



HERMANNY MATOS SILVA SOUSA

SUSTAINABLE VALORIZATION OF PEACH PALM (*Bactris gasipaes*): EXTRACTION, BIOACTIVE COMPOSITION AND FUNCTIONAL PROPERTIES

**LAVRAS – MG
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Thesis submitted to the Federal University of Lavras as part of the requirements of the Postgraduate Program in Food Science, for obtaining the title of Doctor.

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SUSTAINABLE VALORIZATION OF PEACH PALM (*Bactris gasipaes*): EXTRACTION, BIOACTIVE COMPOSITION AND FUNCTIONAL PROPERTIES

VALORIZAÇÃO SUSTENTÁVEL DA PUPUNHA (*Bactris gasipaes*): EXTRAÇÃO, COMPOSIÇÃO BIOATIVA E PROPRIEDADES FUNCIONAIS.

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ABSTRACT

This thesis investigated, in an integrated manner, strategies for the valorization of Amazonian fruits of the Arecaceae family, with emphasis on peach palm (*Bactris gasipaes*), by combining a critical literature review, sustainable extraction of bioactive compounds, and chemical and structural characterization of oils obtained using different protocols. Initially, a bibliometric and thematic review of six promising palm species was conducted to synthesize trends, advances, and recurring gaps in the literature. The analysis revealed limitations related to methodological heterogeneity, limited comparability between studies, and the need for further research into approaches applied to the generation of higher value-added ingredients and inputs. In the experimental stage, the potential for integral valorization of peach palm was evaluated through the obtaining of extracts from different fractions of the fruit (peel, pulp, and seed), comparing conventional solvents (water and 80% ethanol) with alternatives also considered green, including deep eutectic solvents (DES) and supramolecular solvents (SUPRAS). The extracts were characterized in terms of bioactive composition, antioxidant potential, and biological activities, and were also subjected to *in vitro* gastrointestinal digestion simulation to discuss bioaccessibility. The results showed a strong influence of the fruit fraction and the solvent used on the chemical profile and functional performance of the extract, highlighting the potential of green solvents, especially SUPRAS, for the recovery of compounds of interest and to expand the possibilities of application and utilization of co-products. Additionally, the valorization of the lipid fraction of peach palm was investigated by evaluating the effect of two extraction protocols (one non-polar, based on isooctane, and another polar, based on ethanol) on the yield, chemical composition, and structural organization of oils obtained from the peel and pulp. The integrated approach, involving analysis of lipid composition, minor constituents, and thermal, structural, and rheological characterization, demonstrated that the differences observed in the oils should be interpreted as a result of the extraction protocol as a whole, and not just the effect of the solvent in isolation, highlighting direct implications for the functionality and technological potential of these oils. Taken together, the results demonstrate that peach palm is a strategic matrix for integral valorization, with the potential to generate bioactive extracts and oils with properties modulated by the extraction process, offering scientific and technological bases for innovation, waste reduction, and the development of products aligned with sustainability and the Amazonian bioeconomy.

Keywords: Amazonian fruit; integral valorization; green solvents; bioactive compounds; structured vegetable oils.

RESUMO

A presente tese investigou, de forma integrada, estratégias para a valorização de frutos amazônicos da família Arecaceae, com ênfase na pupunha (*Bactris gasipaes*), conectando a revisão crítica da literatura, a extração sustentável de compostos bioativos e a caracterização química e estrutural dos óleos obtidos por diferentes protocolos. Inicialmente, realizou-se uma revisão bibliométrica e temática sobre seis palmeiras promissoras, com o objetivo de sintetizar tendências, avanços e lacunas recorrentes na literatura. A análise evidenciou restrições relacionadas à heterogeneidade metodológica, à limitada comparabilidade entre estudos e à necessidade de aprofundamento em abordagens aplicadas à geração de ingredientes e insumos de maior valor agregado. Na etapa experimental, avaliou-se o potencial de valorização integral da pupunha por meio da obtenção de extratos a partir de diferentes frações do fruto (casca, polpa e semente), comparando solventes convencionais (água e etanol 80%) com alternativas também consideradas verdes, incluindo solventes eutéticos profundos (DES) e solventes supramoleculares (SUPRAS). Os extratos foram caracterizados quanto à composição bioativa, ao potencial antioxidante e às atividades biológicas, além de serem submetidos à simulação de digestão gastrointestinal *in vitro* para discussão da bioacessibilidade. Os resultados evidenciaram forte influência da fração do fruto e do solvente empregado no perfil químico e no desempenho funcional do extrato, destacando o potencial de solventes verdes, especialmente SUPRAS, para a recuperação de compostos de interesse e ampliar possibilidades de aplicação e aproveitamento de coprodutos. Adicionalmente, foi investigada a valorização da fração lipídica da pupunha avaliando o efeito de dois protocolos de extração (um apolar, baseado em isooctano, e outro polar, baseado em etanol) sobre o rendimento, a composição química e a organização estrutural de óleos obtidos da casca e da polpa. A abordagem integrada, envolvendo análise da composição lipídica, constituintes minoritários e caracterização térmica, estrutural e reológica, demonstrou que as diferenças observadas nos óleos devem ser interpretadas como resultado do protocolo de extração como um todo, e não apenas do efeito do solvente isoladamente, evidenciando implicações diretas para funcionalidade e potencial tecnológico destes. Em conjunto, os resultados demonstram que a pupunha é uma matriz estratégica para valorização integral, com potencial para gerar extratos bioativos e óleos com propriedades moduláveis pelo processo de extração, oferecendo bases científicas e tecnológicas para inovação, redução de desperdícios e desenvolvimento de produtos alinhados à sustentabilidade e à bioeconomia amazônica.

Palavras-chave: Fruto amazônico; valorização integral; solventes verdes; compostos bioativos; óleos vegetais estruturados.

IMPACTS INDICATORS

This thesis generates impact by demonstrating, in an integrated and applied manner, how an Amazonian fruit that is widely available, yet still technologically underutilized, can be converted into different classes of high value-added ingredients and inputs through the integral valorization of its fractions. By addressing the peel, pulp, and seed fractions, the study shifts peach palm from its traditional role as a regional food to that of a strategic raw material in the Amazon bioeconomy, reinforcing that coproducts that are frequently discarded may concentrate bioactive compounds and lipid fractions relevant to food and cosmetic applications. The scientific impact is expressed in the organization of existing knowledge and in the identification of methodological gaps that hinder comparisons among studies, while consistent experimental routes for the recovery of compounds of interest are proposed and evaluated. The thesis reinforces that the choice of solvent and process is not merely an operational step, but a determining factor in the selectivity, final composition, and functional potential of extracts. By incorporating alternative solvents regarded as green, such as water, ethanol, deep eutectic solvents, and supramolecular solvents, the work contributes to the consolidation of more sustainable extraction strategies, with the prospect of reducing dependence on conventional solvents, increasing efficiency, and promoting approaches aligned with the principles of green chemistry and the circular economy. In addition, the study broadens the understanding of vegetable oil quality by integrating chemical composition with structural and rheological characterization. This point is particularly relevant because the technological functionality of oils does not depend solely on the fatty acid profile, but also on the multiscale organization of the system (crystallization, crystal network, thermal and mechanical behavior), which determines texture and performance in formulations. By demonstrating that different extraction protocols can produce oils with distinct structural properties, the thesis provides support for directing processes toward specific applications, creating a bridge between process engineering and product development. From a socioeconomic and environmental perspective, the impact lies in the valorization of regional chains and in waste reduction: transforming residual biomass into extracts and oils with market potential increases the efficiency of resource use and may stimulate local innovation, product diversification, and income generation. Finally, the thesis delivers an evidence base and technological pathways that can be scaled up and further explored in future stages (storage stability, application in real matrices, feasibility and safety assessment), strengthening peach palm as a platform for the sustainable development of Amazonian ingredients. This work falls within the thematic areas of the National Extension Policy related to: (5) Environment, (7) Technology and Production, (8) Work, and (6) Health (through the interface with bioactive ingredients and oil quality). It is also aligned with the United Nations (UN) Sustainable Development Goals (SDGs): SDG 12 (Responsible Consumption and Production), SDG 9 (Industry, Innovation and Infrastructure), SDG 8 (Decent Work and Economic Growth), SDG 2 (Zero Hunger and Sustainable Agriculture), and SDG 13 (Climate Action), by proposing more sustainable routes, reducing losses, and increasing the efficiency of resource use in the peach palm chain.

INDICADORES DE IMPACTO

Esta tese gera impacto ao demonstrar, de maneira integrada e aplicada, como um fruto amazônico amplamente disponível, porém ainda subaproveitado tecnologicamente, pode ser convertido em diferentes classes de ingredientes e insumos de alto valor agregado a partir do aproveitamento integral de suas frações. Ao abordar as frações casca, polpa e semente, o trabalho desloca a pupunha do papel tradicional de alimento regional para o de matéria-prima estratégica na bioeconomia amazônica, reforçando que coprodutos frequentemente descartados podem concentrar compostos bioativos e frações lipídicas relevantes para aplicações alimentícias e cosméticas. O impacto científico se expressa na organização do conhecimento existente e na identificação de lacunas metodológicas que dificultam a comparação entre estudos, ao mesmo tempo em que são propostas e avaliadas rotas experimentais consistentes para recuperação de compostos de interesse. A tese reforça que a escolha do solvente e do processo não é apenas uma etapa operacional, mas um fator determinante de seletividade, composição final e potencial funcional de extratos. Ao incorporar solventes alternativos considerados verdes, como água, etanol, eutéticos profundos e supramoleculares, o trabalho contribui para a consolidação de estratégias de extração mais sustentáveis, com perspectiva de reduzir a dependência de solventes convencionais, ampliar a eficiência e favorecer abordagens alinhadas a princípios de química verde e economia circular. Além disso, o estudo amplia o entendimento sobre a qualidade de óleos vegetais ao integrar a composição química com a caracterização estrutural e reológica. Esse ponto é particularmente relevante porque a funcionalidade tecnológica dos óleos não depende apenas do perfil de ácidos graxos, mas da organização multiescalar do sistema (cristalização, rede de cristais, comportamento térmico e mecânico), que condiciona textura e desempenho em formulações. Ao evidenciar que diferentes protocolos de extração podem produzir óleos com propriedades estruturais distintas, a tese fornece subsídios para direcionar processos a aplicações específicas, criando uma ponte entre engenharia de processos e desenvolvimento de produtos. Do ponto de vista socioeconômico e ambiental, o impacto está na valorização de cadeias regionais e na redução de desperdícios: transformar biomassa residual em extratos e óleos com potencial de mercado aumenta a eficiência do uso de recursos e pode estimular inovação local, diversificação de produtos e agregação de renda. Finalmente, a tese entrega uma base de evidências e caminhos tecnológicos que podem ser escalonados e aprofundados em etapas futuras (estabilidade em armazenamento, aplicação em matrizes reais, avaliação de viabilidade e segurança), fortalecendo a pupunha como plataforma para desenvolvimento sustentável de ingredientes amazônicos. Esse trabalho se encaixa nas áreas temáticas da Política Nacional de Extensão relacionadas: (5) Meio ambiente, (7) Tecnologia e produção, (8) Trabalho e (6) Saúde (pela interface com ingredientes bioativos e qualidade de óleos). E possui alinhamento com os Objetivos de Desenvolvimento Sustentável (ODS) da Organização das Nações Unidas (ONU): ODS 12 (Consumo e Produção Responsáveis), ODS 9 (Indústria, Inovação e Infraestrutura), ODS 8 (Trabalho Decente e Crescimento Econômico), ODS 2 (Fome Zero e Agricultura Sustentável) e ODS 13 (Ação Climática), ao propor rotas mais sustentáveis, reduzir perdas e ampliar a eficiência do uso de recursos na cadeia da pupunha.

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FIRST PART

1. GENERAL INTRODUCTION

The valorization of native Amazonian fruits has gained prominence due to their potential to generate high-value-added food ingredients and industrial inputs, while simultaneously strengthening local production chains and strategies for the integral use of biomass (Freitas *et al.*, 2024; Sousa *et al.*, 2021). Within this scenario, palms of the Arecaceae family stand out for providing foods, oils, and various coproducts, and are frequently associated with the complete utilization of the fruit and with applications in foods, biocosmetics, bioenergy, and pharmaceutical uses (Amorim *et al.*, 2024; Morais *et al.*, 2022). In addition, these fruits are recognized for their richness in fatty acids, particularly palmitic (C16:0) and oleic (C18:1) acids, and for containing bioactive compounds with antioxidant activity, such as carotenoids, tocopherols, vitamin A, and phenolics, which supports their technological and functional interest (de Souza *et al.*, 2020; Sousa *et al.*, 2025). Article 1 provided the broad conceptual and bibliographic basis to contextualize peach palm within the group of Amazonian fruits from the Arecaceae family (peach palm, tucumã, buriti, buritirana, macaúba, and murumuru), highlighting integral use, economic relevance, and richness in bioactives, while also pointing out the need to deepen chemical/phytochemical characterization and advance applied studies.

In this context, peach palm (*Bactris gasipaes*) emerges as one of the most promising and versatile matrices. It is a palm native to the Amazon biome, known internationally by different names (such as pejobaye, chontaduro, and pupunha), whose diversity of uses and wide distribution reinforce its socioeconomic and scientific relevance (Felisberto *et al.*, 2020). Despite this, much of its utilization is still concentrated on fruit consumption, whereas the peel and seed fractions, with high potential, remain underexplored in agro-industrial systems, resulting in the recurrent disposal of these fractions containing compounds of interest (Miranda *et al.*, 2024; Dimou *et al.*, 2019).

The peel, in particular, constitutes a structurally complex matrix rich in natural pigments, especially carotenoids and associated lipophilic compounds, with potential to replace synthetic colorants in food and cosmetic formulations (Miranda *et al.*, 2024; Noronha Matos *et al.*, 2019). The seeds, in turn, present a concentrated chemical profile, with lipid reserves and a diversity of phenolic compounds, associated with bioactive properties and the possibility of application in functional ingredients and clean-label strategies (Gualberto *et al.*, 2025; Ibiapina

et al., 2021). Thus, promoting the integral use of the fruit is directly connected to the principles of circular economy, waste mitigation, and the development of new ingredients, while remaining consistent with global trends in resource use efficiency and food security.

The efficient recovery of these compounds depends strongly on the extraction process, in which solvent choice is decisive for selectivity, yield, and safety (Salatti *et al.*, 2019; Foroutani *et al.*, 2024; Morais *et al.*, 2025). In contrast to conventional routes based on organic solvents with greater toxicological/environmental impact, alternatives considered green, such as ethanol, deep eutectic solvents (DES), and supramolecular systems (SUPRAS), have been proposed to overcome matrix barriers and enhance the extraction of molecules with different polarities (Morais *et al.*, 2025; Sousa *et al.*, 2026). In Article 2, peach palm was studied integrally (peel, pulp, and seed), combining ultrasound-assisted extraction and five solvents (water, 80% ethanol, two DES, and SUPRAS), with evaluation of the bioactive profile, biological activities, and in vitro gastrointestinal digestion simulation.

The results of Article 2 showed distinct profiles of phenolics, flavonoids, and carotenoids among the fractions and demonstrated the superiority and selectivity of SUPRAS systems, especially for carotenoids in the peel (with reported values for β -carotene and lycopene), in addition to strong antioxidant activity for peel extracts and good performance in specific biological assays (e.g., inhibition of lipid peroxidation and α -amylase inhibition, depending on the fraction/solvent). In addition, antimicrobial activity against target bacteria and fungi was observed, as well as variations in bioaccessibility throughout simulated digestion, with emphasis on greater compound release in the intestinal phase. Thus, the study concluded that emerging green solvents (especially SUPRAS and DES) may be more efficient than conventional solvents and contribute to obtaining biodegradable and bioactive extracts, although applications at scale still depend on additional evaluations (safety, stability, feasibility, and in vivo bioefficacy).

In addition to the valorization of phenolic compounds and pigments, the lipid fraction of peach palm is part of the growing demand for new sources of vegetable oils, driven by sustainability pressures, diversification of global chains, and the need for specific technological functionalities (Ibiaina *et al.*, 2021; Pereira *et al.*, 2019). In Article 3, this perspective was further explored by demonstrating that vegetable oils should not be evaluated only by their fatty acid composition, but also by the presence of minor constituents and by molecular organization, which directly affect texture and performance in products. In this sense, peach palm is presented as a promising source of oil with relevant composition and the presence of co-extractable carotenoids for lipid valorization, in contrast to the traditional focus on consumption.

Article 3 investigated how the extraction protocol (isooctane-based vs. ethanol-based) in the peel and pulp fractions modulates the chemical composition and multiscale structure of peach palm oils, combining fatty acid and triacylglycerol profiles, carotenoid quantification, thermal analyses (DSC), microscopy (PLM), X-ray scattering/diffraction (SAXS/HAXS), and oscillatory rheology. The work also makes explicit that the two protocols differed not only in solvent polarity, but also in operational conditions, which is why the observed differences should be interpreted as dependent on the “protocol” (solvent + conditions + laboratory context), rather than as an isolated solvent effect.

From the process standpoint, the protocols were described as distinct routes: an apolar protocol with isooctane and Ultra-Turrax homogenization, followed by solvent removal; and a polar protocol with ethanol under incubation/heating and oil separation, with gravimetric quantification of yield. The findings reinforced that yield was significantly affected by the protocol, with higher yields in the ethanol protocol for pulp and peel oils, highlighting the role of extraction conditions in lipid recovery. In structural and functional terms, the study showed that extraction conditions and fruit fraction may favor the formation of crystalline networks and organized lipid domains, with semisolid behavior at 20 °C in specific samples, which broadens the possibilities for technological application of these oils as ingredients in foods and cosmetics.

Thus, the results and discussion presented throughout this thesis support that the integral valorization of Amazonian fruits from the Arecaceae family, particularly peach palm, depends on an integrated approach that combines a critical understanding of the literature, the selection of green solvents to maximize the recovery and functionality of extracts from peel, pulp, and seed, and the evaluation of how different extraction protocols modulate the composition and structural organization of the oils obtained from these fractions. Therefore, the general objective of this thesis was to develop an integrated approach for the valorization of peach palm (*Bactris gasipaes*), connecting the systematic review of the available knowledge to experimental advances in the sustainable extraction of bioactives and lipids, in order to support technological and functional applications of these fractions in food and/or cosmetic formulations, within a perspective of sustainable utilization and circular economy.

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SECOND PART

ARTICLE 1 - UNVEILING THE POWER OF SIX PALMS FROM THE ARECACEAE FAMILY: A BIBLIOMETRIC, NUTRITIONAL, AND BIOACTIVE REVIEW OF LESSER-KNOWN SPECIES.

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Abstract

This study performs a critical and comprehensive analysis of the scientific literature on six fruits native to the Brazilian Amazon belonging to the Arecaceae family: pupunha, tucumã, buriti, buritirana, macaúba and murumuru. These species, despite their high nutritional value and bioactive potential, remain commercially underutilized. Composed of unsaturated fatty acids, carotenoids, fibers, polyphenols and other bioactive compounds, these fruits have antioxidant, anti-inflammatory, cardioprotective and gastroprotective properties, in addition to therapeutic and industrial applications in the food, pharmaceutical and cosmetic sectors. The research was conducted through a bibliometric study in the Scopus database, using specific terms and thematic filters, resulting in 250 publications analyzed. Tools such as RStudio (bibliometrix) and VOSviewer were used to analyze the metadata, allowing mapping of patterns, international

collaborations, publication trends and associations between keywords. The review also included a detailed analysis of the nutritional and functional composition of these fruits based on literature indexed in ScienceDirect, Web of Science, Scopus and Scielo. The results highlight the great potential of these species in promoting food security, enhancing biodiversity and sustainable development in the Amazon, suggesting the need for more investment in research and innovation to fully utilize them.

Keywords: Native Amazonian fruits; Arecaceae; Bioactive compounds; Biodiversity enhancement; Bibliometric analysis.

1. Introduction

Brazil, recognized for its vast biodiversity, is home to a rich variety of fruit species, both native and exotic, which, unfortunately, remain underutilized in terms of commercial and scientific exploitation. The exploitation of these fruits primarily occurs through family farming, with a focus on commercialization in local markets, and is also driven by scientific research initiatives and small industries that process these fruits into products such as jams, sweets, fermented beverages, ice cream, pulps, and juices ^[1–3]. It is estimated that around 44% of these fruit species are concentrated in the Amazon region, highlighting the relevance of this area as an important natural reservoir of food resources and medicinal plants of global value ^[4, 5].

In addition to their potential to promote a local circular economy, these fruits stand out for their nutritional composition, which is rich in macro and micronutrients and bioactive substances with antioxidant properties. Such characteristics can significantly contribute to local populations' dietary supplementation, helping combat malnutrition and chronic diseases associated with an unbalanced diet ^[1, 6, 7]. Among the species that deserve to be highlighted are pupunha (*Bactris Gasipaes*), tucumã (*Astrocaryum vulgare*), buriti (*Mauritia flexuosa*), buritirana (*Mauritiella armata*), macaúba (*Acrocomia aculeata*) and murumuru (*Astrocaryum murumuru*), among others. Despite their great nutritional and economic potential, there is an ongoing need for a critical and comprehensive evaluation of the existing scientific literature on the health benefits of these fruits, aiming at the development of new products and income generation.

Pupunha, for example, is a fruit notable for its richness in oils, serving as a valuable raw material for the food and pharmaceutical industries due to its high levels of unsaturated fatty acids, such as oleic acid (54.23%), and carotenoids, with a particular emphasis on β -carotene,

a precursor of provitamin A ^[8–10]. Tucumã, in turn, stands out for its pulp and seeds with high concentrations of carotenoids, dietary fiber, essential fatty acids (ω -3 and ω -6), and polyphenols, which have demonstrated beneficial effects in the prevention and management of several human diseases, including its anti-inflammatory, cardioprotective, gastroprotective properties, and its function as a source of provitamin A ^[11–13].

Buriti is widely valued by the food, pharmaceutical, and cosmetic industries due to its lipid composition, which is rich in monounsaturated fatty acids, especially oleic acid, as well as carotenoids, such as β -carotene and tocopherols, that confer diverse biological effects ^[14–16]. Buritirana, in turn, is recognized for its nutritional composition, characterized by a high oil content, vitamins, and phenolic compounds, conferring it remarkable antioxidant properties, making it widely used for therapeutic purposes ^[17, 18].

Macaúba has generated growing interest in the food, pharmaceutical, cosmetic, and biodiesel industries due to its exceptional concentration of vegetable oils, which are mainly composed of monounsaturated fatty acids, such as oleic acid, and polyunsaturated fatty acids, such as linoleic acid. These fatty acids are recognized for their health benefits, including anti-inflammatory, cardioprotective, and antioxidant properties ^[19–22]. The oils extracted from macaúba have been explored in several industrial applications, including biodiesel production, due to their high thermal stability and excellent fatty acid profile ^[23]. These properties make macaúba a promising and sustainable alternative to fossil fuels, in addition to contributing to the development of nutraceutical and cosmetic products with antioxidant and photoprotective potential ^[24, 25]. In parallel, murumuru, although it still lacks more in-depth studies, has attracted the attention of the pharmaceutical and cosmetic industries due to its high lipid content, particularly saturated oils, which give the fruit seed emollient and moisturizing properties, and are widely used in skin and hair care products. In addition, the vegetable fats extracted from murumuru are rich in medium-chain fatty acids, such as lauric acid, which demonstrate antimicrobial and anti-inflammatory properties, promoting therapeutic benefits for the treatment of dermatological and inflammatory conditions ^[26, 27].

Therefore, the use of these fruit species can play a crucial role in increasing the diversity of native foods in the market, contributing not only to food and nutritional security but also to strengthening the conservation and sustainable management of Amazonian biodiversity ^[1, 4]. These fruits have demonstrated considerable bioactive potential, primarily attributed to their rich nutrient composition, including lipids, minerals, vitamins, and phenolic compounds, with a particular emphasis on carotenoids, such as β -carotene ^[10, 28, 29]. In addition to their food use, native Amazonian species have shown great interest in the cosmetic and pharmaceutical

industries, which can also contribute to strengthening the local economy by promoting the cultivation and sustainable exploitation of these fruits ^[30].

It is observed that the economic quantification of native fruits remains asymmetrical and fragmented, being fully documented only for some species. According to the Survey of Plant Extraction and Silviculture, buriti (*Mauritia flexuosa*) had a production value of U\$ 534.22 million in 2023, while tucumã registered U\$ 158,059.38 in the same year ^[3,10]. In contrast, for murumuru (*Astrocaryum murumuru*), although the technical-institutional literature indicates that the annual fat production is between 5,000 and 6,000 tonnes, there is no official record of the gross annual production value; however, considering market prices reported for murumuru butter of around U\$ 52.27 kg⁻¹ in January 2023, a high economic potential is inferred, dependent on the proportion effectively destined for commercialization as a lipid derivative ^[27]. For macaúba (*Acrocomia aculeata*), institutional data indicate an average market price of approximately U\$ 287.73 t⁻¹, however, the lack of consolidated national statistics on the annual volume produced per species makes a rigorous estimate of the added economic value impossible ^[19, 20]. A similar situation is observed for pupunha (*Bactris gasipaes*) and buritirana (*Mauritiella armata*), whose production chains have regional relevance but lack an unequivocal historical series of annual production value, due to ambiguities regarding the product classification and the plant part marketed ^[10, 18]. Taken together, these data show that, despite the recognized productive and market potential of these species, their economic importance remains underrepresented in production statistics, reinforcing the need for methodological and institutional improvement in the collection and systematization of information on native fruits.

The primary objective of this study was to conduct a comprehensive and critical analysis of the existing literature on the physicochemical characteristics, nutritional composition, phytochemical profiles, and bioactivity of six native fruits from the Brazilian Amazon, all of which belong to the Arecaceae family. To achieve this, a robust bibliometric analysis was carried out utilizing the Scopus database to identify emerging patterns, trends, and key publications related to these fruits. Subsequently, bibliometric indicators were systematically developed to quantitatively assess the breadth and depth of the research landscape. In addition, the conceptual framework of the cumulative literature on these native fruits was thoroughly examined, allowing for an in-depth understanding of the current state of knowledge and highlighting areas for future research and exploration.

1. Methodology

2.1 Bibliometric study design

The Scopus database was used to search for publications related to the Arecaceae family on May 13, 2024. The search sequence applied was: (“Arecaceae”) AND (“Brazil”) AND (“fruit*”), using the fields “title,” “abstract,” and “keywords.” Boolean operators such as AND and OR were used to combine terms, and truncation (e.g., “fruit*”) was applied to capture variations such as “fruit,” “fruits,” and “fruiting.” Although MeSH terms are not applicable to Scopus, synonymous terms as well as both common and scientific names of relevant species were included to broaden the search. The search was limited to the period from 1995 to 2024. To ensure alignment with the scientific scope of the review, thematic filters were applied based on subject areas. The following areas were selected: "Agricultural and Biological Sciences," "Biochemistry, Genetics, and Molecular Biology," "Pharmacology, Toxicology, and Pharmaceutics," "Medicine," "Chemistry," "Multidisciplinary," "Engineering," "Chemical Engineering," "Immunology and Microbiology," "Neuroscience," and "Materials Science." These subject areas were chosen because they directly relate to the nutritional, biochemical, and technological dimensions of the Arecaceae family, which are the focus of this review. Other areas, such as "Social Sciences," "Arts and Humanities," and "Economics", were excluded because they fall outside the intended scope and could lead to the inclusion of unrelated content.

After exporting the Scopus records, duplicate entries were automatically removed using the *bibliometrix* package (Aria & Cuccurullo, 2017) in RStudio® software (version 2024.04.1-748). The remaining records were screened by two independent reviewers based on titles, abstracts, and keywords to exclude irrelevant documents, such as those focused on ornamental or socio-cultural aspects, or those unrelated to nutritional, biochemical, or technological features of palm species. In cases of disagreement, full-text evaluation was performed, and consensus was reached. Since only peer-reviewed documents indexed in Scopus were included, no additional quality scoring was applied beyond relevance to the research objectives. This approach allowed for the generation of diverse analytical results, including collaboration networks between countries, scientific production by country, author-country affiliations, and multiple correspondence analysis (MCA). Furthermore, VOSviewer® software (Leiden University, Netherlands, version 1.6.20) was used to analyze the co-occurrence of keywords in the documents, with a minimum threshold of four occurrences, resulting in a final set of 34 keywords. This integrated methodology enabled a comprehensive exploration of the bibliometric landscape and keyword associations within the analyzed literature. This screening process resulted in a final set of 250 documents. Among them, 226 were research articles, 14

reviews, 4 book chapters, 3 conference papers, 2 short research articles, and 1 data document. The distribution by language included 223 documents in English, 32 in Portuguese, and 4 in Spanish.

2.2 Analysis of literature review data

To gather publications on specific fruits of the Arecaceae family and present an updated view of their nutritional characteristics, bioactive composition, technological applications, and in vivo studies, this review was conducted. A comprehensive search was performed using both common and scientific names of palm species (e.g., “peach palm,” “*Bactris Gasipaes*,” “*Astrocaryum vulgare*,” “buriti,” “*Mauritiella armata*,” “caraña,” “buritirana,” “*Acrocomia aculeata*,” “macaúba,” “*Astrocaryum murumuru*”). These terms were combined using the Boolean operator AND with functional descriptors such as “Amazonian oilseeds,” “nutraceuticals,” “properties,” “fatty acids,” “bioactive compounds,” and “functional foods.” Synonyms were included when applicable to maximize coverage. The databases consulted included ScienceDirect, Web of Science, Scopus, and Scielo, without restrictions on year or area of publication.

2.3 Bibliometric analysis

The Arecaceae family, commonly referred to as the palm family, represents one of the most ecologically significant plant groups in the Amazon region, encompassing approximately 2,600 species distributed across 181 genera, predominantly in tropical and subtropical regions globally ^[3]. Within the Amazon biome, Arecaceae species are taxonomically classified as monocots and include approximately 35 genera and over 170 species, of which at least 96 produce edible fruits ^[31–33]. Arecaceae plants are primarily found in tropical environments but have also been shown to thrive in arid, desert-like climates ^[34]. The morphological and functional diversity within Arecaceae species varies significantly according to their specific ecosystems, ranging from grass-like forms to large, woody trees ^[34, 35]. Within this context, Arecaceae species are widely recognized for their edible fruits. Pleasant sensory characteristics distinguish them, and they can be enjoyed both fresh and processed, such as juices, jams, and ice creams. Furthermore, these fruits are noted for their nutritional composition, which adds significant value to local diets ^[28, 33].

Between 1995 and 2024, 250 documents focusing on the Arecaceae family have been

published, with contributions from 1,127 authors. A geographical distribution analysis of these publications reveals that Brazil is the leading contributor, accounting for 1,007 publications (Figure 1a), followed by the United States (69), Colombia (18), France (16), Spain (12), Canada (10), Germany (9), Italy (9), Peru (8), and Portugal (7). A collaborative network between countries is also highlighted (Figure 1a), demonstrating that Brazil maintains the highest number of research collaborations, particularly with the United States. When examining countries' productivity based on the number of articles, whether independently or in cooperation with other nations, it is evident that, despite international collaborations, most Brazilian publications still predominantly involve authors from within Brazil. This contrasts with countries such as the United States, Italy, Colombia, Argentina, Chile, Belgium, Germany, Ireland, the United Kingdom, Paraguay, and Portugal, where a more pronounced international research network is observed.

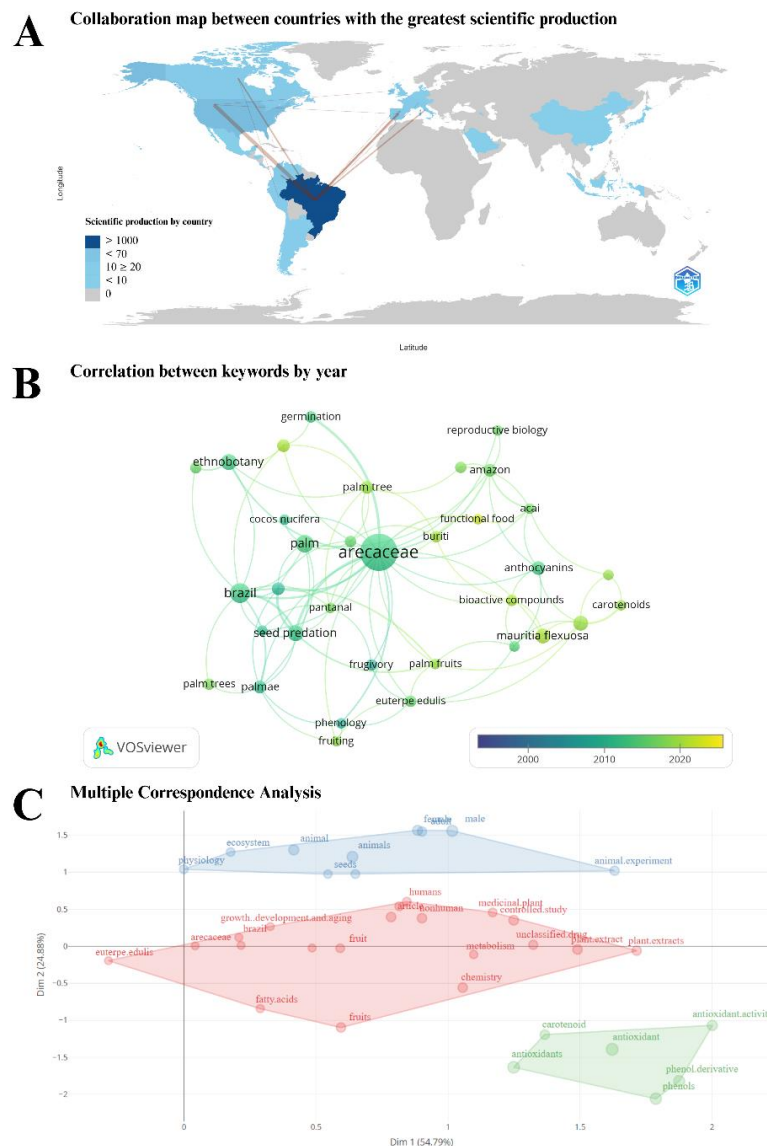


Figure 1. Bibliometric analysis of articles on the Arecaceae family. (A) Collaboration map between countries with the greatest scientific production; (B) Correlation between keywords by year; and (C) Multiple correspondence analysis.

An analysis of the most frequently used keywords in the publications (Figure 1B) reveals that the term "Arecaceae" appears most frequently (50 occurrences), with a peak in 2012, and has the highest total link strength (39) and number of links (24). The term "Brazil" ranks second in frequency (14 occurrences), with significant prominence in 2013, followed by "palm" (11 occurrences), also most frequently used in 2013. Further investigation of the keyword network indicates the emergence of terms such as "palm tree," "palm fruits," "bioactive compounds," "phenolic compounds," "oxidative stress," "carotenoids," and "functional food" starting from 2018, suggesting a shift in the research focus within the

Arecaceae family. The Multiple Correspondence Analysis (MCA) reveals a high degree of alignment in the data, with an information congruence of over 79% between the two principal dimensions (Dim 1 and Dim 2) (Figure 1C), resulting in the formation of three distinct clusters. These clusters reflect different thematic axes: the first, represented by the blue cluster, focuses on ethnobotanical research and ecosystem studies. The second, represented by the red cluster, is centrally positioned around the chemical characterization of Arecaceae fruits. The third, represented by the green cluster, addresses bioactive compounds, predominantly located on the negative axis due to their association with more recent research trends, further corroborating the findings observed in Figure 1B concerning the evolving keyword usage.

