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Review article

Amazonian palm tree fruits: From nutritional value to diversity of new food products

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ABSTRACT

The rapid growth of the world population has increased the demand for new food sources, constituting a major challenge concerning the maximum use of existing food resources. The fruits of Amazonian palm trees have excellent nutritional composition and bioactive compounds. This review highlights four fruits of Amazonian palm trees that are still little explored by the food industry: açai (*Euterpe oleracea*), pupunha (*Bactris gasipaes*), buriti (*Mauritia flexuosa*), and tucumã (*Astrocaryum aculeatum*). This paper aims to inspire new ideas for researching and developing products for the food industry. It also explores the impacts of Amazonian palm fruits on health, highlighting their role in disease prevention through their nutritional effects.

1. Introduction

With the decrease in agricultural land and the rise of climate change, ensuring an adequate food supply for a growing population constitutes a serious challenge for the food industry [1]. The fruits of palm trees native to the Amazon rainforest have great potential to address these matters, especially concerning sustainability and the maximum use of currently existing food resources.

Among the biodiversity of fruit plants of the Amazon rainforest, we have palm trees (*Arecaceae*), which comprise approximately 35 genera and more than 170 species, among which at least 96 produce edible fruits [2]. In particular, the fruits of the Amazonian palm trees, açai (*Euterpe oleracea*), pupunha (*Bactris gasipaes*), buriti (*Mauritia flexuosa*), and tucumã (*Astrocaryum aculeatum*) are usually obtained through extractive activity [3]. The local population highly appreciates these fruits' rich nutritional composition and pleasant sensory characteristics [4]. In addition, Amazonian fruits are rich in bioactive compounds that exhibit antioxidant, immunomodulatory, and anti-inflammatory properties and can slow the progression of degenerative diseases. Such bioactive effects probably result from fibers, phenolic compounds, carotenoids, polyunsaturated fatty acids, vitamins, and micronutrients [4,5].

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However, due to the lack of knowledge about these species' growth conditions, these fruits are still little explored as ingredients by the food industry, thus presenting enormous potential for the research and development of new products. The objective of this review, dedicated to four fruits of Amazonian palm trees still little explored by the industry, is to inspire new ideas of research and development of new food products. It also explores the impacts of Amazonian palm fruits on health, highlighting their role in disease prevention through their nutritional effects. Also, toxicology studies on care and limitations in consuming these fruits will be addressed.

2. Search strategies

The following databases were consulted to collect published articles without specifications for the publication date: PubMed, Web of Science, Science Direct, and Scopus. Gray literature, data conference abstracts, lectures, magazines in general, etc were also consulted. The following combination of keywords was used to search for relevant studies: "Amazonian fruit" AND "Palm trees"; ("Euterpe oleracea" OR "Bactris gasipaes" OR "Mauritia flexuosa" OR "Astrocaryum aculeatum") AND ("Biological effect" OR "Toxicity" OR "Formulation" OR "Sensory").

3. Fruits of Amazonian palm trees

3.1. Açai (*Euterpe oleracea*)

Euterpe oleracea Mart. (*Arecaceae*), popularly called Açai tree, is a palm tree typically found in the Amazon region, Central, and South America [6]. Its fruit is known as açai (Fig. 1A), and its pulp can be obtained mainly from the fruits of two palm species, *Euterpe oleracea* and *Euterpe precatoria* [7]. Because they are morphologically similar species, the main differentiating factor is how the palm trees grow; *E. precatoria* has only a single thin stalk, and *E. oleracea* has multiple stalks [8]. Açai harvesting occurs throughout the year, but the greatest abundance is between July and December for *E. oleracea* [9]. On the other hand, the off-season period occurs between March and June; in this case, the highest productivity is that of *E. precatoria* [10]. Around 247,034 tons of açai were produced in Brazil [11], with Pará being the most prominent state in production with 164,902 tons (66.75 % of the national output).

Fig. 1. Fruits of Amazonian palm trees. A: açai (*Euterpe oleracea*), B: pupunha (*Bactris gasipaes*), C: buriti (*Mauritia flexuosa*), and D: tucumã (*Astrocaryum aculeatum*).

Despite the large production and export of frozen pulp, Brazil is not as prominent regarding the diversity of açai-based products [12]. The leading importer of açai is the United States, with around 77 % of the total exported destined for North American processing industries. At a global level of processed foods containing açai and launched on the world market, 22 % are represented by juices, 12 % energy and sports drinks, 9 % by snacks, 7 % desserts and ice creams, 5 % in the dairy category, and 3 % in sweets and candies, with the United States (30 %), Brazil (19 %), and Canada (8 %) being the most representative countries in the launch of these products [13].

Table 1
Proximate and nutritional composition of the Amazonian palm trees fruits.

