their high content and quality, as detailed in Section 3.1. Currently, macauba pulp and kernel oils are primarily extracted using mechanical pressing (MP). The process encompasses cleaning, peeling, and pulping the fruit, then drying and pressing the pulp to extract the oils. To extract kernel oil, the endocarps are ruptured and separated from the kernels by flotation in a solution with NaCl or clay. Then, the kernels are washed and dried prior to the pressing step. Finally, the extracted kernel oil is filtered to produce the final kernel oil product (Rivaldi et al., 2022).

As detailed in Section 3 and Table S1, the high water content in macauba pulp, reaching up to 62%, renders MP impractical due to the substantial energy requirements involved in the drying process. Furthermore, the extraction of vegetable oils by pressing (also called expeller extraction) has a low yield, generating a cake (co-product) with high oil content (15%–20%).

Over the past decade, numerous research aimed to overcome the drawbacks of traditional extraction methods, and innovative and sustainable processes have been proposed to improve the oil quality and yield.

An innovative and eco-friendly vegetable oil recovery route is aqueous extraction, which may or may not be assisted by enzymes (aqueous extraction processing—AEP and aqueous enzymatic extraction—AEE). The use of enzymes promotes a breakage of the vegetable tissues and facilitates the release of the oil, with no need of previous drying. After extraction, the resulting slurry, composed of solid and the oil fraction, can be separated using two- or three-phase decanter centrifuges. The final crude oils are almost free of phosphatides and, consequently, with low turbidity, similar to the degumming stage in the refining of vegetable oils (Díaz-Suárez et al., 2021; Polmann et al., 2019; Wei et al., 2022). Using two- or three-phase decanters is already a reality in the olive and avocado oil extraction industries.

This innovative oil extraction process separates the continuous oily phase from the other fruit components without altering its composition or organoleptic characteristics (Permal et al., 2020; Wong et al., 2014). This process was successfully applied for high-quality oil recovery from olive and avocado (Abbattista et al., 2021; Altieri et al., 2015; Dahdouh et al., 2023; Gila et al., 2022; Permal et al., 2020; Wong et al., 2014) on scale-up trials. Thus, this technological approach may emerge as an innovative method for oil recovery from different raw materials, such as macauba pulp. A pioneer study applied AEP to macauba pulp, and the results were very promising for both high extraction efficiency (88.7%) and oil quality (0.4%–4.2% oleic acid, low oxidative status, 101–107 µg g^{-1} total carotenoid) (Favaro et al., 2022). Such efficiency was obtained using the commercial enzymatic pool Cellic Ctec3 (AEE). Afterward, another trial was carried out with AEP to recover MPO using a commercial enzymatic pool of pectinases, and 88.6% of extraction efficiency was achieved, and a good standard of quality was also observed (Sorita et al., 2024).

AEP and AEE render, beyond the oil, two other co-products, the liquid fraction and the solid fraction, whose composition depends on the raw material and the conditions of the extraction process (Polmann et al., 2019; Wei et al., 2022). Both fractions can be integrated into a biorefinery to produce other ingredients and/or energy to the own macauba processing. This approach not only reduces the environmental impact due to the non-residue's formation but also adds value to the macauba chain (Sorita et al., 2023).

The avoidance of organic solvents and high energy consumption is totally in line to a sustainable production of macauba. Therefore, a large-scale processing use of AEP/AEE for recovering macauba pulp and kernel oils is an important opportunity for achieving the Sustainable Development Goal (SDG) in edible oil production. Because the co-products generated are not polluted with toxic solvents, they are useful as raw materials for producing several high-added-value products for the food and pharmaceutical industries.

7 | MACAUBA CO-PRODUCTS AND THEIR APPLICATIONS: IMPORTANT FEEDSTOCKS FOR A BIOREFINERY SYSTEM

A bold interest is given to macauba co-products, which can be divided into edible (pulp and kernel cake) and non-edible (epicarp and endocarp), whose applications could reach several industrial segments, as summarized in Table 4. The novelty of this section is to highlight macauba co-products as a feedstock of a possible sustainable system (described in Section 8), following the principles of circular economy and the emergent biorefinery concept.

7.1 | Edible co-products: pulp and kernel cakes

Macauba pulp cake (MPC) and macauba kernel cake (MKC) are the main co-products resulting from the pulp and kernel MP, respectively. As this dry route of oil recovery is the most studied and reported for macauba so far, most of the available scientific literature brings those two kinds of cakes as the raw material for feeding purposes. According to Andrade et al. (2020), MPC and MKC are composed of protein (2.9% and 27.8%), lipids (28.6% and 28.3%), carbohydrates (9.7% and 1%), and fibers (20% and 36%, respectively). Moreover, phytochemicals, such as phenolic compounds with antioxidant capacity, were also identified in those co-products, as reported in Section 4.1.

Regarding food applications, MPC and MKC have been used to improve the nutritional quality of cookies (Gonçalves et al., 2021); to produce edible coating films (Silva et al., 2020); and protein concentrates (Silva et al., 2021), among other uses. MPC and MKC were evaluated as a substrate for probiotic microorganisms (*Bifidobacterium lactis, Lactobacillus casei*, and *Lactobacillus acidophilus*) to produce SCFAs (organic acids), such as lactic (6.6–9.8 and 3.2–9.8 g L^{-1}), propionic (3.1–3.7 and 3.2–4.3 g L^{-1}), butyric (0.25–0.3 and 0.3–0.4 g L^{-1}), and acetic acid (0.8–1.2 and 0.5–1.1 g L^{-1}, for MPC and MKC, respectively) (Andrade et al., 2020). Gonçalves et al. (2021) showed that MPC presented a high pectin concentration (33.3%), which may be used as a food additive due to its gelling, stabilizing, and thickener properties. The valorization of pectin from MPC may be an alternative to traditional pectin sources.

Current food engineering and packaging research has highlighted the development of new bio-based packaging materials that keep and improve the quality of food products (Mücke et al., 2021). An active edible coating with antimicrobial activity against *Pseudomonas aeruginosa* and *S. aureus* was recently developed using MPC.

TABLE 4 Summarization of macauba co-products applications.

Co-product	Application area	Product	Target results	References
Pulp cake	Effluent treatment	Adsorbent	Maximum absorption: Methylene blue: 25.80 mg g^{-1} Congo red: 32.00 mg g^{-1}	Vieira et al. (2012)
Pulp cake	Biofuels	Ethanol	Microorganism: *Candida boidinii* UFMG14 strain Ethanol production: 12 g L^{-1}	Gonçalves et al. (2013)
Pulp cake	Food	Food additives	Improving in nutritional quality cookies: increasing of fiber, protein, and pectin content in cookies	Gonçalves et al. (2021)
Pulp cake	Food	Edible films	Moderate yellowish color, low opacity, good tactile aspect, homogenous and without fractures Permeability of water vapor: 3.61–8.33 g mm m^{-2} day^{-1}	Silva et al. (2020)
Pulp cake	Biotechnology	Enzymes—*α*-amylase production	*Bacillus amyloliquefaciens* pH: 7.0 Time: 24 h Activity: 196.0 U mL^{-1}	Silva et al. (2016)
Pulp cake	Biotechnology	Enzymes—lipase production	*Moniliella spathulate* Maximum activity: 2.47 U mL^{-1} Temperature: 31.5°C and pH 6.7 Functionality in a wide temperature and pH range	Souza et al. (2015)
Pulp and kernel cake	Food	Prebiotic	*Bifidobacterium lactis, Lactobacillus casei*, and *Lactobacillus acidophilus* Lactic (6.6–9.8 and 3.2–9.8 g L^{-1}) Propionic (3.1–3.7 and 3.2–4.3 g L^{-1}) Butyric (0.25–0.3 and 0.3–0.4 g L^{-1}) Acetic acid (0.8–1.2 and 0.5–1.1 g L^{-1}, for MPC and MKC, respectively)	Andrade et al. (2020)
Kernel cake	Food	Emulsifiers	High protein solubility: 77.1% High emulsion stability: 313 min Water- and oil-binding capacity: 3–3.84 mL g^{-1} Emulsifying activity index: 175.7 m^2 g^{-1}	e Silva et al. (2022)
Kernel cake	Food	Plant-based foods	Isoelectric point: pH 4.9 Hydrophobicity: higher in pH 3.5 Oil holding capacity: 153.77% Water holding capacity: 97.29%	Lessa et al. (2022)
Kernel cake	Food	Additives—pulses and vegan foods	*Identification of two proteins fraction*: 7 S globulins (vicilin-like and basic 7 S globulins) 11 S globulins *Solubility concentration*: 0.1 mol L^{-1} of chaotropic salts (NaCl, KCl, and Na_2SO_4)	Silva et al. (2021)
Kernel cake	Biotechnology	Enzymes—dye degradation	*Pleurotus ostreatus* *Pleurotus eryngii* Dye: Carmine indigo dye Temperature: 4–60°C Time: 16 h pH: higher activity in acidic conditions	S Lopes et al. (2020)
Endocarp	Effluent treatment	Biosorbent	Endocarp mass: 150 g pH: 6.5 [Ni (II)]: 10 mg mL^{-1} Retention: 50.05%	Altino et al. (2017)

(Continues)

TABLE 4 (Continued)

Co-product	Application area	Product	Target results	References
Endocarp	Effluents treatment	Biosorbent	Pyrolysis temperature: 250°C pH: 3 [U (VI)]: 5 mg L^{-1} Retention: 86%	Guilhen et al. (2019)
Endocarp	Effluents treatment	Activated carbon	Surface area: 907 m^2 g^{-1} Adsorption capacity: Bisphenol A: 0.148 mmol g^{-1} Ethinylestradiol: 0.104 mmol g^{-1} Amoxicillin: 0.072 mmol g^{-}	Moura et al. (2018)
Endocarp	Effluents treatment	Activated carbon	Surface areas: 951–1002.5 m^2 g^{-1} Atrazine retention: 90%–98%	Vieira et al. (2021)
Endocarp	Effluents treatment	Sulfonated carbon	Specific surface area: 2 m^2 g^{-1} Maximum lead adsorption capacity: 104.2 mg g^{-1}	Souza De Brito et al. (2023)
Endocarp	Effluent treatment	Biosorbent	Removal of Fe^{3+}: 99.73% Removal of mn^{2+}: 94.79 Surface application rate: 10 m^3 m^{-2} h^{-1}	Giraldo-Bareño et al. (2023)
Endocarp	Glycerol purification	Activated charcoal	Surface area: 627 m^2 g^{-1} Pore volume: 0.39 m^3 g^{-1} Glycerol purity (after purification): 95.99%	Barbosa et al. (2022)
Endocarp	Agriculture	Biochar	Application: hydroponic culturing Micronutrients: K: 2610, Ca: 533, Mg: 279, Fe: 1316, B: 257, S: 166, and P: 239 mg kg^{-1}	León-Ovelar et al. (2022)
Endocarp	Civil construction	Bricks	Concentration: 5% Improving thermal insulation capability Decrease of compressive strength	Calvani et al. (2020)
Epicarp	Biofuels	Biogas	Pre-treatment: Flow rate (water): 10 mL min^{-1} Temperature: 200°C Pressure: 14 MPa Time: 40 min Biogas (CH_4): 357.3 mL g^{-1} of macauba epicarp	Ampese et al. (2021)
Epicarp	Thermal energy	Briquettes	Pressure: 1000 PSI Temperature of 120–130°C Time: 5 min Calorific value: 4174.5 kcal kg^{-1}	Costa et al. (2019)

Abbreviations: MKO, macauba kernel oil; MPO, macauba pulp oil.