2. Literature review

2.1 Fruits of the Arecaceae family and their Ethnobotanical characteristics

For society, products derived from several palm trees, such as pupunha (*Bactris Gasipaes*), tucumã (*Astrocaryum vulgare*), buriti (*Mauritia flexuosa*), buritirana (*Mauritiella armata*), macaúba (*Acrocomia aculeata*), murumuru (*Astrocaryum murumuru*) (Figure 2), are strongly associated with economic expansion due to the full use of fruits ^[36]. Such fruits are generally obtained through extractive activities and play fundamental roles in crops, providing oils, fibers, straw, wood, and other materials ^[29, 30, 37]. The fruits of the Arecaceae family are recognized for their richness in polyunsaturated fatty acids and bioactive compounds, which demonstrate antioxidant properties, such as carotenoids, tocopherols, vitamin A, phenolic compounds, and flavonoids, playing a crucial role in promoting health ^[4, 29, 33]. These fruits have great potential for use in food, biocosmetics, biofuels, handicrafts, and for pharmaceutical and medicinal purposes ^[7, 38]. Therefore, advances in research on Amazonian palm trees have led to several studies on the potential application of these fruits. However, more in-depth studies on these fruits' chemical and photochemical composition are necessary to advance *in vitro* and *in vivo* application studies. This is the first literature review that systematically unites the botanical characteristics, nutritional potential, and applications in different scientific and technological contexts on the fruits of pupunha, tucumã, buriti, buritirana, macaúba, and murumuru.

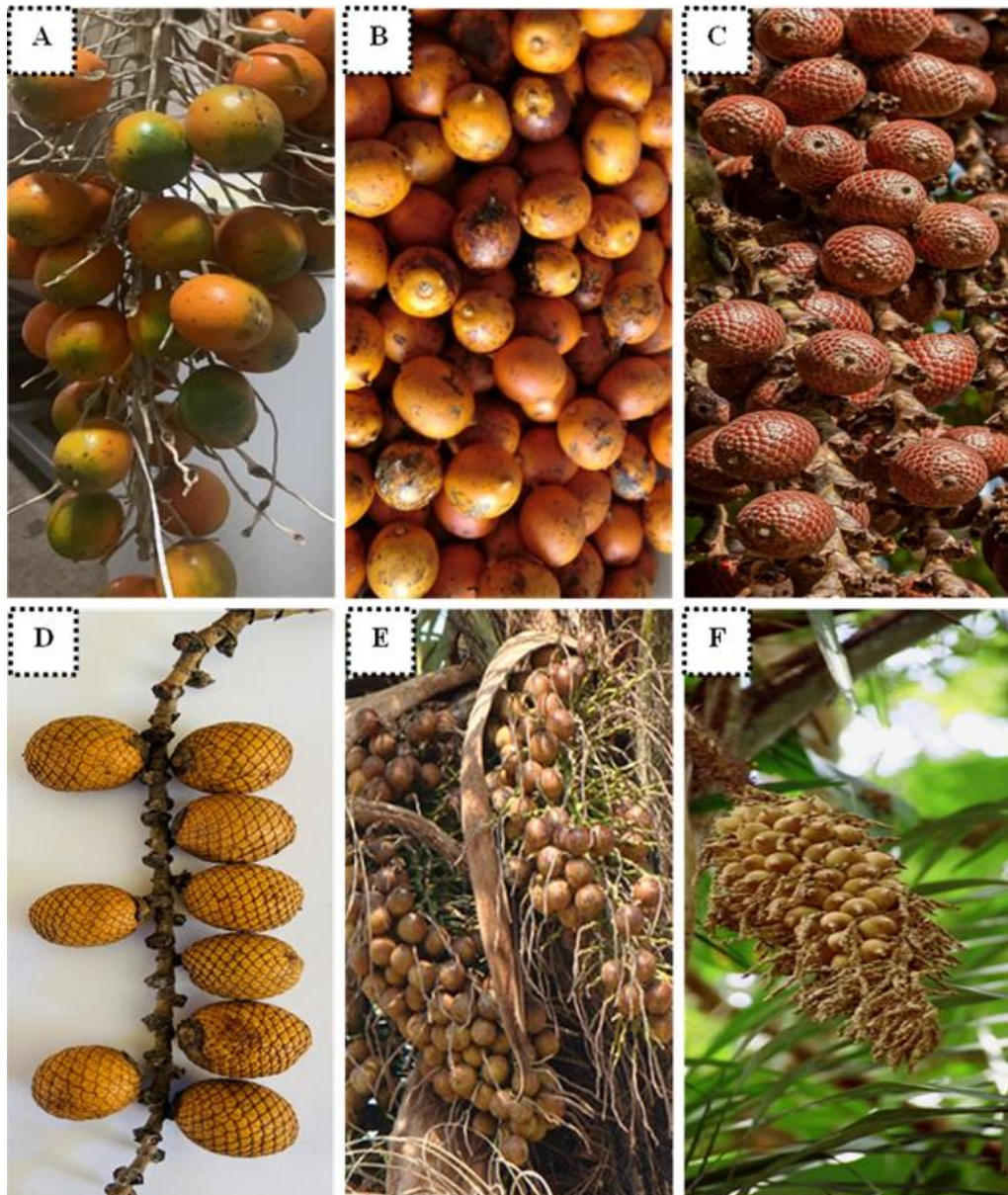


Figure 2. Fruits of the Arecaceae family: (A) pupunha, (B) tucumã, (C) buriti, (D) buritirana, (E) macaúba, (F) murumuru.

3.2 *Pupunha (Bactris Gasipaes)*

The pupunha (Figure 2A) is a species of palm tree in the Arecaceae family, native to the Amazon biome, and known by many names: chontaduro (Colombia), chonta (Ecuador), pejibaye (Costa Rica), and peach palm (North America and other South American countries, including Brazil) ^[11, 14]. The pupunha blooms from August to October in central Amazonia, while fruiting occurs mainly between December and March ^[28, 39, 40]. The pupunha is a tree characterized by being monoecious, allogamous, thorny, and multipurpose, and can reach up to

20 m in height and 15 to 25 cm in diameter. Its leaves are pinnate in the crown, with intrafoliar inflorescence, and are cultivated in tropical climates, mainly in areas of humid forest close to permanent watercourses, where rainfall rates are quite different, ranging from 2,000 to 6,000 mm ^[38, 41]. It produces approximately 5 to 10 bunches annually, containing around 100 fruits each ^[28, 39].

The fruits are distributed in bunches, are drupe-type with edible pulp around a single seed, 4–6 cm long and 3–5 cm wide, with different shapes such as conical, ovoid, or ellipsoid, and varying weights from 20 to 205 g (Figure 2A) ^[10, 30, 39]. In addition, it has a thin skin attached to the pulp, with diverse colors such as red, orange, or yellow, depending on the variety and stage of ripening, and may have the presence or absence of seeds ^[42, 43]. Traditionally, pupunha is consumed after cooking in boiling water with salt or sugar for 20 min to improve flavor, inhibit antinutritional factors, eliminate calcium oxalate crystals from the peel, and inactivate pulp peroxidase enzymes, as these components can irritate the throat mucosa ^[8, 15, 44, 45]. In addition to being consumed directly, there are reports of its use in salads, pies, seed tortillas for children, sweets, risottos, and flours, being consumed more for breakfast and afternoon snacks ^[45, 46]. Food companies such as La Violetera ^[47] and Do Vale ^[48], as well as regional cooperatives like COOPAVAM ^[49], are involved in the production and commercialization of these derivatives.

3.3 Tucumã (*Astrocaryum vulgare*)

Tucumã (Figure 2B), of the genus *Astrocaryum*, is a member of the Arecaceae family native to the legal Amazon ^[50]. In Brazil, this fruit is known by several names, such as tucumã-arara, tucumã-piranga, tucumã-piririca, tucumã-uassurana, tucum-assu, tucum-bravo, tucum-da-serra, tucum-do-matto, and tucum-purupuru ^[51]. Tucumã has two species widespread in the Amazon region: *Astrocaryum aculeatum*, which is found mainly in the states of Acre, Amazonas, Rondônia, and Roraima, and *Astrocaryum vulgare*, which is already seen in the states of Amapá, Pará, Tocantins, Maranhão, Piauí, and Goiás ^[8, 28, 52, 53]. The palm trees are large, up to 25 meters tall, grow along rivers, and have thorny trunks ^[51, 54, 55]. Like most fruits exclusive to the Amazon, the tucumã fruiting period is from January to April. On average, each tucumã tree can produce 2 to 5 bunches of fruit per year, containing 200 to 400 fruits, and each bunch weighs 10 to 30 kg ^[33, 56].

Figure 2B shows the characteristics of the fruit, which has a drupe shape, has only one seed, and the color of the skin and pulp varies from yellow to dark orange ^[51, 57]. The fruit has

a diameter of 5 to 6 cm and a mass of 70 to 75 grams and is consumed fresh or even in the production of regional dishes such as ice cream, sweets, and alcoholic liqueurs ^[8, 50]. On the other hand, the industry uses the pulp, peel, and seed, which were previously discarded as by-products, to extract oil, as they have biologically active compounds that prove the great potential of this fruit ^[26, 57]. According to the literature, tucumã has a fibrous pulp that provides a high content of nutrients such as vitamin A, phenolic compounds, such as catechin, and edible oils rich in saturated fatty acids, being its primary nutrient ^[50, 58]. The cosmetics company Natura, through its Ekos Tucumã product line ^[59], and natural ingredient suppliers such as Beraca, a Clariant group company ^[60], stand out in the commercialization and use of the oil in cosmetic formulations.

3.4 Buriti (*Mauritia flexuosa*)

The buriti (*Mauritia flexuosa*) (Figure 2C) is one of the most widespread palm trees in the Amazon and other Brazilian biomes. It belongs to the Arecaceae family and is known by other names such as buriti-do-brejo, carandá-guaçu, carandaí-guaçu, coqueiro-buriti, itá, palmeira-dos-brejos, buritizeiro, meriti, miriti, muriti, muritim, muruti, aguaje, moriche, canangucha, palma real and moretes ^[61, 62]. The buritizeiro, the buriti palm tree, is found only in South America, widespread in the Amazon region, and is consumed and sold by indigenous, riverside and extractive communities in the region ^[7, 63]. In Brazil, buriti is found in the Amazon and Cerrado biomes, in the states of Pará, Amazonas, Amapá, Rondônia, Goiás, Bahia, Minas Gerais, Mato Grosso, Ceará and Maranhão ^[62, 64, 65].

The buriti tree can reach between 20 and 35 m in height and usually grows in low-lying terrain, with acidic soil and flooded areas such as rivers, marshy areas, or permanently flooded areas ^[62, 65–67]. Each buriti tree produces around 290 kg of fruit annually, with approximately 422 tonnes of buriti produced in Brazil in 2022 ^[68, 69]. Its flowering occurs from December to April, and its fruiting occurs from December to June ^[28, 54]. The buriti is a small fruit, elongated in shape, approximately 5 cm long and 3 cm in diameter, weighing between 25 and 40 g. It has reddish-brown skin in the style of rhomboid scales; its pulp is thin and yellowish; its aroma is sweet, with oily texture and pasty consistency, and globular or semi-spherical seed (Figure 2C). They are consumed in processed forms of sweets, ice cream, juices, jellies, wines, and the production of pulps that are sold in local markets and fairs ^[65, 70, 71]. Buriti is highly valued for its carotenoid-rich oil, which is widely used in cosmetics, dietary supplements, and gourmet products. Companies such as Natura ^[72], Phytoterápica ^[73], Beraca ^[60], and Arte dos Aromas

[74] commercialize the vegetable oil, while the frozen pulp is distributed by local producers from the northern region of Brazil.

3.5 *Buritirana (Mauritiella armata)*

Buritirana (*Mauritiella armata*) (Figure 2D) belongs to the Arecaceae family and is widespread in low-altitude regions throughout the Brazilian Amazon basin and the Cerrado biome [6, 17, 75, 76]. It is a fruit-bearing species, also known as buriti mirim, buriti bravo, yumuna aguajillo, moriche negra and caraña, among other names [17, 29, 77]. It is a dioecious and short palm tree belonging to the genus *Mauritiella*, characterized by thin and solitary trunks, found in clusters protected by roots and rigid spines or needles along its stem, reaching up to 8 meters in height. It has 12 to 14 small fan-shaped leaves and interfoliar inflorescences with hanging branches [29, 78, 79]. The buriti and buritirana palms are similar, however, the difference between them is the stem. The buriti has a single stem with a diameter of 45 cm, while the buritirana has a stem divided into several segments with a diameter of 20 cm [80]. Morphologically, the fruits of the buritirana are similar to those of the buriti (*Mauritia flexuosa*) but are smaller. The buritirana (Figure 2D) has globose to oblong fruits with overlapping orange scales instead of orange or dark red, fleshy and fibrous pulp, and a very thin endocarp surrounding a hard seed. For processing, the fruits are commonly softened in hot water for about 1 hour, then the skin is removed, and the pulp is scraped from the seed. The fruit is then consumed by the local population in natura or used in beverages, sweets, and wines, among others [6, 17, 18, 29, 81]. Buritirana is still limited to artisanal processing, with derivatives such as pulps, sweets, and jams sold at regional markets, especially in the state of Pará, Brazil. To date, there are no records of major companies operating in the production chain of this species.

3.6 *Macaúba (Acrocomia aculeata)*

Macaúba (*Acrocomia aculeata*) (Figure 2E) is an oil palm native to South America, abundantly distributed in Brazil's central-western and southeastern regions, which has high potential for the sustainable development of new food and pharmaceutical products. Its fruits are known in Brazil as macaúba, bocaiúva, coco de espinho, mocajá, coco de catarro, mocayá, coquito, in Argentina as corozo, in Colombia and Venezuela as corosse, in France and Haiti as palma de vino, macaúba, in Spain as coyol, in Mexico, Costa Rica and Honduras as totaí; in Paraguay as bokaja, and in Germany as macaúba [20, 22, 82–84]. The macauba is a hardy,

arborescent, perennial, fruit-bearing palm tree that can reach 15 to 20 m in height; its trunk is 20 to 30 cm in diameter and covered with dark thorns 10 cm long. Its leaves are short and long. It is a palm tree with tolerance to high irradiance and temperatures, fire and drought, diseases and pests, and resists significant climatic variations ^[20, 85]. The fruits (Figure 2E) are spherical, 2.5 to 5 cm in diameter. A palm tree has 2 to 8 bunches, ranging from 250 to 500 fruits per bunch, and can produce between 25,000 and 40,000 kg of fruits/ha/year ^[83, 86, 87]. Its flowering usually occurs from April to June, and the fruits ripen from October to January ^[86, 88]. Macaúba fruits are harvested manually by collecting the fruits that fall to the ground when ripe due to factors such as winds ^[83]. Macaúba has been explored for the production of edible oils, biodiesel, cosmetics, and fiber-rich flour. Companies such as Soleum Brasil ^[89], Inocas ^[90], and Petrobras ^[91] have been investing in its production chain for the extraction of vegetable oil. In the cosmetics sector, brands like Natura ^[92] and Beraca ^[60] incorporate macaúba oil into natural formulations.

3.7 Murumuru (*Astrocaryum murumuru*)

Murumuru (*Astrocaryum murumuru*) (Figure 2F) is a palm tree widely distributed in the Amazon region. The murumuru tree grows primarily in humid and temporarily flooded areas, close to rivers and lakes, sometimes forming large populations, and is of high importance value ^[93–95]. It is a medium-sized palm tree that grows preferably in floodplain soils in the Amazon region ^[96, 97]. Despite its economic potential, murumuru is little commercially exploited due to the number of thorns arranged on the stem and leaves of the plant, making its management difficult. These palm trees, whether solitary or clustered, are covered in thorns throughout their structure, particularly in leaf sheaths that become rigid plates attached to the growing stems ^[26, 98].

The murumuru palm tree measures 10 m to 15 m in height, its stem generally measures 17 cm to 27 cm in diameter, presenting itself as a single-stemmed tree, its leaves are pinnate, ranging from 12 to 20, and measuring 5 m to 6.2 m ^[99, 100]. The murumuru palm produces an average of four bunches per year, with approximately 300 fruits per bunch, and can produce 1,200 fruits per palm tree per year. Its fruits are known in Brazil as Mumbaca, murumuru, murumuru-comum, murumuru-da-terra-firme, murumuruí ^[94, 98, 101]. The murumuru is an asymmetrical fruit, reddish when ripe, pear-shaped to ovoid in shape; its seed is hard and covered by a yellowish, edible, and slightly sweet pulp (Figure 2F). The length of the fruit can vary from 3 cm to 8.5 cm, the diameter can reach 1.2 cm to 4.5 cm, and the average weight is

8 g. Ripe fruits can have an oblong to ovoid shape, and coconuts can have elongated to rounded shapes. The color can vary from light brown to golden yellow^[94, 101]. Murumuru is an important source of vegetable butter, widely used in cosmetic formulations due to its moisturizing and emollient properties. The company Natura, through its Ekos Murumuru line^[102], is one of the main users of this ingredient, alongside other companies such as Beraca^[60] and Phytoterápica^[103].

3. Nutritional characteristics

4.1 Proximal composition and minerals

Table 1 presents the proximal composition of the fruits, highlighting the levels of macro and micronutrients essential for human nutrition. There is wide variability in the parameters of moisture (between 37.40 and 79.35 g·100 g⁻¹), lipids (2.6 to 23.63 g·100 g⁻¹) and energy value (117.16 to 368.78 kcal·100 g⁻¹), evidencing the biochemical diversity among the species analyzed. Notably, the pulps of buritirana (*Mauritiella armata*) and macaúba (*Acrocomia aculeata*) have the highest lipid and caloric contents, with 23.63 and 30.53 g·100 g⁻¹ of lipids and 368.78 and 258.47 kcal·100 g⁻¹, respectively, characteristics that make them promising sources of dietary energy^[18, 22]. On the other hand, the pulp of murumuru (*Astrocaryum murumuru*), although rich in saturated lipids, had the lowest lipid content among the fruits evaluated (2.6 g·100 g⁻¹), and it was not possible to estimate its energy value due to the lack of complete data in the literature^[100]. Regarding the protein composition, the pronounced presence of proteins in the pulps of buritirana (5.96 g 100 g⁻¹) and macaúba (5.31 g 100 g⁻¹) stands out, suggesting a complementary potential in diets with low intake of animal proteins^[18, 22].

On the other hand, tucumã (*Astrocaryum vulgare*) showed the highest carbohydrate content (39.91 g 100 g⁻¹), while macaúba and murumuru exhibited the lowest values (6.92 and 8.56 g 100 g⁻¹, respectively), which may be relevant for formulations with a low glycemic index^[10, 84]. Regarding dietary fiber content, buritirana demonstrated exceptional concentration (65.46 g 100 g⁻¹), followed by macaúba (18.17 g 100 g⁻¹), both significantly surpassing widely consumed fruits, such as banana (10.50 g 100 g⁻¹), mango (6.71 g 100 g⁻¹), pear (11.14 g 100 g⁻¹) and kiwi (2.0 g 100 g⁻¹)^[104, 105]. The intake of just 100 g of buritirana pulp is sufficient to meet or even exceed the daily dietary fiber recommendations for healthy adults, established between 25 and 35 g, based on a 2,000-kcal diet^[3, 106].

Table 1. Physicochemical characteristics and mineral composition of six fruits of the *Arecaceae* family.

Composition (g 100 g⁻¹)	Pupunha (<i>B. gasipaes</i>)	Tucumã (<i>A. vulgare</i>)	Buriti (<i>M. flexuosa</i>)	Buritirana (<i>M. armata</i>)	Macaúba (<i>A. aculeata</i>)	Murumuru (<i>A. murumuru</i>)
Moisture	77.62	37.40	79.35	54.78	40.19	Nd.
Ash	0.45	2.20	1.01	1.58	1.50	Nd.
Lipids	6.59	10.87	7.72	21.01	23.63	2.6
Proteins	1.33	3.08	1.43	5.96	5.31	4.00
Total Crude Fiber	0.49	6.54	6.02	65.46	18.17	-
*Carbohydrates	13.52	39.91	10.49	16.67	11.2	8.56
pH	6.61	6.71	4.05	4.15	5.50	4.26
**Total Acidity	2.01	1.80	0.47	4.90	1.43	6.3
Soluble Solids (°Brix)	4.00	9.50	4.33	-	29.70	8.7
EV (kcal 100 g ⁻¹)	173.76	293.02	117.16	368.78	258.47	Nd.
Minerals (mg 100 g ⁻¹)						
Calcium (Ca)	Trace	182.51	80.49	65.19	113.00	Nd.
Magnesium (Mg)	4.91	22.50	40.34	49.12	123.00	Nd.
Potassium (K)	58.00	70.01	218	672.65	2.36	Nd.

Sodium (Na)	nd.	nd.	11.25	-	0.13	Nd.
Phosphorus (P)	nd.	43.42	6.90	-	6.97	Nd.
Nickel (Ni)	nd.	nd.	0.06	-	-	Nd.
Manganese (Mn)	0.54	1.76	1.79	3.55	0.32	Nd.
Iron (Fe)	2.65	4.39	1.77	2.88	4.14	Nd.
Zinc (Zn)	0.03	0.3651	0.60	2.15	4.52	Nd.
Copper (Cu)	0.43	0.08	0.15	0.44	0.14	Nd.
Selenium (Se)	nd.	nd.	0.05	-	-	Nd.
Chromium (Cr)	nd.	nd.	0.12	-	-	Nd.
References	[10, 28, 181, 182]	[10, 28, 183]	[3, 28, 64, 184]	[3, 18, 81]	[29, 112, 185, 186]	[94, 101, 187, 188]

* Carbohydrates calculated by difference [100 - (moisture + ash + protein + lipid)]; ** total acidity expressed in mg citric acid 100 g⁻¹; nd.: not determined; Trace: below the limit of quantification.

The physiological relevance of dietary fiber is widely recognized, as it is associated with modulation of intestinal transit, improvement of the lipid profile, glycemic control, and reduction of blood pressure, in addition to contributing to the prevention of chronic non-communicable diseases ^[106, 107]. In contrast, pupunha (*Bactris Gasipaes*) and buriti (*Mauritia flexuosa*) presented the lowest fiber contents (0.49 and 6.02 g 100 g⁻¹, respectively), although they stand out for other nutritional and functional attributes, such as their lipid composition and bioactive carotenoids. In addition to macronutrients, the analyzed fruits also proved to be relevant sources of minerals and micronutrients essential for cellular metabolism, enzymatic regulation, and maintenance of organic homeostasis ^[108].

Among the minerals with the highest concentration, potassium stands out, with particularly high presence in buritirana (672.25 mg·100 g⁻¹) and buriti (218 mg·100 g⁻¹). Considering the Recommended Daily Intake (RDI) of potassium for adults at 3,510 mg ^[109], 100 g of buritirana pulp provides approximately 19.15% of this requirement, while buriti contributes approximately 6.21%. Potassium deficiency in the diet is associated with important clinical manifestations, such as muscle fatigue, hypotonia, cardiac arrhythmias, acne, dry skin, and neuromuscular disorders ^[110, 111], reinforcing the role of these fruits as adjuvants in the prevention of mineral deficiencies. The tucumã and macaúba fruits stand out for their significant levels of essential minerals, especially calcium and magnesium.

The calcium concentration in the pulps of these fruits reaches 182.57 mg 100 g⁻¹ and 113 mg 100 g⁻¹, respectively, while the magnesium content in macaúba reaches 123 mg 100 g⁻¹ ^[20, 112]. When compared to the daily intake recommendations for healthy adults — 1300 mg for calcium and 400 mg for magnesium —, these amounts represent a contribution of 14.04% of the RDI of calcium for tucumã, 8.69% for macaúba, and 30.75% of the RDI of magnesium, considering the consumption of 100 g of macaúba pulp. The physiological importance of these minerals lies, in part, in their ability to form stable complexes with phospholipids in cell membranes, playing an essential role in intracellular homeostasis and structural stability of cells ^[113]. Furthermore, studies indicate that the combined action of calcium and magnesium can exert synergistic effects in the control of biochemical processes and the regulation of ion channels ^[114].

Other minerals have also been identified in intermediate concentrations in the fruits of the Arecaceae family. Among them, the most important are sodium (average of 11.25 mg 100 g⁻¹), phosphorus (ranging from 6.90 to 43.42 mg 100 g⁻¹), manganese (0.32 to 1.79 mg 100 g⁻¹), iron (1.77 to 4.39 mg 100 g⁻¹) and zinc (0.03 to 4.52 mg 100 g⁻¹). Buritirana pulp, in particular, has a manganese content that exceeds the recommended levels, providing more than

100% of the recommended daily intake of this element (2.3 mg day^{-1}), highlighting its potential as a food source for preventing nutritional deficiencies. Regarding iron, a fundamental mineral for oxygen transport and immune function, it was observed that the ingestion of 100 g of tucumã and macaúba pulp can supply, respectively, 54.87% and 51.76% of the RDI (set at $8 \text{ mg} \cdot \text{day}^{-1}$ for adults), reinforcing the nutritional value of these fruits in the prevention of iron deficiency anemia ^[115].

Among the fruits investigated, buriti (*Mauritia flexuosa*) was the only one to present quantifications of selenium and chromium at relevant levels, with contents of $0.05 \text{ mg} \cdot 100 \text{ g}^{-1}$ and $0.12 \text{ mg} \cdot 100 \text{ g}^{-1}$, respectively. Considering the daily intake recommendations for these micronutrients — 0.055 mg for selenium and 0.03 mg for chromium —, the ingestion of 100 g of buriti pulp can reach or even exceed the RDI for both minerals. Chromium is essential in several metabolic processes, participating in the modulation of gene expression, glucose homeostasis, lipid and lipoprotein synthesis, and exerting effects on insulin sensitivity ^[116]. Chromium deficiency can lead to glucose intolerance, unintentional weight loss, peripheral neuropathy, and increased cardiovascular risk ^[117], making it essential to have an adequate dietary supply. In turn, selenium is an essential cofactor in the activity of antioxidant enzymes such as glutathione peroxidase and plays a decisive role in the proper functioning of the thyroid gland, in addition to acting in the regulation of immunity and protection against oxidative stress, and is associated with a lower risk of certain types of cancer. Its deficiency can contribute to the emergence of disorders such as hypothyroidism, immune dysfunctions, and cardiovascular diseases ^[116, 118, 119].

4.2 Lipid profile

Table 2 describes the composition of fatty acids present in fruits belonging to the Arecaceae family, highlighting the high nutritional and functional value of their vegetable oils. Among the main fatty acids identified in the pulps of these species, the following stand out: oleic acid (C18:1), palmitic acid (C16:0), linoleic acid (C18:2), stearic acid (C18:0), and α -linolenic acid (C18:3), which make up the majority of the lipid profile of these fruits. Among these, oleic acid, a monounsaturated fatty acid of recognized physiological value, was found in significant proportions in the following species: buriti (75.70%), macaúba (65.71%), tucumã (58.51%), buritirana (56.50%), and pupunha (54.23%) ^[18, 26, 28, 29, 120]. The high oleic acid content in these fruits is especially relevant from the point of view of public health and the prevention of chronic non-communicable diseases ^[121]. Epidemiological and clinical studies

have shown that diets enriched with monounsaturated fatty acids, particularly oleic acid, promote the reduction of plasma levels of low-density lipoproteins (LDL-c), while favoring the maintenance or increase of high-density lipoproteins (HDL-c), contributing to a better lipid profile and lower cardiovascular risk ^[122, 123]. In addition, oleic acid has been associated with the modulation of inflammatory responses, improved insulin sensitivity and protection against cellular oxidative processes, which reinforces its relevance in nutritional strategies for the prevention of metabolic syndromes ^[124, 125].

Table 2. Lipid composition of six fruits of the *Arecaceae* family.

Fatty Acids (%)	Pupunha (<i>B. gasipaes</i>)	Tucumã (<i>A. vulgare</i>)	Buriti (<i>M. flexuosa</i>)	Buritirana (<i>M. armata</i>)	Macaúba (<i>A. aculeata</i>)	Murumuru (<i>A. murumuru</i>)
Caproic (C6:0)	nd.	nd.	0.01	Nd.	2.20	-
Caprylic (C8:0)	nd.	nd.	0.05	Nd.	1.10	1.19
Capric (C10:0)	nd.	nd.	0.01	Nd.	0.11	1.31
Lauric (C12:0)	0.06	0.04	0.03	Nd.	0.59	49.6
Myristic (C14:0)	0.10	0.19	0.12	0.20	0.39	28.25
Pentadecanoic (C15:0)	0.10	0.04	0.07	Nd.	Nd.	Nd.
Palmitic (C16:0)	35.81	30.63	22.18	33.97	20.11	9.00
Margaric (C17:0)	0.09	0.25	0.12	0.31	0.08	Nd.
Stearic (C18:0)	2.28	2.88	2.51	2.00	3.09	2.57
Arachidic (C20:0)	0.24	nd.	0.11	Nd.	0.21	Nd.
Behenic (C22:0)	0.03	0.06	0.02	Nd.	0.06	Nd.
Lignoceric (C24:0)	0.03	0.07	0.09	Nd.	0.08	Nd.
Palmitoleic (C16:1 <i>cis</i> 9)	3.39	nd.	0.30	0.44	2.56	Nd.
Oleic (C18:1 <i>cis</i> 9)	54.23	58.51	75.70	56.50	65.71	11.00

Gondoic (C20:1 cis 11)	nd.	nd.	0.58	1.97	Nd.	Nd.
Linoleic (C18:2 cis 9, 12)	6.59	1.33	4.90	Nd.	5.46	3.14
Linolenic (C18:3 cis 9, 12, 15)	0.62	5.37	8.20	Nd.	1.02	Nd.
Tocopherol (mg kg⁻¹)						
α-Tocopherol	1.17	1.42	614.00	Nd.	143.70	Nd.
β-Tocopherol	7.00	0.56	761.87	Nd.	3.25	Trace
γ-Tocopherol	4.00	Nd.	56.71	Nd.	57.85	Nd.
δ-Tocopherol	Nd.	Nd.	136.00	Nd.	8.15	Nd.
α-tocotrienol	Nd.	Nd.	90.00	Nd.	32.1	Nd.
γ-tocotrienol	Nd.	Nd.	12.00	Nd.	4.84	Nd.
δ-tocotrienol	Nd.	Nd.	18.00	Nd.	0.56	Nd.
Σ Tocopherol	58.00	Nd.	1688.58	Nd.	250.45	Nd.
Phytosterols (mg kg⁻¹)						
β-Sitosterol + sitostanol	Nd.	Nd.	76.60	Nd.	Nd.	Trace
Campesterol	Nd.	Nd.	6.60	Nd.	Nd.	Nd.
Campestenol	Nd.	Nd.	-	Nd.	Nd.	Nd.

Stigmasterol	Nd.	Nd.	16.80	Nd.	Nd.	Nd.
$\Delta 5$ -Avenasterol + $\Delta 7$ -stigmasterol	4.80	Nd.	Trace	Nd.	Nd.	Nd.
$\Delta 7$ -Avenasterol	Nd.	Nd.	-	Nd.	Nd.	Nd.
Total	Nd.	Nd.	100.00	Nd.	Nd.	Nd.
References	[9, 10, 28, 189]	[10, 26, 28, 128, 190]	[3, 64, 184, 191]	[3, 81]	[29, 150, 192, 193]	[26, 94, 101, 187, 188, 194, 195]

nd.: not determined; Trace: below the limit of quantification. For the fatty acid values, summation was not performed ($\Sigma = 100\%$), since the objective was to comprehensively report the quantitative profile of the different compounds present in the oil samples from the respective fruits, highlighting the diversity and individual distribution of each identified fatty acid.

Pupunha oil has a high content of mono- and polyunsaturated fatty acids, such as oleic (54.23%) and linoleic (6.59%) acid (Table 2). The oil extracted from pupunha pulp has characteristics that promote health when ingested, such as the prevention of cardiovascular diseases ^[9]. The oil from this fruit has an antimicrobial function due to the secondary metabolites present in its chemical composition ^[126, 127]. On the other hand, tucumã oil has a lipid composition with mono- and polyunsaturated fatty acids, such as oleic (58.51%), linoleic (1.33%) and linolenic (5.37%) acid, and also the presence of saturated fatty acids, such as palmitic (30.63%) and stearic (2.88%). Despite the excellent potential for producing oil with a high vitamin A content, the use of tucumã is still restricted to consumption by traditional and low-income urban communities ^[128]. Buriti oil is a valuable source of palmitic (22.18%), stearic (2.51%), oleic (75.70%), linoleic (4.9%), and linolenic (8.2%) acids.

Buritirana oil is a source of palmitic (33.97%), stearic (2%) and oleic (56.5%) acids (Table 2). According to Speranza et al. ^[129], due to their high oleic acid content and low linoleic acid content, buriti and buritirana oils are more resistant to oxidation than most liquid oils. In addition, they are considered one of the richest known sources of β -carotene. Macaúba oil is rich mainly in oleic acid (65.71%), palmitic acid (20.11%) and linoleic acid (5.46%). Most studies on macaúba oil from mesocarp aim at its application for biodiesel, and when compared to soybean biodiesel (the primary basis for biodiesel production in Brazil), the output of macaúba biodiesel may be more advantageous due to the lower amount of linolenic acid (less degradation of the oil by oxidation) ^[130]. The carotenoids, tocopherols, and tocotrienols present may contribute to increasing the oil's stability through their antioxidant and conservation properties, and also promote health effects related to edible oil ^[29]. From murumuru, it is possible to extract a whitish, semi-solid fat called murumuru butter, which can be used as a drying agent in the paint industry, as an emollient in the cosmetics industry, or in the manufacture of soaps and creams ^[26]. Murumuru butter is rich in lauric (49.6%), myristic (28.25%), palmitic (9%), stearic (2.57%), linoleic (3.14%), and oleic (11%) acids. In addition, it has potential as an alternative raw material for biodiesel production ^[95–97].

The fat-soluble molecules of the fruits of the Arecaceae family revealed a significant presence of tocopherols, with emphasis on the oil extracted from the pulp of the buriti (*Mauritia flexuosa*), which presented the highest total concentration recorded among the fruits evaluated (1,688.58 mg kg⁻¹), followed by the oils of macaúba (*Acrocomia aculeata*) and pupunha (*Bactris Gasipaes*), with levels of 250.45 and 58.00 mg kg⁻¹, respectively ^[3]. The highlight of buriti lies, exceptionally, in the high concentration of α -tocopherol (614 mg kg⁻¹), the isomer with the most significant biological activity among the components of vitamin E. This value

significantly exceeds the levels observed in widely consumed vegetable oils, such as extra virgin olive oil (163.00 mg kg⁻¹), soybean oil (352.00 mg kg⁻¹), sunflower oil (575.00 mg kg⁻¹) and corn oil (207.00 mg kg⁻¹), as reported by Firestone ^[131] and Swiglo et al. ^[132]. Among the tocopherols identified in the oils of the species analyzed, the isomers α , β , and γ -tocopherol stand out, as well as α -tocotrienol, especially in buriti and macaúba. In addition to its antioxidant role, α -tocopherol has been extensively investigated for its potential to protect against atherogenesis and modulate liver diseases, such as steatosis, by acting on the integrity of cell membranes, regulating gene expression, and neutralizing reactive oxygen species ^[133]. These properties make buriti oil a promising matrix for the development of functional foods and nutritional supplements with preventive and therapeutic potential.

In addition, buriti oil also stands out for its phytosterol content of approximately 100 mg kg⁻¹, with β -sitosterol being the major compound among these plant steroids. Regular intake of foods rich in phytosterols has been associated with reduced serum levels of total cholesterol and LDL-c, both in individuals with dyslipidemia and in people with a normal lipid profile ^[134]. However, recent studies have suggested that high absorption of phytosterols may negatively interfere with the bioavailability of fat-soluble micronutrients, such as α -tocopherol and β -carotene, both essential for antioxidant functions and the synthesis of vitamin A in the body ^[135]. Nevertheless, systematic reviews conducted by Dumolt and Rideout ^[136] and Jones et al. ^[137] confirm that phytosterols are considered safe for human consumption, being classified as GRAS ("Generally Recognized as Safe") by the Food and Drug Administration (FDA), and have not demonstrated mutagenic effects or significant toxicity in experimental models.