Components		*Euterpe oleracea*	*Euterpe precatoria*	*Bactris gasipaes*	*Bactris gasipaes* (White)	*Mauritia flexuosa*	*Astrocaryum aculeatum*	*Astrocaryum vulgare*
Nutritional composition (%)	Moisture	84.10[a] [89]	39.80 [90]	62.43[a] [29]	28.85 [23]	64.45[a] [35]	36.76 [91]	5.68 [92]
	Lipids	48.00 [93]	25.12 [90]	6.88[a] [29]	7.80 [23]	14.28[a] [35]	32.37 [91]	32.73 [92]
	Proteins	12.00 [93]	8.26 [90]	3.90[a] [29]	5 [23]	2.42[a] [35].	9.19 [91]	4.58 [92]
	Ash	4.00 [93]	2.36 [90]	2.74[a] [29]	3.87 [23]	0.93[a] [35]	1.67 [91]	2.52 [92]
	Carbohydrates	36 [93]	64.26 [90]	24.05[a] [29]	43.76 [23]	11.31[a] [35]	20.51 [91]	54.49 [92]
	Total caloric value (kcal/100 g)	nd	515.92 [90]	173.76[a] [29]	266.60 [23]	184.60[a] [35]	362.57[a] [94]	293.02 [95]
	Total dietary fiber	nd	46.82 [90]	4.88 [96]	10 [23]	6.61[a] [35]	nd	nd
	Crude fibre	nd	nd	nd	nd	nd	nd	9.00 [95]
	Insoluble fiber	nd	nd	nd	7.17 [23]	nd	nd	nd
	Soluble fiber	nd	nd	nd	3.20 [23]	nd	nd	nd
Mineral composition (mg/100g)	Sodium	6.80 [93]	nd	nd	0.75 [23]	2.14[a] [35]	11.99 [97]	38.29[a] [98]
	Magnesium	172 [93]	211.46 [90]	81,6 [99]	81.58 [23]	33.88[a] [35]	7.32 [97]	129.69[a] [98]
	Phosphorus	186 [93]	75.88 [90]	Nd	86 [23]	nd	5.63 [97]	43.42[a] [98]
	Potassium	930 [93]	659.24 [90]	109,4 [99]	311 [23]	210.98[a] [35]	85.72 [97]	509.99[a] [98]
	Calcium	423 [93]	385.59 [90]	<1.0 (Below the detection limit) [99]	150 [23]	44.12[a] [35]	88.09 [97]	182.51[a] [98]
	Manganese	13.3 [93]	43.53 [90]	0,54 [99]	81.58 [23]	nd	0.18942 [97]	1.76178[a] [98]
	Iron	7.80 [93]	5.61 [90]	2,65 [99]	2.3 [23]	0.49[a] [35]	0.57293 [97]	4.38763[a] [98]
	Zinc	2.10 [93]	2.84 [90]	<0.2 (Below the detection limit) [99]	4.53 [23]	0.27[a] [35]	0.21394 [97]	0.3651[a] [98]
	Copper	nd	2.10 [90]	0,43 [99]	1.39 [23]	0.06[a] [35]	0.20471 [97]	0.09637[a] [98]
	Selenium	nd	nd	nd	7.62 [23]	nd	nd	nd
	Chromium	nd	nd	nd	nd	nd	0.38828 [97]	nd
	Sulfur	nd	497.54 [90]	nd	nd	nd	nd	nd
Fatty acids (%)	Palmitic acid	25.56 [18]	nd	50.57 [100]	49.71 [23]	15.20 [35]	13.8 [91]	25 [46]
	Palmitoleic acid	3.54 [18]	nd	3.39 [100]	3.87 [23]	0.42 [35]	nd	nd
	Stearic acid	1.84 [18]	nd	2.95 [100]	1.97 [23]	1.56 [35]	8.6 [91]	2.40 [46]
	Oleic acid	52.70 [18]	nd	36.27 [100]	38.42 [23]	78.57 [35]	62.0 [91]	63.50 [46]
	Linoleic acid	0.95 [18]	nd	5.18 [100]	4.51 [23]	1.85 [35]	13.8 [91]	nd
	Linolenic acid	nd	nd	1.17 [100]	0.35 [23]	1.45 [35]	nd	1.30 [46]
	α-linolenic acid	nd	nd	nd	nd	nd	nd	3.50 [46]
	Arachidonic acid	nd	nd	0.24 [100]	nd	nd	nd	nd
	Margaric acid	nd	nd	0.11 [100]	nd	nd	nd	nd
	Myristic acid	nd	nd	0.10 [100]	0.07 [23]	0.07 [35]	1.0 [91]	nd
	Lauric	nd	nd	nd	nd	0.03 [35]	0.8 [91]	nd
	Pentadecanoic	nd	nd	nd	nd	0.06 [35]	nd	nd
	Heptadecanoic	nd	nd	nd	nd	0.15 [35]	nd	nd
	Arachidic	nd	nd	nd	nd	0.10 [35]	nd	nd
	Behenic	nd	nd	nd	nd	0.04 [35]	nd	nd
	Lignoceric	nd	nd	nd	nd	0.06 [35]	nd	nd
	Gadoleic	nd	nd	nd	nd	0.44 [35]	nd	nd
	Polyunsaturated	nd	nd	nd	nd	3.30 [35]	nd	nd
	cis-vaccenic acid	nd	nd	nd	nd	nd	nd	1.20 [46]

[a] Values on wet basis; nd: not determined.

Table 2
Bioactive compounds and instrumental color of Amazonian palm fruits.

Components		*Euterpe oleracea*	*Euterpe precatoria*	Bactris gasipaes	Mauritia flexuosa	*Astrocaryum aculeatum*	*Astrocaryum vulgare*
Anthocyanins (mg/kg)	Cyanidin-3-glucoside	947 [101]	4.60 [101]	nd	nd	nd	nd
	Cyanidin-3-rutinoside	1256 [101]	3135 [101]	nd	nd	nd	nd
	Peonidin-3-rutinoside	44.00 [101]	319 [101]	nd	nd	nd	nd
Non-anthocyanin polyphenols (mg/kg)	Protocatechuic acid	1.77 [101]	2.38 [101]	nd	nd	nd	nd
	p-Hydroxybenzoic acid	1.80 [101]	2.42 [101]	nd	nd	nd	nd
	(+)-Catechin	5.11 [101]	5.46 [101]	nd	nd	nd	nd
	Vanillic acid	5.05 [101]	13.40 [101]	nd	nd	nd	nd
	Apigenin glucoside	nd	9.91 [101]	nd	nd	nd	nd
	Luteolin di-glucoside	7.33 [101]	nd	nd	nd	nd	nd
	Syringic acid	4.02 [101]	10.10 [101]	nd	nd	nd	nd
	Apigenin glucoside	nd	7.82 [101]	nd	nd	nd	nd
	Apigenin di-glucoside	8.13 [101]	nd	nd	nd	nd	nd
	(−)-Epicatechin	1.07 [101]	2.35 [101]	nd	nd	nd	nd
	Unidentified flavone	nd	5.11 [101]	nd	nd	nd	nd
	Taxifolin derivative	7.89 [101]	9.20 [101]	nd	nd	nd	nd
	Isoorientin	34.8 [101]	23.60 [101]	nd	nd	nd	nd
	Orientin	53.1 [101]	47.70 [101]	nd	nd	nd	nd
	Isovitexin derivative	3.71 [101]	nd	nd	nd	nd	nd
	Ferulic acid	0.98 [101]	1.22 [101]	nd	nd	nd	nd
	Taxifolin deoxyhexose	7.91 [101]	7.50 [101]	nd	nd	nd	nd
	Procyanidin dimer	4.37 [101]	52.90 [101]	nd	nd	nd	nd
	Isovitexin	10.6 [101]	4.21 [101]	nd	nd	nd	nd
	Apigenin glucoside	nd	6.31 [101]	nd	nd	nd	nd
	Scoparin	5.83 [101]	nd	nd	nd	nd	nd
	Procyanidin dimer	4.85 [101]	15.50 [101]	nd	nd	nd	nd
	Procyanidin trimer	5.74 [101]	7.11 [101]	nd	nd	nd	nd
	Procyanidin trimer	5.44 [101]	7.23 [101]	nd	nd	nd	nd
Phenolics (%)	Total phenolics (mg AGE/100 g)	nd	nd	nd	362.90 [102]	426.35 [64]	nd
	Flavone derivative	nd	nd	9 [33]	nd	nd	nd
	Maloyl caffeoyl-shikimic acid	nd	nd	9 [33]	nd	nd	nd
	Apigenin 6-C-hexoside sulfate (Isovitexin sulfate)	nd	nd	9 [33]	nd	nd	nd
	Apigenin 6,8-di-C-hexoside (Vicenin-2)	nd	nd	21 [33]	nd	nd	nd
	Apigenin 6-C-hexoside 8-C-pentoside (Neoschaftoside)	nd	nd	3 [33]	nd	nd	nd
	Apigenin 6-C-pentoside 8-C-hexoside (Isoschaftoside)	nd	nd	5 [33]	nd	nd	nd
	Apigenin 6-C-hexoside 8-C-pentoside (Schaftoside)	nd	nd	32 [33]	nd	nd	nd
	Apigenin 6-C-pentoside 8-C-hexoside (Vicenin-1)	nd	nd	4 [33]	nd	nd	nd
	Apigenin 6-C-hexoside 8-C-pentoside (Vicenin-3)	nd	nd	2 [33]	nd	nd	nd
	Apigenin 8-C-hexoside (Vitexin)	nd	nd	2 [33]	nd	nd	nd
	Apigenin 6-C-hexoside (Isovitexin)	nd	nd	3 [33]	nd	nd	nd
Phenolics (mg/g)	Gallic acid	nd	nd	nd	nd	8.31 [103]	nd
	Catechin	nd	nd	nd	nd	1.07 [103]	nd
	Caffeic acid	nd	nd	nd	nd	9.84 [103]	nd
	Ellagic acid	nd	nd	nd	nd	8.45 [103]	nd
	Rutin	nd	nd	nd	nd	12.76 [103]	nd
	Quercetin	nd	nd	nd	nd	1.03 [103]	nd
	Kaempferol	nd	nd	nd	nd	5.13 [103]	nd
	Tannin (mg/100g)	nd	nd	nd	nd	4.03 [64]	nd
	Chlorogenic acid (mg/100g)	nd	nd	nd	nd	0.91 [64]	nd
Total tocopherols (μg/g)	α-tocopherol	nd	nd	117 [104]	nd	nd	142.4 [46]
	β-tocopherol	nd	nd	Tr traces	nd	nd	5.6 [46]