Promising properties, such as tensile strength, thickness, elongation, water and acid solubility, and water vapor permeability, were observed for this product (Silva et al., 2020).

Another study by Silva et al. (2021) suggested that MKC can be a vegetarian complement in pulse diets due to its high protein content. The amino acid profile of MKC showed that arginine (15.5), leucine (6.2), and valine (4.8 g 100 g^{-1}) were the main essential amino acids, whereas glutamic acid (21.7) and aspartic acid (8.7 g 100 g^{-1}) were the main nonessential amino acid presented in MKC. The authors also observed that albumin and globulins were the main protein fractions. Globulins, found in higher concentrations (58.5%), were subdivided into two fractions (7S and 11S) with different physicochemical properties and applications. The functional properties of MKC showed high protein solubility (77.1%) and high emulsion stability (313 min). In addition, high emulsion stability and important gelling properties were detected in MKC: 3.84 water-binding capacity, 3 mL g^{-1} oil-binding capacity, 175.7 m^2 g^{-1} emulsifying activity index, and 10% least gelling concentration (Silva et al., 2022). The study of the technological potential of MKC is important to develop foods enriched with MKC, which may be used as a new food ingredient (as protein concentrate), especially in applications requiring emulsion stabilization and gelling properties, such as in Pickering emulsions, meat alternatives, dressings, and dairy desserts.

MPC and MKC were also used in other fields, such as biofuels, effluent treatment, and biotechnology, as presented in Table 4. MPC was efficiently used as adsorbent material to remove methylene blue and Congo red dyes from wastewater (Vieira et al., 2012), whereas MKC was used as a substrate to produce enzymes by *Pleurotus ostreatus* and *Pleurotus eryngii fungus* with high degradation capacity of the indigo dye (Lopes et al., 2020). Besides that, MPC has shown to be a good inducer of α-amylase production using *Bacillus amyloliquefaciens* in submerged culture (Silva et al., 2016).

7.2 | Non-edible co-products: epicarp and endocarp

Epicarp is a thin, hard, brittle, and fibrous structure with light brown color (when mature) and corresponds to 20% of the fruit, as reported in Section 2. Recent studies have employed this co-product as raw material for bioethanol production due to their cellulose-rich composition, glucose (69%), xylose (19%), mannose (5%), galactose (4%), and arabinose (3%) (Rencoret et al., 2018), which may be a decarbonization strategy for circular economy approaches. This co-product has also been used for charcoal production due to its high calorific value (Costa et al., 2019).

Endocarp is another non-edible co-product from macauba processing. It is also a lignocellulosic material, corresponding to about 33% of the overall fruit mass (Section 2). The research on this co-product is mainly associated with charcoal and activated carbon for various applications and biosorbents (Table 4).

For instance, macauba endocarps show an efficient, low-cost, and environmentally friendly biosorbent in wastewater treatment for the removal of nickel (II) (Altino et al., 2017), uranium (VI) (Guilhen et al., 2019), atrazine pesticides (Vieira et al., 2021), and emerging contaminants (such as bisphenol A, ethinylestradiol, and amoxicillin) (Moura et al., 2018). Furthermore, activated charcoal produced from the macauba endocarp was also effective for removing pigments from crude glycerol (Barbosa et al., 2022) and as substitute for peat in planting substrates for hydroponic hydroculture (León-Ovelar et al., 2022).

Scale-up studies are essential to address the challenges inherent in auto-scale systems, including ensuring consistent efficiency and quality, reducing costs, and meeting stringent regulations. A significant advancement was made in scaling up trials using macauba endocarp, chemically treated with 10% w/v sodium hydroxide, as a biosorbent for removing Al^{3+}, Mn^{2+}, and Fe^{3+} from contaminated surface water. Giraldo-Bareño et al. (2023) demonstrated high process efficiency, achieving removal rates of 99.73% for Fe^{3+} and 94.79% for Mn^{2+}. Additionally, analysis of conductivity, turbidity, pH, color, and metal concentrations revealed that columns constructed with the endocarp co-product effectively reduced these parameters, showcasing the technical feasibility of this biosorbent.

Cellulose and lignin from agricultural co-products, added to the cementitious matrix to filler, and reduce the amount of cement, bring environmental and economic benefits. Due to their high mechanical and impermeable properties, endocarps from macauba fruits successfully enriched Portland/residue composites (up to 5% w/w), improving thermal insulation in civil constructions (Calvani et al., 2020).

A pioneering study by Alves et al. (2022) unveiled the bioenergy potential of macauba endocarp by comprehensively analyzing its pyrolysis kinetics and thermodynamics. By employing non-isothermal thermogravimetric analysis and advanced modeling techniques, the study identified three parallel reactions for devolatilization: hemicellulose, cellulose, and lignin, with activation energies of 90.2–99.5, 113.6–123.9, and 153.0–167.3 kJ mol^{-1}, respectively. Another study by Evaristo et al. (2016) revealed that macauba endocarp activated carbon possesses the highest energy density at 33.14 GJ m^{-3}, whereas the epicarp exhibits the lowest energy density at 31.99 GJ m^{-3}. The above-cited works confirmed the macauba endocarp and epicarp viability as a bioenergy feedstock, positioning the macauba non-edible co-products as a promising and environmentally friendly bioenergy alternative.

In summary, macauba epicarp appears as a raw material with remarkable bioenergy potential to compete as an effective alternative for diversifying and decentralizing energy supplies. At the same time, macauba endocarp emerges as a raw material for diversifying products in a biorefinery system applied for industrial macauba processing.

8 | BIOREFINING MACAUBA: A BIOECONOMY SMART MODEL TO IMPROVE PROFITS AND MITIGATE WASTES IMPACT

Biorefineries offer a promising pathway to align macauba oil production with SDGs. Biorefineries can mitigate the environmental and social impacts associated with traditional food production systems by transforming potential waste products into valuable bio-based materials (Sarkar et al., 2021).

Thus, considering the composition and applicability of macauba co-products (epicarp, pulp, kernel cakes, and endocarp) presented in Section 7 and Table 4 and the greener extraction process (AEP/AEE) suggested in Section 6, a suggested roadmap is illustrated in Figure 2. This

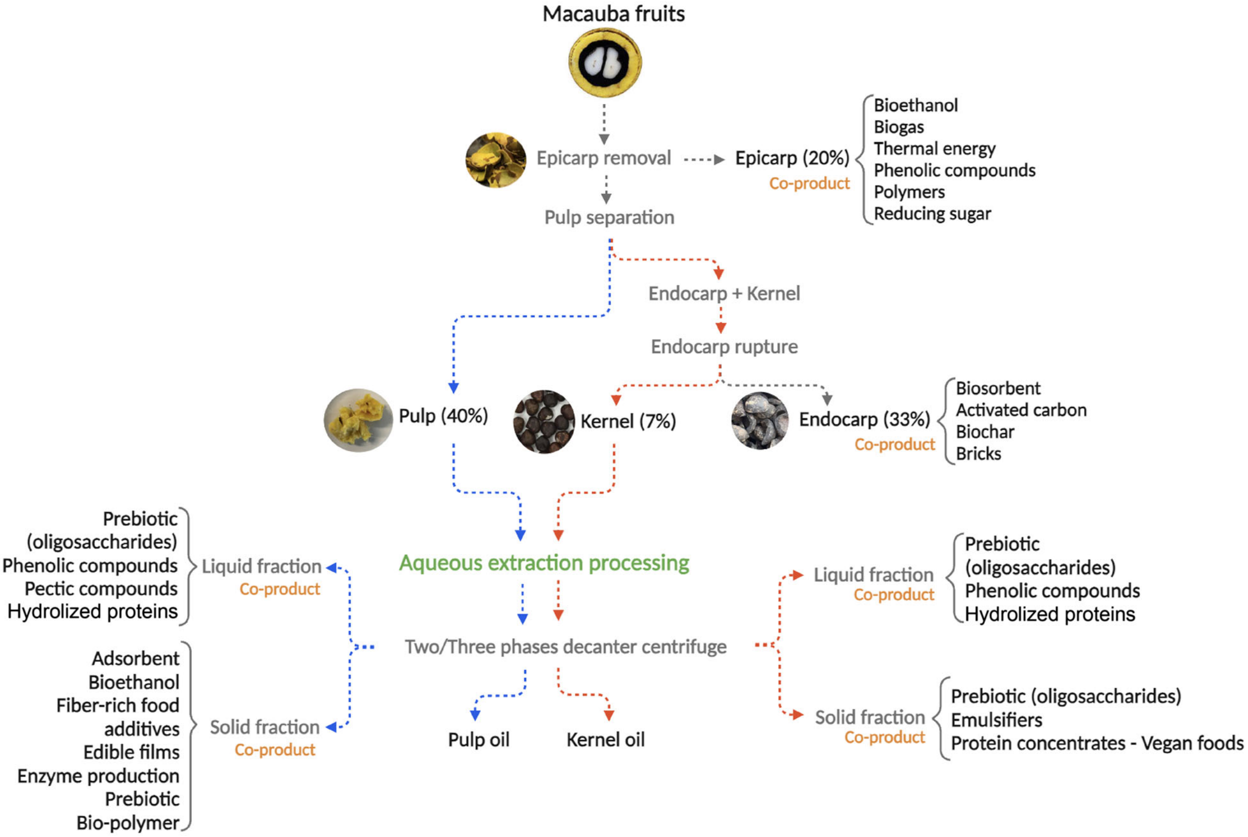

FIGURE 2 Macauba co-products in a biorefinery approach.

roadmap suggests that high-value products, such as biogas, adsorbent materials, emulsifiers, ethanol (2G), and biochar, can be derived from these raw materials. The routes depicted in Figure 2 indicate that chemical, biological, mechanical, and thermal treatments are effective for processing macauba biomass in a biorefinery to produce these high-value products.

Biofuels have garnered significant attention as a renewable energy source, offering substantial economic and environmental benefits. Thus, epicarp emerges as a raw material for energy industries to produce gaseous (biogas) (Ampese et al., 2021), liquid (reducing sugars) (Lacerda et al., 2016), and solid (briquettes) (Costa et al., 2019).