4.3 *Amino acids*

Amino acids are organic molecules that make up proteins and are classified as essential and non-essential. Essential amino acids are essential for the healthy development of the human body. However, they are not synthesized by the body and must therefore be obtained from food, such as histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine ^[138, 139]. The human body synthesizes non-essential amino acids and does not need to be obtained exclusively through diet ^[139]. Fruits are not normally considered protein sources, but they have great potential as a source of non-essential amino acids of plant origin. Even though they have limitations regarding some types of essential amino acids, fruits stand out for having the vast majority of essential amino acids in their chain ^[140], even if some of these amino acids are below the recommended levels ^[141]. Furthermore, plant proteins are advantageous

because they are more available to the population and cheaper ^[142, 143].

Table 3 presents the essential and non-essential amino acids in the pulp of pupunha, tucumã, buriti and macaúba fruits, about the recommended daily intake established by the Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO) for an adult population ^[141]. Data on the amino acid composition of buritirana and murumuru were not found in the literature. The essential amino acids present in tucumã and macaúba pulps stand out for their concentrations of isoleucine (3.3 and 4.12 g 100 g⁻¹), leucine (7.6 and 6.73 g 100 g⁻¹), lysine (5.02 and 5.85 g 100 g⁻¹) and valine (5.83 and 4.75 g 100 g⁻¹) respectively, where they present non-limiting values, being higher than the daily recommendations proposed by FAO and WHO ^[141]. This group of branched-chain amino acids is prominent in the sports nutrition industry ^[144], where it stabilizes the protein structure through hydrophobic interactions, acting as an essential source of energy for skeletal muscle, promoting protein synthesis, preventing catabolism and serving as a substrate for glycogenesis ^[145].

For tryptophan, buriti was the only fruit that presented data in the literature, with a concentration of 2.38 (g 100g⁻¹), which was not limiting. Tryptophan is an important amino acid, as it acts as a precursor of the neurotransmitter serotonin, which in turn is involved in the regulation of sleep, pain, aggression, sexual behavior, food consumption, learning, memory, sensory perception, and depression ^[146]. Regarding non-essential amino acids, low concentrations of arginine (0.29 g 100 g⁻¹), glycine (0.27 g 100 g⁻¹), and tyrosine (0.14 g 100 g⁻¹) were found in the literature for the pupunha pulp. For tucumã, high concentrations of glutamic acid (14.29 g 100 g⁻¹), aspartic acid (11.12 g 100 g⁻¹), glycine (7.65 g 100 g⁻¹), arginine (6.12 g 100 g⁻¹), and alanine (6.10 g 100 g⁻¹) were found. According to Arise et al. ^[147], the amino acids aspartic and glutamic acid have a negative charge and can donate electrons to eliminate free radicals, giving antioxidant potential to hydrolysates. In addition, arginine participates in the synthesis of nitric oxide, a potent vasodilator that can prevent and reduce high blood pressure. The amino acids not shown in Table 3 were excluded because no records were found in the scientific literature consulted for the fruits analyzed; no data were available to allow their reliable description and inclusion.

Table 3. Essential and non-essential amino acids of the four fruits of the *Arecaceae* family and Recommended Daily Intake of Amino Acids (RDI) for adults.

Amino acids (g 100 g ⁻¹ of protein)	Pupunha (<i>B. gasipaes</i>)	Tucumã (<i>A. vulgare</i>)	Buriti (<i>M. flexuosa</i>)	Macaúba (<i>A. aculeata</i>)	RDI (%)
Essential					
Isoleucine	0.16	3.33	1.42	4.12	3
Leucine	0.28	7.36	2.38	6.73	6.1
Lysine	0.21	5.02	1.90	5.85	4.8
Phenylalanine	0.14	5.40	nd.	11.93	3.8
Threonine	0.18	5.54	8.55	5.02	2.5
Valine	0.19	5.83	1.90	4.75	4.0
Methionine	0.08	0.54	Nd.	12.59	1.6
Tryptophan	Nd.	Nd.	2.38	Nd.	0.66
Histidine	0.09	2.82	1.90	Nd.	1.6
Non-essential					
Alanine	Nd.	6.10	Nd.	Nd.	Nd.
Arginine	0.29	6.12	Nd.	Nd.	Nd.
Aspartic acid	Nd.	11.12	Nd.	Nd.	Nd.
Cystine	Nd.	4.24	Nd.	Nd.	Nd.
Glutamic acid	Nd.	14.29	Nd.	Nd.	Nd.
Glycine	0.27	7.65	Nd.	Nd.	Nd.

Proline	Nd.	3.68	Nd.	Nd.	Nd.
Serine	Nd.	6.37	Nd.	Nd.	Nd.
Tyrosine	0.14	4.61	Nd.	Nd.	Nd.
References	[196]	[197]	[191]	[138, 198]	[141]

Nd.: not determined.

4. Phytochemicals and antioxidant potential

5.1 Individual phenolics

Fruits originating from the Amazon region have been widely valued in contemporary scientific literature due to their composition rich in bioactive compounds, such as phenolic acids, carotenoids, and water-soluble and fat-soluble vitamins. These plant species have often been classified as “superfruits” not only for their nutritional value, but mainly for their functional and therapeutic potential. Among the most prominent constituents are phenolic compounds, secondary metabolites synthesized by plants as an adaptive response to environmental challenges and pathogens [115, 148]. Table 4 presents the levels of total phenolic compounds (TPC) identified in fruits of the Arecaceae family, observing a strong correlation between TPC concentration and the antioxidant activity of the fruits. The highest TPC values were recorded in the pulp of buritirana (*Mauritiella armata*) with 682.48 mg gallic acid equivalent (GAE) per 100 g, followed by buriti (*Mauritia flexuosa*) with 435.08 mg GAE 100 g⁻¹, macaúba (*Acrocomia aculeata*) with 269 mg GAE 100 g⁻¹, tucumã (*Astrocaryum vulgare*) with 117.42 mg GAE 100 g⁻¹ and pupunha (*Bactris Gasipaes*) with 46.96 mg GAE 100 g⁻¹ [14, 18, 149, 150]. These results demonstrate the expressive antioxidant potential of these fruits, especially of the species endemic to the Amazon region, whose biochemical composition is still in the process of more detailed characterization.

Among the identified phenolic compounds, chlorogenic acid stands out, found in significant concentrations in buriti (1154.15 µg g⁻¹), pupunha (8.01 µg g⁻¹) and tucumã (8.30 µg g⁻¹). This compound has antioxidant and anti-inflammatory properties, being effective in neutralizing free radicals and modulating inflammatory processes [3, 10]. In addition, caffeic acid, present in buriti (895.53 µg g⁻¹), buritirana (4.16 µg g⁻¹) and tucumã (0.07 µg g⁻¹), is known for its antioxidant and anticancer activities [3, 10, 18]. Ferulic acid, prominent in buriti (184.66 µg g⁻¹) and buritirana (99.39 µg g⁻¹), also contributes to cellular protection against oxidative damage [18, 81]. Flavonoids such as rutin, catechin and epicatechin are abundant in buriti, with concentrations of 1460.00, 961.21 and 1109.93 µg g⁻¹, respectively. These flavonoids have antioxidant and anti-inflammatory properties, helping to prevent cardiovascular diseases and combat oxidative stress. Quercetin, present in buriti (83.27 µg g⁻¹), pupunha (8.01 µg g⁻¹) and tucumã (0.94 µg g⁻¹), also contributes to the antioxidant and anti-inflammatory activity of the fruits [10, 151]. Studies indicate that regular consumption of these fruits can contribute to the

prevention of diseases related to oxidative stress, such as cardiovascular diseases, type 2 diabetes, and certain types of cancer. Furthermore, the phenolic compounds present in these fruits have shown potential in modulating inflammatory processes and promoting cellular health ^[4, 152]. The phenolics individuals not shown in Table 4 were not included due to a lack of records in the scientific literature consulted for the fruits analyzed; there was no available data that would allow for their reliable description and inclusion.

Table 4. Bioactive compounds and antioxidant activity of extracts from six fruits of the *Arecaceae* family.

Phenolics individuals ($\mu\text{g g}^{-1}$)	Pupunha (<i>B. gasipaes</i>)	Tucumã (<i>A. vulgare</i>)	Buriti (<i>M. flexuosa</i>)	Buritirana (<i>M. armata</i>)	Macaúba (<i>A. aculeata</i>)
*Total phenolics	46.96 ^b	117.42 ^b	435.08 ^c	682.48 ^b	269.00 ^b
(+)-Catechin	27.08 ^b	27.08 ^b	961.21 ^b	15.54 ^b	Nd.
(-)-Epicatechin	Nd.	Nd.	1109.93 ^b	6.23 ^b	Nd.
Quercetin	8.01 ^b	0.94 ^b	83.27 ^b	Nd.	Nd.
Myricetin	12.54 ^b	2.01 ^b	145.11 ^b	Nd.	Nd.
Apigenin	32.00 ^b	Nd.	102.48 ^b	Nd.	Nd.
Luteolin	Nd.	Nd.	1060.90 ^b	6.37 ^b	Nd.
Kaempferol	Trace ^b	Trace ^b	41.54 ^b	Nd.	Nd.
<i>p</i> -Coumaric acid	Nd.	Nd.	277.74 ^b	3.68 ^b	Nd.
Caffeic acid	0.07 ^b	0.07 ^b	895.53 ^b	4.16 ^b	Nd.
Ferulic acid	nd.	nd.	184.66 ^b	99.39 ^b	Nd.
Protocatechuic acid	Nd.	Nd.	2175.93 ^b	Nd.	Nd.
Quinic acid	Nd.	Nd.	230.74 ^b	Nd.	Nd.
Chlorogenic acid	8.01 ^b	8.30 ^b	1154.15 ^b	2.02 ^b	Nd.
Gallic acid	19.56 ^b	17.01 ^b	0.06 ^c	2.11 ^b	Nd.
Salicylic acid	Nd.	Nd.	0.16 ^c	2.81 ^b	Nd.
Sinapic acid	Nd.	Nd.	0.34 ^c	9.24 ^b	Nd.
Syringic acid	Nd.	Nd.	0.40 ^c	7.42 ^b	Nd.

Vanillic acid	Nd.	Nd.	0.11 ^c	Nd.	Nd.
Naringenin	Trace ^b	Trace ^b	Traces	15.25 ^b	Nd.
Isoquercitrin	Nd.	Nd.	5.85 ^c	9.93 ^b	Nd.
Rutin	18.58 ^b	7.34 ^b	1460.00 ^b	13.61 ^b	Nd.
Cyn 3- <i>O</i> -rutinoside	Nd.	Nd.	Nd.	Nd.	Nd.
Antioxidant capacity					
DPPH (μmol TE g ⁻¹)	42.18 ^b	40.5 ^b	1302.00 ^a	85.01 ^b	23.89 ^b
FRAP (μmol FeSO ₄ g ⁻¹)	41.61 ^b	105.96 ^b	8890.00 ^a	792.00 ^b	42.02 ^b
ABTS (μmol TE g ⁻¹)	105.03 ^b	591.15 ^b	70.20 ^c	6.62 ^b	Nd.
ORAC (μmol TE g ⁻¹)	602.00	Nd.	2460.00 ^a	16.24 ^b	Nd.
Carotenoids (μg g⁻¹)					
Total carotenoids	34.70 ^b	83.90 ^b	63.68 ^b	27.00 ^b	24.80 ^b
Cis lycopene	8.44 ^b	Nd.	Nd.	Nd.	Nd.
Lycopene	30.8 ^b	Nd.	Nd.	Nd.	Nd.
Cis α-carotene	Nd.	Nd.	Trace ^b	Nd.	Nd.
α-carotene	1.78 ^b	1.68 ^b	25.22 ^b	2.30 ^b	Nd.
Cis β-carotene	4.02 ^b	Nd.	12.17 ^b	0.11 ^b	4.00 ^b
β-carotene	55.51 ^b	47.36 ^b	52.57 ^b	3.73 ^b	56.00 ^b
Lutein	11.94 ^b	44.34 ^b	226.00 ^b	1.98 ^b	62.00 ^b
Cis lutein	2.22 ^b	12.57 ^b	Trace ^b	Nd.	26.00 ^b
Vitamins					

Vitamin A (RE 100 g ⁻¹)	5345.00 ^b	Nd.	1899.33 ^b	Nd.	599.78 ^b
Vitamin C (mg 100 g ⁻¹)	14 ^b	19 ^b	59.93 ^b	Nd.	118.19 ^b
Ascorbic Acid (mg 100 g ⁻¹)	Nd.	Nd.	51.85 ^b	0.40 ^b	15.42 ^b
References	[9, 10, 14, 28, 165, 199]	[10, 28, 148, 190]	[3, 6, 29, 149, 200–205]	[3, 17, 18, 81]	[29, 150, 192, 193]

^a Values expressed on a dry weight basis; ^b values expressed on a fresh weight basis; ^c freeze-dried sample. N.d.: not determined; Trace: below the limit of quantification; TE: Trolox equivalents. * Total phenolics: mg gallic acid equivalent (GAE) 100 g⁻¹; ABTS: 2,20 -azino-bis (3-ethylbenzothiazoline-6-sulphonic acid) free radical scavenging assay; DPPH: 2,2-diphenyl-1-picrylhydrazyl free radical scavenging assay; ORAC: oxygen radical absorbance capacity assay; FRAP: ferric reducing antioxidant power; RAE: retinol activity equivalent.

5.2 Carotenoids and vitamins

Carotenoids, fat-soluble pigments found in various fruits, play essential roles in protecting against oxidative stress, modulating the immune system, and preventing degenerative diseases such as cardiovascular disease, type 2 diabetes, and certain cancers [2, 6, 148, 153]. Among the fruits analyzed, tucumã had the highest total carotenoid content, with 83.9 $\mu\text{g g}^{-1}$, followed by buriti with 63.68 $\mu\text{g g}^{-1}$ and pupunha with 34.7 $\mu\text{g g}^{-1}$. These values indicate the relevance of these fruits as natural sources of carotenoids, especially in regions where access to processed foods is limited. β -Carotene, a precursor of vitamin A, stands out as one of the most abundant carotenoids in these fruits. Pupunha presented 55.51 $\mu\text{g g}^{-1}$ of β -carotene, buriti 52.57 $\mu\text{g g}^{-1}$ and tucumã 47.36 $\mu\text{g g}^{-1}$. The conversion of these values into retinol activity equivalents (RAE), using the conversion factors recommended by the Institute of Medicine [154], results in 27.75 $\mu\text{g RAE } 100 \text{ g}^{-1}$ for pupunha, 26.3 $\mu\text{g RAE } 100 \text{ g}^{-1}$ for buriti and 23.7 $\mu\text{g RAE } 100 \text{ g}^{-1}$ for tucumã. These values indicate that the consumption of these fruits can significantly contribute to the recommended daily intake of vitamin A, which is essential for eye health, skin integrity, and immune function [155].

In addition to β -carotene, the fruits analyzed also exhibit a diverse profile of other carotenoids with well-documented bioactive potential, notably lycopene and lutein. Lycopene, a non-provitamin A carotenoid characterized by its intense red pigmentation, was detected in appreciable concentrations in pupunha, reaching 30 $\mu\text{g g}^{-1}$. This compound has garnered considerable scientific attention due to its strong antioxidant capacity, particularly in neutralizing singlet oxygen and peroxy radicals, thereby attenuating oxidative stress-related pathologies. Its regular dietary intake has been associated with a reduced incidence of several chronic conditions, including atherosclerosis, prostate and gastric cancers, and metabolic syndromes [156–158].

Lutein, another carotenoid of considerable nutritional relevance, belongs to the xanthophyll subclass and exhibits high polarity due to the presence of hydroxyl groups. It is found in particularly elevated concentrations in buriti, with values reaching 226 $\mu\text{g g}^{-1}$, surpassing many commonly known lutein-rich vegetables. It also occurs in significant amounts in macaúba and tucumã, with concentrations of 62 $\mu\text{g g}^{-1}$ and 44.34 $\mu\text{g g}^{-1}$, respectively. Lutein plays a crucial role in ocular health, as it accumulates in the macula lutea of the human retina, where it filters high-energy blue light and mitigates photochemical damage. Its consumption has been linked to the prevention and progression delay of age-related macular degeneration (AMD) and cataracts, as well as to neuroprotective effects through the reduction of

neuroinflammation and oxidative neuronal damage ^[159, 160]. These findings underscore the functional potential of carotenoid-rich fruits from the Arecaceae family as promising dietary sources for maintaining of visual and systemic health.

Regarding water-soluble vitamins, vitamin C stands out as a potent antioxidant. In the present study, macauba had the highest vitamin C content, with 118.19 mg.100 g⁻¹, surpassing other native Brazilian fruits such as cajá (26.5 mg 100 g⁻¹), umbu (18.4 mg 100 g⁻¹) and açaí (84 mg 100 g⁻¹), as well as widely consumed fruits such as pear orange (62.50 mg 100 g of juice) and strawberry (58.8 mg 100 g⁻¹) ^[161–163]. Vitamin C is essential for collagen synthesis, iron absorption, and proper immune system function, in addition to neutralizing free radicals and preventing cellular damage ^[164]. In summary, fruits of the Arecaceae family, such as pupunha, tucumã, buriti, and macaúba, have nutritional profiles rich in carotenoids and vitamins with recognized antioxidant activities and potential health benefits. The consumption of these fruits can be an effective strategy for promoting health, especially in communities that depend on local natural resources for obtaining essential nutrients.

When compared to more widely consumed Amazonian species such as açaí (*Euterpe oleracea*) and guaraná (*Paullinia cupana*), the fruits addressed in this review exhibit equally or more diverse bioactive profiles. For instance, buriti and tucumã are among the richest natural sources of provitamin A carotenoids, surpassing açaí in β -carotene content (especifique o valor) ^[165, 166]. Similarly, the fiber content in fruits like pupunha and macaúba rivals that of guaraná, while murumuru and tucumã oils present high concentrations of lauric and oleic acids, comparable to those found in coconut oil and olive oil, respectively. Although açaí is renowned for its anthocyanin content and antioxidant capacity, the carotenoid- and tocopherol-rich profiles of buriti, murumuru, and macaúba offer distinct functional advantages, particularly in skin health and oxidative stress modulation. These findings highlight the untapped potential of lesser-known Arecaceae fruits and their relevance for diversification in functional food and nutraceutical applications.

5. Biological effects

Table 5 presents *in vitro* and *in vivo* biological research that has validated the traditional use of fruit species belonging to the Arecaceae family in the treatment of various infectious and degenerative diseases, as well as highlighting discoveries about the antimicrobial, antioxidant, anti-inflammatory, hypoglycemic, hypolipidemic, hypocholesterolemic, antithrombotic, and antiproliferative properties of these plants.

Table 5. Antioxidant, biological and health-promoting effects of six fruits of the *Arecaceae* family.

Fruit	Fruit fraction	Method of obtaining	Bioactivity	Health effects	Related compound	References
Pupunha	Pulp	Acetone and ether: hexane extract (1:1 v/v)	Antioxidant (<i>in vitro</i>)	↓ Glycemic index and decreased glucose absorption.	β-carotene and lycopene	[170]
	Pulp	Petroleum ether and methanol extract	Antioxidant (<i>in vitro</i>)	Inhibition of β-carotene oxidation	β-carotene	[206]
	Pulp, peel, and seeds	Ethanolic extract	Antimicrobial activity (<i>in vitro</i>)	Inhibition of <i>Staphylococcus aureus</i> in the first 24 h and decreased growth of <i>P. aeruginosa</i> .	-	[174]
	Pulp	A diet based on commercial feed and a mix of commercial feed and red peach palm	Ant obesogenic (<i>in vivo</i>)	↓ Body mass in the group fed with pupunha increased HDL cholesterol and decreased triglycerides.	Linoleic acid	[177]
Murumuru	Seeds	Essential oil	Antimicrobial	Potential inhibitor of phytopathogens	-	[207]
Tucumã	Pulp and peel	Ethanolic extract	Antioxidant (<i>in vitro</i>)	Cytoprotective effect in human lymphocytes exposed to H ₂ O ₂ .	Tannins, alkaloids, β-carotene and quercetin.	[51]
	Pulp and peel	Ethanolic extract	Genoprotective	Genoprotective action in DNA denaturation.	Carotenoids, such as β-carotene, quercetin, and lipids.	[208]
	Pulp and peel	Hydroalcoholic extract	Antioxidant and genotoxicity (<i>in vitro</i>)	The genotoxic effects of PBMCs depend on the concentration and time of exposure.	Carotenoids, rutin, caffeic and ellagic acids.	[58]
	Pulp and peel	Ethanolic extract	Anti-inflammatory and antioxidant	↑ Antioxidant defenses and reduction of oxidative stress of modulated genes	Phenolic acids and flavonoids	[179]

				related to the inflammatory response.		
	Seeds	Hexane and ethanolic extract	Antimicrobial	Inhibition of four microorganisms: <i>Enterococcus faecalis</i> , <i>Bacillus cereus</i> , <i>Candida albicans</i> , and <i>Listeria monocytogenes</i> .	Phenolic compounds, flavonoids, and terpenes.	[175]
	Pulp and peel	Ethanolic extract	Antimicrobial	↓ Formation of biofilms by <i>Candida</i> in both extracts	Retinoid and carotenoid molecules	[209]
Buriti	Pulp	Flour	Antioxidant (<i>in vitro</i>)	- ↓ TBARS-reactive substances in the heart and liver. - ↓ Oxidative damage in the liver and heart.	-	[172]
				- Showed promising chemopreventive potential.		
	Pulp, shell, and seeds	Methanolic extract of freeze-dried samples	Chemopreventive action (<i>in vitro</i> and <i>in vivo</i>)	- More significant results were found in the shell. - None of the extracts induced lysis of rat erythrocytes, being able to protect blood cells.	Phenol, flavonoids, tannins	[67]
	Pulp e shell	Oil	Antimicrobial (<i>in vitro</i> e <i>in vivo</i>)	- The nanoencapsulated oil showed a significant increase in antimicrobial activity. - Emulsion technique: increased the antimicrobial activity of buriti oil by	Quercetin, eugenol, vanillin and tannins, ellagic acid and catechin	[176]

				59, 62, and 43% against <i>Pseudomonas aeruginosa</i> , <i>Klebsiella pneumonia</i> , and <i>Staphylococcus aureus</i> , respectively.		
				- Herbal products are more efficient for Gram-positive bacteria than Gram-negative bacteria.		
	Pulp	Oil	Anti-inflammatory (<i>in vivo</i>)	- ↑ Wound healing. - ↓ Inflammatory cells	Unsaturated fatty acids	[210]
	Pulp e shell	Oil	Hypocholesterolemic (<i>in vivo</i>)	- ↓ Total cholesterol. - ↓ LDL. - ↓ Triglycerides. - ↓ AST. - Increased serum and liver retinol deposition in offspring.	-	[211]
Macaúba	Pulp	Oil	<i>In vivo model of fructose-induced diabetes and antioxidant and cytotoxic potential (in vitro)</i>	↓ High glucose levels induced by a high fructose diet in rats. Good antioxidant activity in vitro, no sign of cytotoxicity in LLC-PK1 cells.	-	[173]
	Pulp	Oil	Cyclophosphamide-induced toxicity (<i>in vivo</i>)	↑ β-carotene content; ↑ C-kit gene expression Normalized the levels of antioxidant	-	[212]

			enzymes that CP altered.		
			- There was no significant antimicrobial activity against the microorganisms tested <i>Staphylococcus aureus</i> (ATCC 6538);		
Leaf	Extract	Antimicrobial potential (<i>in vitro</i>)	<i>Enterococcus faecalis</i> (ATCC 4083); <i>Escherichia coli</i> (ATCC 25922); <i>Pseudomonas aeruginosa</i> (ATCC 27853); <i>Candida albicans</i> (4006); <i>Candida parapsilosis</i> (40038).	-	[213]
			- Both oils were chemoprotective at all doses; both AO and PO demonstrated immunomodulatory activity.		
Pulp and seeds	Oil	Antigenotoxic, antimutagenic, immunomodulatory, and apoptotic potential (<i>in vivo</i>)	- The oils ↓ have the ability of cyclophosphamide to trigger apoptosis in the liver, spleen, and kidney cells. There was no increase in the frequency or rate of DNA damage.	-	[214]
Pulp	Oil	Cytotoxic, genotoxic, mutagenic (<i>in vivo</i>)	- It did not exhibit cytotoxic, genotoxic, or mutagenic effects	-	[215]

↓: Decreased; ↑: Increased; HDL: high-density lipoprotein; LDL: low-density lipoprotein; H₂O₂: hydrogen peroxide; ATRA: all-trans-retinoic acid; AST: aspartate aminotransferases; AO: seed oil; PO: pulp oil; ATCC: American Type Culture Collection; CP: cyclophosphamide; TBARS: thiobarbituric acid; LLC-PK: porcine kidney cells; PBMC: human peripheral blood mononuclear cells.

These biological activities are primarily attributed to the presence of polyphenols, carotenoids, fatty acids, and tocopherols, which act through various molecular mechanisms. Antioxidant effects are mainly associated with the scavenging of reactive oxygen species (ROS), enhancement of endogenous antioxidant enzyme activity, and inhibition of lipid peroxidation [8, 167]. Anti-inflammatory action is generally linked to the downregulation of pro-inflammatory cytokines (such as TNF- α , IL-6, and IL-1 β), inhibition of cyclooxygenase-2 (COX₂) and inducible nitric oxide synthase (iNOS), as well as the modulation of signaling pathways such as NF- κ B and MAPK [167, 168]. Hypoglycemic effects may involve modulation of glucose uptake through the translocation of the GLUT4 transporter, inhibition of the enzymes α -glucosidase and α -amylase, enhanced insulin sensitivity, and regulation of gene expression related to lipid metabolism [169]. Antitumor properties are often associated with the induction of apoptosis, cell cycle arrest, and inhibition of angiogenesis in cancer cells, generally through mechanisms involving the p53, Bcl-2, and caspase signaling pathways [58].

6.1 Antioxidant activity and anti-inflammatory effects

Several studies have highlighted the remarkable bioactive potential of plant species native to the Amazon region, among which the pupunha (*Bactris Gasipaes*), tucumã (*Astrocaryum vulgare*), and buriti (*Mauritia flexuosa*) stand out. These species have aroused increasing interest due to the significant presence of compounds with antioxidant and anti-inflammatory properties, whose action is closely related to the high concentrations of carotenoid pigments, phenolic compounds, and unsaturated fatty acids. Regarding pupunha, phytochemical analyses revealed that extracts from both the pulp and other plant structures exhibit high antioxidant activity, attributed mainly to the presence of β -carotene. This molecule, characterized by a polyene chain with numerous conjugated dienes, is recognized for its efficiency in neutralizing reactive oxygen species (ROS), including singlet oxygen (¹O₂), superoxide anion ([•]O₂⁻), hydroxyl radical ([•]OH), peroxy radicals (RCOO[•]) and nitric oxide (NO), whose exacerbated production is associated with cellular oxidative damage [8, 167].

As shown in Table 5, the antioxidant and antimicrobial properties are the main focus of research on pupunha. In a study by Quesada et al. [170], the antioxidant activity of hydroethanolic extracts of pupunha pulp was evaluated through laboratory tests, with results indicating significant free radical scavenging capacity. In addition, clinical trials conducted by Hempel et al. [171] demonstrated that compounds such as γ -carotene, lycopene, and β -carotene have high bioavailability after oral ingestion. Approximately six hours after consuming the fruit, between

20.1 and 81.4 nmol/L of γ -carotene isomers were detected in human plasma, with progressive increases in the concentrations of β -carotene and lycopene, reinforcing their effective absorption and possible contribution to systemic redox balance. In addition to its antioxidant role, β -carotene also has an inflammation-modulating effect. Experimental studies, both *in vitro* and *in vivo*, have demonstrated that this carotenoid influences the expression of genes that regulate inflammatory processes, such as COX₂ and iNOS, promoting the reduction of nitric oxide production by the inducible isoform of the enzyme iNOS. Under experimental conditions, concentrations of 25 μ M of β -carotene resulted in the inhibition of up to 50% of the expression of these pro-inflammatory enzymes ^[167, 168], suggesting a relevant role in the attenuation of chronic inflammatory processes.

On the other hand, tucumã's fruits have been widely investigated due to their richness in flavonoids, carotenoids and phenolic compounds, such as quercetin and rutin. Sagrillo et al. ^[51] identified considerable amounts of these bioactive metabolites in the ethanolic extracts obtained from both the peel and the pulp, which demonstrated significant protective capacity against oxidative stress induced by hydrogen peroxide (H₂O₂) in human lymphocyte cultures. The additional presence of phenolic acids, such as gallic, caffeic, and chlorogenic, contributes to the synergistic activity of the extracts, expanding their spectrum of antioxidant action. A study conducted by Cabral et al. ^[58] further evaluated the immunomodulatory properties of these extracts in a model of cellular inflammation induced by phytohemagglutinin. The results showed not only the inhibition of macrophage proliferation but also the induction of cell cycle arrest in the G₀/G₁ phase, in addition to the increase in the activity of endogenous antioxidant enzymes and modulation of gene expression associated with the inflammatory response. *In vivo* tests reinforced the findings obtained in cell culture, indicating the possibility of therapeutic application of tucumã extracts as adjuvants for the prevention or treatment of chronic inflammatory conditions. However, confirmation of these benefits in humans requires robust and well-designed clinical studies.

Buriti pulp has antioxidant effects, as investigated by Nunes Lages et al. ^[172] using an *in vivo* model using Fischer rats. The supply of pulp flour did not generate adverse histological changes in the tissues evaluated, but a significant reduction in the levels of lipid peroxidation products, such as thiobarbituric acid-reactive substances (TBARS), was observed in cardiac tissue. Additionally, less formation of carbonyl proteins was observed in the liver and heart, suggesting a protective effect against oxidative damage in metabolically active tissues. The absence of glycemic or structural changes in the tissues analyzed reinforces the safety of oral administration of buriti flour. In parallel, the regenerative action of buriti oil on injured tissues

was investigated by Silva et al. ^[173], using topical formulations containing this oil incorporated in a liquid crystalline phase, using murumuru butter (*Astrocaryum murumuru*) as a base. Dermal healing tests performed in an animal model revealed that formulations with 1% and 15% buriti oil significantly accelerated tissue regeneration from the third day of treatment, compared to the control groups. This healing effect was attributed to the lipid composition rich in unsaturated fatty acids, which act to promote the proliferation of fibroblasts and attenuate the inflammatory infiltrate, especially in the initial phases of the repair process.

Given this evidence, the native fruits mentioned have considerable potential as natural sources of bioactive substances with the capacity to neutralize free radicals and modulate inflammation, proving to be promising both in the context of functional nutrition and as candidates for therapeutic formulations based on phytotherapeutics. Even so, it is important to highlight the need for advances in clinical and toxicological studies that allow confirming their efficacy and safety in humans.

6.2 Antimicrobial properties

In addition to their recognized antioxidant and anti-inflammatory activities, Amazonian plant species also contain compounds with promising antimicrobial action, becoming the object of growing interest in studies focused on public health and the development of phytotherapeutic alternatives to combat bacterial resistance to conventional antibiotics. Regarding pupunha, studies indicate that the oil extracted from its peel has significant antimicrobial action, especially against *Staphylococcus aureus*, an opportunistic pathogen frequently associated with clinical conditions such as respiratory infections, urinary tract infections, periodontal diseases, and food poisoning ^[174]. Comparative tests have shown that, in some cases, the oil from the pupunha peel surpassed the efficacy of antimicrobials in clinical use, such as gentamicin[®], ciprofloxacin[®], and the combination of piperacillin[®] with tazobactam[®]. More expressive results were observed after 24 and 48 hours of bacterial exposure, especially with Gram-negative strains, suggesting a differentiated mechanism of action ^[174]. However, the specific chemical constituents responsible for such effects have not yet been conclusively identified, highlighting the need for detailed phytochemical investigations.

According to Robles-Martínez et al. ^[175], when investigating the antimicrobial activity of extracts obtained from tucumã seeds, with emphasis on the inhibition and/or disruption of the biofilm of *Candida albicans*, a fungus commonly associated with mucocutaneous and systemic infections, the ethanolic and hexane extracts demonstrated superior results to the

positive control with ethylenediaminetetraacetic acid (EDTA), with the hexane extract presenting the lowest rates of fungal adhesion. The phytochemical analysis revealed that terpenes, phenols, and antioxidant compounds were present in relevant concentrations, which may explain the observed antimicrobial capacity. The action of these compounds on biofilms suggests a potential prophylactic or therapeutic use, particularly in infections resistant to traditional antifungal agents.

On the other hand, buriti has antimicrobial activity, as evaluated by Castro et al. ^[176], who observed the ability of unencapsulated crude oil to inhibit the growth of bacteria of clinical interest, such as *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, and *Staphylococcus aureus*. The antimicrobial performance was attributed, in part, to the oil's physicochemical properties, such as particle size, but also to the presence of bioactive compounds such as quercetin, eugenol, and vanillic acid. Previous studies indicated that nanoemulsions of buriti oil, both in the interesterified and unmodified form, showed antibacterial activity against Gram-negative microorganisms, suggesting that delivering the oil in nanostructured systems can enhance its efficacy and stability. These findings indicate that lipid derivatives and extracts from Amazonian fruits may constitute viable alternatives in the development of new antimicrobial agents, especially given the increase in bacterial resistance to traditional drugs. However, in-depth toxicological, clinical, and pharmacokinetic studies are essential to enable the therapeutic use of these compounds in medical and pharmaceutical contexts.

6.3 Antidiabetic potential

Investigation of the hypoglycemic and lipid metabolism-regulating potential of Amazonian fruits reveals promising prospects for their application in nutritional strategies aimed at the prevention and management of type 2 diabetes mellitus and associated metabolic disorders. Regarding pupunha (*Bactris Gasipaes*), experimental evidence has shown that its pulp has a positive influence on lipid and body metabolism, as demonstrated by Carvalho et al. ^[177] in a trial conducted with adult Wistar rats during critical physiological periods such as lactation and post-lactation. The ingestion of pupunha was associated with reduced plasma triglyceride levels, decreased body weight, and accumulation of adipose tissue, as well as increased HDL cholesterol, known for its cardiovascular protective effect. These effects were attributed to the nutritional composition of the pulp, highlighting the dietary fiber content and the significant presence of linoleic acid, an essential polyunsaturated fatty acid.

Complementing these findings, Takahashi et al. ^[178] elucidated the role of linoleic acid

in the thermogenesis of brown adipose tissue, through the induction of the expression of the Uncoupling Protein 2 gene (UCP₂), whose activity promotes increased energy expenditure and the consequent reduction of body adiposity. This mechanism highlights how bioactive compounds of plant origin can positively interfere in metabolic modulation, representing auxiliary tools in the fight against obesity and type 2 diabetes. In contrast, studies involving macaúba oil (*Acrocomia aculeata*) demonstrated distinct metabolic responses, varying according to the carbon chain of the fatty acids present. According to Du-Toit et al. ^[169], the administration of long-chain fatty acids from macaúba resulted in increased body mass and impaired glucose tolerance in animal models (rats and mice). On the other hand, diets enriched with medium-chain fatty acids did not present negative effects on these parameters, suggesting that the type of fatty acid directly influences metabolic results. Additionally, an increase in liver mass was observed in rats treated with macaúba oil, an effect not reproduced in mice, suggesting the complexity of the interspecies metabolic response and reinforces the importance of individualization in experimental approaches.

6.4 Antitumor

Tucumã is part of the daily diet of the local Amazonian population, and from this, several benefits have been attributed to this fruit, especially regarding its use in traditional medicine. This fruit has been used to prevent strokes, relieve earache, and treat rheumatoid arthritis, due to its anti-inflammatory and antioxidant properties ^[58]. Tucumã, for example, has been the subject of studies that demonstrate its antitumor properties. According to Carneiro et al. ^[55], the effect of tucumã extract on the toxicity of doxorubicin, a chemotherapeutic agent widely used in the treatment of various types of cancer. The results suggest that the consumption of tucumã can help reduce the side effects of chemotherapy, possibly due to the presence of antioxidant compounds that protect cells against damage induced by free radicals generated during treatment. In addition, Jobim et al. ^[179] investigated the pharmacogenomic effects of tucumã on breast cancer cells, observing that extracts from the fruit's peel and pulp showed anticarcinogenic activity *in vitro*, modulating genes related to the cell cycle and apoptosis, fundamental processes in the prevention and control of cancer.