(*continued on next page*)

Table 2 (*continued*)

Components		*Euterpe oleracea*	*Euterpe precatoria*	Bactris gasipaes	Mauritia flexuosa	*Astrocaryum aculeatum*	*Astrocaryum vulgare*
Carotenoid concentration (μg/g)	Total	nd	nd	197.66 [32]	513.87 [32]	62.65 [32]	8390 [44]
	all-*trans*-β-carotene	nd	nd	55.51 [32]	372.32 [32]	47.36 [32]	nd
	all-*trans*-δ-carotene	nd	nd	45.77 [32]	2.09 [32]	0.52 [32]	nd
	all-*trans*-γ-carotene	nd	nd	35.4 [32]	14.76 [32]	0.35 [32]	nd
	cis-γ- carotene 4	nd	nd	28.35 [32]	nd	nd	nd
	9-*cis*-lycopene	nd	nd	8.44 [32]	nd	nd	nd
	cis-δ-carotene 1	nd	nd	5.22 [32]	5.46 [32]	nd	nd
	13-*cis*-β-carotene	nd	nd	4.02 [32]	nd	nd	nd
	cis-γ-carotene 1	nd	nd	3.25 [32]	nd	nd	nd
	cis-γ-carotene 2	nd	nd	2.26 [32]	2.33 [32]	nd	nd
	9-*cis*-β-carotene	nd	nd	2.21 [32]	18.57 [32]	nd	nd
	cis-γ-carotene 3	nd	nd	2.11 [32]	9.88 [32]	0.89 [32]	nd
	cis-δ-carotene 2	nd	nd	2.09 [32]	3.67 [32]	nd	nd
	all-*trans*-α-carotene	nd	nd	1.78 [32]	3.23 [32]	1.68 [32]	nd
	cis-δ-carotene 3	nd	nd	0.86 [32]	2.42 [32]	nd	nd
	cis-γ-carotene 5	nd	nd	0.13 [32]	nd	nd	nd
	all-*trans*-α-cryptoxanthin	nd	nd	0.12 [32]	1.28 [32]	1.30 [32]	nd
	15-*cis*-β-carotene	nd	nd	0.08 [32]	8.87 [32]	0.80 [32]	nd
	5,8-epoxy-β-carotene	nd	nd	0.03 [32]	7.44 [32]	0.76 [32]	nd
	13-*cis*-β-carotene	nd	nd	nd	59.23 [32]	1.60 [32]	nd
	di-*cis*-α-carotene	nd	nd	nd	1.25 [32]	nd	nd
	5,6-epoxy-β-carotene	nd	nd	nd	0.41 [32]	nd	nd
	phytoene	nd	nd	nd	0.34 [32]	nd	nd
	di-*cis*-β-carotene 2	nd	nd	nd	0.11 [32]	nd	nd
	5,6-epoxy-β-cryptoxanthin	nd	nd	nd	0.10 [32]	nd	nd
	all-*trans*-ζ-carotene	nd	nd	nd	0.08 [32]	0.14 [32]	nd
	all-*trans*-lutein	nd	nd	nd	0.03 [32]	0.79 [32]	nd
	all-*trans*-β-cryptoxanthin	nd	nd	nd	nd	1.64 [32]	nd
	zeinoxanthin	nd	nd	nd	nd	1.02 [32]	nd
	cis-β-zeacarotene 2	nd	nd	nd	nd	0.65 [32]	nd
	cis-β-zeacarotene 1	nd	nd	nd	nd	0.60 [32]	nd
	all-*trans*-β-zeacarotene	nd	nd	nd	nd	0.44 [32]	nd
	all-*trans*-neoxanthin	nd	nd	nd	nd	0.26 [32]	nd
	cis-violaxanthin	nd	nd	nd	nd	0.24 [32]	nd
	cis-neoxanthin	nd	nd	nd	nd	0.18 [32]	nd
	all-*trans*-zeaxanthin	nd	nd	nd	nd	0.16 [32]	nd
	cis-lutein	nd	nd	nd	nd	0.04 [32]	nd
	β-carotene	nd	nd	nd	nd	nd	107 [105]
	β-cryptoxanthin	nd	nd	nd	nd	nd	5.9 [105]
Instrumental color	L[a] (luminosity)	28.05 [106]	24.86 [90]	79.7 [28]	49.51 [35]	67.50 [107]	48 [82]
	a[a] (red to green)	3.99 [106]	1.54 [90]	−1.98 [28]	27.41 [35]	16.20 [107]	22 [82]
	b[a] (yellow to blue)	1.87 [106]	−1.12 [90]	34.2 [28]	33.59 [35]	44.40 [107]	26 [82]
	C[a] (chroma)	3.97 [108]	1.94 [90]	nd	43.35 [35]	nd	nd
	h° (hue)	15.63 [108]	−36.22 [90]	nd	50.78 [35]	nd	50 [82]

[a] Values on wet basis; nd: not determined.

Açai is a round fruit with a dark purple color, a diameter between 10 and 20 mm, and a weight ranging from 2.6 to 3.0 g, with 17 % pulp and peel and 83 % seeds [14]. Before crushing or extracting the pulp, the açai undergoes a step of bleaching or pasteurization with water at 80 °C for 10 s [15]. This operation softens the peel of the fruit. The product obtained is a purple-colored juice [14].

Due to the increase in açai exports, different products were developed by the food industry, such as pasteurized açai pulp (with 8 %, 12 %, and 14 % of total solids), açai pulp with guarana, and açai *sorbet* with strawberry, banana, and guarana [16,17]. Using açai in food formulations can improve the sensory attributes and the product's nutritional value.

Açai fruits are considered caloric due to their high levels of lipids (Table 1). The oily extract from açai has garnered significant interest due to its unsaturated fatty acids content (68 %–71 %), with significant levels of oleic acid (60 %), followed by palmitic (22 %) and linoleic (12 %) acids [18]. Due to its promising chemical and biological characteristics, açai oil is an attractive product for the food and cosmetic industries, particularly the pharmaceutical sector [19].

The main bioactive compounds with antioxidant capacity in açai are anthocyanins, responsible for the intense purple color characteristic of the fruit [20]. Cyanidin 3-glucoside and cyanidin 3-rutinoside are its major anthocyanins, and secondarily, other flavonoids are present, such as apigenin, chrysin, epicatechin, luteolin, orientin, and vitexin [21].