AEP/AEE applicability offers an approach to extracting oil from macauba pulp and kernels, generating two rich co-products, the liquid and solid fractions. The liquid co-products of macauba pulp and kernel are rich in sugars, phenolics, and hydrolyzed proteins and can enrich food systems and improve their nutritional profiles in the diet (Sorita et al., 2024).

As macauba pulp and kernel are lignocellulosic-rich materials, their liquid residue is particularly enriched with oligosaccharides (XOS: xylooligosaccharides and COS: cellooligosaccharides), along with phenolic compounds, offering various dietary applications. XOS and COS are prebiotic fibers that promote gut health and can be incorporated into functional food systems like fermented drinks, yogurt, energy bars, dietary supplements, cookies, non-alcoholic carbonated drinks, bread, cheese, and others to improve functional activities such as viscosity, as sugar replacer, prebiotics, sweetener, fat replacer, sodium reduction, flavor enhancer, and texture modifier (Ávila et al., 2020; Chen et al., 2021; Palaniappan et al., 2021; Poletto et al., 2020; Valladares-Diestra et al., 2023).

Phenolic compounds offer biological properties and can enhance products in the diet, such as juices, yogurts, bread, chocolate, meat, cheese, and snacks. When incorporated into foods, they provide dietary health benefits, including antioxidant, anti-inflammatory, cardiovascular, anticarcinogenic, and neuroprotective effects (Alara et al., 2021; Bodoira et al., 2022; Shahidi & Dissanayaka, 2023; Sik et al., 2022; Singh & Yadav, 2022).

Because macauba kernel is rich in protein, using proteases in AEP/AEE can produce a liquid byproduct rich in hydrolyzed proteins, which could be valuable for dietary applications (Li et al., 2017; Liu et al., 2020; Tirgarian et al., 2019). These highly bioavailable pre-digested proteins are ideal for products targeting rapid nutrient absorption, such as functional beverages and protein supplements. Additionally, they can be incorporated into plant-based and vegan foods, meal replacements, and fortified snacks (Hertzler et al., 2020; Kumar et al., 2022). Those applications make hydrolyzed macauba kernel proteins a versatile ingredient for enhancing food products' nutritional profiles for targeted dietary needs. Overall, the liquid co-products from macauba pulp and kernel oils have the potential to enrich a range of food products, significantly enhancing their nutritional and functional value.

Macauba solid co-products, rich in fiber, proteins, and bioactive compounds, offer a wide range of potential dietary applications. The fiber-rich pulp fraction can be incorporated into high-fiber foods like cereals, bread, and biscuits, promoting digestive health and supporting cholesterol management (Khorasaniha et al., 2023; Subiria-Cueto et al., 2021; Suresh et al., 2024). The solid co-product from kernel oil extraction provides a valuable source of plant-based protein for supplements—vegan foods (Silva et al., 2021), shakes (Popova et al., 2023), energy bars, and snacks (Lima et al., 2021)—while also serving as an emulsifier (Silva et al., 2022) in products like sauces and vegan mayonnaise (Alcorta et al., 2021), thereby enhancing the nutritional profile of these foods. Furthermore, with their high fiber content and low simple sugar levels, these co-products can also be used as prebiotics (Andrade et al., 2020) and low-glycemic foods, making them ideal for individuals with diabetes or insulin resistance (Dega & Barbhai, 2023). Additionally, the high fiber, protein, polysaccharide, and phenolic content of the macauba pulp solid co-product make it suitable for producing edible films (Silva et al., 2020). These applications highlight the potential of macauba co-products to enrich the nutritional and functional value of a wide range of food products.

Besides the food applications of the solid co-products, biotechnology and environmental industries also benefit from using cake co-products to produce enzymes and adsorbent material (Lopes et al., 2020; Vieira et al., 2012). The carbohydrate-rich MPC (Section 7) is a potential feedstock for second-generation ethanol production (Gonçalves et al., 2013).

Therefore, the proposed biorefinery approach offers a promising strategy for transforming macauba co-products into high-value products, thus contributing to a sustainable circular bioeconomy.

9 | CHALLENGES AND OPPORTUNITIES FOR THE SUSTAINABLE MACAUBA PRODUCTION CHAIN

Despite its great potential for oil and other valuable products, macauba production faces several challenges and opportunities across all processing stages, as outlined below.

One of the main issues is the seasonality of macauba, which limits fruit availability and can lead to production gaps. As a solution, farmers could adopt an "integrated cropping system," growing macauba alongside other crops or livestock farming (Cardoso et al., 2017). This approach would allow them to maximize land use by harvesting other crops in the off-season, creating a more stable and efficient year-round production cycle.

Another major challenge is the need for efficient harvesting methods. Currently, macauba fruits are collected manually, based on extractivism, as no specialized machinery is designed for this crop (Evaristo et al., 2016). This labor-intensive approach is not feasible for large-scale production. Therefore, developing dedicated machinery or adapting existing equipment for macauba harvesting is crucial to achieving a more efficient and sustainable harvest. If the machinery could also be used for other crops, it would make the investment more viable, as it could serve multiple harvest cycles, improving overall productivity because macauba is a seasonal crop. Furthermore, a robust harvesting process is essential to minimize damage to the fruit, which can trigger the action of lipases and other degradative agents that compromise the quality of the fruit (Evaristo et al., 2016; Oliveira et al., 2022). Specialized machinery would help preserve the fruit's integrity, extending its quality and suitability for further processing.

Another challenge in the aqueous extraction of macauba oil is the variation in oil yield and quality depending on the fruit's maturation stage. As the fruit ripens, its chemical composition, including oil content, fatty acid profile, and oxidative stability, changes (Evaristo et al., 2016; Tilahun et al., 2022), affecting the efficiency of the extraction process. Studies by Tilahun et al. (2022) suggested that post-harvest handling, such as storage conditions and drying, significantly influences the oil content and quality of macauba fruits. Their research highlighted that storage for extended periods, particularly up to 30 days, positively impacts the oil yield, with drying at higher temperatures further optimizing the oil quality, particularly when combined with appropriate storage strategies.

However, after post-harvest and before the extraction process, macauba fruit must be handled carefully to avoid spoilage and preserve the pulp and kernel's quality for processing (Queiroz et al., 2016; Silva et al., 2019). Due to its high moisture content (Table S1), macauba is particularly prone to rapid spoilage in warm, humid climates, which can significantly reduce the quality of the extracted products (Queiroz et al., 2016; Silva et al., 2019). To address this, harvested macauba can be stored in cool or controlled environments, such as refrigerated facilities or ventilated storage areas with low humidity. These conditions help to maintain the fruit's quality, extending the available processing time and minimizing post-harvest losses.

Regarding AEP/AEE scalability, transitioning from small-scale (laboratory or pilot) extraction processes to full-scale industrial macauba oil production presents significant technical and regulatory challenges. For oil to be the primary product, processing equipment must be developed or adapted to ensure consistent efficiency, quality, and yield at scale. Adapting aqueous extraction equipment for other crops with similar oil profiles, such as olives and avocados, for which such processes are already documented (as reported in Section 6), could provide valuable insights into optimizing the method for macauba oil extraction. However, ensuring that these processes remain cost-effective, efficient, and safe while meeting food safety and environmental standards remains a key hurdle.

After the oil extraction, a dedicated processing system for macauba co-products is essential to establish a robust and sustainable production chain that aligns with circular economy principles. For the liquid fraction, membrane filtration methods enable the selective separation of valuable bioactive compounds while treating water, supporting both purification and waste minimization (Antónia Nunes et al., 2019; Foti et al., 2022; Sygouni et al., 2019; Tapia-Quirós et al., 2022). For the solid fraction, rich in pulp fibers, kernel proteins, and residual oils, a system integrating drying, milling, and fractionation is critical to stabilize and maximize the use of these components (Toledo e Silva et al., 2022). This comprehensive approach reduces waste and transforms co-products into valuable materials, advancing resource efficiency and sustainability in macauba processing.

Overall, the macauba production chain holds promising potential and presents opportunities for research and innovation in food technology, sustainable agriculture, environmental engineering, and biotechnology. However, significant challenges remain, including efficient harvesting methods, advanced processing systems, and scalable purification and fractionation technologies to fully utilize macauba's co-products. Addressing these issues will be essential for establishing a robust, sustainable production chain. Despite these challenges, macauba is an excellent model for integrated, sustainable systems aligned with circular economy principles, making it a valuable subject of study across multidisciplinary areas.

10 | CONCLUSIONS

The perceived competition between food and energy production is paradoxical, as energy is essential for food processing. Macauba fruits offer a unique solution by providing edible oil and substantial biomass co-products. Free from toxic compounds, these co-products possess significant potential for various applications in the food, health, and energy sectors. The exploitation of macauba in the biorefinery concept is a promising strategy to be in line with a robust bioeconomy development. Therefore, macauba fruit has emerged recently as a sustainable alternative to conventional vegetable oil sources and other food ingredient production. Macauba is rich in essential nutrients, which include fatty acids, protein, minerals, vitamins, and dietary fiber, playing a vital role in human nutrition. Moreover, many phytochemicals (phenolic compounds, tocopherols, tocotrienol, triterpene, steroids, and stilbene) were identified in macauba fractions and associated with several potential bioactivities, such as antioxidant, anti-inflammatory, antidiabetic, and others. Nevertheless, continued in vitro, in vivo, and clinical trials are crucial to confirm the human health benefits of macauba products and demonstrate their functional properties. Additionally, a significant gap exists in understanding how the body absorbs, metabolizes, and utilizes nutritional and bioactive compounds. Further research is needed to clarify the bioavailability of these components, which is essential for fully assessing their health benefits and potential applications in nutrition and health. By combining eco-friendly oil extraction with comprehensive utilization of all biomass components, macauba has the potential to become a basis of the emerging bio-based industry.

AUTHOR CONTRIBUTIONS

Guilherme Dallarmi Sorita: Conceptualization; investigation; data curation; formal analysis; methodology; writing—original draft. **Simone Palma Favaro**: Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—review and editing. **Rossano Gambetta**: Writing—review and editing. **Alan Ambrosi**: Conceptualization; data curation; funding acquisition; writing—review and editing; supervision; resources; project administration; investigation. **Marco Di Luccio**: Conceptualization; data curation; funding acquisition; investigation; project administration; resources; supervision; writing—review and editing.