Regarding buriti, a study evaluated the mutagenic and antimutagenic potential of the oil extracted from the fruit in Swiss mice, using micronucleus and comet tests. The results indicated that buriti oil did not present genotoxic effects, suggesting that it is safe for consumption. In addition, treatment with buriti oil demonstrated antimutagenic activity, reducing DNA damage

induced by chemotherapeutic agents, which may contribute to the protection of healthy cells during cancer treatment ^[180]. Although studies on other fruits are scarcer, there are indications that their bioactive compounds, such as carotenoids, may exert antitumor effects. Future research is needed to confirm these properties and understand the mechanisms involved, aiming to explore the therapeutic potential of pupunha in the fight against cancer. In summary, the available scientific evidence suggests that fruits such as tucumã and buriti have promising antitumor properties, mainly due to the presence of bioactive compounds with antioxidant activity and modulation of cellular processes related to cancer. These fruits may represent valuable natural sources for the development of complementary therapies for cancer treatment, contributing to the reduction of chemotherapy side effects and promoting cellular health.

6. Future perspectives on the use of these native fruits in industry

The fruits of the Arecaceae family (Figure 3) are usually harvested for local consumption by the population where the fruits are found and to supply local markets. Industries do not usually use these fruits in the food industry due to their seasonality and perishability. Therefore, there is a great challenge in making these fruits more attractive for industrial use. For this reason, it is essential to optimize the processing conditions of these fruits to explore new applications, making them viable from a nutritional and economic point of view. The fruits of the Arecaceae family have high nutritional value and are rich in bioactive compounds such as fatty acids (palmitic, stearic, oleic, linoleic), phenolic acids (gallic, chlorogenic and caffeic), flavonoids ((+) catechin, (-)-epicatechin, rutin and luteolin), phytosterols, tocopherols and carotenoids (α -carotene, β -carotene and lutein). These compounds are responsible for antioxidant activity and potential health benefits, such as antimicrobial, chemopreventive, cardioprotective, anti-inflammatory, and anti-obesity effects.

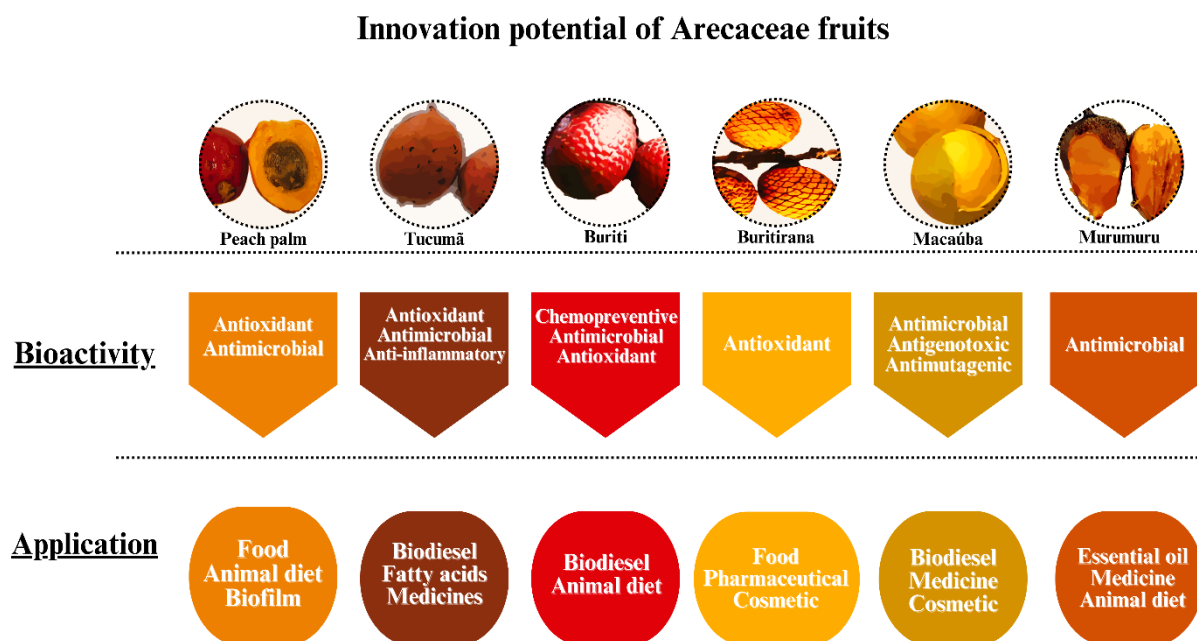


Figure 3. Innovation potential of Arecaceae fruits.

Despite their rich nutritional and phytochemical composition, murumuru (*Astrocaryum murumuru*), macaúba (*Acrocomia aculeata*), and buritirana (*Mauritiella armata*) require more attention, considering the limited studies reported in the literature. Seasonality and perishability can be seen as incentives for these fruits to be available to consumers throughout the year, without directly depending on seasonality. Incentives for the production and use of these fruits are a viable opportunity for generating employment and income in Amazonian communities, producing artisanal materials from the leaves and stems, making sweets, juices and jellies, extracting oil for use in the food, cosmetics and pharmaceutical industries, and even using these oils to produce less polluting and better-quality biodiesel due to their oxidative stability, as is the case with buriti and macaúba.

Given the data presented in this literature review, it is evident that the fruits of the Arecaceae family possess potential and are worthy of exploration, particularly the lesser-explored native Brazilian fruits, which hold technological and functional potential for potential benefits to human health. The review also emphasizes the need for additional research on the composition of the different parts of the fruits, health effects, processing, and full use of these raw materials. In addition, it is crucial to investigate the mechanisms and synergism between the bioactive compounds of these fruits, as well as their effects, especially in human models, to evaluate the bioavailability of these compounds in Amazonian fruits. Therefore, this review can contribute to disseminating information about these fruits, whose consumption and applications

have the potential to promote healthy eating.

7. Conclusions

The critical analysis of the scientific literature carried out in this study highlights the remarkable nutritional, functional, and bioactive potential of six fruit species native to the Amazon belonging to the Arecaceae family: pupunha (*Bactris Gasipaes*), tucumã (*Astrocaryum vulgare*), buriti (*Mauritia flexuosa*), buritirana (*Mauritiella armata*), macaúba (*Acrocomia aculeata*), and murumuru (*Astrocaryum murumuru*). These fruits stand out not only for the diversity of bioactive compounds, such as unsaturated fatty acids, carotenoids, polyphenols, and fat-soluble vitamins, but also for their multiple applications in the food, pharmaceutical, cosmetic, and energy industries. The data obtained through the bibliometric analysis demonstrate that, although there are significant advances in the knowledge about their properties, there are still relevant gaps to be explored in clinical, toxicological, and technological studies. Evidence suggests that the scientific and commercial valorization of these fruits can play a strategic role in promoting food and nutritional security, stimulating the local bioeconomy, and conserving Amazonian ecosystems, especially when associated with sustainable management practices and strengthening family farming. Furthermore, incorporating these resources into higher value-added products represents a concrete opportunity for innovation and socioeconomic inclusion for traditional and extractive communities.

The knowledge accumulated to date highlights the importance of expanding interdisciplinary research aimed at elucidating the molecular mechanisms responsible for the biological effects attributed to these species, with an emphasis on their antioxidant, anti-inflammatory, antimicrobial, antidiabetic, and antitumor properties. Controlled clinical studies and standardized protocols for the extraction and analysis of bioactive compounds are urgently needed to consolidate the efficacy and safety of using these fruits in therapeutic and nutritional contexts. Therefore, this work reinforces the need for public policies that encourage research, development, and innovation based on native fruits of Brazilian biodiversity, respecting traditional knowledge, promoting the conservation of genetic resources, and ensuring fair and equitable sharing of the benefits arising from their exploitation. Strengthening the production chains of these fruits, combined with the generation of qualified technical-scientific knowledge, constitutes a viable and promising path to reconcile sustainable development, food sovereignty, and the valorization of Amazonian biodiversity.

Declarations

Compliance with Ethical Standards

Declaration of competing interests: The authors declare that they have no known competing financial interests or personal relationships that could be perceived to influence the work reported in this paper.

Availability of Data and Material

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Code Availability

Not Applicable

Consent for Publication

All authors have given their consent for publication.

Authorship Contribution Statement

Hermanny Matos Silva Sousa: Conceptualization, Investigation, Writing - original draft, Writing - review & editing. **Rômulo Alves Moraes:** Supervision, Writing - review & editing. **Gabriela Fonseca Leal:** Conceptualization, Investigation, Writing - original draft, Writing - review & editing. **Glêndara Aparecida de Souza Martins:** Supervision, Writing - review & editing. **Fabiana Queiroz:** Supervision, Writing - review & editing.

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ARTICLE 2 - GREEN SOLVENTS AS SUSTAINABLE TOOLS FOR THE INTEGRAL VALORIZATION OF PEACH PALM (*Bactris gasipaes*): BIOACTIVE COMPOSITION, ANTIOXIDANT POTENTIAL, SIMULATION OF IN VITRO GASTROINTESTINAL DIGESTION, AND MICROBIOLOGICAL INHIBITION

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Green solvents as sustainable tools for the integral valorization of peach palm (*Bactris gasipaes*): Bioactive composition, antioxidant potential, simulation of *in vitro* gastrointestinal digestion, and microbiological inhibition

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ABSTRACT

The peach palm (*Bactris gasipaes*) is an Amazonian species with high nutritional and functional potential, whose fractions (peel, pulp, and seeds) remain underexplored in terms of full utilization. This study investigated the bioactive composition of these fractions and assessed the application of emerging green solvents, including deep eutectic solvents and supramolecular solvents, for the extraction of bioactive compounds, as well as their biological activities and simulated *in vitro* digestion. The results revealed distinct profiles of phenolic compounds, carotenoids, and flavonoids among the fractions. Extraction using supramolecular solvents demonstrated superior efficiency and selectivity, particularly for carotenoids from the peel (β -carotene: 67.2 and lycopene: 169.95 mg 100 g⁻¹). The obtained extracts exhibited strong antioxidant activity in the peel, with supramolecular solvents (ABTS: 91.84%, DPPH: 80.04%), and in the β -carotene/linoleic acid assay for both peel and pulp (82.77% and 71.93%, respectively). In addition, high trigonelline levels were observed in the peel and pulp (4511.41 and 4800.95 μ g g⁻¹) with the choline chloride: lactic acid solvent. In biological assays, supramolecular solvents stood out in lipid peroxidation inhibition analysis with peel (63.92%) and pulp (58.04%), while α -amylase inhibition was most relevant in pulp with water (62.35%), choline chloride: lactic acid (61.72%) and choline chloride: acetic acid (59.62%) solvents. Antimicrobial effects were also observed in deep eutectic solvents and supramolecular solvents against the bacteria *S. aureus*, *E. coli*, *L. monocytogenes*, *S. enterica*, as well as the fungi *A. flavus*, *A. niger*, and *A. ochraceus*. *In vitro* digestion assays revealed that the bioaccessibility of compounds varied among fractions, with seeds showing greater stability of ferulic acid during the intestinal phase, suggesting different release possibilities and potential application in functional formulations with antioxidant effects. Overall, the findings highlight that the valorization of peach palm using green solvents represents an efficient approach for obtaining multifunctional extracts with potential for future applications, while emphasizing the need for further studies to assess toxicological safety, formulation stability, and large-scale feasibility. Furthermore, this approach contributes to the integral use of Amazonian resources.

1. Introduction

The Amazon biome is recognized as one of the largest biodiversity reserves on the planet, harboring a wide variety of plant species with high nutritional, functional, and socioeconomic value (da Silva et al., 2021). Among these species, fruits and palms stand out for sustaining

local communities through the supply of food, raw materials, and income, as well as representing potential sources of new ingredients for the food, cosmetic, and pharmaceutical industries (Morais et al., 2024; Sousa et al., 2021). The valorization of Amazonian resources not only promotes regional development but also contributes to forest conservation, reinforcing the strategic importance of the Amazon for

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sustainable innovation. In this context, peach palm (*Bactris gasipaes*) plays a prominent role due to its dual aptitude for both fruit and heart of palm production. In heart of palm exploitation, the stem is typically harvested before the reproductive stage, preventing fruit formation and leading to their frequent disposal as low-value by-products (Moreira et al., 2017). In contrast, in the Brazilian Amazon, particularly among low-income farmers and riverine communities, peach palm is cultivated almost exclusively for its fruits, which play an important role in the local diet (Noronha Matos et al., 2019; Sousa et al., 2025).

Each plant produces an average of ten bunches per year, with rounded fruits approximately 4 cm in diameter, whose coloration varies from white to yellow, orange, and red (dos Santos et al., 2024). The pulp presents a high content of total carotenoids (up to 300 $\mu\text{g g}^{-1}$), vitamin A, and phenolic compounds with significant antioxidant potential, as demonstrated by β -carotene/linoleic acid (inhibition of 300.01%) and DPPH assays (41.18 g pulp g^{-1} DPPH) (dos Santos et al., 2024; Sousa et al., 2025). Additionally, it contains monounsaturated lipids, predominantly oleic acid (61%), which has been linked to cardioprotective effects (Teixeira et al., 2022). The seeds are notable for their high oil content (above 30% of the dry fraction), rich in lauric acid (49.82%) and myristic acid (21.53%), as well as phenolic compounds (Gualberto et al., 2025; Pinheiro et al., 2022). These attributes underscore the versatility of the peach palm as a matrix for integrated exploitation, with potential applications in various industrial sectors.

Despite their significant biotechnological potential, most fractions of the peach palm fruit (*Bactris gasipaes*) remain underutilized in agro-industrial systems, resulting in the systematic disposal of high-value biomass and the consequent loss of opportunities for technological innovation. The peel, for example, constitutes a structurally complex matrix, rich in natural pigments, especially carotenoids and associated lipophilic compounds, whose stability, bioavailability, and coloring capacity make them promising substitutes for synthetic dyes in the food, cosmetic, and pharmaceutical industries. Furthermore, the seeds present a chemically dense profile, characterized by substantial lipid reserves and a diverse spectrum of phenolic constituents with proven antioxidant and bioactive properties, offering potential applications in functional foods, nutraceuticals, and clean-label preservation strategies (Gualberto et al., 2025; Miranda et al., 2024). Promoting the valorization of these by-products not only mitigates the generation of agro-industrial waste, but also stimulates the development of new functional ingredients and circular economy solutions. Such measures strengthen the sustainability and economic resilience of the peach palm fruit production chain, while supporting broader global trends related to resource efficiency, waste minimization, and food security.

For the recovery of such compounds, the choice of solvent plays a central role. Traditional methods based on organic solvents present disadvantages associated with toxicity, environmental impact, and food safety (Leite, de Assis, et al., 2021a). In this scenario, green solvents such as deep eutectic solvents (DESs) and supramolecular solvents (SUPRAS) have emerged as promising alternatives. DESs are biodegradable, low-volatility, and versatile systems that have been efficiently applied in the extraction of carotenoids, phenolics, and lipids (Foroutani et al., 2024; García et al., 2016; Liu et al., 2018; Morais, Polmann, et al., 2025). SUPRAS, formed by the self-assembly of amphiphilic molecules, offer high mass transfer capacity and selectivity in the extraction of lipophilic compounds and flavonoids (Keddar et al., 2020; Leite, de Assis, et al., 2021b; Yu et al., 2024). However, the practical application of these solvents in food or nutraceutical formulations remains dependent on comprehensive toxicological assessment and regulatory approval, and in this study they were used exclusively as extraction media. Complementarily, the *in vitro* digestion assessment of these fractions (pulp, peel, and seeds) enables the estimation of the bioaccessibility of bioactive compounds, providing relevant information for their future application in food and nutraceutical formulations.

Despite recent advances, a significant gap remains in the comprehensive exploitation of peach palm fractions using emerging green

solvents, particularly in the comparative evaluation of their efficiency and the stability of extracted compounds during *in vitro* digestion. Thus, this study aimed to investigate the bioactive composition of peach palm fruit fractions and evaluate the application of DESs and SUPRAS in the extraction of these compounds, in comparison with conventional solvents. Additionally, it aimed to analyze the bioaccessibility of metabolites and carbohydrate after simulated gastrointestinal digestion, as well as to evaluate the antimicrobial properties of the extracts against both Gram-positive and Gram-negative bacteria and toxigenic fungi, in order to identify the solvent with the greatest potential for obtaining multifunctional extracts that may support future applications in food, cosmetic, or pharmaceutical research.

2. Materials and methods

2.1. Chemical reagents

All chemical reagents used in this study were of analytical grade: DPPH, ABTS, Folin-Ciocalteu reagent, copper sulfate, potassium sulfate, potassium persulfate, petroleum ether, aluminum chloride, sodium molybdate, vanillin, thiobarbituric acid, ferric chloride, neocuproin, sodium carbonate, sodium phosphate, tripyridyl triazine (TPTZ), ethanol, acetone, ascorbic acid, gallic acid, glacial acetic acid, oxalic acid, sulfuric acid, lactic acid, malic acid, β -carotene, and Tween 40, all purchased from Sigma-Aldrich® (São Paulo, Brazil). Octanoic acid and choline chloride were obtained from ACS Científica (São Paulo, Brazil). HPLC standards for catechin, quercetin, vanillin, trigonelline, theobromine, catechin, vanillin, resveratrol, gallic, chlorogenic, caffeic, syringic, *p*-, *o*- and *m*-coumaric, ferulic, rosmarinic and trans-cinnamic acids, syringic acid, ferulic acid, sucrose, glucose, fructose and xylose were also acquired from Sigma-Aldrich® (São Paulo, Brazil). BHI broth, Mueller-Hinton agar, malt extract agar were purchased from Kasvi (Curitiba, PR, Brazil). For simulated *in vitro* gastrointestinal digestion: sodium bicarbonate, potassium chloride, sodium chloride, magnesium chloride hexahydrate, potassium monophosphate, ammonium carbonate, sodium hydroxide, calcium chloride, and hydrochloric acid, were supplied by Neon Chemistry (São Paulo, Brazil). Enzymes α -amylase (30 U mg^{-1}), pepsin (250 U mg^{-1}), and pancreatin (activity equivalent to 8 $\times$ USP) were purchased from Sigma-Aldrich® (São Paulo, Brazil).

2.2. Collection of peach palm fruits

Fruits of peach palm (*Bactris gasipaes*) were collected ripe and without physical damage, in the rural area of the municipality of Redenção, in the State of Pará, Brazil (latitude $-08^{\circ}01'43''$ S, longitude $-50^{\circ}01'53''$ W), during January 2023 to March 2023. The fruits were treated with water containing chlorine at 100 ppm for 15 min for sanitization. Then, the pulp, peels, and seeds were separated manually with a stainless-steel knife (Fig. 1). The pulp, peels, and seeds of peach palm were dried at 45 $^{\circ}\text{C}$ in an oven with air circulation (TE-394/I, TECNAL, Brazil). Then, the samples were ground in a knife mill (TE-650, TECNAL, Brazil) and sieved to reach a standard particle size of 1.00 mm. The different parts of the dried fruits were stored in low-density polyethylene packaging and kept at -18 ± 2 $^{\circ}\text{C}$ until analysis.

2.3. Preparation of solvents

2.3.1. Preparation of deep eutectic solvents (DES)

The preparation of deep eutectic solvents (DES) was performed according to the method described by Oliveira et al. (2021). Choline chloride was used as a hydrogen bond acceptor (HBA) combined with acetic and lactic acids as hydrogen bond donors (HBDs). The choice of DES was based on Leal et al. (2025), who identified the most efficient solvents for bioactive extraction. Reagents were weighed in a molar ratio of 1:2 (w/v) and stirred in a water bath (TE-0541 Tecnal) at 70 $^{\circ}\text{C}$



Fig. 1. Peach Palm fruit.

for 60 min until a clear and homogeneous solution was obtained. Distilled water (30%) was then added to reduce viscosity and facilitate extraction.

2.3.2. Synthesis of supramolecular solvents (SUPRAS)

Supramolecular solvents (SUPRAS) based on octanoic acid were obtained following the adapted methodology described by Salatti-Dorado et al. (2019). Briefly, a mixture of 2 mL of octanoic acid in 14 mL of ethanol was prepared, to which 24 mL of 0.01 M aqueous HCl solution was added to promote coacervation. The resulting system was subjected to magnetic stirring at $30 \times g$ for 10 min (stirrer model MA085/1, Marconi, Brazil) and subsequently centrifuged at $1400 \times g$ for 10 min to allow phase separation. As a result, an upper phase corresponding to SUPRAS and a lower equilibrium solution were obtained, both of which were stored under refrigeration at 4°C for up to 1 month.

2.4. Recovery of bioactive compounds using green solvents

Extracts from the pulp, peel, and seeds of peach palm (*Bactris gasipaes*) were obtained by ultrasound-assisted extraction using five solvents: water, 80% ethanol (v/v), deep eutectic solvent (DES) choline chloride:lactic acid (ChCl:Lat), DES choline chloride:acetic acid (ChCl:Ace), and SUPRAS. For water, 80% ethanol (Et 80%), ChCl:Lat, and ChCl:Ace, 5 g of each sample were mixed with 80 mL of each solvent. Samples were sonicated in an ultrasonic bath (40 kHz, 1000 W, Solid-Steel®, São Paulo, Brazil) at 45°C for 30 min. Subsequently, the extracts were kept under agitation at 45°C for 60 min in a refrigerated incubator (MA 830/A, Marconi, São Paulo, Brazil), filtered through Whatman No.

541 (125 mm), and stored in amber vials at -18°C until further analysis (Fig. 2). For SUPRAS, 2 g of each sample was mixed with 10 mL of the equilibrium phase and 4 mL of the SUPRAS phase. Samples were then sonicated (40 kHz, 1000 W, SolidSteel®, São Paulo, Brazil) at 45°C for 30 min, followed by agitation at 45°C for 60 min in a refrigerated incubator (MA 830/A, Marconi®, São Paulo, Brazil). Extracts were centrifuged at 4500 rpm for 12 min using a Daiki centrifuge (DT4500), and the upper phase was collected and stored in amber vials at -18°C until analysis (Fig. 2). It is important to note that SUPRAS extraction intrinsically operates with smaller solvent volumes due to its supramolecular preconcentration mechanism. Therefore, the solvent/sample ratio employed here follows the optimized conditions described in the reference methodology, and direct volume-based comparison with conventional solvents is not applicable; consequently, extraction efficiency was compared based on normalized analytical yields. These extracts were used to determine the contents of total phenolics, fast blue assay, total flavonoids and flavonols, condensed tannins, orthodiphenols, carotenoids, and individual phenolics by high-performance liquid chromatography (HPLC). Antioxidant capacity was evaluated using ABTS+, DPPH, ORAC, FRAP, CUPRAC, TRC, phosphomolybdenum, and β -carotene/linoleic acid assays.

2.5. Phytochemicals

Total phenolic content (TPC) was determined using the Folin-Ciocalteu method, according to Singleton and Rossi (1965). For the oxidation reaction, 25 μL of Folin-Ciocalteu reagent (2.0 N) was added to 200 μL of ultrapure water and 25 μL of extract. After 5 min, 25

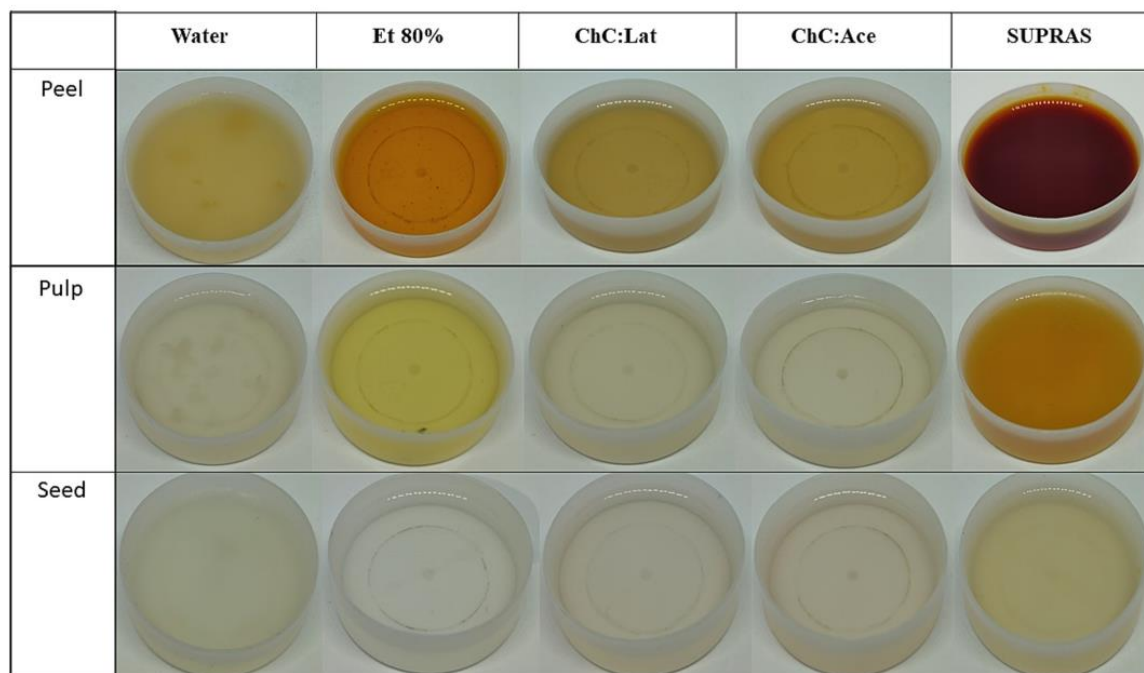


Fig. 2. Extracts of peel, pulp, and seed fractions obtained with different extraction solvents.

μL of a 10% sodium carbonate solution (Na_2CO_3) was added. The solution was kept in the dark at room temperature for 2 h, and absorbance was measured using a microplate reader (Biochrom EZ Read 2000) at 725 nm. Results were expressed as mg gallic acid equivalents per 100 g of sample ($\text{mg GAE } 100 \text{ g}^{-1}$). Total flavonoid content was quantified following the method described by Herald et al. (2012). Absorbance was measured at 510 nm, and results were calculated from a catechin standard curve ($50\text{--}500 \text{ mg L}^{-1}$), expressed as mg catechin equivalents per 100 g of sample ($\text{mg } 100 \text{ CE g}^{-1}$). Total flavonol content was determined according to Margraf et al. (2015), with adaptations by Morais et al. (2024). Absorbance was measured at 440 nm, and quantification was performed using a quercetin standard curve ($7\text{--}80 \text{ mg L}^{-1}$). Results were expressed as mg quercetin equivalents per 100 g of sample ($\text{mg QE } 100 \text{ g}^{-1}$).

Condensed tannins were determined using the vanillin assay, as described by Horszwald and Andlauer (2011), with adaptations by Margraf et al. (2015). Absorbance was measured at 500 nm, and concentrations were obtained from a catechin standard curve ($20\text{--}120 \text{ mg L}^{-1}$). Results were expressed as mg catechin equivalents per 100 g of sample ($\text{mg } 100 \text{ CE g}^{-1}$). Ortho-diphenols were determined by sodium molybdate complexation, following the method of Durán et al. (1991), with modifications by Margraf et al. (2015). Absorbance was measured at 370 nm, and quantification was based on a caffeic acid standard curve ($20\text{--}160 \text{ mg L}^{-1}$). Results were expressed as mg caffeic acid equivalents per 100 g of sample ($\text{mg CAE } 100 \text{ g}^{-1}$). Carotenoid content was determined from extracts obtained in section 2.5, with absorbance readings at 450 nm for β -carotene and 470 nm for lycopene, using the extraction solution as blank (Rodríguez-Amaya, 2001). Results were expressed as $\text{mg } 100 \text{ g}^{-1}$ of β -carotene or lycopene.

2.6. Antioxidant potential

The antioxidant potential of the extracts was determined by measuring the scavenging activity of the stable free radical DPPH, as

described by Cheng and Moore (2006). The ABTS⁺ radical cation decolorization assay was performed following Rufino et al. (2007). Results were expressed as the percentage of DPPH free radical scavenging (%FRS), according to Eq. (1):

$$\%FRS = \frac{ABS \text{ Control} - ABS \text{ Sample}}{ABS \text{ Sample}} \times 100 \quad (1)$$

Where: ABS control is the absorbance of the control sample, and ABS sample is the absorbance of the extract.

The ferric reducing antioxidant power (FRAP) was determined according to the method described by Benzie and Strain (1996). Absorbance was measured at 595 nm. The reducing power was quantified using an ascorbic acid standard curve, and results were expressed as mg ascorbic acid equivalents per 100 g of sample ($\text{mg AAE } 100 \text{ g}^{-1}$). Total reducing capacity (TRC) of hydrophilic and lipophilic compounds was determined according to Berker et al. (2013). Absorbance was recorded at 665 nm. Quantification was performed using a quercetin standard curve ($50\text{--}720 \text{ mg L}^{-1}$), and results were expressed as mg quercetin equivalents per 100 g of sample ($\text{mg QE } 100 \text{ g}^{-1}$). The β -carotene/linoleic acid assay was carried out according to Rufino et al. (2006). Absorbance was immediately measured at 470 nm. The percentage of oxidation inhibition was calculated using Eq. (2):

$$\%Oxidation \text{ inhibition} = \frac{(Sample \text{ initial } ABS - sample \text{ final } ABS)}{(Control \text{ initial } ABS - control \text{ final } ABS)} \quad (2)$$

2.7. In vitro biological properties

2.7.1. Lipid peroxidation inhibition (LPI)

Fe^{2+} -induced lipid peroxidation in phospholipids, triacylglycerols, and proteins present in egg yolk was evaluated according to Daker et al. (2007) and Margraf et al. (2015), with minor modifications. Absorbance was measured at 532 nm, allowing the monitoring of lipid peroxidation products. A control assay (AC) was performed by replacing the extracts

with the corresponding extraction solvent used for each sample. Lipid peroxidation inhibition (%) was calculated using Eq. (3):

$$LPI(\%) = \frac{Ac - Aa}{Ac} \times 100 \quad (3)$$

Where: LPI is the lipid peroxidation inhibition (%), Ac is the absorbance of the control sample, and Aa is the absorbance of the extract.

2.7.2. α -Amylase inhibition

The evaluation of the extracts' α -amylase inhibitory activity was conducted using the method described by Ademiluyi and Oboh (2013). In this assay, 50 μ L of the extract was mixed with 500 μ L of an α -amylase solution, which had been prepared in a 20 mM sodium phosphate buffer (pH 6.9), and then incubated at 25 °C for 10 min. After this step, 500 μ L of a 1% starch solution was added to the mixture, and the incubation was continued for an additional 10 min at the same temperature. The reaction was initiated by introducing 1 mL of a 60 nM 3,5-dinitrosalicylic acid (DNS) solution, and the mixture was then heated at 95 °C for 5 min. After heating, the samples were quickly cooled in an ice bath and maintained at approximately 4 °C. To terminate the reaction, 10 mL of distilled water was added, and the absorbance of the final solution was recorded at 540 nm using a UV-Vis spectrophotometer. A control sample was prepared by substituting the extract with 50 μ L of 20 mM sodium phosphate buffer (pH 6.9), and α -amylase inhibition was determined following the described method (Eq. 4).

$$\alpha - \text{amylase inhibition} = \frac{Ac - Aa}{Ac} \times 100 \quad (4)$$

Where: Ac is the absorbance of the control sample, and Aa is the absorbance of the sample.

2.8. Individual phenolics by HPLC

Identification and quantification of individual phenolics were performed in extracts obtained from section 2.5. Analyses were carried out at the Chemical Analysis and Prospecting Center of the Federal University of Lavras, using a high-performance liquid chromatograph (HPLC-DAD-UV-Vis, Shimadzu) equipped with a quaternary pump LC-20 AT, degasser DGU-20 A5 (serial no.: L20244808404), autosampler SIL-20 A (serial no.: L20164503197), controller CBM-20 A (serial no.: L20234505269), column oven CTO-20 AC (serial no.: L20214503287), detectors SPD-M20 A (serial no.: L20154503047) and RID-10 A (serial no.: C20934806770), and fraction collector FRC-10 A (serial no.: C20374504580). Chromatographic conditions were as follows: oven temperature 35 °C; Shim-pack VP-ODS column (250 mm $\times$ 4.6 mm $\times$ 5 μ m) coupled to a Shim-pack GVP-ODS precolumn (10 mm $\times$ 4.6 mm $\times$ 5 μ m). The mobile phase consisted of 2% (v/v) glacial acetic acid in ultrapure water (mobile phase A) and 70:28:2% (v/v/v) methanol/water/acetic acid (mobile phase B), at a flow rate of 1.0 mL min⁻¹, using a gradient elution program as follows: 0–5 min, 5% B; 5–35 min, linear increase to 50% B; 35–55 min, linear increase to 95% B; 55–60 min, held at 95% B; and 60–65 min, returned to initial conditions (5% B) for column re-equilibration. The injection volume was 20 μ L, and phenolic compounds were detected at an absorbance of 280 nm. Standard solutions were prepared by diluting trigonelline, theobromine, catechin, vanillin, resveratrol, gallic acid, chlorogenic acid, caffeic acid, syringic acid, *p*-, *o*-, and *m*-coumaric acids, ferulic acid, rosmarinic acid, and trans-cinnamic acid in methanol. Calibration curves were obtained from injections of ten concentrations of each standard in duplicate. Phenolic compounds and alkaloids were identified by comparing sample retention times with those of authentic standards. Results were expressed as mg 100 g⁻¹ of fresh sample.

2.9. Carbohydrates profile by HPLC

For the carbohydrate profile analysis, 2.5 g of samples were

homogenized in 50 mL of ultrapure water (Milli-Q) subsequently placed in an ultrasonic bath for 30 min at 45 °C. Subsequently, they were centrifuged and filtered through a hydrophilic PTFE (polytetrafluoroethylene) membrane filter with 0.22 μ m pore size, followed by storage at -18 °C until chromatographic injection (Sousa et al., 2025). Carbohydrate determination and quantification were carried out by high-performance liquid chromatography (HPLC) under the following conditions: Agilent 1260 Infinity II system equipped with a refractive index detector (RID) set at 40 °C, using a Supelcogel C610H chromatographic column (30 cm $\times$ 7.8 mm, Sigma-Aldrich) coupled with a Supelguard C610H pre-column (5 cm $\times$ 4.6 mm, Sigma-Aldrich®). The mobile phase consisted of 0.1% H₃PO₄ (prepared with deionized water and phosphoric acid), operated at a flow rate of 0.5 mL min⁻¹ (isocratic), with a total run time of 18 min and column oven temperature of 40 °C. Glucose, sucrose, xylose and fructose were used as external standards, and identification was based on retention time matching. Results were expressed as mean $\pm$ standard deviation (g L⁻¹).

2.10. In vitro digestion

In vitro gastrointestinal digestion and the bioaccessibility of peach palm (*Bactris gasipaes*) peel, pulp, and seed samples were conducted following the COST INFOGEST consensus protocol FA1005 (Brodkorb et al., 2019). Samples were analyzed separately before and after each digestive phase. The assay was performed in duplicate. At the end of each stage, the liquid fraction was collected and centrifuged at 2480 g for 10 min. The supernatants were then subjected to characterization of the phenolic and carbohydrates profile, assessment of antioxidant potential, and evaluation of *in vitro* biological properties. The same analyses were also performed on the undigested samples, allowing comparisons with the results obtained after gastrointestinal simulation.