3.2. Pupunha (Bactris gasipaes)

Bactris gasipaes kunth is a typical palm tree from northern Brazil; thorns cover its strain, producing a fruit called pupunha (Fig. 1B). The pupunha tree flowering period occurs from October to December, and its fruit harvest occurs between December and March. Still, it may be extended longer due to the abundance of rain and soil fertility [22]. An important recent finding was a new variety of white pupunha with biometric aspects and a harvest period like the traditional species [23].

The pupunha tree produces an average of 5–10 bunches annually, but some palm trees may grow up to 25 bunches. Each bunch contains approximately 100 fruits, reaching up to 400 fruits per bunch. A pupunha tree can produce 10 to 120 Kg of fruit; thus, harvesting 1 ha of palm trees can generate 4–10 tons per year [24]. The most current production quantity available was 8873 tons in 2017 [25].

Pupunhas are oblong, cylindrical, or conical flat fruits 2–7 cm long and have a thin epicarp covering their mesocarp. Their pericarp is fibrous, and their color varies between white, red, yellow, and orange [26]. The fruits can be classified into three categories: microcarp (fruit <20 g), mesocarp (fruit with 21–70 g), and macrocarp (fruit >70 g) [27].

Pupunha is usually consumed after cooking, in meals such as breakfast or afternoon snacks [28]. This fruit has great potential for use in food formulations, such as bakery products (cakes, biscuits, bread), or as a source of natural pigment due to its high carotenoid content. Pupunha is gluten-free; therefore, its use as an ingredient in gluten-free bakery products is excellent for preparing products aimed at celiac consumers [29].

The pupunha has a lipid content of 8 %–23 %, with prevalence of unsaturated fatty acids (Table 2). For this reason, fruit intake may reduce total cholesterol, triglycerides, and low-density lipoproteins in the blood. The fruit is also a source of essential fatty acids, especially linoleic acid (omega 6) and linolenic acid (omega 3) [30].

The different pupunha coloring phenotypes are due to carotenoids, natural pigments responsible for its hue ranging from yellow to orange [31]. The main carotenoids already reported were violaxanthin, lutein, zeaxanthin, 15-*cis*-β-carotene, 13-*cis*-β-carotene, all-*trans*-β-carotene, 9-*cis*-β-carotene, and α-carotene [32]. The first report on the phenolic compound profile of cooked pupunha fruit pulps [33] showed that the orange and yellow pupunha pulps presented the same profile of phenolic compounds, with schaftoside being the main compound in the yellow (45 %) and orange (32 %) varieties.

3.3. Buriti (Mauritia flexuosa)

The palm *Mauritia flexuosa* L. belongs to the Arecaceae family and the *Mauritia* genus, and it can be found in Brazilian regions comprising the Amazon to the Cerrado biomes [34]. The fruits of the palm trees of the Amazon biome have a more intense dark yellow and red color, while the fruits of the Cerrado present a bright yellow tone [35]. In Brazil, the swamps dominated by *M. flexuosa* are known as buritizais (burity forests), flourishing from September to December and bearing fruits from January to July [9]. The buritizais appear commonly in the Amazon region, which makes large quantities of fruits accessible to the population for harvesting, both for their consumption and for commercialization [36]. In 2022, around 422 tons of buriti were produced in Brazil [11]; among the Federation units, Pará had 271 tons.

The buriti fruit (Fig. 1C) is elongated, spherical, 4–7 cm long, 3–5 cm in diameter, and 25–40 g weight. It has an epicarp with rhomboid scales of reddish-brown coloration, a mesocarp with an orange hue and a sweet aroma, an oily texture and pasty consistency, globular or semispherical seed [37,38].

The primary use of the fruit is to make pulps that are typically destined for markets and fairs in the Amazon region, and the pulp is used to make ice creams, jellies, creams, liqueurs, and vitamins [38,39].

Tables 1 and 2 present the proximate, nutritional, and bioactive composition of *Mauritia flexuosa*. According to Cândido & Silva, the total lipid content (14.28 %) (Table 1) stands out, with 17.27 % saturated fatty acids and an optimal relationship between saturated/unsaturated fatty acids. Darnet et al. [40] reported that the tocopherol content of buriti is very high, about 1169 μg/g of dry matter.

Buriti is the natural source that has the highest β-carotene content ever found in nature [32] and is therefore considered the largest source of provitamin A (3531 μg RAE/100 g) of Brazilian biodiversity [41]. Koolen et al. [36] identified 13 phenolic compounds in buriti, namely: (+)-catechin, caffeic acid hexoside, chlorogenic acid, quercetin, naringenin, myricetin, vitexin, scoparin, rutin, cyanidin-3-rutinoside, cyanidin-3-glucoside, (−)-epicatechin, and kaempferol.

3.4. Tucumã (Astrocaryum aculeatum)

Astrocaryum spp. are palm trees native to the Amazon region of South America. Their fruits are popularly known as tucumã-do-Amazonas (*Astrocaryum aculeatum*) and tucumã-do-Pará (*Astrocaryum vulgare*). *Astrocaryum aculeatum* is found mainly in the states of Acre, Amazonas, Rondônia, and Roraima. *Astrocaryum vulgare*, in turn, is found in the states of Amapá, Pará, Tocantins, Maranhão, Piauí, and Goiás [42]. The harvest of the tucumã-do-Amazonas takes place from February to August, while the tucumã-do-Pará bears fruits from January to April, but if well handled, it can bear fruit all year round [9]. The palm tree has a productivity of 12–50 kg/year, which begins slowly when the tree reaches seven years old. The fruits grow between 200 and 400 units per bunch [9,43].

Tucumã fruits (Fig. 1D) are ellipsoid, globose, smooth, 5–6 cm in diameter, and 70–75 g of weight per fruit. The epicarp and mesocarp of fruit show colors ranging from yellow, orange, and red [44]. The pulp of the fruit has a sweet taste. It is highly estimated in the preparation of wines, ice cream, and juices, besides being used by the cosmetics industry, with economically viable exploitation potential for the income of local farmers [45].

In addition to its remarkable sensory characteristics, tucumã presents a promising composition of bioactive compounds (Table 2)

associated with health benefits, such as α-tocopherol, fatty acids, flavonoids, polysaccharides, carotenoids (mainly β-carotene, 13-*cis*-β-carotene, α-carotene, β-cryptoxanthin, and α-cryptoxanthin) and phenolic compounds (catechins, quercetin, and gallic acid) [5,32,44,46]. Among the chemical constituents of tucumã, the lipid fraction is predominant, containing an average of 30 % saturated fatty acids and 70 % unsaturated fatty acids, of which approximately 65 % are represented by oleic acid [47].

4. Biological effects of fruits of Amazonian palm trees

4.1. Açai (Euterpe oleracea)

In the last decade, several studies have demonstrated the action of açai consumption in preventing and treating diseases. In this context, Pala et al. [48] evaluated the influence of consuming 200 g of açai pulp/day for four weeks by healthy volunteer women aged 24 ± 3 years. They found that the consumption of açai did not interfere with anthropometric parameters, systemic blood pressure values, insulin resistance, total cholesterol, low-density lipoproteins (LDL), high-density lipoproteins (HDL), triacylglycerol (TAG), and apolipoprotein B (apo B). On the other hand, consuming açai increased the transfer of esters from cholesterol to HDL and increased the concentration of apolipoprotein AI (apo AI) in the volunteers. The authors concluded that açai might play a beneficial role against atherosclerosis by promoting favorable actions in plasma HDL metabolism and antioxidant defense.