ACKNOWLEDGMENTS

The National Council for Scientific and Technological Development (CNPq, # 307576/2018-3, 420275/2018-5, 12/2020 MAI/DAI), the Coordination for the Improvement of Higher Education (CAPES, PROEX), and the Ministry of Agriculture and Livestock (MAPA, 21000.074917/2019-39) for the financial support.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used ChatGPT/OpenAI to improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

ORCID

Guilherme Dallarmi Sorita https://orcid.org/0000-0002-6263-6587

REFERENCES

Abay, K. A., Breisinger, C., Glauber, J., Kurdi, S., Laborde, D., & Siddig, K. (2023). The Russia-Ukraine war: Implications for global and regional food security and potential policy responses. *Global Food Security*, *36*, 100675. https://doi.org/10.1016/j.gfs.2023.100675

Abbattista, R., Ventura, G., Calvano, C. D., Cataldi, T. R. I., & Losito, I. (2021). Bioactive compounds in waste by-products from olive oil production: Applications and structural characterization by mass spectrometry techniques. *Foods*, *10*(6), 1236. https://doi.org/10.3390/foods10061236

Acelen BR. (2023). *Acelen: Liderança na transição energética e produção de combustiveis renováveis no Brasil*. https://www.acelen.com.br/comunicacao/acelen-inova-em-combustiveis-renovaveis-e-investira-mais-de-r-12-bi/

Adrada, B. E., Moseley, T. W., Kapoor, M. M., Scoggins, M. E., Patel, M. M., Perez, F., Nia, E. S., Khazai, L., Arribas, E., Rauch, G. M., & Guirguis, M. S. (2023). Triple-negative breast cancer: Histopathologic features, genomics, and treatment. *Radiographics*, *43*(10), e230034. https://doi.org/10.1148/rg.230034

Alara, O. R., Abdurahman, N. H., & Ukaegbu, C. I. (2021). Extraction of phenolic compounds: A review. *Current Research in Food Science*, *4*, 200–214. https://doi.org/10.1016/j.crfs.2021.03.011

Alcorta, A., Porta, A., Tárrega, A., Alvarez, M. D., & Vaquero, M. P (2021). Foods for plant-based diets: Challenges and innovations. *Foods*, *10*(2), 293. https://doi.org/10.3390/FOODS10020293

Aleixo, D. T., Gualberto, A. C. M., Valle, A. B. C. D. S., Da Silva, L. C., Ferreira, K. C. B., Lemos, A. S. D. O., Fabri, R. L., Tavares, G. D., Cazarim, M. D. S., Gameiro, J., & Pittella, F. (2024). Macauba oil carried by polymeric micelles reduces migration and proliferation of triple-negative breast cancer cells. *RSC Pharmaceutics*, *1*, 524–535. https://doi.org/10.1039/D4PM00158C

Al-Shammary, A. A. G., Al-Shihmani, L. S. S., Fernández-Gálvez, J., & Caballero-Calvo, A. (2024). Optimizing sustainable agriculture: A comprehensive review of agronomic practices and their impacts on soil attributes. *Journal of Environmental Management*, *364*, 121487. https://doi.org/10.1016/J.JENVMAN.2024.121487

Altieri, G., Genovese, F., Tauriello, A., & Di Renzo, G. C. (2015). Innovative plant for the separation of high quality virgin olive oil (VOO) at industrial scale. *Journal of Food Engineering*, *166*, 325–334. https://doi.org/10.1016/j.jfoodeng.2015.06.033

Altino, H. O. N., Costa, B. E. S., & Cunha, R. N. D. (2017). Biosorption optimization of Ni(II) ions on Macauba (*Acrocomia aculeata*) oil extraction residue using fixed-bed column. *Journal of Environmental Chemical Engineering*, *5*(5), 4895–4905. https://doi.org/10.1016/j.jece.2017.09.025

Alves, J. L. F., da Silva, J. C. G., Mumbach, G. D., Alves, R. F., de Sena, R. F., Machado, R. A. F., & Marangoni, C. (2022). Potential of macauba endocarp (*Acrocomia aculeata*) for bioenergy production: Multi-component kinetic study and estimation of thermodynamic parameters of activation. *Thermochimica Acta*, *708*, 179134. https://doi.org/10.1016/j.tca.2021.179134

Ampese, L. C., Buller, L. S., Myers, J., Timko, M. T., Martins, G., & Forster-Carneiro, T. (2021). Valorization of Macaúba husks from biodiesel production using subcritical water hydrolysis pretreatment followed by anaerobic digestion. *Journal of Environmental Chemical Engineering*, *9*(4), 105656. https://doi.org/10.1016/j.jece.2021.105656

Andrade, A. C., Marinho, J. F. U., de Souza, A. C., de Sousa Tavares, T., Dias, D. R., Schwan, R. F., Nunes, C. A., & Bastos, S. C. (2020). Prebiotic potential of pulp and kernel cake from Jerivá (*Syagrus romanzoffiana*) and Macaúba palm fruits (*Acrocomia aculeata*). *Food Research International*, *136*, 109595. https://doi.org/10.1016/j.foodres.2020.109595

Antónia Nunes, M., Pawlowski, S., Costa, A. S. G., Alves, R. C., Oliveira, M. B. P. P., & Velizarov, S. (2019). Valorization of olive pomace by a green integrated approach applying sustainable extraction and membrane-assisted concentration. *Science of the Total Environment*, *652*, 40–47. https://doi.org/10.1016/j.scitotenv.2018.10.204

Antoniassi, R., Freitas, S. C. D., Silva, T. D. S., Santiago, M. C. P. D. A., Wilhelm, A. E., & Junqueira, N. T. V. (2020). Impact of genotype on fatty acid profile, oil content and nutritional value of the sweet fruits of *Acrocomia aculeata*. *Revista Brasileira De Fruticultura*, *42*(6), 1–10. https://doi.org/10.1590/0100-29452020796

Arena, A. C., Jorge, B. C., Silva, M. C., de Barros, A. L., Fernandes, A. A. H., Nóbrega, R. H., Martinez, E. R. M., Cardoso, C. A. L., Anselmo-Franci, J. A., & Muzzi, R. M. (2018). *Acrocomia aculeata* oil: Beneficial effects on cyclophosphamide-induced reproductive toxicity in male rats. *Andrologia*, *50*(6), e13028. https://doi.org/10.1111/and.13028

Ávila, P. F., Martins, M., de Almeida Costa, F. A., & Goldbeck, R. (2020). Xylooligosaccharides production by commercial enzyme mixture from agricultural wastes and their prebiotic and antioxidant potential. *Bioactive Carbohydrates and Dietary Fibre*, *24*, 100234. https://doi.org/10.1016/j.bcdf.2020.100234

Ayompe, L. M., Schaafsma, M., & Egoh, B. N. (2021). Towards sustainable palm oil production: The positive and negative impacts on ecosystem services and human wellbeing. *Journal of Cleaner Production*, *278*, 123914. https://doi.org/10.1016/j.jclepro.2020.123914

Azzi, A. (2019). Tocopherols, tocotrienols and tocomonoenols: Many similar molecules but only one vitamin E. *Redox Biology*, *26*, 101259. https://doi.org/10.1016/j.redox.2019.101259

Barbosa, S. L., De Freitas, M. S., Dos Santos, W. T. P., Nelson, D. L., De Freitas Marques, M. B., Klein, S. I., Clososki, G. C., Caires, F. J., Nassar, E. J., Zanatta, L. D., Agblevor, F. A., Afonso, C. A. M., & Moraes Baroni, A. C. (2022). Preparation of activated charcoal from *Acrocomia aculeata* for purification of pretreated crude glycerol. *Biomass Conversion and Biorefinery*, *12*, 2441–2449. https://doi.org/10.1007/s13399-020-00745-7/Published

Bodoira, R., Rossi, Y., Velez, A., Montenegro, M., Martínez, M., Ribotta, P., & Maestri, D. (2022). Impact of storage conditions on the composition and antioxidant activity of peanut skin phenolic-based extract. *International Journal of Food Science and Technology*, *57*(10), 6471–6479. https://doi.org/10.1111/ijfs.15964

Bora, P. S., & Rocha, R. V. M. (2004). Macaiba palm: Fatty acid and amino acid composition of fruits. *Ciencia y Tecnologia Alimentaria*, *4*(3), 158–162. https://doi.org/10.1080/11358120409487755

Calvani, C. C., Goncalves, A.-M. B., Silva, M. J., Oliveira, S. L., Marangoni, B. S., Reis, D. D. D., & Cena, C. (2020). Portland cement/*Acrocomia aculeata* endocarp bricks: Thermal insulation and mechanical properties. *Materials*, *13*(9), 2081. https://doi.org/10.3390/ma13092081

Canavaciolo Gonzales, V. L., Pérez Sierra, Y., Mas Ferreiro, R. M., Oyarzábal Yera, Á., Rodríguez Leyes, E. A., Molina Cuevas, V., & Gámez Menéndez, R. (2013). *Compounds from the fruits of Acrocomia crispa and Acrocomia aculeata against inflammation and oxidative stress* (Patent WO2013/189467A3). https://patentimages.storage.googleapis.com/ee/c1/38/48fbd3ebe7af98/WO2013189467A3.pdf

Cardoso, A., Laviola, B. G., Santos, G. S., de Sousa, H. U., de Oliveira, H. B., Veras, L. C., Ciannella, R., & Favaro, S. P. (2017). Opportunities and challenges for sustainable production of *A. aculeata* through agroforestry systems. *Industrial Crops and Products*, *107*, 573–580. https://doi.org/10.1016/j.indcrop.2017.04.023

Chen, Y., Xie, Y., Ajuwon, K. M., Zhong, R., Li, T., Chen, L., Zhang, H., Beckers, Y., & Everaert, N. (2021). Xylo-oligosaccharides, preparation and application to human and animal health: A review. *Frontiers in Nutrition*, *8*, 731930. https://doi.org/10.3389/FNUT.2021.731930/BIBTEX

Ciconini, G., Favaro, S. P., Roscoe, R., Miranda, C. H. B., Tapeti, C. F., Miyahira, M. A. M., Bearari, L., Galvani, F., Borsato, A. V., Colnago, L. A., & Naka, M. H. (2013). Biometry and oil contents of *Acrocomia aculeata* fruits from the Cerrados and Pantanal biomes in Mato Grosso do Sul, Brazil. *Industrial Crops and Products*, *45*, 208–214. https://doi.org/10.1016/j.indcrop.2012.12.008

Coimbra, M. C., & Jorge, N. (2011). Proximate composition of guariroba (*Syagrus oleracea*), jerivá (*Syagrus romanzoffiana*) and macaúba (*Acrocomia aculeata*) palm fruits. *Food Research International*, *44*(7), 2139–2142. https://doi.org/10.1016/j.foodres.2011.03.032

Coimbra, M. C., & Jorge, N. (2012). Fatty acids and bioactive compounds of the pulps and kernels of Brazilian palm species, guariroba (*Syagrus oleraces*), jerivá (*Syagrus romanzoffiana*) and macaúba (*Acrocomia aculeata*). *Journal of the Science of Food and Agriculture*, *92*(3), 679–684. https://doi.org/10.1002/jsfa.4630

Colombo, C. A., Berton, L. H. C., Diaz, B. G., & Ferrari, R. A. (2018). Macauba: A promising tropical palm for the production of vegetable oil. *OCL—Oilseeds and Fats, Crops and Lipids*, *25*(1), D108. https://doi.org/10.1051/ocl/2017038