2.10.1. In vitro gastrointestinal digestion phases

In the initial step, 0.25 g of each fraction (pulp, peel, and seed) was mixed with 3.5 mL of simulated salivary fluid (25 μ L of CaCl₂ and 0.975 μ L of H₂O), and the pH was adjusted to 7.0 with 1 M NaOH. Then, 0.5 mL of α -amylase solution (75 U mL⁻¹) was added, with vigorous vortexing for 2 min at room temperature (25 °C). After the oral step, 7.5 mL of simulated gastric fluid (20 μ L of CaCl₂ and 0.700 μ L of H₂O) was added to each sample. The pH was adjusted to 3.0 using 6 M HCl, followed by the addition of 1.6 mL of pepsin solution (2000 U mL⁻¹). Digestion occurred for 2 h at 37 °C in a refrigerated incubator (MA 830/A, Marconi, São Paulo, Brazil) at 150 rpm. In the final step, 11 mL of simulated intestinal fluid (40 μ L of CaCl₂, 2.5 mL of bile salts - 0.8 mM sodium glycodeoxycholate, 0.45 mM sodium taurodeoxycholate, and 0.75 mM sodium taurocholate; and 1.46 mL of 1 M NaOH) was added. The pH was adjusted to 7.0, and then 5 mL of pancreatin (activity equivalent to 8 $\times$ USP) was added. Digestion was carried out for 2 h at 37 °C under continuous stirring. After completing each digestion step, the tubes were cooled on ice to stop the enzymatic reactions. Supernatants from the oral, gastric, and intestinal phases were collected and stored at refrigeration temperatures for subsequent analysis.

2.10.2. Bioaccessibility index

The effect of digestion on the bioaccessibility of the phenolic and carbohydrates profile of peach palm fractions was evaluated to quantify the proportion of phenolic compounds released throughout the digestive process and that remain available for absorption by the organism (Ortega et al., 2011 Bioaccessibility was calculated using Eq. (5):

$$\text{Bioaccessibility index (\%)} = \frac{A}{B} \times 100 \quad (5)$$

Where A = total phenolic/carbohydrates content after *in vitro* digestion, and B = total phenolic/carbohydrates content before *in vitro* digestion.

2.11. Evaluation of antimicrobial properties

2.11.1. Microorganisms used

The following microorganisms were used in this study: *Staphylococcus aureus* ATCC 25923, *Escherichia coli* ATCC 25922, *Listeria monocytogenes* ATCC 19117, and *Salmonella enterica* ATCC 14028. For antifungal assays, isolates of *Aspergillus flavus* URMICRO 10704, *Aspergillus niger* URMICRO 10715, and *Aspergillus ochraceus* URMICRO 10506 were provided by the Microbiological Resources Unit of the Federal University of Lavras (SisGen No. C356129/Brazil). For bacteria, minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC) tests were performed, while fungi were evaluated using the disk diffusion method.

2.11.2. Minimum inhibitory concentration (MIC)

MIC was determined in Brain Heart Infusion (BHI) broth using the microdilution method in 96-well plates, according to CLSI guideline M26-A (CLSI, 1999) and ISO 20776-1 (ISO, 2019), with minor modifications. Plant extracts were diluted in 0.2% DMSO at ratios of 1, 1:1, 1:2, 1:4, 1:8, and 1:16, resulting in six concentrations. Bacterial suspensions were prepared in BHI broth and standardized using the McFarland scale 0.5, corresponding to approximately 10^8 CFU mL⁻¹. Each well received 180 µL of BHI broth, 10 µL of bacterial suspension, and 10 µL of extract at the respective dilution. The plates were incubated at 37 °C for 48 h. After incubation, the absorbance was measured at 625 nm, based on the formation of turbidity. MIC was defined as the lowest extract concentration at which no visible growth was observed. All assays were performed in triplicate.

2.11.3. Minimum bactericidal concentration (MBC)

Based on MIC results, five extract concentrations ($\frac{1}{4} \times$, $\frac{1}{2} \times$, $1 \times$, $2 \times$, and $4 \times$ MIC) were selected. Each well contained 180 µL of BHI broth, 10 µL of bacterial suspension, and 10 µL of extract. After incubation at 37 °C for 48 h, 100 µL from each well was spread-plated onto Mueller-Hinton agar plates. Plates were incubated at 37 °C for 48 h, and microbial growth was evaluated by colony formation. MBC was defined as the lowest extract concentration capable of completely inhibiting bacterial growth, according to CLSI guideline M26-A (CLSI, 1999), with adaptations. Since *Listeria monocytogenes* may enter a VBNC (viable but non-culturable) state after antimicrobial exposure, an additional recovery step was included: aliquots were incubated for 18 h in BHI broth supplemented with 1% glucose to avoid false negatives and ensure accurate assessment of bactericidal activity. All assays were performed in duplicate.

2.11.4. Disk diffusion assay

Antifungal activity was assessed using the disk diffusion method in agar, as described in CLSI guideline M44 (CLSI, 2018), with modifications. Only extracts showing antibacterial inhibition were tested. Fungi were grown on malt extract agar (MEA) and incubated at 25 ± 0.7 °C for 7 days. After incubation, conidial suspensions were prepared in 0.1% peptone saline solution, adjusted to a concentration of 10^7 conidia/mL (with a viability of 99%). Petri dishes containing MEA were inoculated with 100 µL of suspension and spread uniformly with a Drigalski loop. Sterile filter paper discs (8 mm diameter) were placed on the medium and impregnated with 20 µL of extract. Plates were incubated at 25 ± 0.9 °C for 7 days. Inhibition zones (mm) were measured, excluding the diameter of the paper disc. The experiment was performed with four independent replicates.

2.12. Statistical analysis

Results were expressed as mean $\pm$ standard deviation. Data were analyzed by analysis of variance (ANOVA), followed by Tukey's test for mean comparison at a significance level of 5% ($p < 0.05$), using Statistica software, version 10.0 (StatSoft Inc., Tulsa, OK, USA). Pearson's

correlation and principal component analysis (PCA) were applied to evaluate associations between bioactive compounds and antioxidant capacity. OriginPro software, version 2022 (OriginLab Corporation, Northampton, MA, USA) was used for statistical analysis and graphical plotting. Antibacterial activity results were analyzed using ANOVA followed by the Scott-Knott test at a 5% significance level ($p < 0.05$), using Statistica software, version 10.0 (StatSoft Inc., Tulsa, OK, USA).

3. Results and discussion

3.1. Phytochemicals

Carotenoid extraction was performed from different fractions of peach palm (peel, pulp, and seed), using environmentally friendly solvents: water, 80% ethanol (Et 80%), choline chloride:lactic acid (ChCl:Lat), choline chloride:acetic acid (ChCl:Ac), and SUPRAS (Table 1). Carotenoids are of great importance for human health, with β -carotene standing out as a recognized precursor of provitamin A. This compound plays essential roles in the human body, including reducing the risk of degenerative diseases, neutralizing free radicals, maintaining eye health, and strengthening the immune system (Barboza et al., 2022; Sandri et al., 2017). In the peel fraction, the concentrations of β -carotene and lycopene, obtained using the SUPRAS solvent, were 67.2 mg 100 g⁻¹ and 169.95 mg 100 g⁻¹, respectively. These values significantly exceeded those reported by Miranda et al. (2024), who observed 34.74 mg 100 g⁻¹ of β -carotene in peach palm peel, as well as the findings of Menezes Silva et al. (2023), who reported 46.76 mg 100 g⁻¹. Furthermore, the levels found were considerably higher than those recorded for buri peel, also extracted with SUPRAS, which reached only 5.82 mg 100 g⁻¹ of β -carotene (Leite, de Assis, et al., 2021). Overall, the results indicated that in both peel and pulp, the supramolecular solvent demonstrated superior performance compared with DES and the other green solvents tested, showing statistically significant differences ($p < 0.05$).

In the pulp fraction, β -carotene and lycopene concentrations extracted with the supramolecular solvent SUPRAS were 6.54 mg 100 g⁻¹ and 11.72 mg 100 g⁻¹, respectively. These values were higher than those reported by Sousa et al. (2025), who obtained 3.47 mg 100 g⁻¹, although lower than those observed for buri pulp extracted with the same solvent (26.7 mg 100 g⁻¹ of β -carotene) (Leite, de Assis, et al., 2021). Regarding the seed fraction, despite its opaque-white coloration, which is visually indicative of a low presence of natural pigments, detectable carotenoid concentrations were quantified. SUPRAS enabled the extraction of 2.11 mg 100 g⁻¹ of β -carotene and 3.81 mg 100 g⁻¹ of lycopene, values that outperformed the other solvents evaluated, with significant differences compared with the remaining solvents ($p < 0.05$), which yielded considerably lower concentrations of these compounds. Overall, the results confirm the superiority of the SUPRAS system over the other solvents tested, with statistically significant differences between them ($p < 0.05$), highlighting its efficiency in extracting hydrophobic compounds, such as carotenoids. This efficiency is directly related to its physicochemical properties, especially dispersive, dipole-dipole, and hydrophobic interactions, which lead to the formation of stable microenvironments during self-assembly and coacervation. Such microenvironments favor both solubilization and protection of carotenoids, reducing their degradation and ensuring higher extraction yields (Ballesteros-Gómez et al., 2010; Leite, de Assis, et al., 2021; Ueda et al., 2023).

For total phenolics determined by the Folin-Ciocalteu method, precipitate formation was observed in the DES (ChCl:Lat and ChCl:Ac), which precluded quantification of these compounds. These DES cause drastic pH shifts and contain reducing components that interact non-specifically with the Folin reagent, promoting the formation of insoluble colloidal aggregates that persist even after centrifugation or filtration. Because this turbidity is chemically induced and cannot be eliminated by physical separation, no reliable absorbance readings can be obtained. This phenomenon has also been reported by Leal et al.

Table 1

Bioactive compounds in the peel, pulp, and seeds of the peach palm were extracted with different solvents.

Analyses	Peel	Pulp	Seeds
β-Carotene (mg 100 g⁻¹)			
Water	3.33 ± 0.01d	2.38 ± 0.03bc	0.31 ± 0.09e
Et 80%	11.31 ± 0.04b	2.21 ± 0.05c	0.47 ± 0.04d
ChCl:Lat	6.1 ± 0.02c	2.18 ± 0.01c	0.95 ± 0.02c
ChCl:Ace	6.67 ± 0.02c	2.62 ± 0.02b	1.58 ± 0.03b
SUPRAS	67.2 ± 0.67a	6.54 ± 0.29a	2.11 ± 0.01a
Lycopene (mg 100 g⁻¹)			
Water	2.13 ± 0.02d	1.61 ± 0.01b	0.18 ± 0.07e
Et 80%	9.15 ± 0.02b	1.34 ± 0.01b	0.3 ± 0.02d
ChCl:Lat	3.49 ± 0.01 cd	1.41 ± 0.02b	0.66 ± 0.01c
ChCl:Ace	4.34 ± 0.02c	1.42 ± 0.02b	1.04 ± 0.02b
SUPRAS	169.95 ± 1.45a	11.72 ± 0.3a	3.81 ± 0.03a
Flavonoids (mg 100 CE g⁻¹)			
Water	6 ± 0.01d	3.67 ± 0.03c	0.87 ± 0.01d
Et 80%	9.47 ± 0.12c	2.41 ± 0.03d	0.76 ± 0.02d
ChCl:Lat	10.41 ± 0.01b	4.25 ± 0.01b	1.7 ± 0.01c
ChCl:Ace	10.25 ± 0.02b	4.11 ± 0.02b	2.34 ± 0.01b
SUPRAS	83.98 ± 0.29a	17.18 ± 0.16a	5.1 ± 0.1a
Flavonols (mg QE 100 g⁻¹)			
Water	27.65 ± 1.79c	33.43 ± 0.87c	21.22 ± 0.20c
Et 80%	65.17 ± 2.26b	68.53 ± 0.62b	125.44 ± 3.97b
ChCl:Lat	23.13 ± 1.30d	17.68 ± 1.29d	8.67 ± 0.27d
ChCl:Ace	27.79 ± 0.96c	6.05 ± 0.66e	9.76 ± 0.89d
SUPRAS	184.46 ± 0.35a	90.61 ± 2.14a	157.24 ± 0.30a
Condensed Tannins (mg 100 CE g⁻¹)			
Water	234.17 ± 2.89c	187.60 ± 1.49a	Nd.
Et 80%	505.83 ± 7.64a	109.16 ± 2.89b	Nd.
ChCl:Lat	268.33 ± 1.44b	10.60 ± 1.68d	538.33 ± 5.20a
ChCl:Ace	15.83 ± 2.89d	50.66 ± 4.54c	384.17 ± 2.89b
SUPRAS	Nd.	Nd.	Nd.
TPC (mg GAE 100 g⁻¹)			
Water	224.53 ± 0.77c	127.45 ± 1.2b	93.85 ± 0.86b
Et 80%	331.68 ± 0.89b	234.32 ± 0.96a	76.70 ± 1.21c
ChCl:Lat	Nd.	Nd.	Nd.
ChCl:Ace	Nd.	Nd.	Nd.
SUPRAS	649.87 ± 1.11a	94.45 ± 0.8c	124.97 ± 0.74a
Ortho-Diphenols (mg CAE 100 g⁻¹)			
Water	69.82 ± 0.80c	30.76 ± 0.39c	30.89 ± 0.85c
Et 80%	74.18 ± 0.68b	53.06 ± 1.49b	34.39 ± 0.75b
ChCl:Lat	44.01 ± 0.39e	23.58 ± 1.26d	6.74 ± 0.26d
ChCl:Ace	125.68 ± 0.32a	64.56 ± 2.50a	51.91 ± 0.41a
SUPRAS	65.42 ± 1.38d	32.12 ± 0.92c	7.26 ± 0.51d
DPPH (% inhibition)			
Water	52.16 ± 0.97c	19.21 ± 0.48a	10.96 ± 1.85e
Et 80%	70.35 ± 0.43b	12.36 ± 0.43c	33.82 ± 1.61c
ChCl:Lat	23.03 ± 0.69e	3.54 ± 0.83d	69.10 ± 0.99a
ChCl:Ace	31.42 ± 1.01d	15.20 ± 1.21b	56.76 ± 0.89b
SUPRAS	80.04 ± 0.2a	10.56 ± 0.45c	17.04 ± 0.45d
ABTS⁺ (% inhibition)			
Water	32.04 ± 0.67b	24.5 ± 0.58a	19.73 ± 0.29d
Et 80%	13.1 ± 0.21e	27.4 ± 0.35b	15.42 ± 0.42e
ChCl:Lat	22.53 ± 1.17c	13.2 ± 0.28c	40.90 ± 0.28a
ChCl:Ace	19.45 ± 0.37d	11.4 ± 0.3d	32.31 ± 0.44b
SUPRAS	91.84 ± 0.7a	13.18 ± 1.06c	24.32 ± 0.14c
FRAP (mg AAE 100 g⁻¹)			
Water	44.81 ± 0.79d	37.49 ± 0.99c	45.81 ± 0.16d
Et 80%	158.02 ± 0.62a	93.21 ± 0.98a	75.02 ± 0.69b
ChCl:Lat	88.28 ± 0.18b	66.67 ± 1.22b	92.45 ± 0.94a
ChCl:Ace	49.83 ± 1.30c	39.03 ± 1.77c	64.16 ± 0.89c
SUPRAS	Nd.	Nd.	Nd.
β-Carotene/linoleic acid (%Protection)			
Water	53.91 ± 1.96d	44.85 ± 1.45e	26.24 ± 0.17e
Et 80%	70.26 ± 0.17b	65.58 ± 1.9b	40.52 ± 0.34d
ChCl:Lat	67.50 ± 1.22bc	51.25 ± 1.02d	81.38 ± 1.06a
ChCl:Ace	65.83 ± 1.03c	55.78 ± 0.94c	64.45 ± 1.22b
SUPRAS	82.77 ± 0.94a	71.93 ± 1.47a	57.65 ± 1.7c
TRC (mg QE 100 g⁻¹)			
Water	5.89 ± 1.73e	105.50 ± 1.67d	121.33 ± 2.20c
Et 80%	109.67 ± 1.67c	166.33 ± 0.83b	193.56 ± 1.27b
ChCl:Lat	193.94 ± 2.55b	141.72 ± 2.10c	29.78 ± 0.42d
ChCl:Ace	83.83 ± 1.44d	6.72 ± 0.96e	5.22 ± 2.41e
SUPRAS	899.50 ± 4.41a	881.44 ± 2.68a	1130.61 ± 0.96a
LPI (% inhibition)			

Table 1 (continued)

Analyses	Peel	Pulp	Seeds
Water	21.81 ± 0.3d	24.32 ± 0.2d	26.28 ± 0.15b
Et 80%	44.44 ± 5.26b	30.51 ± 0.7c	53.34 ± 1.03a
ChCl:Lat	4.8 ± 0.81e	5.67 ± 0.8e	5.25 ± 0.54c
ChCl:Ace	29.03 ± 0.06c	39.68 ± 1.1b	32.24 ± 0.43b
SUPRAS	63.92 ± 0.83a	58.04 ± 0.95a	58.91 ± 0.43a
α-Amylase inhibition (% inhibition)			
Water	35.72 ± 2.11b	62.35 ± 5.36a	46.9 ± 1.03a
Et 80%	47.80 ± 2.97a	38.17 ± 3.33b	29.45 ± 3.47b
ChCl:Lat	31.24 ± 1.43b	61.72 ± 2.62a	10.66 ± 0.68c
ChCl:Ace	53.62 ± 1.69a	59.62 ± 2.89a	31.99 ± 0.89b
SUPRAS	37.81 ± 4.71b	19.66 ± 1.31c	2.16 ± 1.03d

Note: Results are expressed as mean ± standard deviation ($n = 3$). Means followed by the same lowercase letter within the same column do not differ significantly according to Tukey's test at 5% probability ($p < 0.05$). **Et80%**: 80% (v/v) aqueous ethanol; **ChCl:Lat**: choline chloride:lactic; **ChCl:Ace**: choline chloride:acetic; **SUPRAS**: supramolecular solvent; **Nd**: not detected; **GAE**: gallic acid equivalents; **CE**: catechin equivalents; **QE**: quercetin equivalents; **CAE**: caffeic acid equivalents; **AAE**: ascorbic acid equivalents; **LPI**: lipid peroxidation inhibition.

(2025) and Lee et al. (2023). According to the classification criteria proposed by Vasco et al. (2008), phenolic compounds can be categorized as low content (<100 mg GAE 100 g⁻¹), medium content (100–500 mg GAE 100 g⁻¹), and high content (>500 mg GAE 100 g⁻¹). Accordingly, the peach palm extracts were classified by solvent, revealing statistically significant differences ($p < 0.05$). Peel exhibited 224.53 mg GAE 100 g⁻¹ in water and 331.68 mg GAE 100 g⁻¹ in 80% ethanol. Pulp extracted with 80% ethanol reached 234.32 mg GAE 100 g⁻¹, whereas seed extracted with SUPRAS presented 124.97 mg GAE 100 g⁻¹. Based on Vasco et al. (2008), these values fall within the medium-content category. In contrast, peel extracted with SUPRAS showed 649.87 mg GAE 100 g⁻¹ and was therefore classified as a high-phenolic-content matrix. These intermediate to high concentrations are particularly relevant because phenolic compounds are directly associated with antioxidant capacity and may enhance the technological and nutritional valorization potential of peach palm. Recent evidence suggests that phenolic-rich diets are related to hypoglycemic, anti-inflammatory, and antimicrobial effects (Amorim et al., 2024; Souza et al., 2020; Morais et al., 2024; Rodrigues et al., 2024).

Regarding condensed tannins, the most significant results were obtained with 80% ethanol for the peel (505.83 mg 100 CE g⁻¹) and with ChCl:Lat for the seed (538.33 mg 100 CE g⁻¹), with statistical significance ($p < 0.05$). For flavonoids, the highest concentrations were recorded in extracts obtained with SUPRAS, 83.98 mg 100 CE g⁻¹ in peel, 17.18 mg 100 CE g⁻¹ in pulp, and 5.10 mg 100 CE g⁻¹ in seed ($p < 0.05$). For flavonols, values were likewise higher with the same solvent: 184.46 mg QE 100 g⁻¹ for peel, 90.61 mg QE 100 g⁻¹ for pulp, and 157.24 mg QE 100 g⁻¹ for seed ($p < 0.05$). These findings corroborate those of Yu et al. (2024), who highlighted the efficiency of octanoic-acid-based SUPRAS in extracting phenolics, achieving up to eight-fold higher yields than conventional solvents due to intensified hydrogen-bonding interactions that promote a more robust and selective extraction mechanism. Synergistically, the high concentrations of condensed tannins, flavonoids, and flavonols potentiate antioxidant and anti-inflammatory effects, favoring the neutralization of reactive species and the modulation of processes linked to oxidative stress, which may reduce the incidence of chronic diseases.

For *ortho-diphenols*, the best results were observed with ChCl:Ace across the three fractions analyzed: peel (123.68 mg CAE 100 g⁻¹), pulp (64.56 mg CAE 100 g⁻¹), and seed (51.91 mg CAE 100 g⁻¹), with statistical significance ($p < 0.05$). Next in performance was 80% ethanol, with concentrations of 74.18 mg CAE 100 g⁻¹ for peel, 53.06 mg CAE 100 g⁻¹ for pulp, and 34.39 mg CAE 100 g⁻¹ for seed, in agreement with Morais et al. (2024) regarding the efficiency of ethanol for extracting *ortho-diphenolic* compounds. *Ortho-diphenols* possess high free-radical-

scavenging capacity and are key contributors to antioxidant potential (Lee et al., 2020). This activity is associated with active functional groups ($-\text{OH}$ or $-\text{NH}_2$) in the *ortho* position, which show greater reactivity due to the possibility of forming intramolecular hydrogen bonds, conferring enhanced stability and antioxidant efficacy. Thus, identifying high levels of these compounds in peach palm increases its relevance as a bioactive and nutraceutical resource (Bendary et al., 2013; Luzio et al., 2021).

3.2. Antioxidant potential

Assessment of antioxidant potential is crucial for evaluating the ability of extracts to protect against reactive oxygen species, such as hydroxyl ($\text{OH}^\bullet$) and superoxide ($\text{O}_2^{\bullet-}$) radicals, which are linked to lipid peroxidation and cellular membrane damage (Duan et al., 2020; Shi et al., 2017). Accordingly, DPPH, ABTS, FRAP, β -carotene/linoleic acid, and total reducing capacity assays were performed using five solvents across the different fractions: peel, pulp, and seed (Table 1), all of which showed statistical differences ($p < 0.05$). In the peel fraction, SUPRAS exhibited the best performance in the DPPH, ABTS, and β -carotene/linoleic acid assays, achieving high free-radical inhibition percentages (80.04%, 91.84%, and 82.77%, respectively). These outcomes can be directly associated with the high concentrations of total phenolics, flavonoids, and flavonols present in the extract. Thus, the results demonstrate that peel extracts obtained with green solvents, such as SUPRAS, display high antioxidant capacity, positioning them as promising sources of bioactive compounds for functional food applications and the prevention of disorders associated with oxidative stress.

For pulp, the highest performance was observed in the β -carotene/linoleic acid assay, with SUPRAS and 80% ethanol reaching 71.93% and 65.58% inhibition, respectively. These results were superior to those obtained for baru pulp (63.93% – DPPH and 33.23% – ABTS) reported by Morais, Sousa, et al. (2025), and also exceeded values observed in traditionally consumed fruits such as pineapple (75.4%) (Hadidi et al., 2020), in addition to outperforming those reported for peach palm pulp (41.18% DPPH) by Sousa et al. (2025). In the ferric-reducing assay (FRAP), which evaluates Fe^{3+} -reducing capacity via electron transfer, 80% ethanol and $\text{ChCl}:\text{Lat}$ provided the best performances, albeit with a statistically significant difference between them ($p < 0.05$). Peel and pulp stood out with 80% ethanol, showing 158.02 and 93.21 mg AAE 100 g^{-1} , respectively. These results indicate that peach palm pulp, particularly when extracted with SUPRAS and 80% ethanol, exhibits significant antioxidant capacity, reinforcing its potential as a functional source of bioactive compounds for oxidative stress prevention.

For seed, the deep eutectic solvent $\text{ChCl}:\text{Lat}$ was the most efficient, yielding 81.38% inhibition in the β -carotene/linoleic acid assay and 69.10% in the DPPH assay. In FRAP, the best seed result was recorded with $\text{ChCl}:\text{Lat}$, reaching 92.45 mg AAE 100 g^{-1} . These findings suggest that peach palm seed is a promising source of phenolic compounds with high antioxidant capacity, reinforcing its potential for integral utilization and indicating functional applications aimed at protection against oxidative and inflammatory processes in the body. Overall, the antioxidant potential observed across the different peach palm fractions was correlated with the concentrations of TPC, flavonoids, flavonols, and ortho-diphenols, compounds known for their high reactivity toward reactive oxygen species (Barboza et al., 2022; Carmona-Hernández et al., 2021; Vella et al., 2023). These findings underscore the potential of these fractions as promising matrices for extracting bioactive compounds and for developing products aimed at preventing oxidative stress or formulating new functional foods. Nevertheless, complementary studies using cell models and *in vivo* assays are warranted to gain a more comprehensive understanding of how these extracts may modulate physiological processes associated with reducing pathologies linked to oxidative stress. Such studies will help validate the observed biological efficacy and consolidate the potential applications of these matrices in health-promotion strategies.

3.3. *In vitro* biological properties

Lipid-rich foods are more susceptible to lipid oxidation, a process that compromises their stability and nutritional quality, ultimately causing structural and functional damage to biomolecules. Lipid peroxidation occurs when fatty acids or acyl side chains are degraded by free radicals or reactive oxygen species (ROS), triggering a series of harmful reactions (Duan et al., 2020; Khanum & Thevanayagam, 2017). Given that peach palm is a fruit with a high lipid content (6.59% – (Sousa et al., 2025)), it is essential to evaluate its protective capacity against lipid peroxidation, as illustrated in Fig. 3. For the lipid peroxidation inhibition (LPI) assay, the peel and pulp fractions extracted with SUPRAS exhibited the best results, achieving 63.92% and 58.04% inhibition, respectively (Table 1). In the seed fraction, no significant differences ($p < 0.05$) were observed between SUPRAS and 80% ethanol, which achieved 58.91% and 53.34% inhibition, respectively (Table 1). This antioxidant action can largely be attributed to the presence of polyphenols such as quercetin, gallic acid, and catechin, compounds known for their free-radical scavenging activity and reduction of ROS (Cruz et al., 2024; Deng et al., 2024; Zhang et al., 2023).

The enzyme α -amylase plays a central role in carbohydrate metabolism, promoting the hydrolysis of polysaccharides into simple sugars. Its inhibition reduces the rate of carbohydrate digestion, mitigating postprandial glycemic spikes and contributing to the prevention of hyperglycemia and hypertension (Chen et al., 2013; Kwon et al., 2007; Wang et al., 2010). In the α -amylase inhibition assay, the pulp fraction showed the highest inhibition percentages, 62.35%, 61.72%, and 59.62% with water, $\text{ChCl}:\text{Lat}$, and $\text{ChCl}:\text{Ace}$ solvents, respectively, with no significant differences among them ($p < 0.05$) (Table 1). These results are consistent with those of Faria et al. (2021), who reported 65% inhibition for peach palm. These values were higher than those reported by Rybak and Wojdyło (2023) for plum pulp (32.57%) and by Karatoprak et al. (2021) for lemon pulp (17.83%). The peel fraction also exhibited expressive activity, with inhibition rates of 53.62% and 47.8% for $\text{ChCl}:\text{Lat}$ and 80% ethanol, respectively, surpassing the 43% inhibition observed for lemon peel by Ernawita et al. (2016). For the seed fraction, water was the most effective solvent, achieving 46.9% inhibition. According to Ademiluyi and Oboh (2013) and Gomes et al. (2021), α -amylase inhibition is directly associated with the presence of phenolic compounds, mainly in glycosylated forms, which are hydrophilic molecules. Since α -amylase acts in an aqueous environment, these phenolic compounds are expected to have a greater affinity for the enzyme, which explains the high inhibition observed in aqueous extracts of pulp and seed. These findings are particularly relevant to the functional food industry, as they suggest that peach palm fractions may serve as bioactive matrices with therapeutic potential for managing type 2 diabetes through modulation of α -amylase activity.

3.4. Individual phenolic content

The peel, pulp, and seed fractions of peach palm presented a considerable diversity of individual phenolic compounds, with 10, 11, and 10 compounds identified, respectively, in addition to two alkaloids: trigonelline, the primary compound detected, and theobromine (Table 2), with statistical differences observed ($p < 0.05$). The presence of these compounds provides the different fruit fractions with a wide range of biological properties relevant to human health and of potential interest for future applications in pharmaceutical, food, and cosmetic research.

Trigonelline, an alkaloid derived from nicotinic acid (vitamin B_3), plays a crucial physiological role in plants, serving as a regulator of growth and development. In humans, this compound exhibits anti-cariogenic and antimicrobial effects (Nguyen et al., 2024), as well as hypoglycemic (Aldakinah et al., 2017; Choi et al., 2021), hypocholesterolemic (Bhandarkar et al., 2021), and antioxidant (Bhandarkar et al., 2021; Pinheiro et al., 2021; Lone et al., 2020). Although it is most

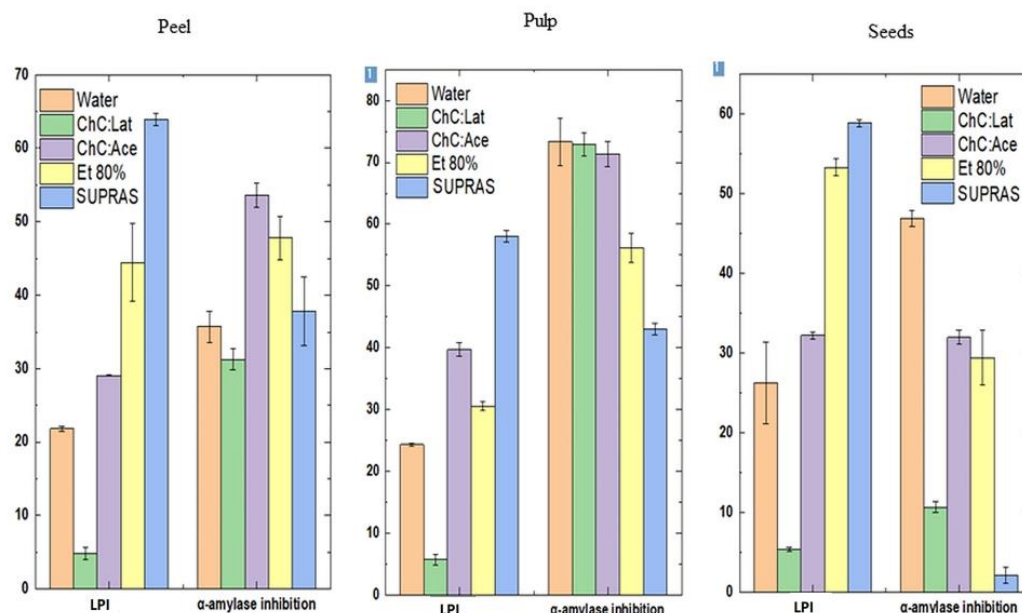


Fig. 3. Graph of Lipid peroxidase inhibition (LPI) and α -amylase inhibition.

abundant in coffee beans, which may contain around $7200 \mu\text{g g}^{-1}$ (Konstantinidis et al., 2023; Nguyen et al., 2024), the present study found remarkable concentrations in peach palm, similar to those found in coffee. Values of 4511.41 , 4800.95 , and $2850.10 \mu\text{g g}^{-1}$ were detected in the peel, pulp, and seed, respectively, when extracted with ChCl:Lat, considered the most efficient solvent for this alkaloid. These findings highlight the potential of peach palm as a viable alternative for the pharmaceutical market in trigonelline production.

Another alkaloid, theobromine, was also identified and exhibited relevant concentrations, particularly in pulp ($72.79 \text{ mg } 100 \text{ g}^{-1}$) and seed ($68.43 \text{ mg } 100 \text{ g}^{-1}$), both of which were extracted with ChCl:Lat. This extraction method showed significant differences ($p < 0.05$) compared with the other solvents. The literature reports multiple health-related effects of theobromine, including anti-inflammatory, hypoglycemic, anti-urolithiasis, and neuroprotective activities (Cadoná et al., 2022; Monteiro et al., 2025; M. Zhang et al., 2024). The high concentrations of this alkaloid reinforce the potential of peach palm as a natural source of bioactive compounds of biomedical interest.

Among the phenolic compounds identified, catechin, *m*-coumaric acid, and ferulic acid stood out, with higher concentrations in extracts obtained with SUPRAS and ChCl:Lat. Catechin showed remarkable levels in peel ($795.22 \mu\text{g g}^{-1}$) and pulp ($60.32 \mu\text{g g}^{-1}$) with SUPRAS, results higher than those reported by Sousa et al. (2025), who found $27.08 \mu\text{g g}^{-1}$ in peach palm pulp. This compound is widely studied for its anti-inflammatory, neuroprotective, and cardioprotective properties (Gadkari & Balaraman, 2015; Pedro et al., 2020), adding value to the fruit. *m*-Coumaric acid also presented relevant concentrations, especially in pulp ($57.57 \mu\text{g g}^{-1}$ - SUPRAS) and seed ($32.7 \mu\text{g g}^{-1}$ - ChCl:Lat). Derived from cinnamic acid, this compound may give rise to derivatives such as caffeic, chlorogenic, and ferulic acids, as well as curcumin (Hu et al., 2017; Mancilla-Montelongo et al., 2019). According to the literature, these compounds exhibit anticancer (Gießel et al., 2019), anti-inflammatory, antibacterial, antifungal (Lima et al., 2018), antidiabetic (Adisakwattana et al., 2013), and neuroprotective properties (Lan et al., 2017), further confirming peach palm as a relevant bioactive matrix.

Ferulic acid was particularly abundant in pulp ($144.14 \mu\text{g g}^{-1}$) and

seed ($33.4 \mu\text{g g}^{-1}$), both extracted with SUPRAS, with values exceeding those of other Arecaceae fruits, such as buritirana (99.39 and $111.69 \mu\text{g g}^{-1}$ in pulp and peel, respectively) (Morais et al., 2024), açai ($7.60 \mu\text{g g}^{-1}$), and bacaba ($10.80 \mu\text{g g}^{-1}$) (Morais et al., 2022). Complementarily, chlorogenic acid was also identified, mainly in peel ($19.44 \mu\text{g g}^{-1}$) and pulp ($3.49 \mu\text{g g}^{-1}$) with water and in seed ($2.40 \mu\text{g g}^{-1}$) with ChCl:Lat, indicating that different peach palm fractions contribute to this phenolic compound. Ferulic acid is well recognized for its potent antioxidant and anti-inflammatory action, with protective effects against cardiovascular diseases, cancer, diabetes, and neurodegenerative disorders (Li et al., 2021). Chlorogenic acid, in turn, has garnered considerable scientific interest due to its ability to modulate glucose and lipid metabolism, thereby contributing to glycemic control, reducing obesity risk, and preventing metabolic disorders (Abdalla et al., 2021). Additionally, this compound has been associated with hepatoprotective effects and the attenuation of oxidative damage in various tissues (Makarova et al., 2025). The simultaneous presence of ferulic and chlorogenic acids in peach palm fractions suggests a relevant synergistic effect, potentially enhancing oxidative stress neutralization, reinforcing cellular protection mechanisms, and broadening the fruit's functional benefits (Li et al., 2021). Thus, the results demonstrate that peach palm represents a strategic Amazonian matrix for obtaining phenolic-rich extracts with proven health benefits, especially when explored through innovative green solvents.

Other phenolic compounds, even at lower concentrations, significantly contributed to the bioactive profile of peach palm. There is consistent evidence that phenolic acids play a fundamental role in the antioxidant, anti-inflammatory, and antimicrobial potential of fruits (Monteiro et al., 2025; Parra-Pacheco et al., 2024; Zaky et al., 2024), as supported by DPPH, ABTS, FRAP, *ortho*-diphenols, β -carotene/linoleic acid, TRC, LPI, and α -amylase inhibition assays. Therefore, the phenolics and alkaloids present in peach palm fractions confer functional properties of strategic interest to multiple industrial sectors. Their applicability as natural substitutes for synthetic antioxidants enhances the valorization of the fruit and may support future research exploring their potential use in food, pharmaceutical, and cosmetic contexts.