Silva et al. [49] aimed to analyze the effects of açai seed extract and oil (*Euterpe oleracea* Mart.) on different human colon adenocarcinoma cell lines (Caco-2, HT-29, and HCT-116). The cytotoxic effect of *E. oleracea* Mart. seed oil at 0.25, 2.5, 25, and 100 μg/ml was analyzed with an MTT assay (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide). After 24 h of treatment with açai seed oil, the IC50 was calculated. This resulted in greater sensitivity in the HCT-116 strain with an IC50 of 11.8 μg/ml, and the most resistant strain was HT-29 with an IC50 of 51.2 μg/ml. It shows that the percentage of cells in the early and late stages of apoptosis in the Caco-2 and HCT-116 lines treated with 25 μg/ml of açai seed oil increased. There was no induction of apoptosis for HT-29 at the concentration analyzed. Therefore, the authors suggest that açai seed oil has antitumor potential in colorectal adenocarcinoma cells.

De Liz et al. [50] conducted a randomized crossover study with 30 healthy adults recruited to ingest 200 ml/day of açai juice for four weeks, with a *washout* period of four weeks. After this period, the intake of açai juice increased high-density lipoprotein concentrations by 7.7 %, promoting a significant increase in total antioxidant capacity (66.7 %), catalase enzyme activity (275.1 %), and glutathione peroxidase enzyme (15.3 %). In addition, the same authors verified a decrease in oxidative stress index (55.7 %) compared to the baseline. The authors concluded that regular consumption of açai juice positively impacted HDL levels and the activity of antioxidant enzymes, which may contribute to maintaining cardiovascular health.

Souza et al. [51] evaluated the effects of the consumption of 200 g of açai pulp by healthy women per day for four weeks on an extensive panel of inflammatory biomarkers: cell adhesion molecules (ICAM-1, IVAM-1, P-selectin, MCP-1, and fractalcin), interleukins (IL-1β, IL-6, IL-8, IL-10, and IL-17) and adipokines (adiponectin, leptin, visfatin, and adipsin). The volunteers were evaluated before and after the nutritional intervention. The consumption of açai pulp decreased the concentrations of *p*-selectin, leptin, and visfatin in the women's serum. These results show that consuming açai pulp modulates important biomarkers of the inflammatory process in healthy women.

The effect of açai supplementation and aerobic physical training (AET) on the structure and cardiac function of rats subjected to a high-fat diet was studied by Lavorato et al. [52]. These authors provided male Fischer rats with five types of diets: control (C), high-fat diet (H), high-fat diet + açai (HA), high-fat diet + AET (HT), and high-fat diet + açai + AET (HAT). The high-fat diets (H and HT) comprised 21.8 % lard and 1 % cholesterol, while the HA and HAT diets were supplemented with 1 % lyophilized açai pulp. As a result, AET and açai supplementation inhibited the increased of collagen content in the left ventricular, the harmful effects on transient the single myocyte intracellular calcium, and contractility in cardiomyocytes. The authors also found increased oxidative stress from consuming a high-fat diet. Thus, AET and açai supplementation softened the damage caused by a high-fat diet in cardiac structure and function, although the combination of these treatments did not offer additional effects.

The açai anthocyanin-rich extract was used by Song et al. [53] to verify the anti-obesity activity and modulating effect of the intestinal microbiota. Thirty-six male SPF C57BL/6J mice were randomly divided into three groups and fed a low-fat, high-fat, or high-fat diet supplemented with açai anthocyanin extract for 14 weeks. The results indicated that treatment with the extract alleviated obesity induced by the high-fat diet, insulin resistance, and hepatic steatosis. In addition, the microbial changes caused by the extract improved the health of obese rats.

The effect of açai intake in the treatment of depression in mice was studied by Souza-Monteiro et al. [54], who administered clarified açai juice (10 μL/g, orally) for four days and then a saline or lipopolysaccharide solution (0.5 mg/kg, ip) to induce depression-like behavior. Only four doses of juice were sufficient to eliminate the behavior, desperation changes, and anhedonia observed in the electromyographic measurements of rats with induced depression.

4.2. Pupunha (Bactris gasipaes)

One of the first studies that verified the biological effects of pupunha was carried out by Yuyama et al. [55], who evaluated the bioavailability of vitamin A, derived from the provitamin A compounds of pupunha, by determining the reserves of vitamin A and carotenes in the liver and plasma of male Wistar rats. The animals were subjected to the following treatments: diets containing 0, 2, 4, and 8 UI retinyl palmitate/g of feed (control groups) and diets containing 4 UI of provitamin A of pupunha/g of feed (test group). Baseline vitamin A levels in the control group (0 UI retinyl palmitate/g feed) were, on average, 0.17 μg/g in the liver and 3.50 μg/100 g in plasma. At the end of the experiment, the mean vitamin A levels in the liver were 53.45 μg/g (test group), and in plasma, 28.33

μg/100 g. When comparing the concentrations of carotenes in the liver and plasma of the treated animals to those of the control group, a significant difference was detected only in the liver. The authors concluded that the vitamin A of pupunha is highly bioavailable, with an efficiency of 171 %, compared to the control groups.

Jiménez et al. [56] estimated the effect of the intake of cooked pupunha fruits and pupunha chips on the glycemic index (GI). Twelve healthy (non-smoking) volunteers were selected, who ingested the samples after an overnight fast of 12–14 h in portions of 25 g of available carbohydrates. The mean GI values were 35 ± 6 in the individuals who consumed the cooked fruit (low GI) and 60 ± 7 in the individuals who consumed the pupunha chips (moderate GI). The difference was attributed to the processing steps of the chips (grinding, molding, and baking), which favor the availability of starch by digestive enzymes during hydrolysis.

Carotenoids from residues (biomass) of *Bactris gasipaes* obtained by an ionic liquid-based process were investigated by Santamarina et al. [57] in terms of safety, anti-inflammatory and antioxidant activity in an animal model with a high-fat kidney diet. Two different extracts were performed: (1) using an ethanolic solution of 1-butyl-3-methylimidazolium tetrafluoroborate (IL) or (2) using mixtures of acetone and ether, here called volatile organic solvents (VOS). The carotenoids from the *Bactris gasipaes* extract developed with ILs were superior in anti-inflammatory and antioxidant effects in the kidney compared to the extract obtained by the VOS-mediated process. Carotenoids obtained from ILs showed protective properties against the harmful effects of high-fat diet intake. It also has an antioxidant function by reducing the by-products of oxidative stress, increasing antioxidant enzymes, and promoting an anti-inflammatory environment in the kidney.

4.3. Buriti (*Mauritia flexuosa*)

Aquino et al. [58] addressed the effect of ingesting buriti oil in rats with iron overload by administering $FeSO_4$. For this, Wistar rats (n = 32) were used, allocated into two control groups (a diet containing soybean oil or buriti oil) and two groups that received a high daily oral dose of $FeSO_4$ (60 mg/kg of body weight) and fed a diet containing soybean oil or buriti oil. To evaluate the effect of the treatment, somatic and hematological parameters, serum lipids, superoxide dismutase (SOD), and glutathione peroxidase (GPx) were determined after 17 days of iron overload. The authors concluded that buriti oil presented systemic and hepatic antioxidant protection in rats with iron overload, possibly related to its high profile of carotenoids, tocopherol, and fatty acids.