Costa, G. L. A., Buccini, D. F., Arruda, A. L. A., Favaro, S. P., & Moreno, S. E. (2020). Phytochemical profile, anti-inflammatory, antimutagenic and antioxidant properties *Acrocomia aculeata* (Jacq.) Lodd. pulp oil. *Food Science and Technology (Brazil)*, *40*(4), 963–971. https://doi.org/10.1590/fst.25319

Costa, S. E. L., Santos, R. C., Castro, R. V. O., Castro, A. F. N. M., Magalhães, M. A., Carneiro, A. C. O., Santos, C. P. S., Gomes, I. R. F., & Rocha, S. M. G. (2019). Briquettes quality produced with the macauba epicarp (*Acrocomia aculeata*) and *Pinus* sp. wood. *Revista Arvore*, *43*(5), e430501. https://doi.org/10.1590/1806-90882019000500001

Dahdouh, A., Khay, I., Le Brech, Y., El Maakoul, A., & Bakhouya, M. (2023). Olive oil industry: A review of waste stream composition, environmental impacts, and energy valorization paths. *Environmental Science and Pollution Research*, *30*, 45473–45497. https://doi.org/10.1007/s11356-023-25867-z

Das, A. K., Nanda, P. K., Madane, P., Biswas, S., Das, A., Zhang, W., & Lorenzo, J. M. (2020). A comprehensive review on antioxidant dietary fiber enriched meat-based functional foods. *Trends in Food Science and Technology*, *99*, 323–336. https://doi.org/10.1016/j.tifs.2020.03.010

Da Silva, B. P., De Medeiros Silva, G., & Parente, J. P. (2009). Chemical properties and adjuvant activity of a galactoglucomannan from *Acrocomia aculeata*. *Carbohydrate Polymers*, *75*(3), 380–384. https://doi.org/10.1016/j.carbpol.2008.09.031

Dega, V., & Barbhai, M. D. (2023). Exploring the underutilized novel foods and starches for formulation of low glycemic therapeutic foods: A review. *Frontiers in Nutrition*, *10*, 1162462. https://doi.org/10.3389/FNUT.2023.1162462/BIBTEX

del Río, J. C., Evaristo, A. B., Marques, G., Martín-Ramos, P., Martín-Gil, J., & Gutiérrez, A. (2016). Chemical composition and thermal behavior of the pulp and kernel oils from macauba palm (*Acrocomia aculeata*) fruit. *Industrial Crops and Products*, *84*, 294–304. https://doi.org/10.1016/j.indcrop.2016.02.018

Denagbe, W., Covis, R., Guegan, J. P., Robinson, J. C., Bereau, D., & Benvegnu, T. (2024). Structure and emulsifying properties of unprecedent glucomannan oligo- and polysaccharides from Amazonia *Acrocomia aculeata* palm fruit. *Carbohydrate Polymers*, *324*, 121510. https://doi.org/10.1016/j.carbpol.2023.121510

Díaz-Suárez, P., Rosales-Quintero, A., Fernandez-Lafuente, R., Pola-Sánchez, E., Hernández-Cruz, M. C., Ovando-Chacón, S. L., Rodrigues, R. C., & Tacias-Pascacio, V. G. (2021). Aqueous enzymatic extraction of *Ricinus communis* seeds oil using Viscozyme L. *Industrial Crops & Products*, *170*, 113811. https://doi.org/10.1016/j.indcrop.2021.113811

Dos Santos Correia, F., B Da Silva, W., Jolner S De Almeida, F., Da Silva Bulhões, K., & A De França Leme, S. (2022). Analysis of the proximate composition, bioactive markers and antioxidant activity present in the mesocarp of *Acrocomia aculeata* fruit harvested in the State of Mato Grosso. *Revista Virtual De Quimica*, *14*(2), 207–213. https://doi.org/10.21577/1984-6835.20220010

Evaristo, A. B., Grossi, J. A. S., Pimentel, L. D., De Melo Goulart, S., Martins, A. D., Dos Santos, V. L., & Motoike, S. (2016). Harvest and post-harvest conditions influencing macauba (*Acrocomia aculeata*) oil quality attributes. *Industrial Crops and Products*, *85*, 63–73. https://doi.org/10.1016/j.indcrop.2016.02.052

Evaristo, A. B., Martino, D. C., Ferrarez, A. H., Donato, D. B., Carneiro, A. D. C. O., & Grossi, J. A. S. (2016). Potencial energético dos resíduos do fruto da macaúba e sua utilização na produção de carvão vegetal. *Ciência Florestal*, *26*(2), 571–577. https://doi.org/10.5902/1980509822757

Favaro, S. P., Smidt, M. A., Miranda, C. H. B., Leal, W. G. D. O., Carvalho, F. B. D. P., & Rivaldi, J. D. (2022). Aqueous extraction to high yield and quality of macauba (*Acrocomia aculeata*) pulp oil. *Applied Food Research*, *2*(1), 100060. https://doi.org/10.1016/j.afres.2022.100060

Favaro, S. P., Tapeti, C. F., Miranda, C. H. B., Ciaconini, G., Miyahira, M. A. M., & Roscoe, R. (2017). Macauba (*Acrocomia aculeata*) pulp oil quality is negatively affected by drying fruits at 60°C. *Brazilian*

Archives of Biology and Technology, *60*, e17160373. https://doi.org/10.1590/1678-4324-2017160373

Fonseca, J. V. d. S., Batista, J. D. F., de Oliveira, M. C., Diniz, N. C. M., Lima, M. d. S., Madruga, M. S., Magnani, M., & Borges, G. d. S. C. (2021). Low-fat and rich-fibers macauba (*Acrocomia* spp.) sauces: Physical and oxidative stability, nutritional quality and sensory characteristics. *Food Bioscience*, *43*, 101272. https://doi.org/10.1016/j.fbio.2021.101272

Foti, P., Occhipinti, P. S., Romeo, F. V., Timpanaro, N., Musumeci, T., Randazzo, C. L., & Caggia, C. (2022). Phenols recovered from olive mill wastewater as natural booster to fortify blood orange juice. *Food Chemistry*, *393*, 133428. https://doi.org/10.1016/J.FOODCHEM.2022.133428

Gila, A., Aguilera, M. P., Sánchez-Ortíz, A., Jiménez, A., & Beltrán, G. (2022). Effect of centrifugal force (G) on stability of natural emulsions (water/oil) present in fresh virgin olive oils. *Journal of Food Engineering*, *334*, 111169. https://doi.org/10.1016/j.jfoodeng.2022.111169

Giraldo-Bareño, Y. Y., Pinzón-García, A. D., Sousa, D. V. M., Bomfim Filho, L. F. O., Lopes, D. H. A., Cortés, N. S., Morávia, M. C. S. A., Sinisterra, R. D., & Orlando, R. M. (2023). Efficient and easily scaled-up biosorbent based on natural and chemically modified macauba (*Acrocomia aculeata*) to remove Al^{3+}, Mn^{2+} and Fe^{3+} from surface water contaminated with iron mining tailings. *Talanta*, *256*, 124273. https://doi.org/10.1016/j.talanta.2023.124273

Gomes, B. M., Santos, L., Silva, G., & Martins, V. G. M. (2021). Ultrasound-assisted extraction of compounds Phenolics from bocaiuva peel (*Acrocomia aculeata*). *Revista Brasileira De Agrotecnologia*, *11*(2), 995–999. https://doi.org/10.18378/rebagro.v12i2.8776

Gonçalves, D. B., Batista, A. F., Rodrigues, M. Q. R. B., Nogueira, K. M. V., & Santos, V. L. (2013). Ethanol production from macaúba (*Acrocomia aculeata*) presscake hemicellulosic hydrolysate by *Candida boidinii* UFMG14. *Bioresource Technology*, *146*, 261–266. https://doi.org/10.1016/j.biortech.2013.07.075

de Ávila Gonçalves, S., Quiroga, F., Vilaça, A. C., Lancetti, R., Blanco Canallis, M. S., Caño de Andrade, M. H., & Ribotta, P. D. (2021). Physical–chemical evaluation of flours from brewery and macauba residues and their uses in the elaboration of cookies. *Journal of Food Processing and Preservation*, *45*(9), e15700. https://doi.org/10.1111/jfpp.15700

Gonçalves, T. d. O., Filbido, G. S., de Oliveira Pinheiro, A. P., Pinto Piereti, P. D., Dalla Villa, R., & de Oliveira, A. P. (2020). In vitro bioaccessibility of the Cu, Fe, Mn and Zn in the baru almond and bocaiúva pulp and, macronutrients characterization. *Journal of Food Composition and Analysis*, *86*, 103356. https://doi.org/10.1016/j.jfca.2019.103356

Guilhen, S. N., Mašek, O., Ortiz, N., Izidoro, J. C., & Fungaro, D. A. (2019). Pyrolytic temperature evaluation of macauba biochar for uranium adsorption from aqueous solutions. *Biomass and Bioenergy*, *122*, 381–390. https://doi.org/10.1016/j.biombioe.2019.01.008

Hertzler, S. R., Lieblein-Boff, J. C., Weiler, M., & Allgeier, C. (2020). Plant proteins: Assessing their nutritional quality and effects on health and physical function. *Nutrients*, *12*(12), 3704. https://doi.org/10.3390/NU12123704

Hiane, P. A., Baldasso, P. A., Marangoni, S., & Macedo, M. L. R. (2006). Chemical and nutritional evaluation of kernels of bocaiuva, *Acrocomia aculeata* (Jacq.) Lodd. *Ciencia e Tecnologia De Alimentos*, *26*(3), 683–689. https://doi.org/10.1590/S0101-20612006000300031

Hu, Y., Lin, Q., Zhao, H., Li, X., Sang, S., McClements, D. J., Long, J., Jin, Z., Wang, J., & Qiu, C. (2023). Bioaccessibility and bioavailability of phytochemicals: Influencing factors, improvements, and evaluations. *Food Hydrocolloids*, *135*, 108165. https://doi.org/10.1016/j.foodhyd.2022.108165

Hussain, Z., Thu, H. E., Khan, S., Sohail, M., Sarfraz, R. M., Mahmood, A., & Abourehab, M. A. S. (2022). Phytonanomedicines, a state-of-the-art strategy for targeted delivery of anti-inflammatory phytochemicals: A review of improved pharmacokinetic profile and therapeutic efficacy. *Journal of Drug Delivery Science and Technology*, *77*, 103895. https://doi.org/10.1016/j.jddst.2022.103895

International Energy Agency. (2023). *World energy outlook 2023*. https://www.Iea.Org/Reports/World-Energy-Outlook-2023

Khalil, A., Tazeddinova, D., Aljoumaa, K., Kazhmukhanbetkyzy, Z. A., Orazov, A., & Toshev, A. D. (2021). Carotenoids: Therapeutic strategy in the battle against viral emerging diseases, COVID-19: An overview. *Preventive Nutrition and Food Science*, *26*(3), 241–261. https://doi.org/10.3746/pnf.2021.26.3.241

Khorasaniha, R., Olof, H., Voisin, A., Armstrong, K., Wine, E., Vasanthan, T., & Armstrong, H. (2023). Diversity of fibers in common foods: Key to advancing dietary research. *Food Hydrocolloids*, *139*, 108495. https://doi.org/10.1016/J.FOODHYD.2023.108495

Kumar, M., Tomar, M., Punia, S., Dhakane-Lad, J., Dhumal, S., Changan, S., Senapathy, M., Berwal, M. K., Sampathrajan, V., Sayed, A. A. S., Chandran, D., Pandiselvam, R., Rais, N., Mahato, D. K., Udikeri, S. S., Satankar, V., Anitha, T., Reetu, Radha, … Kennedy, J. F. (2022). Plant-based proteins and their multifaceted industrial applications. *LWT*, *154*, 112620. https://doi.org/10.1016/J.LWT.2021.112620

da Silva Lacerda, V., López-Sotelo, J. B., Correa-Guimarães, A., Martín-Ramos, P., Hernández-Navarro, S., Sánchez-Bascones, M., Navas-Gracia, L. M., Pérez-Lebeña, E., & Martín-Gil, J. (2016). Efficient microwave-assisted acid hydrolysis of lignocellulosic materials into total reducing sugars in ionic liquids. *Cellulose Chemistry and Technology*, *50*(8), 761–770.