Table 2

Composition of phenolic compounds in peel, pulp, and seed of peach palm extracted with different solvents.

Individual phenolic content ($\mu\text{g g}^{-1}$)					
Peel	Water	Et 80%	ChC:Lat	ChC:Ace	SUPRAS
Trigonelline	917.69 $\pm 0.16\text{c}$	706.33 $\pm 0.17\text{d}$	4511.41 $\pm 0.05\text{a}$	3449.21 $\pm 0.02\text{b}$	452.25 $\pm$ 0.02e
Galic acid	7.84 $\pm$ 0.02c	Nd.	Nd.	17.26 $\pm$ 0.02a	11.53 $\pm$ 0.01b
Catechin	14.34 $\pm$ 0.03d	3.61 $\pm$ 0.04e	15.86 $\pm$ 0.02c	19.52 $\pm$ 0.02b	795.32 $\pm$ 0.02a
Theobromine	Nd.	Nd.	Nd.	Nd.	2.05 $\pm$ 0.02a
Vanillin	Nd.	2.01 $\pm$ 0.04c	1.77 $\pm$ 0.02d	2.97 $\pm$ 0.01b	17.45 $\pm$ 0.02a
Chlorogenic acid	19.44 $\pm$ 0.16a	Nd.	Nd.	1.80 $\pm$ 0.03b	Nd.
p-Coumaric acid	3.82 $\pm$ 0.07b	2.45 $\pm$ 0.04e	3.66 $\pm$ 0.02c	3.45 $\pm$ 0.02d	4.62 $\pm$ 0.02a
Ferulic acid	7.44 $\pm$ 0.08b	Nd.	5.58 $\pm$ 0.01c	2.85 $\pm$ 0.02d	11.99 $\pm$ 0.01a
m-Coumaric acid	27.04 $\pm$ 0.04b	8.45 $\pm$ 0.02e	8.99 $\pm$ 0.01d	9.33 $\pm$ 0.02c	57.57 $\pm$ 0.02a
Coumarin	Nd.	14.78 $\pm$ 0.04a	Nd.	Nd.	Nd.
o-Coumaric acid	Nd.	Nd.	2.74 $\pm$ 0.02a	2.65 $\pm$ 0.02b	Nd.
Rosmarinic acid	Nd.	Nd.	10.11 $\pm$ 0.02a	8.73 $\pm$ 0.02b	Nd.
Pulp					
Trigonelline	102.71 $\pm 0.03\text{e}$	335.6 $\pm$ 0.01c	4800.95 $\pm 0.02\text{a}$	2592.41 $\pm 0.01\text{b}$	326.38 $\pm$ 0.01d
Galic acid	1.96 $\pm$ 0.02c	Nd.	Nd.	13.64 $\pm$ 0.01a	7.77 $\pm$ 0.01b
Catechin	Nd.	Nd.	2.68 $\pm$ 0.01b	Nd.	60.32 $\pm$ 0.01a
Theobromine	10.33 $\pm$ 0.33a	Nd.	Nd.	72.79 $\pm$ 0.02a	Nd.
Vanillin	Nd.	1.07 $\pm$ 0.02b	0.92 $\pm$ 0.02c	Nd.	19.42 $\pm$ 0.01a
Chlorogenic acid	3.49 $\pm$ 0.01a	Nd.	Nd.	Nd.	Nd.
Syringic acid	Nd.	1.85 $\pm$ 0.01b	Nd.	Nd.	5.49 $\pm$ 0.01a
p-Coumaric acid	Nd.	Nd.	1.88 $\pm$ 0.01a	1.32 $\pm$ 0.01b	Nd.
Ferulic acid	Nd.	Nd.	6.46 $\pm$ 0.01c	14.32 $\pm$ 0.02b	144.14 $\pm$ 0.02a
m-Coumaric acid	11.54 $\pm$ 0.01a	5.62 $\pm$ 0.01e	7.74 $\pm$ 0.02b	6.84 $\pm$ 0.01c	6.63 $\pm$ 0.02d
Coumarin	Nd.	9.32 $\pm$ 0.01a	Nd.	Nd.	Nd.
o-Coumaric acid	Nd.	Nd.	Nd.	Nd.	2.4 $\pm$ 0.02a
Rosmarinic acid	Nd.	Nd.	7.16 $\pm$ 0.02b	7.11 $\pm$ 0.01a	Nd.
Seeds					
Trigonelline	Nd.	302.52 $\pm 0.01\text{c}$	2850.1 $\pm$ 0.02a	2093.96 $\pm 0.02\text{b}$	124.26 $\pm$ 0.01d
Galic acid	13.92 $\pm$ 0.02c	Nd.	12.94 $\pm$ 0.01d	15.26 $\pm$ 0.01b	17.37 $\pm$ 0.01a
Theobromine	Nd.	Nd.	5.14 $\pm$ 0.01c	68.43 $\pm$ 0.07a	6.66 $\pm$ 0.02b
Chlorogenic acid	Nd.	1.80 $\pm$ 0.02b	2.40 $\pm$ 0.01a	Nd.	Nd.
Caffeic acid	Nd.	Nd.	1.62 $\pm$ 0.32b	Nd.	3.92 $\pm$ 0.01a
Vanillin	5.42 $\pm$ 0.01b	0.71 $\pm$ 0.01d	1.47 $\pm$ 0.02c	Nd.	20.1 $\pm$ 0.02a
p-Coumaric acid	2.96 $\pm$ 0.01b	1.39 $\pm$ 0.01c	8.9 $\pm$ 0.02a	Nd.	2.53 $\pm$ 0.03b
Ferulic acid	8.29 $\pm$ 0.01b	7.56 $\pm$ 0.01c	0.75 $\pm$ 0.01d	Nd.	33.40 $\pm$ 0.03a
m-Coumaric acid	nd.	1.02 $\pm$ 0.01c	32.7 $\pm$ 0.02a	Nd.	2.84 $\pm$ 0.02b
Rosmarinic acid	nd.	19.50 $\pm$ 0.02b	1.47 $\pm$ 0.02c	24.17 $\pm$ 0.01a	Nd.

Table 2 (continued)

Individual phenolic content ($\mu\text{g g}^{-1}$)					
Peel	Water	Et 80%	ChC:Lat	ChC:Ace	SUPRAS
Resveratrol	Nd.	Nd.	Nd.	Nd.	10.05 $\pm$ 0.02a
trans-Cinnamic	Nd.	Nd.	Nd.	Nd.	3.37 $\pm$ 0.01a

Note: Results are expressed as mean $\pm$ standard deviation ($n = 3$); means followed by the same lowercase letter in the same row do not differ significantly according to Tukey's test at 5% probability ($p \leq 0.05$). **Nd.**: not detected.

3.5. Multivariate analysis of the extracts obtained

A multivariate analysis was performed to assess the relationships between bioactive compounds and antioxidant capacities of the different peach palm fractions. Fig. 4 illustrates the correlations observed between identified phytochemicals and antioxidant capacity in peel (Fig. 4A), pulp (Fig. 4B), and seed (Fig. 4C). In peel and pulp, positive interactions were observed between total phenolics, flavonoids, β -carotene, and lycopene with antioxidant assays (DPPH, ABTS, TRC, LPI, and β -carotene/linoleic acid). For seeds, positive correlations were mainly observed between flavonoids, flavonols, and condensed tannins using the same antioxidant evaluation methods. Among individual phenolic compounds, catechin, vanillin, and ferulic acid stood out, all showing high correlations ($r \geq 0.80$) with antioxidant potential (DPPH, ABTS, and LPI).

Principal component analysis (PCA) demonstrated that the total variance explained was 77.6%, 73.6%, and 76.4% for peel, pulp, and seed, respectively. The principal components showed eigenvalues greater than 1, confirming the statistical relevance of the variability explained. For peel, the largest eigenvalue (14.97) was associated with PC1, which accounted for 57.6% of the variability, followed by PC2, with an eigenvalue of 5.2, explaining 20% of the variance. In pulp, eigenvalues were 13.27 (PC1) and 6.6 (PC2), corresponding to 49.1% and 24.5% of the variability, respectively. For the seed, the eigenvalues were 12.1 (PC1) and 7.0 (PC2), explaining 48.3% and 28.1% of the total variability, respectively. In peel (Fig. 4A), PC1 showed direct correlations with ferulic acid, gallic acid, catechin, vanillin, *p*- and *m*-coumaric acids, theobromine, β -carotene, and lycopene, mainly associated with the ABTS assay. Conversely, trigonelline, chlorogenic acid, and *o*-coumaric acid did not show positive correlations with antioxidant tests. PC2 was characterized by correlations between flavonoids and total phenolics with DPPH, LPI, α -amylase inhibition, and β -carotene/linoleic acid assays. These findings suggest that phenolics in the peel play a fundamental role in neutralizing free radicals, with potential antioxidant action both *in vitro* and *in vivo*.

In pulp (Fig. 4B), PC1 highlighted positive correlations between syringic acid, catechin, flavonoids, and total phenolics with TRC, LPI, and β -carotene/linoleic acid assays. PC2 showed associations between DPPH, ABTS, and FRAP with *m*-coumaric acid, condensed tannins, chlorogenic acid, and coumarin. By contrast, some compounds, such as gallic acid, *p*-coumaric acid, and rosmarinic acid, showed negative correlations (-0.1 to -0.66) with antioxidant parameters, suggesting that their contribution to antioxidant potential in pulp may be less expressive compared with other compounds. In seeds (Fig. 4C), PC1 was influenced by gallic acid, ferulic acid, vanillin, resveratrol, and trans-cinnamic acid, all of which were correlated with TRC. PC2 was primarily determined by theobromine, trigonelline, condensed tannins, chlorogenic acid, and *m*-coumaric acid, exhibiting associations with antioxidant activities as measured by DPPH, ABTS, and β -carotene/linoleic acid assays. These results reinforce that, despite presenting lower pigment concentrations, seeds significantly contribute to total antioxidant potential due to their diverse content of phenolics and bioactive alkaloids.

Overall, the high antioxidant capacity of peach palm peel, pulp, and

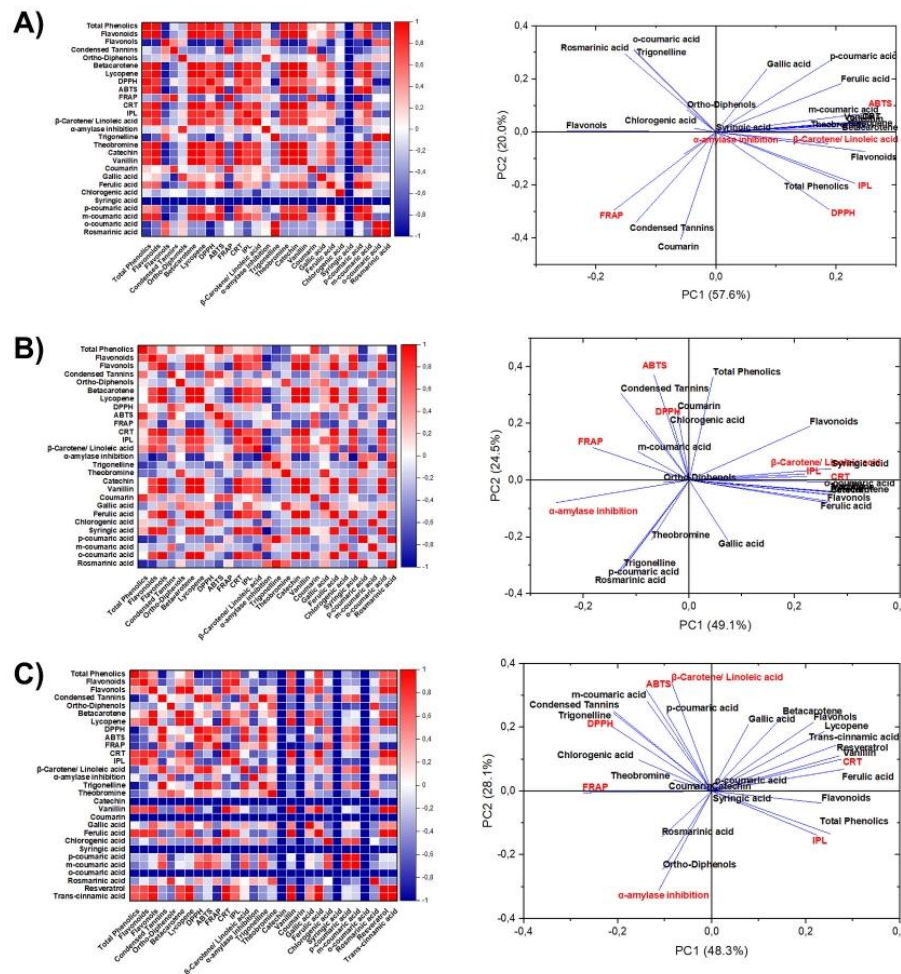


Fig. 4. Correlation and Principal Component Analysis (PCA) of total and individual phytochemicals and antioxidant potential of peach palm peel (A), pulp (B), and seeds (C). LPI: lipid peroxidation inhibition; TRC: total reducing capacity.

seed extracts can be attributed to the diversity and high concentrations of identified phenolic compounds. Acting as free-radical scavengers and lipid peroxidation inhibitors, these compounds contribute to preserving cellular integrity and modulating inflammatory processes, thereby reducing the impact of oxidative stress in biological systems. In this context, peach palm exhibits bioactive properties of broad interest, supporting future investigations into its potential functional roles in food, pharmaceutical, and cosmetic research (Leite, de Assis, et al., 2021; Morais et al., 2024; Sousa et al., 2025). These perspectives underscore the significance of the peach palm as a strategic resource for enhancing the value of sustainable production chains, thereby aligning health benefits with technological innovation.

3.6. *In vitro* gastrointestinal digestion simulation

The evaluation of compound behavior during gastrointestinal digestion enables the estimation of their stability and actual absorption potential in the human body. Simulated gastrointestinal digestion had a significant impact on the phenolic profile (Table 3) and antioxidant capacity (Fig. 5) of the pulp, peel, and seed fractions, with statistically

significant differences ($p < 0.05$). In general, a progressive decline in compound concentrations was observed throughout the oral, gastric, and intestinal phases. However, some phenolics displayed distinct behavior, suggesting structural transformations and differential release from the food matrix. Trigonelline, abundant in peel and pulp, showed a strong reduction after the oral phase to 112.80 and 92.64 mg L⁻¹, reaching low bioaccessibility values of 3.01% and 26.89%, respectively, consistent with its instability in acidic environments, where alkaloids and nitrogenated derivatives are rapidly degraded in the simulated gastrointestinal tract (Morais et al., 2025b). Conversely, ferulic acid in seeds exhibited a remarkable increase compared with the initial condition, rising to 10.27 mg L⁻¹, with bioaccessibility above 79.25%, indicating probable release of conjugated forms bound to the cell wall, a phenomenon frequently described for hydroxycinnamic acids during digestion (Li et al., 2021; Li et al., 2023). This behavior may have contributed to the maintenance of reduced activity observed in FRAP and TRC assays during the intestinal phase (Fig. 5d and f), highlighting the relevance of the seed fraction as a source of bioaccessible phenolics after digestion.

The presence of catechin in pulp and peel also reinforced this

Table 3

Phenolic profile before and after simulated *in vitro* digestion of pulp, peel, and seed of peach palm, and the bioaccessibility index of individual phenolics.

Phenolics	MF	RT	Non-digested (mg L ⁻¹)	Oral phase (mg L ⁻¹)	Gastric phase (mg L ⁻¹)	Intestinal phase (mg L ⁻¹)	Bioaccessibility (%)
Pulp							
Trigonelline	C ₇ H ₇ NO ₂	3.49	102.71 ± 0.03a	92.64 ± 1.03b	60.22 ± 2.75c	27.61 ± 2.45d	26.88
Gallic acid	C ₇ H ₆ O ₅	6.65	1.96 ± 0.02c	87.02 ± 0.40a	79.65 ± 3.32b	Nd.	Nd.
Theobromine	C ₇ H ₈ N ₄ O ₂	9.30	10.33 ± 0.33a	6.92 ± 0.79b	4.04 ± 0.03c	0.04 ± 0.01d	0.38
Catechin	C ₁₅ H ₁₄ O ₆	10.49	Nd.	13.14 ± 0.04a	10.30 ± 0.01b	Nd.	Nd.
Ferulic acid	C ₁₀ H ₁₀ O ₄	23.57	Nd.	0.84 ± 0.09a	0.77 ± 0.04a	0.39 ± 0.02b	Nd.
<i>o</i> -coumaric acid	C ₉ H ₈ O ₃	32.35	Nd.	0.10 ± 0.01a	0.09 ± 0.02a	Nd.	Nd.
<i>p</i> -coumaric acid	C ₉ H ₈ O ₃	20.65	Nd.	Nd.	Nd.	0.18 ± 0.01	Nd.
Peel							
Trigonelline	C ₇ H ₇ NO ₂	3.49	917.69 ± 0.16a	112.80 ± 16.56b	45.58 ± 0.37c	27.63 ± 0.20d	3.01
Theobromine	C ₇ H ₈ N ₄ O ₂	9.30	Nd.	0.18 ± 0.03a	0.19 ± 0.04a	0.10 ± 0.02b	Nd.
Catechin	C ₁₅ H ₁₄ O ₆	10.49	57.19 ± 2.14a	30.33 ± 0.10b	20.18 ± 1.07c	14.34 ± 0.03d	25.07
Ferulic acid	C ₁₀ H ₁₀ O ₄	23.57	7.44 ± 0.08a	1.16 ± 0.37c	0.40 ± 0.05d	3.37 ± 0.07b	45.29
<i>p</i> -coumaric acid	C ₉ H ₈ O ₃	20.65	3.82 ± 0.07a	0.20 ± 0.04b	0.17 ± 0.01b	Nd.	Nd.
Seeds							
Trigonelline	C ₇ H ₇ NO ₂	3.49	50.18 ± 0.05b	66.15 ± 3.44a	32.27 ± 0.26c	16.83 ± 0.41d	33.53
Theobromine	C ₇ H ₈ N ₄ O ₂	9.30	Nd.	0.60 ± 0.01	0.05 ± 0.01	0.25 ± 0.05	Nd.
Ferulic acid	C ₁₀ H ₁₀ O ₄	23.57	8.29 ± 0.01b	10.27 ± 0.27a	5.31 ± 0.08d	6.57 ± 0.01b	79.25
Carbohydrates							
	MF	RT	Non-digested (g L ⁻¹)	Oral phase (g L ⁻¹)	Gastric phase (g L ⁻¹)	Intestinal phase (g L ⁻¹)	Bioaccessibility (%)
Pulp							
Sucrose	C ₁₂ H ₂₂ O ₁₁	NL	13.48 ± 0.32a	1.76 ± 0.44d	10.15 ± 0.97b	2.81 ± 0.14c	20.84
Glucose	C ₆ H ₁₂ O ₆	NL	6.40 ± 0.02a	0.33 ± 0.05c	0.32 ± 0.51c	2.09 ± 0.69b	32.65
Fructose	C ₆ H ₁₂ O ₆	NL	5.32 ± 0.28a	Nd.	Nd.	5.77 ± 0.48a	Nd.
Xylose	C ₅ H ₁₀ O ₅	NL	Nd.	Nd.	Nd.	0.05 ± 0.01	Nd.
Peel							
Sucrose	C ₁₂ H ₂₂ O ₁₁	NL	8.68 ± 0.27a	4.18 ± 0.58b	0.40 ± 0.01c	0.17 ± 0.09c	1.95
Glucose	C ₆ H ₁₂ O ₆	NL	7.69 ± 0.85a	5.22 ± 0.63b	0.25 ± 0.10c	0.05 ± 0.01d	0.65
Fructose	C ₆ H ₁₂ O ₆	NL	2.25 ± 0.69a	0.35 ± 0.41b	0.04 ± 0.01c	0.63 ± 0.02b	28
Xylose	C ₅ H ₁₀ O ₅	NL	0.58 ± 0.05a	0.26 ± 0.07b	0.21 ± 0.01b	0.18 ± 0.01b	31.03
Seeds							
Sucrose	C ₁₂ H ₂₂ O ₁₁	NL	2.29 ± 0.05a	0.27 ± 0.09c	0.64 ± 0.03c	1.22 ± 0.25b	53.27
Glucose	C ₆ H ₁₂ O ₆	NL	Nd.	Nd.	0.22 ± 0.02	Nd.	Nd.
Fructose	C ₆ H ₁₂ O ₆	NL	1.36 ± 0.25a	0.23 ± 0.02b	0.07 ± 0.01c	0.30 ± 0.02b	22.05
Xylose	C ₅ H ₁₀ O ₅	NL	Nd.	Nd.	0.29 ± 0.09a	0.11 ± 0.02a	Nd.

Note: Results are presented as mean ± standard deviation ($n = 2$); means followed by the same lowercase letter in the same row do not differ statistically ($p \leq 0.05$). Nd: not detected; MF: molecular formula; RT: retention time; NL: not informed.

selective release effect. Although initial levels decreased considerably throughout the process to 10.30 and 20.18 mg L⁻¹, respectively, their detection in the oral and gastric phases, but not in the intestinal phase, suggests degradation or transformation into derivatives not quantified by the method used (Wojtunik-Kulesza et al., 2020). This finding is consistent with Morais et al. (2025b), who emphasized the susceptibility of flavanols to oxidation and intestinal pH, with direct implications for reducing free-radical scavenging activity. This dynamic partly explains the decrease in DPPH and ABTS values at the end of digestion (Fig. 5a and c), particularly in pulp, where free phenolics appear to be rapidly metabolized. Nevertheless, the release of simple phenolic acids, such as *p*-coumaric acid, detected only in the intestinal phase of pulp, suggests that matrix-bound compounds may emerge at later stages, partially sustaining residual antioxidant potential (Ketanawa et al., 2022).

In peel, the initially high concentrations of trigonelline (917.69 mg L⁻¹) and catechin (57.19 mg L⁻¹) decreased markedly during the oral phase to 112.89 and 30.33 mg L⁻¹, respectively, while ferulic acid showed moderate bioaccessibility, sustaining the antioxidant potential detected by FRAP. This result indicates that, despite the sharp reduction of major compounds, the peel still contributes to maintaining the reducing capacity. By contrast, seeds stood out for their greater stability of phenolics and the unique behavior of ferulic acid, which explains the more consistent TRC performance and the inhibitory effect observed in the LPI assay (Fig. 5e). This association between phenolic composition and lipid protection reinforces the hypothesis that bound phenolic compounds, released in the intestinal phase, are primarily responsible for prolonging antioxidant potential (Bohn et al., 2018).

In addition to the effects on antioxidant potential, the results of α -amylase inhibition (Fig. 5b) reveal another relevant functional aspect.

The progressive reduction in inhibitory capacity during digestion may be associated with the degradation of flavanols and phenolic acids, compounds previously described as enzymatic modulators (Andrade et al., 2022). A similar trend was observed by Morais et al. (2025b) in which the pulp and seed of buriirana showed reductions of 22.81% and 13.25% in phenolics, and 37.08% and 45.12% in flavonoids, respectively. This suggests that the hypoglycemic efficacy of plant extracts may be limited by the instability of phenolics under gastrointestinal conditions, although the partial persistence of activity indicates the possibility of active metabolites that have yet to be characterized. In summary, the analysis of the fractions demonstrates that the digestibility of phenolic compounds and the behavior of different antioxidant activities are not linear but rather result from the interaction among degradation, transformation, and release of bound molecules. While pulp contributes mainly in the initial phase with free phenolics, peel presents an intermediate profile, and seed emerges as the most promising fraction for intestinal bioaccessibility, especially due to the relative stability of ferulic acid. These results highlight the potential for integral utilization of the fruit as a source of bioactive compounds with different release phases, expanding the perspectives for the development of functional and nutraceutical ingredients from residues and by-products.

The evaluation of carbohydrate behavior during simulated gastrointestinal digestion provides insights into their stability, hydrolysis, and release dynamics, determining their metabolic fate. Significant differences ($p < 0.05$) were observed among pulp, peel, and seed fractions (Table 3), with a progressive transformation of disaccharides into monosaccharides, accompanied by selective degradation and delayed release of certain sugars. This dynamic reflects complex interactions between carbohydrate structure and the food matrix (Minekus et al.,

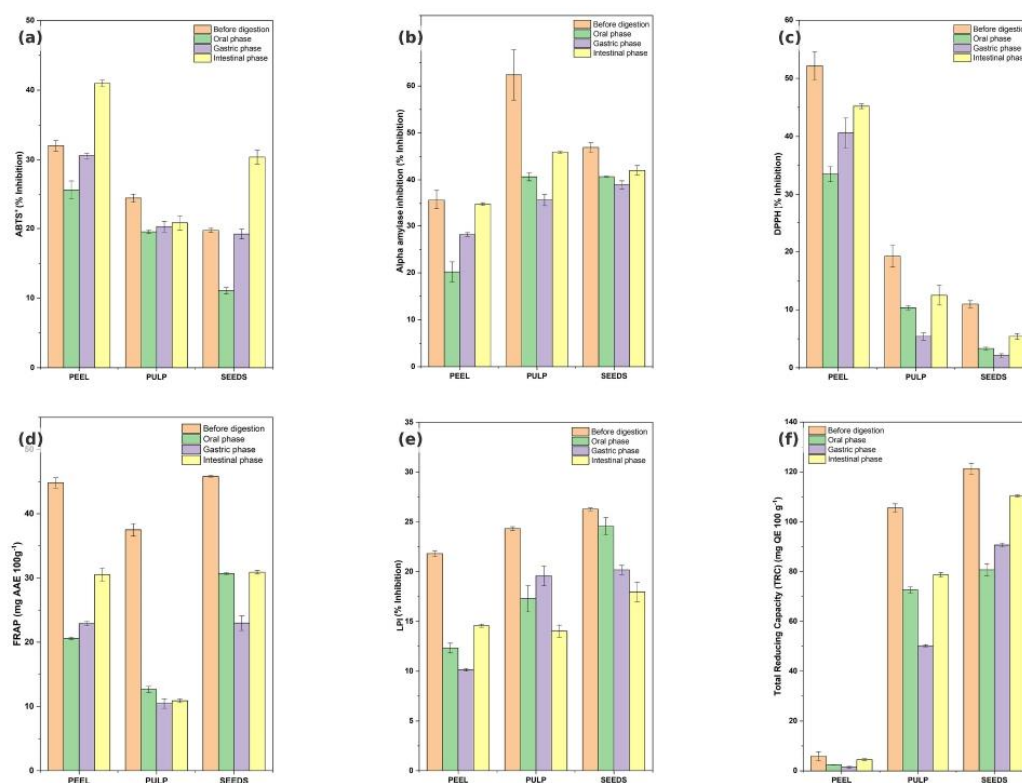


Fig. 5. Antioxidant activity and *in vitro* digestibility of peel, pulp, and seeds during simulated gastrointestinal digestion: (a) ABTS^{•+} radical scavenging activity (% inhibition), (b) α -amylase inhibition (% inhibition), (c) DPPH radical scavenging activity (% inhibition), (d) ferric reducing antioxidant power (FRAP, mg AAE 100 g⁻¹), (e) lipid peroxidation inhibition (LPI, % inhibition), and (f) total reducing capacity (TRC, mg QE 100 g⁻¹). Results are expressed as mean $\pm$ standard deviation ($n = 3$). Different digestion phases: before digestion, oral, gastric, and intestinal.

2014). In the pulp, sucrose markedly decreased during the oral phase but partially recovered in the gastric phase before declining again in the intestinal phase, with 20.84% bioaccessibility, suggesting effects of hydrolysis and matrix entrapment (Welcome, 2018). Glucose remained at low levels initially but increased to 2.09 g L⁻¹ in the intestinal phase (32.65% bioaccessibility), probably due to sucrose degradation (Diot et al., 2021). Fructose was absent in the early phases but appeared in the intestinal phase (5.77 g L⁻¹), consistent with delayed release of conjugated forms (Ferreira-Lazarte et al., 2020). Minor sugars, such as xylose, showed low recoveries, possibly associated with partial degradation or microbial interactions (Di Cairano et al., 2022).

The peel exhibited rapid sucrose hydrolysis and low intestinal availability (1.95% bioaccessibility). Glucose followed a similar trend, confirming the limited release of monosaccharides (Leon et al., 2023). In contrast, fructose reached moderate bioaccessibility (28%), while xylose remained detectable in all phases, reaching 31.03% bioaccessibility, consistent with hemicellulosic degradation and potential prebiotic contributions (Saura-Calixto et al., 2010). Seeds displayed a distinct pattern, with sucrose significantly increasing to 1.22 g L⁻¹ in the intestinal phase (53.27% bioaccessibility), suggesting the release of bound forms facilitated by cell wall disruption (Leon et al., 2023; Atzler et al., 2021). Fructose persisted at low levels (22.05% bioaccessibility), whereas xylose appeared in later phases, reinforcing the role of structural carbohydrates (Ferreira-Lazarte et al., 2020).

Overall, the digestion dynamics highlight that carbohydrate release and stability are strongly matrix-dependent. The pulp mainly contributed to intestinal fructose availability (5.77 g L⁻¹), the peel provided

moderate amounts of xylose (0.18 g L⁻¹) and fructose (0.63 g L⁻¹), and the seeds exhibited a distinctive ability to release bound sucrose (2.29 g L⁻¹). These differences may influence glycemic response, colonic fermentation potential, and the development of functional applications. Thus, while pulp represents a conventional source of free sugars, the seed fraction stands out for its high sucrose bioaccessibility, and the peel contributes complementary pentoses, reinforcing the potential for integral utilization of peach palm in nutraceutical formulations (Alongi et al., 2019; Holscher, 2017; Xavier & Mariutti, 2021).

3.7. Microbiological inhibition analysis

3.7.1. Determination of minimum inhibitory concentration (MIC)

The evaluation of the antimicrobial activity of peach palm extracts revealed marked differences according to the type of solvent used and the fruit fraction analyzed. Overall, alternative solvents such as lactic acid- and acetic acid-based eutectics, in addition to SUPRAS, were more efficient in extracting compounds with antimicrobial activity. In contrast, neither the aqueous nor the ethanolic extracts showed significant activity (Table 4).

In the bacterial assays, the extracts obtained with the lactic acid-based eutectic solvent stood out due to the lowest MIC (Table 5), particularly against *Staphylococcus aureus* and *Listeria monocytogenes*, reaching values of 97.66 μ g mL⁻¹. These results suggest that the organic acids present in the system not only favor the solubilization of phenolics and other bioactive compounds but also contribute directly to antimicrobial activity through mechanisms related to intracellular

Table 4

Antimicrobial activity of peach palm extracts obtained with different solvents.

Solvents	MIC ($\mu\text{g mL}^{-1}$)			
	<i>S. aureus</i>	<i>L. monocytogenes</i>	<i>E. coli</i>	<i>Salmonella sp.</i>
SUPRAS Peel	195.31	195.31	195.31	195.31
SUPRAS Pulp	195.31	195.31	195.31	195.31
SUPRAS Seed	195.31	195.31	195.31	195.31
Water Peel	Nd.	Nd.	Nd.	Nd.
Water Pulp	Nd.	Nd.	Nd.	Nd.
Water Seed	Nd.	Nd.	Nd.	Nd.
ChC: Ace Peel	390.63	781.25	195.31	Nd.
ChC: Ace Pulp	390.63	781.25	195.31	Nd.
ChC: Ace Seed	390.63	781.25	195.31	Nd.
Et 80% Peel	Nd.	Nd.	Nd.	Nd.
Et 80% Pulp	Nd.	Nd.	Nd.	Nd.
Et 80% Seed	Nd.	Nd.	Nd.	Nd.
ChC: Lat Peel	97.66	97.66	781.25	Nd.
ChC: Lat Pulp	97.66	97.66	Nd.	Nd.
ChC: Lat Seed	97.66	195.31	Nd.	Nd.
Antibiotic*	0.12	0.5	1	1

Note: **Nd.**: No antimicrobial activity observed. *Amoxicillin was used as the positive control for the bacterium.

Table 5

Minimum bactericidal concentration of peach palm extracts obtained with different solvents.

Solvents	MBC ($\mu\text{g mL}^{-1}$)			
	<i>S. aureus</i>	<i>L. monocytogenes</i>	<i>E. coli</i>	<i>S. enterica</i>
SUPRAS Peel	195.31	195.31	195.31	195.31
SUPRAS Pulp	195.31	195.31	195.31	195.31
SUPRAS Seed	195.31	195.31	195.31	195.31
ChC: Ace Peel	390.63	781.25	195.31	Nd.
ChC: Ace Pulp	390.63	781.25	195.31	Nd.
ChC: Ace Seed	390.63	781.25	195.31	Nd.
ChC: Lat Peel	97.66	97.66	781.25	Nd.
ChC: Lat Pulp	97.66	97.66	Nd.	Nd.
ChC: Lat Seed	97.66	195.31	Nd.	Nd.

Note: **Nd.**: No antimicrobial activity observed.

acidification and membrane destabilization (Oussaid et al., 2017). This effect was particularly evident in Gram-positive bacteria, which are more susceptible to the action of phenolic compounds and low-molecular-weight acids (Sousa et al., 2015).

The extracts obtained with SUPRAS demonstrated a distinct profile, showing uniform activity against all evaluated bacteria, including Gram-negative strains such as *Escherichia coli* and *Salmonella enterica*. This characteristic may be related to the system's ability to extract amphiphilic compounds, such as carotenoids and terpenoids, which have an affinity for the outer membrane of Gram-negative bacteria (Ballesteros-Gómez et al., 2010; Torres-Valenzuela et al., 2019). Although the MIC and MBC values ($195.31 \mu\text{g mL}^{-1}$) are not low when compared to reference antibiotics, the broader spectrum of action reinforces the potential of SUPRAS as a solvent for obtaining bioactive extracts with applications in combined systems. This behavior is consistent with reports in studies on other palm species, such as buriti, in which supramolecular extracts, despite requiring high concentrations for inhibition, demonstrated the ability to modulate the action of conventional antibiotics (Leite, Barreto, et al., 2021).

3.7.2. Disk diffusion

Table 6 shows the antifungal performance of peach palm extracts against *Aspergillus flavus*, *A. niger*, and *A. ochraceus*. Regarding antifungal tests, the extracts obtained using the lactic acid-based eutectic solvent from the pulp exhibited the largest inhibition zones against *A. flavus*, *A. niger*, and *A. ochraceus*, with values ranging from 18 to 23 mm, demonstrating a broad spectrum of action. Extracts obtained with the acetic acid-based solvent showed moderate activity. In contrast, those

Table 6

Antifungal activity of peach palm extracts obtained with different solvents.

Solvent	<i>A. flavus</i>	<i>A. niger</i>	<i>A. ochraceus</i>
ChC: Lat Pulp	18.75 ^{Aa}	22.75 ^{Aa}	23.00 ^{Aa}
ChC: Lat Peel	18.00 ^{Aa}	17.50 ^{Ba}	22.75 ^{Aa}
ChC: Lat Seed	12.75 ^{Ba}	20.50 ^{Aa}	22.75 ^{Aa}
ChC: Ace Pulp	8.25 ^{Ca}	11.25 ^{Cb}	12.50 ^{Cb}
ChC: Ace Peel	8.00 ^{Ca}	12.75 ^{Cb}	12.00 ^{Cb}
ChC: Ace Seed	7.75 ^{Ca}	12.75 ^{Cb}	13.00 ^{Cb}
SUPRAS Pulp	0.00 ^{Da}	14.50 ^{Bb}	14.75 ^{Bb}
SUPRAS Peel	0.00 ^{Da}	14.50 ^{Bb}	14.50 ^{Bb}
SUPRAS Seed	0.00 ^{Da}	11.75 ^{Cb}	15.25 ^{Bb}

Note: Uppercase letters in the column indicate comparisons among extracts for each fungus; lowercase letters in the row indicate comparisons among fungi for each extract, based on the Scott-Knott test ($p < 0.05$).

obtained with SUPRAS exhibited a selective effect, with no inhibition against *A. flavus* but consistent results against *A. niger* and *A. ochraceus*. This selectivity may be attributed to the limited diffusion of hydrophobic compounds in agar medium (Mahdavi et al., 2020), highlighting the importance of interpreting disk diffusion results with caution and considering MIC and MBC assays as more reliable parameters for this type of matrix.