According to Leão et al. [59], the fruits of buriti (*M. flexuosa*) can act in the prevention of the neurocytotoxic and behavioral effects of methyl mercury (MeHg). The study involved the administration of two diets in male Wistar rats: food with a commercial diet consisting of 23 % crude protein, 4 % ether extract, 5 % crude fibrous, 10 % mineral matter, 1.3 % calcium, and 0.85 % phosphorus (n = 14) and with the intake of commercial feed added buriti pulp (1:1 g/g) and ultrapure water (n = 14) for seven days. After the intervention, two subgroups, commercial feed (n = 7) and group supplemented with buriti feed (n = 7), were exposed to 5 mg/kg/day of MeHg by gavage for three days. A high T-maze device was used to evaluate the effect of MeHg on the acquisition of aversive memory and the panic behavior of the rats. After the behavioral test, the animals' hippocampus was removed to determine lipid peroxidation. Pretreatment with feed supplemented with *M. flexuosa* showed a protective effect against cognitive deficits caused by MeHg and prevented cytoplasmic membrane damage induced by lipid peroxidation in the hippocampus region.

In another study to evaluate the topical action of buriti oil in induced myositis in rats, Barbosa et al. [60] observed the effect of administering 0.5 ml of buriti oil in the posterior region of the right gastrocnemius muscle of the animals for 7 and 14 days, after induction of myositis by injection of 0.2 ml 1 % acetic acid with a hypodermic needle and insulin syringe in the right gastrocnemius muscle. The following treatments were performed in 36 male rats divided into three groups: control group, induced myositis group, and induced myositis group treated with buriti oil. In the myositis group treated with buriti oil, neutrophils decreased significantly compared to the induced myositis group ($p < 0.001$) in both experimental times. When assessing the number of fibroblasts at the two treatment times (7 and 14 days), a statistically significant difference was observed between the induced myositis and induced myositis treated with buriti oil groups, which suggests the effect of tissue repair of the induced lesion and proliferation of fibroblasts, as a result of the direct action of buriti oil.

The anti-inflammatory activity of the epicarp, mesocarp, and endocarp of *M. flexuosa* fruits was evaluated in female Swiss rats (*Mus musculus* Linnaeus, 1758) by Amorim et al. [61] to assess its physiological benefits. For the experiments, 100 mg of pulverized material epicarp (peel), mesocarp (pulp), or endocarp of *M. flexuosa* fruits were reconstituted separately in 1 ml of water. The dose ingested by the animals was 0.1 ml/10 g of body weight per gavage. To start the treatment, the rats were divided into five groups (n = 8 animals/group): pre-treated orally with sterile distilled water (negative control), indomethacin 10 mg/kg (reference drug), or aqueous extracts of epicarp, mesocarp, and endocarp (1000 mg/kg). The buriti fruits showed physiological benefits and the ability to modify biochemical and cellular steps of the inflammatory cascade, suggesting that dietary supplements containing the fruit can be combined. According to the authors, the findings were the result of high oral doses (500 or 1000 mg/kg); that is, from a nutrition point of view, food supplements containing *M. flexuosa* can be combined with pharmacological therapeutic agents to regulate homeostasis, as well as be administered as an important part of a balanced diet, aiming to prevent diseases of inflammatory origin.

Lage et al. [62] evaluated the antioxidant potential of buriti pulp flour in a survey of 36 female Fisher rats divided into four groups: (1) control, (2) control + buriti pulp flour, (3) diabetic, and (4) diabetic + buriti pulp flour. Groups 1 and 3 received the standard AIN-93 M diet, and groups 2 and 4 received the standard diet containing 2 % buriti pulp flour. Treatment with buriti pulp flour did not cause histopathological changes. Still, it promoted a significant reduction in the levels of thiobarbituric acid reactive substances (TBARS) in the heart and carbonylated proteins in the liver and heart of the animals. No effect on blood glucose and tissue histology was observed due to treatment with buriti pulp flour. However, the flour decreased oxidative damage in the liver and heart, indicating possible antioxidant potential.

Another research developed with buriti oil was carried out by Silva et al. [63], who evaluated the potential for wound healing using

topical formulations containing *M. flexuosa* in a crystalline liquid phase composed of murumuru butter (*Astrocaryum murumuru* Mart., Arecaceae). The level of healing was analyzed from a 1 cm^2 thick wound made in the dorsal region of the 48 rats (*Rattus norvegicus albinus*). The rats were divided into four groups: group treated with distilled water (1), treated with formulations with murumuru butter (2), containing 1 % (3), and 15 % (4) buriti oil for 21 days. Skin healing tests showed that formulations with 1 % and 15 % buriti oil could heal wounds significantly from day three compared to the murumuru-only and distilled water-treated groups. Formulations containing buriti oil accelerated wound healing in rats due to their rich composition of unsaturated fatty acids, which decreased inflammatory cells and promoted fibroblast proliferation in the early stages.

4.4. Tucumã (*Astrocaryum aculeatum*)

Sagrillo et al. [64] conducted an *in vitro* study to evaluate the cytoprotective potential of tucumã pulp extracts in human lymphocytes exposed to hydrogen peroxide (H_2O_2). The authors observed that the pulp and peel extracts were rich in β-carotene and quercetin and that both extracts showed significant amounts of rutin (peel: 25.64; pulp: 14.51), gallic acid (peel: 3.18; pulp: 10.85), caffeic acid (peel: 6.99; pulp: 0.66), and chlorogenic acid (peel: 2.55; pulp: 0.91), all expressed in mg/100 g of fresh fruit. The research showed that the extracts of tucumã partially reversed the cytotoxicity caused by H_2O_2, with the best protective effect observed at concentrations of 600 and 900 μg/ml of ethanolic extracts of the pulp and peel of tucumã. The authors clarified that the extract's cytoprotection involves apoptosis modulation since caspases 1, 3, and 8 significantly reduced the cells exposed to H_2O_2. Therefore, the results confirm the positive effect of tucumã extracts on the cytosis and genotoxicity of lymphocytes exposed to H_2O_2, probably due to the antioxidant activity of the bioactive molecules of the extracts of the peel and pulp of tucumã.

Carneiro et al. [65] evaluated the genotoxicity/antigenotoxicity activity of tucumã oil using the micronucleus test in micronucleated polychromatic erythrocytes. The study was conducted with healthy male Swiss mice (6–7 weeks of age). Genotoxic/antigenotoxic activity was assessed by administering 500, 1,000, and 2000 mg/kg body weight of fixed tucumã oil, with or without subsequent intraperitoneal injection of doxorubicin (0.3 mL - 15 mg/kg per body weight) which is considered a micronucleus inducer, in addition to a negative group (water) and dimethyl sulfoxide (600 μL). The study identified that the simultaneous administration of each concentration of fixed tucumã oil with an intraperitoneal injection of doxorubicin promoted a reduction of 34.72 %–38.19 % in the frequency of micronucleated polychromatic erythrocytes in 24-h treatments and a decrease from 63.70 % to 66.12 % for treatments of 48 h, compared to the group treated only with doxorubicin chemotherapy. These results were attributed to the presence of carotenoids and polyphenols in tucumã. Thus, the authors indicated the efficiency of the fixed crude oil as antigenotoxic in all studied concentrations, with a protective effect against damage to cellular DNA.