León-Ovelar, R., Fernández-Boy, M. E., & Knicker, H. (2022). Characterization of the residue (endocarp) of *Acrocomia aculeata* and its biochars as a potential source for soilless growing media. *Horticulturae*, *8*(8), 739. https://doi.org/10.3390/horticulturae8080739

Lescano, C. H., Iwamoto, R. D., Sanjinez-Argandoña, E. J., & Kassuya, C. A. L. (2015). Diuretic and anti-inflammatory activities of the microencapsulated *Acrocomia aculeata* (Arecaceae) oil on Wistar rats. *Journal of Medicinal Food*, *18*(6), 656–662. https://doi.org/10.1089/jmf.2014.0077

Lescano, C. H., Oliveira, I. P., Silva, L. R., Baldivia, D. S., Sanjinez-Argandoña, E. J., Arruda, E. J., Moraes, I. C. F., & Lima, F. F. (2015). Nutrients content, characterization and oil extraction from *Acrocomia aculeata* (Jacq.) Lodd. fruits. *African Journal of Food Science*, *9*(3), 113–119. https://doi.org/10.5897/AJFS2014.1212

Lessa, V. L., Harumi Omura, M., Pacheco, S., Basílio de Oliveira, E., & Ribeiro de Barros, F. A. (2022). Obtention and evaluation of physico-chemical and techno-functional properties of macauba (*Acrocomia aculeata*) kernel protein isolate. *Food Research International*, *161*, 111848. https://doi.org/10.1016/j.foodres.2022.111848

Li, P., Zhang, W., Han, X., Liu, J., Liu, Y., Gasmalla, M. A. A., & Yang, R. (2017). Demulsification of oil-rich emulsion and characterization of protein hydrolysates from peanut cream emulsion of aqueous extraction processing. *Journal of Food Engineering*, *204*, 64–72. https://doi.org/10.1016/j.jfoodeng.2017.02.009

Lima, D. S., Egea, M. B., Cabassa, I. d. C. C., Almeida, A. B. d., Sousa, T. L. d., Lima, T. M. d., Loss, R. A., Volp, A. C. P., Vasconcelos, L. G. d., Dall'Oglio, E. L., Hernandes, T., & Takeuchi, K. P. (2021). Technological quality and sensory acceptability of nutritive bars produced with Brazil nut and baru almond coproducts. *LWT*, *137*, 110467. https://doi.org/10.1016/J.LWT.2020.110467

Liu, J., Zhang, W., Li, P., Jiang, Z., & Yang, R. (2020). Isolation of peanut protein aggregates using aqueous extraction processing combined with membrane separation. *International Journal of Food Science and Technology*, *55*(9), 3203–3214. https://doi.org/10.1111/ijfs.14584

Machado, W., Guimarães, M. F., Lira, F. F., Santos, J. V. F., Takahashi, L. S. A., Leal, A. C., & Coelho, G. T. C. P. (2015). Evaluation of two fruit ecotypes (totai and sclerocarpa) of macaúba (*Acrocomia aculeata*). *Industrial Crops and Products*, *63*, 287–293. https://doi.org/10.1016/j.indcrop.2014.11.002

Madeira, D. D. C., Motoike, S. Y., Simiqueli, G. F., Kuki, K. N., de Melo Goulart, S., Rigolon, T. C. B., Nogueira, P. T. S., da Silva Castro, A., & de Oliveira Couto, E. G. (2024). Phenotypic characterization and genetic diversity of macauba (*Acrocomia aculeata*) accessions based on oil attributes and fruit biometrics. *Genetic Resources and Crop Evolution*, *71*(7), 3433–3451. https://doi.org/10.1007/S10722-024-01856-0/FIGURES/7

Magosso, M. F., Carvalho, P. C., Shneider, B. U. C., Pessatto, L. R., Pesarini, J. R., Silva, P. V. B., Correa, W. A., Kassuya, C. A. L., Muzzi, R. M., & Oliveira, R. J. (2016). *Acrocomia aculeata* prevents toxicogenetic damage caused by the antitumor agent cyclophosphamide. *Genetics and Molecular Research*, *15*(2). https://doi.org/10.4238/gmr.15027816

Menegotto, A. L. L., Souza, L. E. S. d., Colla, L. M., Costa, J. A. V., Sehn, E., Bittencourt, P. R. S., de Moraes Flores, É. L., Canan, C., & Colla, E. (2019). Investigation of techno-functional and physicochemical properties of *Spirulina platensis* protein concentrate for food enrichment. *LWT*, *114*, 108267. https://doi.org/10.1016/j.lwt.2019.108267

Monteiro-Alfredo, T., Dos Santos, J. M., Antunes, K. Á., Cunha, J., Da Silva Baldivia, D., Pires, A. S., Marques, I., Abrantes, A. M., Botelho, M. F., Monteiro, L., Gonçalves, A. C., Botelho, W. H., Paula De Araújo Boleti, A., Cabral, C., Oliveira, P. J., Lucas Dos Santos, E., Matafome, P., & De Picoli Souza, K. (2023). *Acrocomia aculeata* associated with doxorubicin: Cardioprotection and anticancer activity. *Frontiers in Pharmacology*, *14*, 1223933. https://doi.org/10.3389/fphar.2023.1223933

Monteiro-Alfredo, T., Matafome, P., Iacia, B. P., Antunes, K. Á., dos Santos, J. M., da Silva Melo Da Cunha, J., Oliveira, S., Oliveira, A. S., Campos, J. F., Magalhães, M., Cabral, C., Seiça, R., Cardoso, C. A. L., de Oliveira, C. F. R., dos Santos, E. L., & de Picoli Souza, K. (2020). *Acrocomia aculeata* (Jacq.) Lodd. ex Mart. leaves increase SIRT1 levels and improve stress resistance. *Oxidative Medicine and Cellular Longevity*, *2020*, 1–16. https://doi.org/10.1155/2020/5238650

Monteiro-Alfredo, T., Oliveira, S., Amaro, A., Rosendo-Silva, D., Antunes, K., Pires, A. S., Teixo, R., Abrantes, A. M., Botelho, M. F., Castelo-Branco, M., Seiça, R., Silva, S., de Picoli Souza, K., & Matafome, P. (2021). Hypoglycaemic and antioxidant properties of *Acrocomia aculeata* (Jacq.) Lodd ex Mart. extract are associated with better vascular function of type 2 diabetic rats. *Nutrients*, *13*(8), 2856. https://doi.org/10.3390/nu13082856

Montoya-Arroyo, A., Alfaro-Solís, J. D., Esquivel, P., Jiménez, V. M., & Frank, J. (2021). Vitamin E profiles in *Acrocomia aculeata* from three regions in Costa Rica. *Journal of Food Composition and Analysis*, *100*, 103936. https://doi.org/10.1016/j.jfca.2021.103936

Moura, F. C. C., Rios, R. D. F., & Galvão, B. R. L. (2018). Emerging contaminants removal by granular activated carbon obtained from residual Macauba biomass. *Environmental Science and Pollution Research*, *25*(26), 26482–26492. https://doi.org/10.1007/s11356-018-2713-8

Mücke, N., da Silva, T. B. V., de Oliveira, A., Moreira, T. F. M., Venancio, C. D. S., Marques, L. L. M., Valderrama, P., Gonçalves, O. H., da Silva-Buzanello, R. A., Yamashita, F., Shirai, M. A., Genena, A. K., & Leimann, F. V. (2021). Use of water-soluble curcumin in TPS/PBAT packaging material: Interference on reactive extrusion and oxidative stability of chia oil. *Food and Bioprocess Technology*, *14*(3), 471–482. https://doi.org/10.1007/s11947-021-02584-4

Munhoz, C. L., Guimarães, R. D. C. A., Sanjinez-Argandoña, E. J., & Maldonade, I. R. (2018). Lipid nutritional quality of the pulp and kernel of bocaiuva (*Acrocomia aculeata* (Jacq.) Lodd. *Ambiência*, *14*(2). https://doi.org/10.5935/ambiencia.2018.02.10

Nunes, Â. A., Buccini, D. F., dos Santos Jaques, J. A., Portugal, L. C., Guimarães, R. C. A., Favaro, S. P., de Araújo Caldas, R., & Carvalho, C. M. E. (2020). Effect of dietary *Acrocomia aculeata* kernel oil rich in medium chain fatty acids on type 2 diabetic rats. *Journal of Functional Foods*, *75*, 104295. https://doi.org/10.1016/j.jff.2020.104295

Nunes, Â. A., Buccini, D. F., Jaques, J. A. S., Portugal, L. C., Guimarães, R. C. A., Favaro, S. P., Caldas, R. A., & Carvalho, C. M. E. (2018). Effect of *Acrocomia aculeata* kernel oil on adiposity in type 2 diabetic rats. *Plant Foods for Human Nutrition*, *73*(1), 61–67. https://doi.org/10.1007/s11130-017-0648-8

Oliveira, C. D., Pereira e Silveira, B. M., Fernanda de Assis, N., Rios, G. R., Siqueira-Silva, A. I., Baffa Júnior, J. C., Viana, P. A., & Pereira, E. G. (2022). Synchronization between photosynthetic responses to seasonality during fruit development and fatty acid profile of mesocarp oil in macauba (*Acrocomia aculeata*). *Biocatalysis and Agricultural Biotechnology*, *43*, 102423. https://doi.org/10.1016/j.bcab.2022.102423