In general, the peel and pulp exhibited higher activity than the seed, which can be attributed to the greater concentration of phenolics and tannins in these fractions (Bataglion et al., 2014; Koolen et al., 2013). This pattern is consistent with observations in other species of the *Arecaceae* family, in which protective and storage tissues contain higher levels of secondary metabolites with defensive functions, such as those found in buriti (Leite, de Assis, et al., 2021). Although the MIC values observed are still higher than those of conventional antibiotics, the results demonstrate the potential of peach palm as a source of compounds with antimicrobial activity. Rather than directly replacing antimicrobials used in clinical practice, the studied extracts may act as adjuvants, either in food preservation or in combined formulations capable of reducing the therapeutic doses of antibiotics (Figueredo et al., 2013; Saraiva et al., 2011). The use of green solvents, such as DES and SUPRAS, further reinforces the sustainable perspective of this study, integrating the valorization of biodiversity resources with the search for safer and more ecological alternatives for bioactive extraction.

4. Conclusion

The present study demonstrated that peach palm (*Bactris gasipaes*) is a food matrix of high functional value, with peel, pulp, and seed fractions exhibiting distinct profiles of bioactive compounds and relevant biological activities. The application of emerging green solvents, especially supramolecular systems (SUPRAS) and deep eutectic solvents (DES), proved to be more efficient and selective than conventional solvents, with SUPRAS standing out for enhancing the extraction of carotenoids, flavonoids, and total phenolics by overcoming plant matrix barriers and facilitating the recovery of hydrophobic molecules. The results also revealed high antioxidant activity and consistent antimicrobial action against the bacteria *S. aureus*, *E. coli*, *L. monocytogenes*, and *S. enterica* as well as the toxigenic fungi *A. flavus*, *A. niger*, and *A. ochraceus*, reinforcing the multifunctional character of the extracts. Furthermore, the *in vitro* digestibility assays demonstrated that compound bioaccessibility varies among fractions, with the seed being the most stable in the intestinal phase, suggesting potential applications in formulations targeting intestinal health and glycemic control. Collectively, the findings highlight the potential of green solvents for the valorization of peach palm and for obtaining biodegradable and bioactive extracts. However, any practical application in food, cosmetic, or pharmaceutical sectors remains dependent on further studies addressing toxicological safety, formulation stability, large-scale feasibility, and *in vivo* bioavailability.

CRedit authorship contribution statement

Hermanny Matos Silva Sousa: Conceptualization, Data curation, Formal analysis, Investigation, Validation, Visualization, Writing – original draft. **Gabriela Fonsêca Leal:** Data curation, Formal analysis, Investigation, Validation, Visualization. **Wellington Barros dos Santos:** Formal analysis, Investigation, Validation. **Rômulo Alves Moraes:** Formal analysis, Data curation, Writing – original draft. **Glendara Aparecida de Souza Martins:** Conceptualization, Resources, Supervision, Project administration, Visualization, Writing – review & editing. **Fabiana Queiroz:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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ARTICLE 3 - INFLUENCE OF EXTRACTION METHOD ON STRUCTURAL, RHEOLOGICAL, AND NUTRITIONAL CHARACTERIZATION OF PEACH PALM (*Bactris gasipaes*) FRUITS PULP AND PEEL OILS

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Abstract

This study investigated how the extraction protocol (isooctane-based vs ethanol-based) and fruit fraction (pulp vs peel) shape the chemical composition and multiscale structure of peach palm (*Bactris gasipaes*) oils. Oils were characterized by fatty-acid and triacylglycerol profiling, carotenoid quantification, differential scanning calorimetry, polarized light microscopy, small- and wide-angle X-ray scattering, and oscillatory rheology. All samples were rich in oleic acid (up to 63.98%) and showed favorable nutritional indices, while carotenoids were detected at high levels. Thermal analysis indicated extraction protocol- and fraction-dependent transitions, with pulp oil obtained by the isooctane-based protocol and peel oil obtained by the ethanol-based protocol exhibiting structured (solid/semi-solid) behavior at 20 °C. Microscopy, scattering and rheology supported the development of interconnected crystal networks and organized lipid domains in these structured oils. Overall, extraction conditions

modulated lipid organization and functionality, supporting peach palm pulp and peel oils as sustainable ingredients for food and cosmetic formulations.

Keywords: Green solvent; Lipid structure; Carotenoids; Physical properties; Brazilian fruit.

1. Introduction

Vegetable oils play a central role in the human diet, serving as primary energy sources, providing essential fatty acids, and transporting lipophilic bioactive compounds (Polmann et al., 2024; Gualberto et al., 2025; Morais et al., 2022, Tian et al., 2023). Oils are widely used as ingredients in a wide range of food products. Based on their fatty acid composition and presence of highly relevant minor constituents, such as carotenoids, tocopherols, and phytosterols (Ibiapina et al., 2021), vegetable oils greatly affect the nutritional and technological (e.g., rheological and sensory) functionalities of food products.

In the current scenario, the demand for novel and sustainable lipid sources has intensified due to the need to diversify the global oil supply chain, reduce dependence on a limited number of commodity oils, and mitigate the environmental and socio-economic impacts associated with conventional oilseed cultivation, such as land-use change, deforestation, and high agricultural inputs (Tian et al., 2023). In addition to sustainability concerns, economic factors, including price volatility, supply insecurity, and growing industrial demand for tailored lipid functionalities, have further driven the search for alternative vegetable fats.

In this context, there is increasing interest in the valorization of lipid sources from underexplored regions, particularly Amazonia, which can be sourced from non-intensive systems, agroforestry practices, or extractive chains, contributing to biodiversity conservation and local economic development (Montoro-Alonso et al., 2025).

Peach palm (*Bactris gasipaes*), an Amazonian species of the *Arecaceae* family, is a promising source of edible oils. Its fruits present significant lipid contents (approximately 7.5% in the peel and 6.5% in the pulp), and the extracted oils are characterized by a predominance of unsaturated fatty acids, particularly oleic acid (54%), resulting in a relevant proportion of polyunsaturated fatty acids, which are nutritionally desirable and technologically relevant for food and cosmetic applications (Ibiapina et al., 2021; Sousa et al., 2025). Moreover, notable concentrations of natural pigments, especially carotenoids (around 34.74 mg 100 g⁻¹ in the peel), can be co-extracted with the oil, conferring it remarkable health-promoting capacity (Miranda et al., 2024; Sousa et al., 2025). Yet, despite its chemical characteristics, peach palm

fruit remains underexploited for lipid valorization, as its industrial use is still largely focused on fresh consumption and starch-rich products, while lipid-rich fractions are often overlooked. The integrated utilization of peach palm fruit fractions, particularly the peel, which is commonly discarded during processing, represents a strategic opportunity to obtain high-value-added oil. This approach aligns with current trends in sustainable food production by reducing agro-industrial waste, improving resource efficiency, and promoting the circular economy, while simultaneously enabling the development of novel lipid ingredients from an underutilized raw material.

The extraction process used to separate the lipid fraction plays a decisive role in the yield and characteristics of vegetable oils. Traditional apolar solvents, such as isooctane and *n*-hexane, are effective at solubilizing nonpolar lipids, but their toxicity and environmental concerns have spurred the search for safer, more sustainable alternatives (Freitas et al., 2024; Morais et al., 2025). Ethanol, on the other hand, is classified as a green solvent, combining characteristics of low toxicity, biodegradability, and intermediate polarity, allowing the simultaneous extraction of neutral lipids and nonpolar compounds, such as carotenoids (Gomaa et al., 2022; Menezes Silva et al., 2023). Therefore, the comparative evaluation of solvents with different polarities could provide valuable insights for a better understanding of the interactions among the solvent, matrix, and target compounds, as well as their influence on the physicochemical and structural characteristics of the extracted oils. Furthermore, the technological performance and functional properties of oils are closely related to their molecular organization and their thermal and rheological properties. The fatty acid composition of triacylglycerols, particularly the proportion of monounsaturated fatty acids (MUFA), together with minor lipid components, such as carotenoids, can influence triacylglycerol crystallization pathways and affect polymorphism, viscosity, and melting behavior (Sivakanthan et al., 2022). These attributes are essential for predicting product stability, texture, and performance in food formulations.

Despite the remarkable chemical and functional attributes of the lipid fraction of peach palm fruits, limited studies have explored the multiscale relationships between its oil structure and properties, as well as the influence of extraction solvents on its chemical composition and crystallization behavior. Based on these premises, the aim of the present study was to investigate how distinct extraction protocols influence the chemical characterization (fatty acids, triacylglycerols) of the recovered oils and their structural (differential scanning calorimetry, polarized light microscopy, small- and wide-angle X-ray scattering), rheological (frequency sweep), and nutritional (quantification of β -Carotene and lycopene) properties of

the lipid fraction of peach palm fruits. The novelty of this study lies in the integrative characterization of peach palm oils using complementary techniques, providing the first comprehensive correlation between chemical composition, structural hierarchy, and functional performance, advancing the sustainable use of Amazonian palm lipids in food systems.

2. Materials and methods

2.1 Chemicals and reagents

Isooctane ($\geq 99.0\%$) and pentane ($\geq 99.0\%$) were purchased from Sigma Aldrich (Milan, Italy). Absolute ethanol was purchased from Sigma Aldrich (São Paulo, Brazil). The fatty acid standards used were 20, including saturated (SFA) (lauric (12:0), myristic (C14:0), pentadecanoic (C15:0), palmitic (C16:0), heptadecanoic (C17:0), stearic (C18:0), arachidic (C20:0), heinacosanoic (C21:0), behenic (C22:0), tricosanoic (C23:0), and lignoceric (C24:0) acids), monounsaturated (MUFA) (palmitoleic acid *n*7 (C16:1 *n*-7) and *n*9 (C16:1 *n*-9), heptadecenoic (C17:1), oleic (C18:1), and eicosenoic (C20:1) acids), and polyunsaturated (PUFA) (linoleic (18:2), α -linolenic (C18:3), eicosadienoic (C20:2), and *cis*-13,16-docosadienoic (C22:2) acids) purchased from Sigma Aldrich (Milan, Italy).

2.2 Sample

The peach palms were obtained in the state of Pará, Brazil (latitude 08°01'43" S, longitude 50°01'53" W), located in the Amazon region. The fruits were washed and sanitized with 100 ppm sodium hypochlorite. The fruits were then pulped, separated into peel, pulp, and seed fractions, and dried in an oven with air circulation (Solab - SL102) at 50 °C until constant weight. The dried pulp and peel were ground in a knife mill to a standard size of 1.00 mm (TECNAL - TE₆₅₀), yielding peach palm pulp and peel flours. The flours were vacuum-packed and stored at -20 °C until analysis.

2.3 Oil extraction protocols

Oils were extracted from peach palm pulp (PU) and peel (PE) flours using two extraction protocols, which differed in both solvent polarity and operating conditions. For the non-polar

protocol, 50 g of PU-ISO or PE-ISO flour was mixed with 500 mL of isooctane analytical grade (A.G) (solid-to-solvent ratio 1:10, w/v) in glass bottles and homogenized using an Ultra-Turrax (T18, IKA) at 10,000 rpm for 15 min. The mixtures were filtered through quantitative filter paper, and the solvent was removed using a rotary evaporator (Heidolph) coupled to a vacuum pump (Vacuum Pump V-700, Büchi, Switzerland). The recovered oils were re-dissolved in pentane (A.G), transferred to amber vials, and the pentane was evaporated under a nitrogen stream.

For the polar protocol, 50 g of PU-ET or PE-ET flour was mixed with 500 mL of ethanol (A.G) (1:10, w/v), incubated at 50 °C for 4 h under constant agitation, and then filtered and centrifuged at 17,000 rpm at 4 °C to separate the solvent from the oil. The headspace of the vials containing the extracted oils was flushed with nitrogen, and samples were stored at −20 °C until analysis. Extraction yield was determined gravimetrically as the ratio of the mass of oil recovered after solvent removal and the initial dry mass of flour used, and expressed as a percentage (%).

2.4 Chemical characterization

2.4.1 Fatty acid composition

The reference procedure was performed according to the method described by the International Olive Council (IOC method T20-33-rev-1, 2017). Aliquots of 0.1 g of oil were mixed with 2 mL of *n*-heptane and 0.2 mL of 2 N methanolic KOH solution, shaken vigorously for 30 s and then left to stratify. The upper phase containing fatty acids methyl esters was analyzed (injection volume 1 µL). The analysis was carried out on a Gas Chromatograph (GC) Trace 1300 (Thermo Fisher Scientific) coupled to an FID detector. The chromatographic conditions were as follows: capillary column of fused silica SP-2330 (Supelco, USA), 60 m long with 0.32 mm internal diameter, filled with 0.2 µm polyethylene glycol. The operating conditions were: Split injection, 50:1 ratio; Column temperature: 100 °C for 5 min, programmed for an elevation rate of 5 °C per min to 200 °C, then an elevation rate of 3 °C per min to 240 °C held for 8 min (total run time 40 min). Helium was the carrier gas at 130 kPa constant pressure. Injector and detector temperatures are both 250 °C. The qualitative composition was determined by comparing peak retention times with the relevant fatty acid standards. The quantitative composition was expressed as relative peak area (%).

2.4.2 Nutritional and health indices

Based on the fatty acid composition of PU and PE extracted oils, the nutritional value (NVI), atherogenicity (AI), thrombogenicity (TI) and hypo- and hypercholesterolemic (HH) were calculated (Chen & Liu, 2020; Polmann *et al.*, 2024) according to the following equations:

$$NVI = \frac{(C18:0+C18:1)}{(C16:0)} \quad (1)$$

$$AI = \frac{C12:0+4 \times C14:0+C16:0}{\sum MUFA + \sum FA\omega6 + \sum FA\omega3} \quad (2)$$

$$TI = \frac{C14:0+C16:0+C18:0}{(0.5 \times \sum MUFA) + (0.5 \times \sum FA\omega6) + (0.5 \times \sum FA\omega3)} \quad (3)$$

$$HH = \frac{(C18:1 + \sum PUFA)}{(C12:0+C14:00+C16:00)} \quad (4)$$

Where C12:0, C14:0, C16:0, C18:0 and C18:1 represent the relative mass percentages of lauric, myristic, palmitic, stearic and oleic acids, respectively; MUFA refers to the relative mass percentage of monounsaturated fatty acids; FA ω6 and FA ω3 indicate the relative mass percentages of omega-6, omega-3 fatty acids, PUFA refers to the relative mass percentage of polyunsaturated fatty acids,

2.4.3 Estimation of triacylglycerol composition

The composition of triacylglycerols (TAG) was estimated using the *PrOleos* software, as reported by Antoniosi Filho *et al.* (1995). The algorithm estimates the triacylglycerol content based on the *1,3-random 2-random* distribution hypothesis, which predicts the molar percentage of triacylglycerols in vegetable oils. This method utilizes a random distribution model (without preference for the *sn* 1, 2, and 3 positions) of free fatty acids on the glycerol backbone, using the fatty acid composition of the sample as input data.

2.4.4 Determination of β-carotene and lycopene by HPLC

β -Carotene and lycopene were extracted under subdued light and in a nitrogen atmosphere according to the method proposed by Bot et al. (2018), with minor modifications. Chromatographic separation was carried out at 25 °C using a YMC C30 column. Aliquots of 200 μ L of PU-ET, PU-ISO, PE-ET, and PE-ISO of oil melted at 40°C were diluted in 2.0 mL of solvent mixture A–B (50:50, v/v) and filtered through a 0.20 μ m membrane filter prior to HPLC analysis. The mobile phase consisted of two eluents: eluent A, composed of methanol and methyl tert-butyl ether (MTBE) (90:10, v/v) containing 0.1% (w/v) BHT, and eluent B, composed of MTBE (10:90, v/v) also containing 0.1% (w/v) BHT. Both mobile phases were freshly prepared and vacuum-filtered before use. Elution was performed at a flow rate of 1.0 mL/min. Detection was carried out using a diode-array detector at 450 nm for β -carotene and 470 nm for lycopene. The gradient elution profile, expressed as the proportion of solvent A, was as follows: 0–2 min, 88–73%; 2–4 min, 73–57%; 4–6 min, 57–43%; 6–8 min, 43–20%; 8–9.5 min, 20–0%; 9.5–14 min, 0–0%; 14–15 min, 0–88%; and 15–22 min, 88–88%. Carotenoids were quantified using external calibration curves, using peak areas. Concentrations obtained from the chromatograms were corrected for the total dilution factor applied during sample preparation. All analyses were performed in duplicate, and data processing was carried out using STAR software version 5.3 (Varian).

2.5 *Physical properties*

2.5.1 *Differential Scanning Calorimetry (DSC)*

To perform calorimetric analyses, aliquots of each oil sample were accurately weighed (~5 mg) in 40 μ L aluminum pans and sealed (Mettler-Toledo, Greifensee, Switzerland). The pans were then placed in the sensor cell of a DSC 3 StarE® System (Mettler-Toledo) and subjected to the following temperature ramp: 20 °C for 3 min; 20 to 80 °C at 5 °C min⁻¹ (to remove thermal history); 80 °C for 3 min; 80 to -50 °C at -5 °C min⁻¹; -50 °C for 3 min; -50 to 80 °C at 5 °C min⁻¹. Normalized heat flow (W g⁻¹) was recorded using an empty pan as reference, and the entire analysis was performed under gentle nitrogen flow to limit sample oxidation. Peak temperatures and transition enthalpies were calculated from the obtained thermograms by using the STARe program ver. 16.10 (Mettler-Toledo).

2.5.2 *Synchrotron X-ray Diffraction*

Small-angle X-ray scattering (SAXS) and wide-angle X-ray scattering (XRD) analyses were performed at 20 °C at the SOLEIL synchrotron light facility in Saint-Aubin, France, using the SWING beamline with photon energies of approximately 12 keV (SAXS) and 16 keV (XRD). Four peach palm oil samples (PU-ET, PU-ISO, PE-ET, and PE-ISO) were loaded into glass capillaries. The scattering intensity was recorded by a detector positioned at distances of approximately 0.5 m and 6.5 m from the sample, allowing data acquisition over a scattering vector q range from 1.5×10^{-3} to $1.4 \times 10^{-1} \text{ \AA}^{-1}$. For each sample, data were initially collected with a short exposure time (~ 0.2 s) to minimize potential radiation damage and avoid artifacts in the low q region. Subsequent recordings were made with longer exposure times (~ 15 s) using a wider light beam to improve the signal-to-noise ratio at high q values. The intensities obtained at both exposure times were radially processed and combined into a single $I(q)$ scattering curve, discarding segments with evidence of radiation-induced degradation. The solvent (ultra-pure water) scattering intensity was recorded under the same conditions and subtracted from the data for each sample, resulting in the corrected $I(q)$ intensity (Nogueira et al., 2023). For data interpretation, Porod's Law was applied in the high- q region to analyze the interfaces between domains of contrasting electron density. Additionally, the Guinier Equation was used in the low- q region, allowing the estimation of the radius of gyration (R_g) of the dispersed particles present in the oils (Chen et al., 2022). The curve fitting of $I(q)$ was performed in the Guinier regime, where the equation $I(q) = I(0)\exp(-q^2 R_g^2/3)$ was applied to determine the radius of gyration. This approach allowed the evaluation of the structural and supramolecular properties of the different lipid samples, depending on the solvent and the portion of the fruit used in the extraction.

2.5.3 Rheological analysis

The rheological properties of the oils were assessed using a controlled-stress rheometer (Haake Rheostress 6000, Thermo Scientific, Karlsruhe, Germany). A plate-plate geometry (35 mm, 1 mm gap) was used to carry out frequency sweep analyses within a 0.1 to 100 Hz range at 20 °C. A shear stress value comprised within the linear viscoelastic domain of each oil was applied for all frequency sweep tests. Before testing, the samples were allowed to rest for 5 min to ensure relaxation of internal stress.

2.6 Polarized light microscope (PLM)

The samples were prepared by pouring a small amount of oil onto a glass microscope slide and then covering it with a coverslip. Then, gentle pressure was applied to ensure adequate thickness for measurement. The samples were preheated to 60 °C for 10 min to erase the crystal memory, then cooled at 5 °C min⁻¹ to 20 °C using a water-cooling system attached to the microscope. Images were captured at 40× magnification using a microscope (Leica Microsystems, Wetzlar, Germany) operated with Leica Suite Las EZ software (Leica Microsystems, Heerbrugg, Switzerland), and saved in JPEG format.

2.7 Statistical analysis

The results were expressed as mean ± standard deviation. Measurements were performed in duplicate or triplicate, as indicated in the corresponding tables and figure captions. Data were analyzed using analysis of variance (ANOVA) at a 5% significance level ($p < 0.05$) using Statistica 10.0 software (StatSoft Inc., Tulsa, OK, USA). Prior to parametric comparisons, data were checked for normality and homogeneity of variances. When the homogeneity assumption was met, differences among means were assessed by ANOVA followed by Tukey's test. When variances were not homogeneous, Welch's ANOVA was applied. Synchrotron SAXS and XRD data were analyzed using the SasView software (SasView-6.1.1).

3 Results and discussion

3.1 Chemical characterization

Extraction yield was significantly affected by the extraction protocol ($p < 0.05$), with the ethanol-based protocol providing higher yields than the isooctane-based protocol for both pulp and peel oils (Table 1). Moreover, yields were slightly higher for pulp oils than for peel oils. No significant protocol × fraction interaction was detected, indicating that the yield increase observed from the isooctane-based to the ethanol-based protocol was comparable for both pulp and peel oils.

The fatty acid composition of the extracted oils is also reported in Table 1. Twenty fatty acids were identified in the analyzed peach palm oils, with wide variation between the pulp and

peel samples, and additional variations observed between the extraction protocol. The results showed that the samples had a predominance of monounsaturated fatty acids (MUFAs), followed by saturated fatty acids (SFA) and polyunsaturated fatty acids (PUFAs), as shown in Table 1. This distribution is typical of tropical oils from fruits of the *Arecaceae* family (Gualberto et al., 2025; Ibiapina et al., 2021).

Table 1. Fatty acids and health indices oils from pulp and peels oils of peach palm.

Analysis	PU-ISO	PU-ET	PE-ISO	PE-ET
Yield (%)	15±0.1 ^c	20±0.17 ^a	13±0.12 ^d	18±0.23 ^b
Fatty acid (%)				
C12:0 - Lauric acid	0.05 ± 0.01 ^a	0.01 ± 0.00 ^a	0.02 ± 0.00 ^a	0.02 ± 0.00 ^a
C14:0 - Myristic acid	0.15 ± 0.01 ^a	0.07 ± 0.01 ^b	0.11 ± 0.00 ^a	0.08 ± 0.01 ^b
C15:0 - Pentadecanoic acid	0.04 ± 0.00 ^a	0.04 ± 0.00 ^a	0.06 ± 0.00 ^a	0.06 ± 0.00 ^a
C16:0 - Palmitic acid	17.96 ± 0.1 ^c	33.92 ± 0.25 ^a	30.44 ± 0.41 ^b	34.05 ± 0.20 ^a
C16:1 ω9 - Palmitoleic acid	0.20 ± 0.29 ^a	0.49 ± 0.20 ^a	0.06 ± 0.00 ^b	0.07 ± 0.00 ^b
C16:1 ω7 - Palmitoleic acid	4.70 ± 0.25 ^a	3.96 ± 0.01 ^{bc}	4.34 ± 0.20 ^{ab}	3.80 ± 0.01 ^c
C17:0 - Heptadecanoic acid	0.07 ± 0.01 ^a	0.05 ± 0.05 ^a	0.06 ± 0.00 ^a	0.06 ± 0.00 ^a
C17:1 ω8- Heptadecenoic acid	0.05 ± 0.00 ^a	0.04 ± 0.00 ^a	0.05 ± 0.01 ^a	0.05 ± 0.00 ^a
C18:0 - Stearic acid	1.29 ± 0.10 ^c	1.55 ± 0.11 ^a	1.34 ± 0.01 ^b	1.47 ± 0.22 ^{ab}
C18:1 ω9 - Oleic acid	63.98 ± 0.23 ^a	53.06 ± 0.37 ^b	53.22 ± 0.06 ^b	51.80 ± 0.51 ^b
C18:2 ω6 - Linoleic acid	7.64 ± 0.01 ^a	5.36 ± 0.02 ^c	7.79 ± 0.05 ^a	6.18 ± 0.03 ^b
C20:0 - Arachidic acid	0.18 ± 0.00 ^a	0.13 ± 0.00 ^b	0.18 ± 0.01 ^a	0.18 ± 0.00 ^a
C18:3 ω3 - α-Linolenic acid	3.14 ± 0.02 ^a	1.18 ± 0.02 ^c	2.03 ± 0.02 ^b	1.91 ± 0.28 ^b
C20:1 ω9 - Eicosenoic acid	0.13 ± 0.00 ^a	0.06 ± 0.00 ^b	0.10 ± 0.02 ^a	0.08 ± 0.00 ^{ab}
C21:0 - Heinecosanoic acid	0.01 ± 0.00 ^a	0.01 ± 0.00 ^a	0.01 ± 0.00 ^a	0.01 ± 0.00 ^a
C20:2 - Eicosadienoic acid	ND	ND	ND	ND
C22:0 - Behenic acid	0.40 ± 0.00 ^a	0.04 ± 0.01 ^b	0.08 ± 0.03 ^b	0.04 ± 0.01 ^b
C24:0 - Lignoceric acid	ND	0.03 ± 0.00 ^b	0.08 ± 0.00 ^a	0.08 ± 0.00 ^a
Saturated (SFA)	20.16 ± 1.33 ^c	35.83 ± 0.74 ^a	32.36 ± 0.19 ^b	36.09 ± 0.44 ^a
Monounsaturated (MUFA)	69.06 ± 0.52 ^a	57.61 ± 0.12 ^b	57.78 ± 0.94 ^b	55.79 ± 0.38 ^c
Polyunsaturated (PUFA)	10.78 ± 0.11 ^a	6.57 ± 0.56 ^c	9.86 ± 0.65 ^a	8.13 ± 0.10 ^b

Health indices

Nutritional value index (NVI)	3.62	1.61	1.79	1.64
Atherogenic index (AI)	0.23	0.53	0.46	0.51
Thrombogenic index (TI)	0.39	0.99	0.81	0.91
Hypocholesterolemic/ hypercholesterolemic (H/H)	4.14	1.76	2.06	1.84

Data are expressed as mean $\pm$ standard deviation ($n = 2$). Equal letters on the same line show no significant difference (Tukey's test and t-test, $p < 0.05$). ND: not detected.

Palmitic acid (C16:0) was the predominant SFA, ranging from 17.96 to 34.05%, which was comparable to the value reported for peach palm pulp oil (35.81%) by Sousa et al. (2025). Its proportion was higher in oils obtained using the ethanol-based extraction protocol (PU-ET and PE-ET). Considering that the two extraction protocols differed in both solvent and operating conditions, this pattern was interpreted as protocol-dependent and may have been associated with the co-extraction of lipid fractions more strongly linked to structural components (e.g., waxes and complex lipids), which are abundant in outer plant tissues (Molska et al., 2022). Although excessive intake of palmitic acid has been associated with atherogenic effects, it has also been reported as a relevant structural lipid in biological membranes and as a precursor of other lipid-derived compounds, with technological applications in food systems (Cruz et al., 2020; Dimou et al., 2019; Mwaurah et al., 2020; Sousa et al., 2025).

Oleic acid (C18:1) (51.80–63.98%) was the main MUFA in all peach palm oil samples, with the highest proportion observed in PU-ISO. These values were higher than those reported by Sousa et al. (2025) for peach palm pulp oil (54.23%) and by Gualberto et al. (2025) for oil obtained from the seed of the same species (11.08%), both were extracted with a nonpolar solvent. Overall, the isooctane-based protocol, particularly for pulp (PU-ISO), yielded a lipid profile with a stronger predominance of oleic acid, which supported its nutritional and functional potential among tropical vegetable oils. This trend was consistent with the preferential solubilization of less polar, highly unsaturated lipid species under the isooctane-based protocol, given the affinity of non-polar solvents for long aliphatic chains (El Kourchi et al., 2024). Oleic acid is widely recognized for its health-promoting attributes, including improved lipid markers and anti-inflammatory effects (FAO, 2022; Gualberto et al., 2025; Taboada et al., 2022).

The PUFA fraction was mainly composed of linoleic (C18:2 ω -6) and α -linolenic (C18:3 ω -3) acids, both essential fatty acids that must be obtained from the diet. Linoleic acid

was found at higher levels in the isooctane-based oils, especially PE-ISO (7.79%) and PU-ISO (7.64%), which again suggested a protocol-dependent selectivity toward less polar lipid species, as discussed by El Kourchi et al. (2024). These results highlighted peach palm oils as relevant sources of essential fatty acids. However, the ω -6/ ω -3 ratio varied among samples, ranging from 2.43 to 4.54, and should therefore be considered when discussing their nutritional quality, since excessive ω -6/ ω -3 intake ratios have been associated with adverse health outcomes, including oxidative stress (Edin et al., 2020).

When comparing fractions, peel oils obtained via the ethanol-based protocol (PE-ET) showed the highest SFA proportion, particularly palmitic acid. However, this behavior was not uniform across protocols, as PE-ISO showed lower SFA levels than PU-ET, whereas PU-ISO showed higher MUFA levels, mainly oleic acid. Such protocol- and fraction-dependent profiles could be relevant for targeted applications in food or cosmetic formulations, depending on desired compositional attributes.

PU-ISO oil, had the highest Nutritional Value Index (NVI), reflecting a healthier lipid profile, with a predominance of unsaturated fatty acids, especially oleic acid. These fatty acids are associated with reduced LDL cholesterol and inflammation, and they contribute to cardiovascular protection (Chen & Liu, 2020; El Kourchi et al., 2024). In contrast, ethanol-based oils (PU-ET and PE-ET) had lower NVI and H/H values, suggesting a higher proportion of saturated fatty acids and, consequently, a lower potential benefit to the lipid profile. Nevertheless, all oils presented low atherogenic (AI) and thrombogenic (TI) indices (≤ 1), which indicates a reduced risk of arterial plaque formation and blood clots, due to the relevant presence of mono- and polyunsaturated fats, recognized for their protective action on the cardiovascular system (Amakhmakh et al., 2025; Dal Bosco et al., 2022; Plaha et al., 2023).

Data reported in Table 1 were used to estimate the triacylglycerol (TAG) composition of peach palm pulp and peel oils obtained under the different extraction protocols. For TAG calculation, only fatty acids representing $> 0.5\%$ of the total peak area were considered (Table 2). A strong agreement was observed between the gas chromatography-based inputs and the TAG predictions generated by the PrOleos software ($r > 0.97$) (Filho et al., 1995). PrOleos includes TAG profiles for a wide range of vegetable oils and their mixtures, particularly those rich in unsaturated fatty acids.

Table 2. Composition of triacylglycerols from pulp and peel oils of peach palm.

Triacylglycerol (wt%)	PU-ISO	PU-ET	PE-ISO	PE-ET
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PPP	0.59	4.06	2.99	3.76
PPoP	0.56	1.80	1.30	1.34
SPP	–	0.54	–	0.55
POP	6.34	19.05	15.73	17.97
PLP	0.75	2.16	2.30	2.23
POPo	1.01	–	4.55	–
PPoP	–	5.61	–	–
PPoO	–	–	–	4.26
PoOPo	0.63	–	–	–
PLPo	–	0.63	0.66	0.52
PLLp	–	–	0.59	0.72
HOP	0.78	–	–	–
SOP	0.79	1.69	1.35	1.75
POO	22.54	29.72	27.52	28.57
PLO	5.30	6.74	8.06	7.10
PoOO	7.13	–	3.99	–
OPoO	–	4.39	–	3.39
OLPo	–	0.99	–	0.84
PLLO	2.50	–	2.06	2.30
PoLO	1.68	–	1.16	–
PLL	–	–	0.60	–
PoLLO	0.80	–	–	–
HOO	1.40	–	–	–
SOO	1.41	1.32	1.17	1.39
OOO	26.70	15.45	16.10	15.14
OLO	9.42	5.26	7.06	5.64
OOLn	4.45	–	1.81	1.82
OLL	1.10	0.60	1.03	0.70
OLLn	1.04	–	–	–

*Triacylglycerols composition was estimated and data are expressed as mean $\pm$ standard deviation ($n = 2$). Equal letters on the same line show no significant difference (Tukey's test and t-test, $p < 0.05$). **M**, myristic acid; **P**, palmitic acid; **Po**, palmitoleic acid; **S**, stearic acid; **O**, oleic acid; **L**, linoleic acid; **G**,

cis-11-eicosenoic acid (gondoic acid); **La**, lauric acid; **Pe**, pentadecanoic acid; **H**, heptadecanoic acid; **A**, arachidonic acid; **Ln**, alpha linolenic acid; **Ga**, gadoleic acid.

The predicted TAG composition of peach palm oil showed a predominance of diunsaturated species, represented mainly by POO (22.54–29.72%), followed by triunsaturated OOO (15.14–26.70%) and monounsaturated POP (6.34–19.05%). These results corroborate those obtained by Morais et al. (2024), who investigated oils extracted from different fractions of buritirana (*Mauritiella armata*), and by Sousa et al. (2025), who analyzed the TAG profile of oils from the peel of buriti (*Mauritia flexuosa*), both belonging to the *Arecaceae* family. The similarity observed between the results confirms the data presented in Table 1, since the fatty acid composition showed oleic, linoleic, and palmitic acids as the main constituents.

On the other hand, the PrOleos-based stereospecific prediction suggested that oleic and linoleic acids were preferentially located at the *sn*-2 position of the glycerol backbone, a distribution pattern often associated with TAGs of higher nutritional value. This molecular configuration favors intestinal absorption and reduces plasma cholesterol levels, as demonstrated by Chen et al. (2020) and Polmann et al. (2024). Additionally, the predominance of POO and OOO species confers intermediate plasticity to peach palm oil, typical of semi-solid lipid matrices. This physicochemical property is particularly desirable for food applications that require a creamy texture, good oxidative stability, and adequate rheological behavior during processing and storage. Thus, the observed triacylglyceride composition reinforces the technological and nutritional potential of peach palm oil as a high-value functional ingredient.

Table 3 reports the concentrations of β -carotene and lycopene in peach palm pulp and peel oils. β -Carotene was the predominant carotenoid in all samples, whereas lycopene occurred at lower levels and was not detected in PU-ET oil (Table 3). β -Carotene content differed among samples ($p < 0.05$), with higher values observed for PU-ET and PE-ISO, intermediate levels for PE-ET, and the lowest in PU-ISO. Lycopene also differed among the oils in which it was detected ($p < 0.05$), with the highest level in PE-ISO, followed by PU-ISO and PE-ET, while PU-ET remained not detected (Table 3). Because the extraction procedures differed in solvent polarity, operating conditions and laboratory context, these differences were interpreted as protocol-dependent rather than strictly solvent-driven. Similar matrix- and protocol-related selectivity in carotenoid recovery has been reported for vegetable oils and lipid-rich systems (Freitas et al., 2024; Menezes Silva et al., 2023; Wijngaard et al., 2012).

Table 3. β -Carotene and lycopene contents of peach palm pulp and peel oils

Samples	β-Carotene ($\mu\text{g/mL oil}$)	Lycopene ($\mu\text{g/mL oil}$)
PU-ISO	8.55 ± 0.01^d	2.76 ± 0.00^b
PU-ET	10.77 ± 0.01^a	ND
PE-ISO	10.53 ± 0.02^b	3.37 ± 0.05^a
PE-ET	9.87 ± 0.01^c	1.99 ± 0.03^c

Data are expressed as mean $\pm$ standard deviation ($n = 2$). Different superscript letters within the same column show no significant difference (Welch's one-way ANOVA, $p < 0.05$). ND: not detected.