Baldissera et al. [66] studied the enzymatic activity of the purinergic immune system in the serum of mice with alloxan-induced diabetes. They were treated with tucumã oil extracted from the fruit pulp via cold pressing. The female Swiss mice were divided into four groups (six mice per group): (1) control/water, (2) control/tucumã oil, (3) diabetic/water, and (4) diabetic/tucumã oil. The animals were treated for 14 days with a daily dose of 5.0 ml/kg of tucumã oil via oral gavage. The authors found that tucumã oil prevented increased blood glucose in the diabetic group/tucumã oil compared to the diabetic group/water group. The treatment with tucumã oil proved efficient in modulating the alterations resulting from hyperglycemia, maintaining normal levels of ATP, ADP, AMP, and adenosine. These results show the tucumã oil protective effect against inflammation caused by diabetes mellitus.

Cabral et al. [67], when evaluating the anti-inflammatory and antioxidant properties of tucumã extract (30 μg/ml) against phytohemagglutinin-induced inflammation in cell cultures, indicated that the extract might be a therapeutic adjuvant in the prevention or treatment of inflammatory diseases. The results were obtained by cell viability and cytotoxicity assays, gene expression of interleukins IL-1β, IL-6, and IL-10, levels of reactive oxygen species (ROS), nitric oxide (NO), and thiols, as well as the activities of antioxidant enzymes in RAW cells 264.7 stimulated with phytohemagglutinin to mimic inflammation. The authors observed that tucumã extract inhibited the proliferation of macrophages, promoted the reduction of oxidative stress, and modulated genes related to inflammatory response, in addition to increasing antioxidant defenses and interrupting the cell cycle in the G0/G1 phase. The results suggested that tucumã can reverse abnormal cell proliferation and positively regulate the expression of anti-inflammatory cytokines.

Jantsch et al. [68] evaluated the action of tucumã extract on memory and redox balance of the cerebral cortex of hyperlipidemic rats. The study was conducted over 30 days, during which tucumã extract (250 mg/kg body weight) was administered in Wistar rats, followed by induction of hyperlipidemia via intraperitoneal administration of Poloxamer-407. As a result, hyperlipidemia affects brain function through oxidative damage. Still, the tucumã extract prevented memory loss and oxidative damage of proteins and lipids. It allowed for a better antioxidant response in the cerebral cortex of rats with hyperlipidemia, which evidenced the neuroprotective effect and the nutraceutical applicability of tucumã.

The potential of the tucumã extract in the prevention of molecular damage to retinal epithelium cells (RPE) was evaluated by Bonadiman et al. [69]. *In vitro* protocols were performed to verify the cytoprotective effect with different concentrations of tucumã extract (5, 10, 50, 100, and 500 μg/ml) in RPE cells exposed to the oxidizing agent hydrated paraquat dichloride at a 30 μM for 6 h. The concentrations of 5, 10, and 50 μg/ml of tucumã extract did not cause apoptosis and necrosis in ARPE-19 cells. In the cells exposed to the oxidizing agent hydrated paraquat dichloride and treated with 50 μg/ml of tucumã extract, there was a decrease in oxidative markers (TBARS, nitrite, superoxide anion, reactive oxygen species). Such results indicate that the extract prevented oxidative damage caused by paraquat in ARPE-19 cells. In addition, the tucumã extract significantly prevented DNA damage caused by paraquat. Therefore, cell viability improvements and necrosis and apoptosis prevention were observed. Additionally, oxidative and molecular damage was reduced, explained by the presence of antioxidants in tucumã extract.

Table 3
Application of Amazonian palm fruits in food products.

Type of food	Induced sample	Objective	Added ratio	Main findings	Reference
Açai					
Yogurt	Natural juice of *E. oleracea* (10 % w/w) Centrifuged *E. oleracea* juice (10 % w/w)	Natural pigment	10 %	The yogurt enriched with juice (10 %, w/w) presented characteristics similar to typical commercial yogurt with blueberry juice.	[109]
Yogurt	Lyophilized pulp of *E. oleracea*	Improve nutritional value	7 %	The inclusion of pulp of *E. oleracea* increased the content of mono- and polyunsaturated fatty acids in probiotic yogurts and the production of conjugated α-linolenic and linoleic acids during the fermentation of skimmed milk.	[110]
Ice cream	Pulp of *E. oleracea*	Improving survival of *Lactobacillus rhamnosus* GG to simulated gastrointestinal stress	20 %	Ice cream of *E. oleracea* pulp is a suitable matrix for *L. rhamnosus* GG, improving the *in vitro* survival under simulated gastrointestinal conditions.	[111]
Dairy drinks with probiotic bacteria	Pulp of *E. oleracea*	Improving rheological properties, nutritional composition, and sensory attributes	15, 22.5, and 30 %	Viscosity was positively affected by the higher levels of hydrolyzed collagen and *E. oleracea* pulp, increase in lipid and carbohydrate contents and energy value. The formulation with 22.5 % *E. oleracea* pulp achieved the highest sensory acceptance.	[81]
Mixed milk beverage fermented by kefir	Pulp of *E. oleracea*	Improving production throughput and sensory attributes	10, 30, 50, 70, and 90 %	The inclusion of *E. oleracea* increased 12 % the kefir biomass, 93 % the fermentation yield, and sensory acceptance.	[112]
White chocolate	Organic lyophilized powder of *E. oleracea* pulp (100 % fruit) Spray-dried powder of *E. oleracea* pulp (70 % fruit)	Improving sensory characteristics	Lyophilized organic powder of *E. oleracea* pulp (10 %) Spray-dried powder of *E. oleracea* pulp (14.3 %)	Chocolates with lyophilized and spray-dried *E. oleracea* pulp achieved a sensory acceptance index greater than 5 for the taste attribute.	[113]
Mixed jam (*E. oleracea* and honey from *Theobroma cacao)*	*E. oleracea* (1:10, w/w, pulp and water)	Improving nutritional value and sensory attributes	40, 50, and 60 %	Sensory acceptance index higher than 4 (acceptable sensory characteristics for commercialization)	[114]
Chewable sweets	Spray-dried powder of *E. oleracea* pulp	effect on sensory attributes	10.4 %	The inclusion of *E. oleracea* powder pulp explored the flavor and color potential of the fruit and eliminate the inclusion of vegetable fat generally used in the formulation of the product.	[115]
Pork hamburger	Lyophilized *E. oleracea* extract	Oxidative and color stability	250, 500, 750 mg/kg	Lyophilized extract improved the antioxidant activity but caused changes in color at medium and high levels.	[83]
Pupunha					
Spaghetti noodles and *twist noodles*	Cooked *Bactris gasipaes* pulp flour	Improving quality attributes	15 %	In the cooking test for spaghetti and twisted pasta, the pupunha flour did not significantly change the quality characteristics and texture of the products.	[116]
Mayonnaise	*Bactris gasipaes oil*	Increasing the bioaccessibility of carotenoids	38.7 %	The bioaccessibility of carotenoids incorporated in the product was approximately 11 times higher than that of the lyophilized fruit. The product had high sensory acceptance for all sensory attributes, high thermal and gravitational stability,	[84]