Oliveira, D. M., Clemente, E., & da Costa, J. M. C. (2014). Bioactive compounds and physicochemical parameters of grugru palm (*Acrocomia aculeata*) from Brazil: Pulp and powder. *Food Science and Technology Research*, *20*(1), 7–12. https://doi.org/10.3136/fstr.20.7

Oliveira Da Silva, A., Cortez-Vega, W. R., Prentice, C., & Fonseca, G. G. (2020). Development and characterization of biopolymer films based on bocaiuva (*Acromonia aculeata*) flour. *International Journal of Biological Macromolecules*, *155*, 1157–1168. https://doi.org/10.1016/j.ijbiomac.2019.11.083

Palaniappan, A., Antony, U., & Emmambux, M. N. (2021). Current status of xylooligosaccharides: Production, characterization, health benefits and food application. *Trends in Food Science & Technology*, *111*, 506–519. https://doi.org/10.1016/J.TIFS.2021.02.047

Pereira, B. d. N., Cavalcante, D. D., Bezerra, K. C. B., & Oliveira, A. M. C. d. (2021). Macaúba (*Acrocomia aculeata*): Determinação da composição centesimal e seu potencial para a saúde. *Research,* *Society and Development*, *10*(15), e120101522689. https://doi.org/10.33448/rsd-v10i15.22689

Permal, R., Chang, W. L., Chen, T., Seale, B., Hamid, N., & Kam, R. (2020). Optimising the spray drying of avocado wastewater and use of the powder as a food preservative for preventing lipid peroxidation. *Foods*, *9*(9), 1187. https://doi.org/10.3390/foods9091187

Pires, P., da, C. L., da Silva César, A., Cardoso, A. N., Favaro, S. P., & Conejero, M. A. (2023). Strategies to improve the competitiveness of an agroindustrial system for a macauba based oil production in Minas Gerais State, Brazil. *Land Use Policy*, *126*, 106552. https://doi.org/10.1016/j.landusepol.2023.106552

Perez G, S., Perez G, R. M., Perez G, C., Zavala S, M. A., & Vargas S, R. (1997). Coyolosa, a new hypoglycemic from *Acrocomia mexicana*. *Pharmaceutica Acta Helvetiae*, *72*, 105–111.

Poletto, P., Pereira, G. N., Monteiro, C. R. M., Pereira, M. A. F., Bordignon, S. E., & de Oliveira, D. (2020). Xylooligosaccharides: Transforming the lignocellulosic biomasses into valuable 5-carbon sugar prebiotics. *Process Biochemistry*, *91*, 352–363. https://doi.org/10.1016/j.procbio.2020.01.005

Polmann, G., Badia, V., Frena, M., Teixeira, G. L., Rigo, E., Block, J. M., & Camino Feltes, M. M. (2019). Enzyme-assisted aqueous extraction combined with experimental designs allow the obtaining of a high-quality and yield pecan nut oil. *LWT*, *113*, 108283. https://doi.org/10.1016/j.lwt.2019.108283

Popova, A., Mihaylova, D., & Lante, A. (2023). Insights and perspectives on plant-based beverages. *Plants*, *12*(19), 3345. https://doi.org/10.3390/plants12193345

Prasad, M., Jayaraman, S., Eladl, M. A., El-Sherbiny, M., Abdelrahman, M. A. E., Veeraraghavan, V. P., Vengadassalapathy, S., Umapathy, V. R., Jaffer Hussain, S. F., Krishnamoorthy, K., Sekar, D., Palanisamy, C. P., Mohan, S. K., & Rajagopal, P. (2022). A comprehensive review on therapeutic perspectives of phytosterols in insulin resistance: A mechanistic approach. *Molecules (Basel, Switzerland)*, *27*(5), 1595. https://doi.org/10.3390/molecules27051595

Prates-Valério, P., Celayeta, J. M. F., & Cren, E. C. (2019). Quality parameters of mechanically extracted edible macauba oils (*Acrocomia aculeata*) for potential food and alternative industrial feedstock application. *European Journal of Lipid Science and Technology*, *121*(5), 1800329. https://doi.org/10.1002/ejlt.201800329

Queiroz, L. A. L., Nascimento, C. S., Silveira, A. L. M., Santos, V. L., & Andrade, M. H. C. (2016). Microorganisms in macauba fruits (*Acrocomia aculeata*) after different post-harvest treatments and storage. *The Journal of Engineering and Exact Sciences*, *2*(3), 001–013. https://doi.org/10.18540/jcecvl2iss3pp001-013

Ramos, M. I. L., Ramos Filho, M. M., Hiane, P. A., Braga Neto, J. A., & Siqueira, E. M. A. (2008a). Nutritional quality of the pulp of bocaiuva *Acrocomia aculeata* (Jacq.) Lodd. *Food Science and Technology*, *28*, 90–94.

Ramos, M. I. L., Ramos Filho, M. M., Hiane, P. A., Braga Neto, J. A., & Siqueira, E. M. A. (2008b). Qualidade nutricional da polpa de bocaiúva *Acrocomia aculeata* (Jacq.) Lodd. *Ciência e Tecnologia De Alimentos*, *28*, 90–94. https://doi.org/10.1590/S0101-20612008000500015

Rencoret, J., Kim, H., Evaristo, A. B., Gutiérrez, A., Ralph, J., & del Río, J. C. (2018). Variability in lignin composition and structure in cell walls of different parts of Macaúba (*Acrocomia aculeata*) palm fruit. *Journal of Agricultural and Food Chemistry*, *66*(1), 138–153. https://doi.org/10.1021/acs.jafc.7b04638

Rivaldi, J. D., Smidt, M., Rodas, J., & Velázquez, M. E. (2022). *Manual de recolección, almacenamiento y procesamiento de frutos de Mbokaja (Acrocomia aculeata)* (Vol., *2*). ISBN 978-99925-3-755-8.

Rosa, A. C. S., Stevanato, N., Santos Garcia, V. A., & Silva, C. (2020). Simultaneous extraction of the oil from the kernel and pulp of macauba fruit using a green solvent. *Journal of Food Processing and Preservation*, *44*(11), e14855. https://doi.org/10.1111/jfpp.14855

Sampaio, R. S. L., Pereira, R. L. S., Coutinho, H. D. M., Almeida-Bezerra, J. W., Bezerra Morais-Braga, M. F., Santana, M. d. S., Silva, M. E. P. d., Santos, A. T. L. d., Fonseca, V. J. A., Costa, A. R., Silva, V. B. d., Rodrigues, F. C., Bezerra, J. J. L., Raposo, A., Lima, J. P. M. d., & Barros, L. M. (2023). Chemical composition and antimicrobial potential of *Acrocomia aculeata* (Jacq.) Lodd. ex Mart. and *Syagrus cearensis* Noblick (Arecaceae). *Microbial Pathogenesis*, *180*, 106147. https://doi.org/10.1016/j.micpath.2023.106147

Sant' Ana, C. T., Agrizzi Verediano, T., Grancieri, M., Toledo, R. C. L., Tako, E., Costa, N. M. B., Martino, H. S. D., & de Barros, F. A. R. (2023). Macauba (*Acrocomia aculeata*) pulp oil prevents adipogenesis, inflammation and oxidative stress in mice fed a high-fat diet. *Nutrients*, *15*(5), 1252. https://doi.org/10.3390/nu15051252

Sant' Ana, C. T., Verediano, T. A., Grancieri, M., Lopes Toledo, R. C., Costa, N. M. B., Martino, H. S. D., & Barros, F. A. R. D. (2024). Macauba (*Acrocomia aculeata*) pulp oil has the potential to enhance the intestinal barrier morphology, goblet cell proliferation and gut microbiota composition in mice fed a high-fat diet. *British Journal of Nutrition*, *131*(6), 987–996. https://doi.org/10.1017/S0007114523002623

Sarkar, N., Chakraborty, D., Dutta, R., Agrahari, P., Bharathi, S. D., Singh, A. A., & Jacob, S. (2021). A comprehensive review on oilseed cakes and their potential as a feedstock for integrated biorefinery. *Journal of Advanced Biotechnology and Experimental Therapeutics*, *4*(3), 376–387. https://doi.org/10.5455/jabet.2021.d137

Schex, R., Lieb, V. M., Jiménez, V. M., Esquivel, P., Schweiggert, R. M., Carle, R., & Steingass, C. B. (2018). HPLC-DAD-APCI/ESI-MSn analysis of carotenoids and α-tocopherol in Costa Rican *Acrocomia aculeata* fruits of varying maturity stages. *Food Research International*, *105*, 645–653. https://doi.org/10.1016/j.foodres.2017.11.041

Shahidi, F., & Dissanayaka, C. S. (2023). Phenolic-protein interactions: Insight from in-silico analyses—A review. *Food Production, Processing and Nutrition*, *5*(1), 1–21. https://doi.org/10.1186/S43014-022-00121-0

Siamig. (2022). *Empresas apostam em biocombustíveis como negócio do futuro*. https://siamig.com.br/noticias/empresas-apostam-em-biocombustiveis-como-negocio-do-futuro

Sik, B., Székelyhidi, R., Lakatos, E., Kapcsándi, V., & Ajtony, Z. (2022). Analytical procedures for determination of phenolics active herbal ingredients in fortified functional foods: An overview. *European Food Research and Technology*, *248*(2), 329–344. https://doi.org/10.1007/S00217-021-03908-6

Silva, G. N., Grossi, J. A. S., Carvalho, M. S., Kuki, K. N., Goulart, S. D. M., & Pimentel, L. D. (2019). Air drying of macauba fruits: Maintaining oil quality for biodiesel production. *Acta Scientiarum. Agronomy*, *42*(1), e43451. https://doi.org/10.4025/actasciagron.v42i1.43451

Silva, I. F., Langbehn, R. K., Silva, R. G. C., Pantoja, L. d. A., Vanzela, A. P. F. C., & Santos, A. S. d. (2016). α-Amylase production by *Bacillus amyloliquefaciens* utilizing macauba cake (*Acrocomia aculeata*) and peach palm flour (*Bactris gasipaes* – kunth) as substrates. *Biocatalysis and Biotransformation*, *34*(2), 76–82. https://doi.org/10.1080/10242422.2016.1227794

e Silva, S. H. T., Bader-Mittermaier, S., Silva, L. B., Doer, G., & Eisner, P. (2021). Electrophoretic characterization, amino acid composition and solubility properties of Macauba (*Acrocomia aculeata* L.) kernel globulins. *Food Bioscience*, *40*, 100908. https://doi.org/10.1016/j.fbio.2021.100908

e Silva, S. H. T., Silva, L. B., Eisner, P., & Bader-Mittermaier, S. (2022). Production of protein concentrates from macauba (*Acrocomia aculeata* and *Acrocomia totai*) kernels by sieve fractionation. *Foods*, *11*(22), 3608. https://doi.org/10.3390/foods11223608