Differences between pulp and peel oils were consistent with the natural distribution of carotenoids across fruit tissues. Peel tissues, which are more exposed to light and environmental stress, have been reported to accumulate higher levels of photoprotective pigments, which could contribute to the higher lycopene levels observed in peel oils (Miranda et al., 2024; Noronha Matos et al., 2019). The absence of lycopene in PU-ET further suggested that carotenoid recovery depended on the interplay between matrix characteristics and extraction conditions, which may have influenced pigment release and/or degradation during processing.

Carotenoids may also have contributed to the physicochemical behavior of these oils, as lipophilic pigments can partition into the liquid phase and, depending on concentration and molecular interactions, affect crystallization and microstructure development. In this sense, previous studies have reported that TAG composition and crystalline organization can modulate the incorporation and stability of lipophilic bioactives in oils and fat-based matrices (Bu et al., 2022; Saini et al., 2022). Overall, peach palm oils showed measurable levels of β -carotene and lycopene, with statistically significant but moderate differences among samples (Table 3).

3.2 *Physical properties*

Differential scanning calorimetry (DSC) analysis (Fig. 1 and Table 4) revealed complex crystallization and melting behaviors for peach palm peel and pulp oils, which depended on the extraction protocol and the anatomical fraction. The multiple thermal events observed reflected the heterogeneous TAG composition (Table 2) of the samples and the coexistence of different crystalline arrangements, typical of lipid systems with a wide distribution of saturated and unsaturated TAG species (Alarcon et al., 2020; Rajagukguk et al., 2023). From a technological perspective, particular attention was given to the thermal transitions occurring at or above room

temperature ($\approx 20^\circ\text{C}$), as these events determined whether the oils behaved as liquid or solid/semi-solid fats under practical application conditions (Alarcon et al., 2020; Rajagukguk et al., 2023).

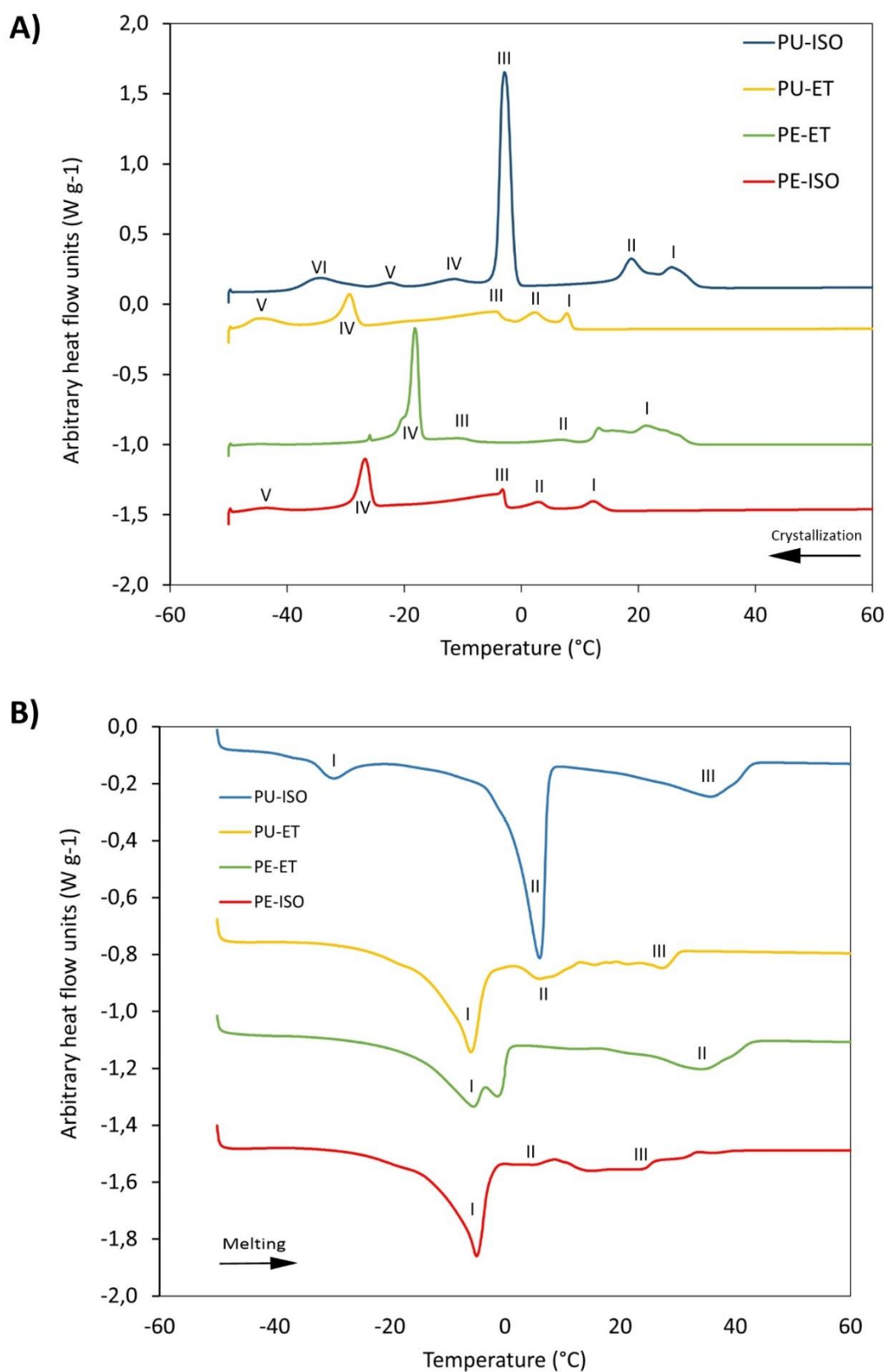


Fig. 1 Crystallization - EXO (A) and melting - ENDO (B) curves by Differential Scanning Calorimetry (DSC) of peach palm pulp and peel oils.

During the crystallization step (Fig. 1A), all oils exhibited exothermic events at subzero temperatures (approximately from -45 to -2 °C), which were consistent with the crystallization of low-melting TAG fractions enriched in unsaturated fatty acids. These low-temperature events may be associated with the formation of metastable polymorphic forms (e.g., α and β') in lipid matrices rich in oleic and linoleic acids, and were mainly relevant for frozen food applications, with limited technological relevance at ambient temperature (Bu et al., 2022; Saini et al., 2022). In addition to these subzero events, PU-ISO and PE-ET also showed crystallization peaks in the 20 – 30 °C range. Specifically, PU-ISO displayed a prominent exothermic event within this interval, and PE-ET showed a crystallization peak around ~ 21 °C with substantial enthalpy (ΔH up to $+19.46$ J g $^{-1}$) (Table 4). These higher-temperature events suggested the crystallization of higher-melting lipid fractions that were expected to contribute more directly to structure formation at ambient conditions. Notably, the magnitude of crystallization enthalpy reflected the extent of crystallization under the applied conditions, whereas polymorphic stability and crystal packing required confirmation by complementary structural analyses.

Table 4. Thermal parameters of oil samples by DSC of peach palm pulp and peel oils

			PU-ISO	PU-ET	PE-ISO	PE-ET
Crystallization	Peak 1	Peak (°C)	27.25	7.87	12.36	21.38
		ΔH (J g $^{-1}$)	+19.48	+1.43	+2.43	+17.23
	Peak 2	Peak (°C)	18.9	2.37	3.02	6.86
		ΔH (J g $^{-1}$)	+22.27	+2.31	+1.65	+0.96
	Peak 3	Peak (°C)	-2.55	-4.3	-3.13	-10.15
		ΔH (J g $^{-1}$)	+39.18	+10.02	+11.19	+0.81
	Peak 4	Peak (°C)	-11.7	-29.29	-26.62	-18.03
		ΔH (J g $^{-1}$)	+2.07	+7.65	+9.78	+19.46
	Peak 5	Peak (°C)	-22.5	-44.9	-43.90	-
		ΔH (J g $^{-1}$)	+0.94	+4.09	+1.45	-

Melting	Peak 6	Peak (°C)	-34.6	-	-	-
		ΔH (J g ⁻¹)	+6.21	-	-	-
	Peak 1	Peak (°C)	-29.86	-5.99	-4.97	-5.55
		ΔH (J g ⁻¹)	-5.30	-28.71	-28.72	-31.92
	Peak 2	Peak (°C)	5.86	6.13	5.23	34.21
		ΔH (J g ⁻¹)	-48.15	-3.76	-0.67	-14.11
	Peak 3	Peak (°C)	35.70	27.55	23.23	-
		ΔH (J g ⁻¹)	-21.29	-3.11	-9.43	-

The melting profiles (Fig. 1B) clearly differentiated the oils in terms of room-temperature behavior. PU-ISO and PE-ET exhibited melting events extending to or above 20 °C, explaining their solid or semi-solid character at room temperature, whereas PU-ET and PE-ISO showed melting transitions predominantly below 20 °C, confirming a liquid behavior at ambient conditions. The solid character of PU-ISO could be associated with the formation of a well-connected crystalline network composed mainly of organized unsaturated TAGs (POO and OOO) (Pereira et al., 2019; Polmann et al., 2024). In contrast, the higher melting transitions observed for PE-ET suggested a larger contribution of higher-melting TAG fractions (e.g., POP and PPP), which crystallized at higher temperatures and were expected to promote a more structured lipid phase (Rajagukguk et al., 2023; Tomaszewska-Gras et al., 2021).

Overall, DSC results indicated that the room-temperature consistency of peach palm oils depended on the combined influence of extraction protocol and fruit fraction, rather than on solvent polarity alone. These thermal trends were subsequently discussed alongside microstructural and scattering/rheological evidence in the following sections.

PLM micrographs acquired at 20 °C showed marked differences in crystal morphology and density among peach palm pulp and peel oils as a function of the extraction protocol (Fig. 2). In general, birefringent domains typical of crystallized TAG structures were observed, with distinct patterns across samples. PU-ISO exhibited elongated, needle-like crystals heterogeneously distributed, with the formation of branched aggregates, suggesting the coexistence of multiple crystalline populations and a well-developed network at 20 °C (Fig. 2F). This microstructure was consistent with the DSC profiles, which showed crystallization/melting events extending to around room temperature for PU-ISO, supporting

its structured character under ambient conditions (Fig. 1 and Table 4). The prevalence of fine, elongated crystals has been reported for lipid systems enriched in unsaturated TAGs, in which reduced intermolecular packing tends to favor smaller and less symmetric crystal morphologies (Domingues et al., 2022).

On the other hand, the PU-ET micrograph revealed extremely fine, uniformly distributed crystals with intense anisotropic brightness, suggesting a more homogeneous crystal field at 20 °C (Fig. 2E). The lower enthalpy of crystallization ($\Delta H = 2.31 \text{ J g}^{-1}$) and the shift of the melting peaks to lower temperatures (-5.99°C) confirm the presence of smaller and more ordered crystals, characteristic of the predominant transition to the β' polymorph, similar to that found in palm oil cooled to 20 °C by De Witte et al. (2024). This behavior may be related to the protocol polar nature, which interferes with intermolecular interactions between TAGs and alters nucleation during crystal formation (Zeb & Murkovic, 2011). The PE-ISO oil presented large, radiating crystals with needle-like morphology and a star-like appearance, indicative of a less compact structure and incomplete crystallization field at 20 °C (Fig. 2H). This morphology is associated with the high concentration of unsaturated fatty acids and TAGs with double bonds, whose insertion between the acyl chains interferes with nucleation and crystal growth (Pinna et al., 2025). The irregular birefringence and dark zones observed suggested the coexistence of amorphous and semicrystalline regions (Polińska et al., 2021), consistent with the greater thermal disorder detected in the DSC (multiple peaks and ΔH variable between 1.45 and 11.19 J g^{-1}), as observed in the chromoplasts of mango and papaya by Schweiggert et al. (2012).

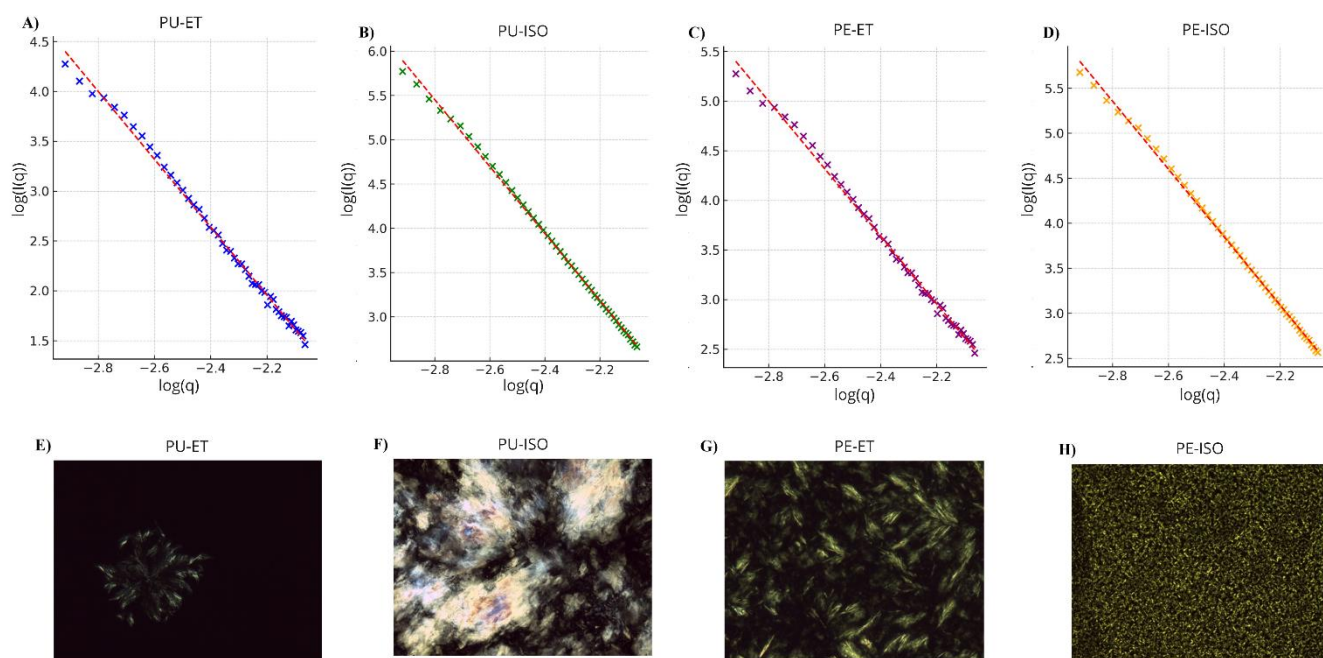


Fig. 2 Comparison between power-law regime plots (PU-ET – A, PU-ISO – B, PE-ET – C, PE-ISO – D) and polarized light microscopy (PLM) micrographs (PU-ET – E, PU-ISO – F, PE-ET – G, PE-ISO – H) of peach palm pulp and peel oils recorded at 20 °C.

In contrast, the PE-ET oil presented a micrographic field dominated by small, compact, and strongly birefringent crystals with a uniform granular pattern (Fig. 2G), similar to that observed in sunflower oil by Biswas et al. (2017). This structure evidences a more stable and energetically favorable system, in agreement with the DSC, which showed higher crystallization peaks (10.0 – 21.0°C) and considerable enthalpy ($\Delta H = 17.23 \text{ J g}^{-1}$). Because the extraction procedures differed in solvent and operating conditions (and were performed in different laboratories), these differences were discussed as protocol-dependent rather than strictly solvent-driven (Gomaa et al., 2022; Pinna et al., 2025). Taken together, the PLM micrographs confirm the strong influence of the extraction protocol and the fruit fraction on the morphology and spatial distribution of crystals. Isooctane promoted more disordered and heterogeneous structures due to the greater extraction of unsaturated compounds, while ethanol produced more organized and compact systems. These findings corroborate the DSC results and demonstrate that fatty acid content modulates lipid crystallization, influencing both thermal stability and optical anisotropy. The observation of distinct birefringence patterns and crystal

sizes across the samples also indicates the presence of distinct TAG polymorphs, a phenomenon that can be confirmed and quantified by SAXS and XRD structural analyses.

The structural characterization of oils extracted from peach palm peel and pulp with solvents of different polarity was conducted using SAXS, with the results analyzed according to Porod's Law (Fig. 2 and Table 5). The result could be relatively well fitted on a log-log scale to the $I(q)$ curve as a function of q , allowing investigation of the degree of interface definition in lipid systems (Santos et al., 2021). The relationship $I(q) \sim q^{-n}$, in which the exponent $n = 6 - d_s$ is associated with the nature and regularity of the interfaces between domains of contrasting electron density. The exponent gives information about the surface fractal dimension d_s , which is 2 for smooth surfaces ($n = 4$) and higher values up to 3 ($n = 3$) for highly rough surfaces. Thus, the exponent reveals differences in the internal organization of the samples depending on the portion of the fruit used and the type of solvent employed in the extraction process (Silva et al., 2024).

Table 5. Synthesis of the correlation between SAXS (Porod and Guinier regimes), PLM and XRD from pulp and peel oils of peach palm.

Samples	SAXS				XRD	
	Porod exponent (n)	Rg (nm)	PLM	Interpretation	Q ($\text{\AA}^{-1}$)	d ($\text{\AA}$)
PU-ET	-3.41	107	Long and oriented domains	Partially ordered structure	0.15	41.9
					0.22	28.6
					0.42	15.0
					1.35	4.65
PU-ISO	-3.78	117	Small, dense crystals	High organization and regular interfaces	0.15	41.9
					0.22	28.6
					0.42	15.0
					1.35	4.65
PE-ET	-3.15	123	Heterogeneous, birefringent	Diffuse interfaces, irregular structure	0.15	41.9
					0.22	28.6
					0.42	15.0
					1.38	4.55
PE-ISO	-3.47	115	Clustered crystals	Moderate order with crowding	0.15	41.9
					0.22	28.6
					0.42	15.0
					1.38	4.55

The comparison between the structural data obtained by SAXS and PLM images (Fig. 2) reveals important information about the supramolecular organization and morphology of the oils extracted from peach palm pulp and peel by using different solvents. The analysis using the Guinier equation complements the structural characterization of the samples by providing an estimate of the radius of gyration (R_g) (Table 5), representative of the average size of the domains or aggregates present in the oils (Heiden-Hecht et al., 2024; Mastrangelo et al., 2020). The values obtained showed good agreement with the structural observations from the SAXS data and PLM images. The PU-ISO presented the steepest Porod slope ($n = -3.78$; $R^2 = 0.999$) and a radius of gyration (R_g) of 117 nm, indicating well-defined interfaces. This result suggests that isooctane favors the extraction of more homogeneous and organized lipid fractions, preserving native lamellar structures (Andrade & Negrão, 2025; Liu et al., 2023). The PLM image (Fig. 2F) corroborates this finding, exhibiting small, dense, and strongly birefringent crystals. This compact organization is associated with the predominance of POO and OOO-type TAGs, as well as the high oleic acid content (63.98%), which promote molecular flexibility without compromising acyl chain packing (Andrade & Negrão, 2025; Liu et al., 2023).

PU-ET showed a lower Porod slope ($n = -3.41$; $R^2 = 0.997$) and an R_g of 107 nm, indicating fewer regular interfaces and elongated domains. This difference may be associated with the greater presence of polar compounds and the lower fraction of unsaturated TAGs, which introduce heterogeneity into the lamellar arrangement. Ethanol, by interacting with polar lipids and protein or phospholipid residues, tends to generate less cohesive microdomains, which is also reflected in the PLM images, which show thin, oriented crystals with lower optical density. In the peel samples, a reverse trend was observed. The PE-ISO showed $n = -3.47$ ($R^2 = 0.999$) and R_g of 115 nm, indicating a moderately ordered structure with agglomerated crystals and well-defined interfaces, although less uniform than those of the pulp. This behavior reflects the balance between the lipid network and the high proportion of mono- and di-unsaturated TAGs (POO, OOO, POP), which favor molecular plasticity (Bu et al., 2022; Saini et al., 2022). On the other hand, the PE-ET presented the lowest degree of interface definition ($n = -3.15$; $R^2 = 0.98$) and the highest R_g (123 nm), suggesting diffuse and heterogeneous structures. This morphology, also observed in the PLM through irregular birefringent domains, can be attributed to the greater diversity of compounds extracted with the polar solvent, such as phospholipids, oxidized pigments, and short-chain lipids, which promote partial disruption of the lamellar organization (Andrade & Negrão, 2025; Freitas et al., 2024).

The results from SAXS in low and high are consistent with the thermal and morphological data previously discussed: oils with higher unsaturation content (PU-ISO and

PE-ISO) present less dense packing and well-defined interfaces, while those with higher saturation and extracted with ethanol (PU-ET and PE-ET) exhibit more compact but less uniform structures (De Witte, Penagos, Rondou, et al., 2024; Olsmats et al., 2025). This structural modulation is a direct result of solvent selectivity, which controls the relative proportion of TAG species with different saturation patterns, including more unsaturated TAGs (SU_2 and U_3) and more saturated TAGs (S_2U and S_3), where S and U denote saturated and unsaturated fatty acyl chains, respectively, thereby affecting the degree of ordering of the lipid matrix. On the other hand, more disorganized structures can facilitate the incorporation of polar bioactive compounds or facilitate dispersion in hydrophilic matrices, albeit with lower physicochemical stability (Olsmats & Rennie, 2024; Rondou et al., 2024). Thus, the choice of solvent for lipid extraction not only influenced the yield and chemical composition of the oil but also modulated its nanostructure, directly impacting its technological and functional properties.

XRD scattering analysis was performed to investigate the presence of ordered phases in the oils extracted from the pulp and peel of peach palm, considering the influence of the extraction solvents ethanol and isooctane. In all diffractograms (Fig. 3), distinct shoulders were observed in the region of $Q \approx 0.15, 0.22, 0.42$, and $1.35\text{--}1.38 \text{ \AA}^{-1}$, which correspond to crystalline or semicrystalline structures present in the oils (Ferreira & da Silva, 2023). Table 5 presents the estimated interplanar spacing values (d), calculated according to Bragg's equation ($d = 2\pi/q$). The spacings obtained were approximately 41.9, 28.6, 15.0, and 4.6 $\text{\AA}$ (Table 5), suggesting the coexistence of structural features at different hierarchical levels in all samples. The larger spacings are indicative of lamellar organization, while the reflection at 4.6 $\text{\AA}$ is typically related to short-range packing of hydrocarbon chains in ordered lipid domains.

The peak located at $Q \approx 1.35\text{--}1.38 \text{ \AA}^{-1}$ ($d \approx 4.6 \text{ \AA}$) is commonly associated with the packing of the acyl chains of triacylglycerols (TAGs) (De Witte, Penagos, Rondou, et al., 2024; De Witte, Penagos, Van de Walle, et al., 2024), and suggests the presence of β or β' type crystalline phases, which are typical in partially crystallized lipids (Domingues et al., 2022; Peyronel et al., 2023). The lower Q peaks, in turn, may be related to the lamellar organization of lipids, vesicles, or structured aggregates, evidencing the existence of regions of supramolecular ordering in the analyzed oils (De Witte, Penagos, Rondou, et al., 2024; De Witte, Penagos, Van de Walle, et al., 2024; Mazzanti, 2021). The presence and position of the peaks were similar between the oils extracted with ethanol and isooctane, for both the pulp and the peel. However, differences in peak relative intensities suggest that the type of solvent can affect the proportions of crystalline phases or the extent of organization without destroying the

structure (Zhang et al., 2025). Specifically, the oils extracted with isooctane (PE-ISO and PU-ISO) showed more defined peaks in some regions, suggesting greater preservation of the ordered lipid phases, as this nonpolar solvent tends to preserve the integrity of native structures.

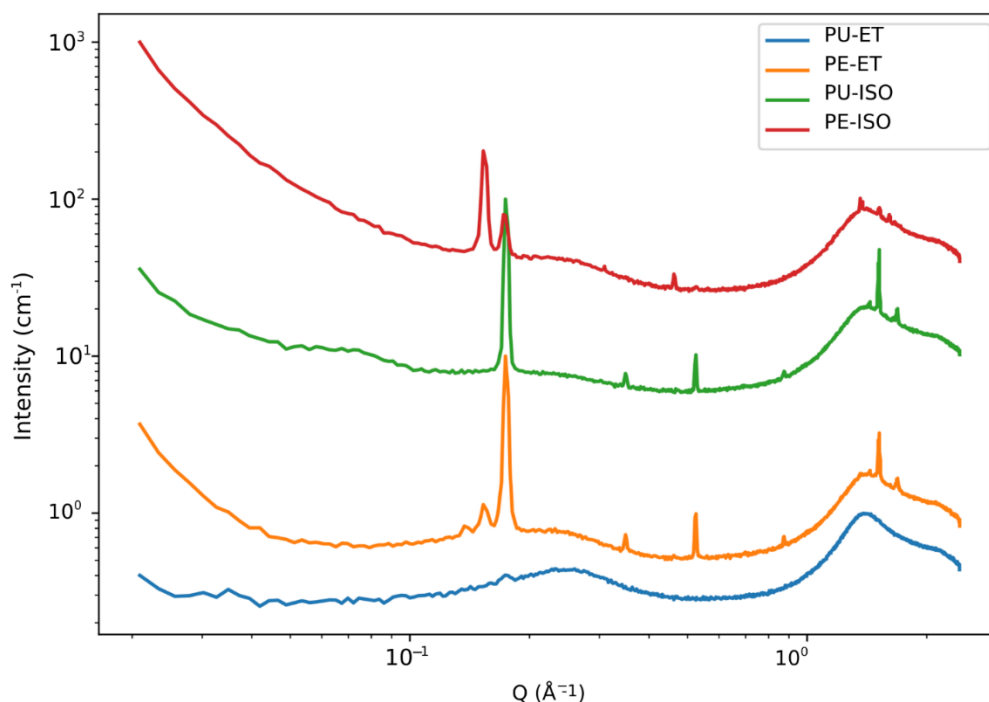


Fig. 3 Wide-angle X-ray scattering (XRD) graph from pulp and peel oils of peach palm.

Overall, XRD analyses revealed that the isooctane-based protocol tended to a more regular nanostructure and well-defined interfaces, whereas ethanol-based oils resulted in greater heterogeneity and lower crystallinity. This structural modulation may affect the technological properties of the oils, demonstrating that more ordered systems would exhibit greater thermal and oxidative stability, while more disorganized systems would favor the incorporation of bioactive compounds and dispersion in hydrophilic matrices. Thus, the supramolecular structure of peach palm oils is likely to reflect the synergistic interactions among the chemical composition (fatty acids and TAGs), bioactive pigments, and the extraction solvent, demonstrating the potential of these oils as multifunctional ingredients for food and cosmetic applications.

To probe the technological potential of the extracted oils, oscillatory rheological analysis was conducted at 20 °C only for the samples that exhibited a structured (solid/semi-solid) character at this temperature, namely peach palm pulp (PU-ISO) and peel (PE-ET) oils (Fig. 4). As shown in Fig. 4, both samples presented elastic modulus (G') values higher than

viscous modulus (G'') across the entire frequency range (0.1–100 Hz), indicating predominantly elastic behavior. Such behavior is knowingly attributable to a cohesive microstructure able to tolerate moderate oscillatory deformation without incurring in irreversible deformation (Pommella et al., 2020).

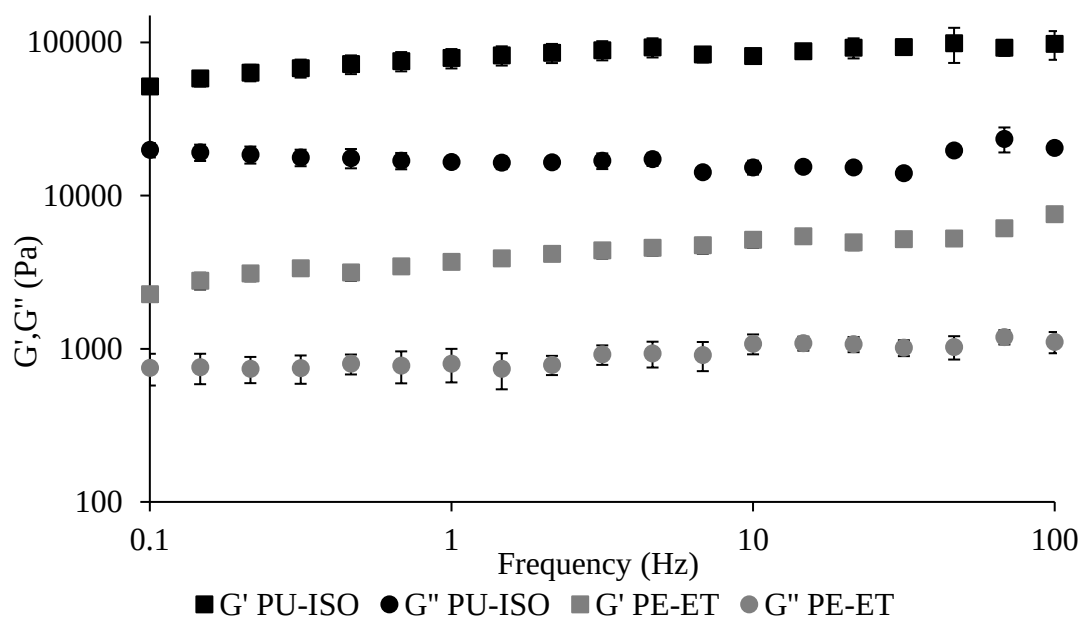


Fig. 4 Frequency sweep curves (G' and G'') at 20°C of peach palm oils.

The PU-ISO sample presented high G' values, reaching almost 80000 Pa at 1 Hz, whereas G'' remained low and practically constant throughout the entire analyzed frequency range (Fig. 4). These values fell within the range of other tropical oils conventionally used as plastic fats in food formulations (Attia et al., 2020). The reported behavior suggests the formation of a strongly structured and mechanically resistant lipid network, consistent with the SAXS results, and is possibly associated with the presence of small, densely packed crystals observed in the PLM and the high proportion of unsaturated TAGs of the POO and OOO types, which favor stable β' packings (De Witte et al., 2024). The high concentration of oleic acid (63.98%) and β' may also contribute to network rigidity, as these compounds modulate intermolecular interactions and stabilize organized lipid domains (Andrade & Negrão, 2025; Guimarães et al., 2023).

On the other hand, PE-ET oil exhibited lower G' values, (~ 3700 Pa) at 1 Hz, accompanied by an increase in G'' at higher frequencies, indicating a weaker structure and more fluid behavior. This profile is characteristic of systems with greater energy dissipation and

lower crystalline connectivity, possibly resulting from the disruption of lipid self-assembly by polar compounds extracted with ethanol-based extraction protocol (Andrade & Negrão, 2025; Li et al., 2022; Liu et al., 2023). This interpretation was consistent with SAXS and XRD analyses, which revealed more diffuse interfaces, a larger radius of gyration, and less intense Bragg peaks, indicating a lower degree of crystallinity and greater structural heterogeneity.

4 Conclusions

The results of this study showed that the composition, supramolecular organization, and technological functionality of peach palm oils depended on the fruit fraction and the extraction protocol. The oils exhibited high oleic acid contents, which were associated with favorable nutritional lipid indices, including low atherogenicity and thrombogenicity and comparatively high H/H ratios. In addition, measurable levels of carotenoids (β -carotene and lycopene) highlighted the potential of these oils as sources of lipophilic bioactive compounds. Across samples, differences in TAG distribution and fatty-acid profiles were reflected in thermal transitions (DSC), crystal morphology (PLM), and nanostructural/crystalline features (SAXS/XRD), supporting a consistent relationship between degree of unsaturation, ordering of lipid assemblies, and physical/structural stability at room temperature. Oils obtained under the isooctane-based protocol, particularly PU-ISO, exhibited a more structured behavior at 20 °C, as indicated by melting/crystallization events extending toward room temperature and by the development of an interconnected crystalline network. In contrast, PE-ET showed a weaker viscoelastic network and more heterogeneous structural signatures, despite exhibiting thermal events near room temperature, highlighting the combined role of matrix fraction and extraction conditions in determining oil organization. Overall, this work provides an integrative characterization of peach palm pulp and peel oils by correlating chemical composition with multiscale structural and rheological behavior. The findings reinforce the peel as a valuable and sustainable lipid source, supporting its potential use in functional foods and cosmetic formulations within a circular bioeconomy framework.

Credit authorship contribution statement

Hermanny Sousa: Conceptualization, Data curation, Formal analysis, Investigation, Validation, Visualization, Writing – original draft. **Rômulo Moraes:** Formal analysis, Data curation, Validation, Writing – original draft, Writing – review & editing. **Federico Basso:** Conceptualization, Data curation, Formal analysis, Investigation, Validation, Visualization.

Roberta Pratolino: Data curation, Formal analysis, Investigation, Validation, Visualization. **Luana Pereira:** Data curation, Formal analysis, Investigation, Validation, Visualization. **Gabriela Fonsêca:** Data curation, Formal analysis, Investigation, Validation, Visualization. **Monica Anese:** Supervision, Visualization, Writing – review & editing. **Fabiana Queiroz:** Project administration, Supervision, Visualization, Writing – review & editing. **Paulo Peixoto:** Project administration, Supervision, Visualization, Writing – review & editing. **Sonia Calligaris:** Project administration, Supervision, Visualization, Writing – review & editing. **Glêndara Martins:** Conceptualization, Resources, Supervision, Project administration, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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THIRD PART

2. FINAL CONSIDERATIONS

This thesis consolidated an integrated approach for the valorization of peach palm (*Bactris gasipaes*), an Amazonian palm of the *Arecaceae* family, connecting the critical synthesis of the available knowledge, the exploration of sustainable routes for the recovery of bioactive compounds from different fruit fractions, and the understanding of how extraction protocols modulate the composition and structural organization of vegetable oils, with technological and nutritional implications. In Article 1, the bibliometric analysis and critical review showed that, although there is growing interest in *Arecaceae* fruits, relevant gaps still persist regarding methodological standardization, comparability among studies, and the translation of results into applications. This broad perspective was essential to justify peach palm as a strategic matrix, especially when considering the potential for integral fruit valorization and the conversion of peel and seed, which are often underutilized, into sources of ingredients and inputs with higher added value.

Article 2 demonstrated, in practical terms, that the fruit fractions (peel, pulp, and seed) and the nature of the solvent decisively influence the profile of recovered compounds and the functional performance of the extracts. By comparing conventional solvents with emerging green alternatives (DES and SUPRAS), the study reinforced that it is possible to obtain extracts with expressive bioactive composition and relevant antioxidant/biological responses, in addition to discussing bioaccessibility under simulated gastrointestinal digestion. These findings support the feasibility of more sustainable routes for obtaining bioactive ingredients from different peach palm fractions, expanding the possibilities for coproduct valorization and reducing dependence on traditional solvents.

In turn, Article 3 advanced the understanding of the lipid fraction of peach palm by showing that differences among oils obtained from peel and pulp should not be interpreted only as a solvent effect, but as a consequence of the extraction protocol as a whole (solvent, operational conditions, and separation steps). The chemical and structural characterization showed that changes in the protocol may alter yield, composition, and multiscale organization (with effects on thermal and rheological behavior), which is decisive for defining the technological use and stability of the oil. Thus, the work contributes by proposing a more robust and applied interpretation of vegetable oil quality, going beyond yield and incorporating structure and functionality.

Taken together, the three studies reinforce that peach palm should be treated as a matrix with high potential for integral valorization, in which different fractions may give rise to distinct products: bioactive extracts with application as functional ingredients and oils with protocol-dependent properties, potentially directed toward food and cosmetic uses. As future perspectives, it is recommended to advance toward pilot-scale evaluations and feasibility indicators (cost, solvent recovery, storage stability, quality standardization), in addition to further investigating safety and efficacy through complementary approaches (including *in vivo* models and/or application studies in real formulations). These steps are essential to transform the demonstrated potential into a consistent technological basis for innovation, value addition, and waste reduction in the peach palm chain, while maintaining alignment with the principles of sustainability and the Amazon bioeconomy.