Simiqueli, G. F., Resende, M. D. V. d., Motoike, S. Y., & Henriques, E. (2018). Inbreeding depression as a cause of fruit abortion in structured populations of macaw palm (*Acrocomia aculeata*): Implications for breeding programs. *Industrial Crops and Products*, *112*, 652–659. https://doi.org/10.1016/j.indcrop.2017.12.068

Singh, N., & Yadav, S. S. (2022). A review on health benefits of phenolics derived from dietary spices. *Current Research in Food Science*, *5*, 1508–1523. https://doi.org/10.1016/J.CRFS.2022.09.009

S Lopes, L., Vieira, N., R Da Luz, J. M., S Silva, M. D. C., Cardoso, W. S., & M Kasuya, M. C. (2020). Production of fungal enzymes in Macaúba coconut and enzymatic degradation of textile dye. *Biocatalysis and Agricultural Biotechnology*, *26*, 101651. https://doi.org/10.1016/j.bcab.2020.101651

Sorita, G. D., de Oliveira, A., Moreira, T. F. M., Leimann, F. V., & Ferreira, S. R. S. (2022). Green-based processes applied for valorization of peanut by-product: In vitro evaluation of antioxidant and enzymatic inhibition capacities. *The Journal of Supercritical Fluids*, *186*, 105602. https://doi.org/10.1016/j.supflu.2022.105602

Sorita, G. D., Favaro, S. P., Ambrosi, A., & Di Luccio, M. (2023). Aqueous extraction processing: An innovative and sustainable approach for recovery of unconventional oils. *Trends in Food Science and Technology*, *133*, 99–113. https://doi.org/10.1016/j.tifs.2023.01.019

Sorita, G. D., Favaro, S. P., Rodrigues, D. D. S., Silva Junior, W. P. D., Leal, W. G. D. O., Ambrosi, A., & Di Luccio, M. (2024). Aqueous enzymatic extraction of macauba (*Acrocomia aculeata*) pulp oil: A green and sustainable approach for high-quality oil production. *Food Research International*, *182*, 114160. https://doi.org/10.1016/j.foodres.2024.114160

Sorita, G. D., Leimann, F. V., & Ferreira, S. R. S. (2020). Biorefinery approach: Is it an upgrade opportunity for peanut by-products? *Trends in Food Science and Technology*, *105*, 56–69. https://doi.org/10.1016/j.tifs.2020.08.011

Souza, G. K., Albrecht Schuquel, I. T., Moura, V. M., Belloto, A. C., Rovigatti Chiavelli, L. U., Ruiz, A. L. T. G., Shiozawa, L., de Carvalho, J. E., Garcia, F. P., Kaplum, V., da Silva Rodrigues, J. H., Scariot, D. B., Delvecchio, R., Machado-Ferreira, E., Santana, R., Gomes Soares, C. A., Nakamura, C. V., de Oliveira Santin, S. M., & Pomini, A. M. (2017). X-ray structure of O-methyl-acrocol and anti-cancer, anti-parasitic, anti-bacterial and anti-Zika virus evaluations of the Brazilian palm tree *Acrocomia totai*. *Industrial Crops and Products*, *109*, 483–492. https://doi.org/10.1016/j.indcrop.2017.08.066

Souza, G. K., Kischkel, B., Freitas, C. F., Negri, M., Back, D., Johann, G., Hioka, N., Schuquel, I. T. A., Santin, S. M. O., & Pomini, A. M. (2019). Antiproliferative activity and energy calculations of a new triterpene isolated from the palm tree *Acrocomia totai*. *Natural Product Research*, *35*(22), 4225–4234. https://doi.org/10.1080/14786419.2019.1696331

Souza, L. T. A., Oliveira, J. S., Rodrigues, M. Q. R. B., dos Santos, V. L., Pessela, B. C., & Resende, R. R. (2015). Macaúba (*Acrocomia aculeata*) cake from biodiesel processing: A low-cost substrate to produce lipases from *Moniliella spathulata* R25L270 with potential application in the oleochemical industry. *Microbial Cell Factories*, *14*(1), 87. https://doi.org/10.1186/s12934-015-0266-9

Souza De Brito, I. S., Nascentes, C. C., Pinto, P. S., Ferreira de Paula, F. G., & Teixeira, A. P. d. C. (2023). Low temperature sulfonated biochar from Macauba's endocarp for lead adsorption from wastewater. *Next Materials*, *1*(3), 100028. https://doi.org/10.1016/j.nxmate.2023.100028

Subiria-Cueto, R., Coria-Oliveros, A. J., Wall-Medrano, A., Rodrigo-García, J., González-Aguilar, G. A., Martinez-Ruiz, N. D. R., & Alvarez-Parrilla, E. (2021). Antioxidant dietary fiber-based bakery products: A new alternative for using plant-by-products. *Food Science and Technology*, *42*, ctaAR57520. https://doi.org/10.1590/FST.57520

Suresh, A., Shobna, Salaria, M., Morya, S., Khalid, W., Afzal, F. A., Khan, A. A., Safdar, S., Khalid, M. Z., & Mukonzo Kasongo, E. L. (2024). Dietary fiber: An unmatched food component for sustainable health. *Food and Agricultural Immunology*, *35*(1), 2384420. https://doi.org/10.1080/09540105.2024.2384420

Sygouni, V., Pantziaros, A. G., Iakovides, I. C., Sfetsa, E., Bogdou, P. I., Christoforou, E. A., & Paraskeva, C. A. (2019). Treatment of two-phase olive mill wastewater and recovery of phenolic compounds using membrane technology. *Membranes*, *9*(2), 27. https://doi.org/10.3390/membranes9020027

Tapia-Quirós, P., Montenegro-Landívar, M. F., Reig, M., Vecino, X., Saurina, J., Granados, M., & Cortina, J. L. (2022). Integration of membrane processes for the recovery and separation of polyphenols from winery and olive mill wastes using green solvent-based processing. *Journal of Environmental Management*, *307*, 114555. https://doi.org/10.1016/j.jenvman.2022.114555

Tilahun, W. W., Grossi, J. A. S., & Favaro, S. P. (2022). Combination of storage followed by drying assures higher yield and quality of macauba (*Acrocomia aculeata*) pulp oil. *Applied Food Research*, *2*(1), 100090. https://doi.org/10.1016/j.afres.2022.100090

Tiozon, R. J. N., Fernie, A. R., & Sreenivasulu, N. (2021). Meeting human dietary vitamin requirements in the staple rice via strategies of biofortification and post-harvest fortification. *Trends in Food Science and Technology*, *109*, 65–82. https://doi.org/10.1016/j.tifs.2021.01.023

Tirgarian, B., Farmani, J., & Milani, J. M. (2019). Enzyme-assisted aqueous extraction of oil and protein hydrolysate from sesame seed. *Journal of Food Measurement and Characterization*, *13*, 2118–2129.

Toledo e Silva, S. H., Silva, L. B., Eisner, P., & Bader-Mittermaier, S. (2022). Production of protein concentrates from macauba (*Acrocomia aculeata* and *Acrocomia totai*) kernels by sieve fractionation. *Foods*, *11*(22), 3608. https://doi.org/10.3390/FOODS11223608

Trentini, C. P., Santos, K. A., Antonio da Silva, E., & Garcia, V. A. S., Cardozo-Filho, L., & da Silva, C. (2017). Oil extraction from macauba pulp using compressed propane. *Journal of Supercritical Fluids*, *126*, 72–78. https://doi.org/10.1016/j.supflu.2017.02.018

USDA. (2022). *Major vegetable oils: World supply and distribution*. https://www.fas.usda.gov/data/oilseeds-world-markets-and-trade

Valladares-Diestra, K. K., de Souza Vandenberghe, L. P., Vieira, S., Goyzueta-Mamani, L. D., de Mattos, P. B. G., Manzoki, M. C., Soccol, V. T., & Soccol, C. R. (2023). The potential of xylooligosaccharides as prebiotics and their sustainable production from agro-industrial by-products. *Foods*, *12*(14), 2681. https://doi.org/10.3390/foods12142681

Vargas-Carpintero, R., Hilger, T., Mössinger, J., Souza, R. F., Barroso Armas, J. C., Tiede, K., & Lewandowski, I. (2021). *Acrocomia* spp.: Neglected crop, ballyhooed multipurpose palm or fit for the bioeconomy? A review. *Agronomy for Sustainable Development*, *41*(6), 75. https://doi.org/10.1007/s13593-021-00729-5

Vieira, S. S., Magriotis, Z. M., Santos, N. A. V., Cardoso, M. D. G., & Saczk, A. A. (2012). Macauba palm (*Acrocomia aculeata*) cake from biodiesel processing: An efficient and low cost substrate for the adsorption of dyes. *Chemical Engineering Journal*, *183*, 152–161. https://doi.org/10.1016/j.cej.2011.12.047

Vieira, W. T., Bispo, M. D., de Melo Farias, S., de Almeida, A. D. S. V., da Silva, T. L., Vieira, M. G. A., Soletti, J. I., & Balliano, T. L. (2021). Activated carbon from macauba endocarp (*Acrocomia aculeata*) for removal of atrazine: Experimental and theoretical investigation using descriptors based on DFT. *Journal of Environmental Chemical Engineering*, *9*(2), 105155. https://doi.org/10.1016/j.jece.2021.105155

Wei, C., Xiao, K., Li, H., Qi, Y., Zou, Z., & Liu, Z. (2022). Optimization of ultrasound assisted aqueous enzymatic extraction of oil from *Cinnamomum camphora* seeds. *LWT*, *164*, 113689. https://doi.org/10.1016/j.lwt.2022.113689

Wong, M., Eyres, L., & Ravetti, L. (2014). Modern aqueous oil extraction-centrifugation systems for olive and avocado oils. In *Green vegetable oil processing: Revised first edition*. (pp. 19–51). Elsevier Inc. https://doi.org/10.1016/B978-0-9888565-3-0.50005-4

Zeng, X.-F., Varady, K. A., Wang, X.-D., Targher, G., Byrne, C. D., Tayyem, R., Latella, G., Bergheim, I., Valenzuela, R., George, J., Newberry, C., Zheng, J.-S., George, E. S., Spearman, C. W., Kontogianni, M. D., Ristic-Medic, D., Peres, W. A. F., Depboylu, G. Y., Yang, W., … Zheng, M.-H. (2024). The role of dietary modification in the prevention and management of metabolic dysfunction-associated fatty liver disease: An international multidisciplinary expert consensus. *Metabolism*, *161*, 156028. https://doi.org/10.1016/J.METABOL.2024.156028

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Sorita, G. D., Favaro, S. P., Gambetta, R., Ambrosi, A., & Di Luccio, M. (2025). Macauba (*Acrocomia* ssp.) fruits: A comprehensive review of nutritional and phytochemical profiles, health benefits, and sustainable oil production. *Comprehensive Reviews in Food Science and Food Safety*, *24*, e70097. https://doi.org/10.1111/1541-4337.70097