(*continued on next page*)

Table 3 (*continued*)

Type of food	Induced sample	Objective	Added ratio	Main findings	Reference
				and antioxidant activity of 4.80 (scavenger ROO·, α-tocopherol as a reference).	
Biscuits	*Bactris gasipaes* pulp flour and whole fruit (pulp + peel) flour	Hygroscopic behavior of the two types of flour at 25 °C and production two types of gluten-free biscuits, characterization, and sensory evaluation	40 %	Both pupunha flours had a high content of carbohydrates and lipids, and both products were susceptible to increased moisture during storage at relative humidity above 70 %. The biscuits with the two types of flour showed reasonable rates of sensory acceptability and purchase intent.	[28]
Extruded maize breakfast cereal enriched with whole flour of *Bactris gasipaes*	Whole flour *Bactris gasipaes*	Formulating and conducting the physical-chemical, technological, and microbiological characterization	7.3, 24, 42.7, and 50 %	The recommended operating conditions: 25 % pupunha flour and 16.2 % moisture. The product had desirable attributes for consumers and potential for commercialization.	[117]
Cakes	Peel flour of *Bactris gasipaes*	Evaluating the color and sensory attributes	2.5, 5.0, 7.5, and 10 %	The inclusion of pupunha flour increased the total carotenoid content. Sensory evaluated attributes were acceptable for the cake formulated with 7.5 % pupunha flour replacing wheat flour.	[118]
Bread	Dehydrated whole pulp of *Bactris gasipaes*	Improving the chemical composition	100 and 150 g	A higher contents of ash, lipids, and dietary fiber in bread added 100 and 150 g of dehydrated pulp compared to the control bread.	[119]
Frankfurt sausages	Oily extract of exocarp and mesocarp	Applying the oily extract of carotenoids, as a natural dye, partially replacing nitrite	9, 19, 29, 42, and 97 ml/kg	Increase in L, b*, C, and h with an increase in the percentage of extract and a decrease in the amount of nitrite in the formulation.	[26]
Buriti					
Dairy drink	Lyophilized powder of *Mauritia flexuousa* pulp	Enriching dairy foods	1, 3, and 5 %	A significantly high content of bioactive compounds and DPPH radical scavenging capacity.	[120]
Biscuits	*Mauritia flexuosa oil*	Nutritional enrichment	15 %	Higher levels of monounsaturated fatty acids and β-carotene.	[121]
Chocolate cakes	*partially defatted Mauritia flexuosa bran*	Effect on the technological and sensorial characteristics	Replacement of 10 %, 20 %, and 30 % of wheat flour	The by-product of improved the symmetry index of the formulations. Cake with 20 % of buriti bran presented the best scores of acceptance, purchase intention, and preference.	[122]
Olive oil with buriti flavour	Dried pulp oil of *Mauritia flexuosa*	Elaborating a *Mauritia flexuosa* flavored oil for culinary purposes	25, 50, and 75 %	Low smoke point (not for frying). Formulations with 50 and 25 % of the oil were more suitable for producing and commercializing aromatized *Mauritia flexuosa* oil.	[123]
Biscuits	*Mauritia flexuosa oil*	Nutritional enrichment and sensory improvement	7.5 and 15 %	The highest concentration of vitamin A was observed in the biscuit with 15 % *Mauritia flexuosa* oil. All formulations showed good sensory acceptance.	[124]
Gluten-free biscuits	Endocarp flour *Mauritia flexuosa*	Obtaining a product that meets the dietary needs of celiac patients	Replacement of 0.5, 10, 15, and 20 % of endocarp flour of *Mauritia flexuosa* in standard flour	Replacement of standard flour with up to 15 % of endocarp flour of *Mauritia flexuosa* increased dietary fiber and mineral contents without causing significant changes in the product's sensory attributes. The inclusion of 20 % of buriti flour resulted in undesirable changes in the color and texture.	[125]

5. Toxicity

Toxicology studies of açai indicate that it is nontoxic in doses customarily consumed by the general population [70,71]. Marques et al. [72] evaluated the genotoxic potential of açai oil gavage in male Wistar rat cells at doses of 30, 100, and 300 mg/kg for 14 days, with a 24-h interval between gavages. Cytogenetic tests (comet assay and micronucleus test) showed that *E. oleracea* oil showed no

genotoxic effects on rat tissues in the three tested doses.

Despite the pupunha's important nutritional properties, the fruit must go through a cooking stage before consumption to disable antinutritional factors such as calcium oxalate and protease inhibitors [73]. Ingestion of small doses of calcium oxalate causes an intense burning sensation in the throat, swelling of the airways, and asphyxia. It can be fatal if ingested in large quantities [74]. Protease inhibitors, in turn, bind to trypsin or chymotrypsin, forming complexes that limit the digestive function of these enzymes [75].

Santos et al. [76] investigated peach palm flour's safety and nutritional aspects, evaluating the cytotoxic effects of the material produced in L929 cells and its impact on protein digestion when incorporated into a dairy food matrix. The cytotoxicity of phenolic extracts from peach palm flour was carried out in L929 cells. The phenolic extract obtained from peach palm flour was diluted in the culture medium at 0.000128, 0.00064, 0.0032, 0.016, 0.08, 0.4, 2, and 10 mg/ml Furthermore, peach palm flour (25 %) was added to yogurt formulations and subjected to the INFOGEST *in vitro* digestion protocol. Peach palm flour extracts were non-cytotoxic up to a 0.4 mg/ml concentration. The authors report that the cytotoxic potential of peach palm is not negligible since the IC50 was 0.940 mg/ml. The results of *in vitro* protein digestion, calculated from the release of free NH_2 groups, demonstrated that peach palm flour provided inhibition of protein digestion in yogurt. Therefore, this is the first to show that the phenolic extract from peach palm flour has cytotoxic potential in L929 cells and can inhibit protein digestion *in vitro*. The importance of the pupunha cooking stage as an alternative to reducing antinutritional compounds before making the flour can be highlighted when analyzing this research.

Regarding the toxic effects of buriti, the only study was developedby Silva et al. [28], who assessed the *in-silico* risk predicted by the PredSkin web app version 1.0. The research results indicated that no compounds identified in *M. flexuosa* oil raised any toxicological warnings in human skin sensitization tests.

The current literature has few studies on the toxicity of tucumã; however, De Souza Filho et al. [77] observed that acute treatment with tucumã extract showed genoprotective effects against DNA denaturation in mononuclear cells of human peripheral blood. However, some genotoxic effects were observed at 100–500 g/ml concentrations and higher concentrations of tucumã extract.

Guex et al. [78] conducted acute and subacute oral toxicity studies of crude tucumã pulp extract in Wistar rats. Acute toxicity was performed in two groups: control (3 ml of distilled water/kg) and test (single dose of 2000 mg/kg). Both treatments were oral, by gavage, lasting 14 days. For testing the oral toxicity of repeated doses for 28 days, the animals were divided into four groups according to gender: (group 1) control: 3 ml of distilled water/3 ml/kg; (groups 2, 3, and 4): crude extract of tucumã pulp administered at doses of 200, 400, and 600 mg/kg, respectively. After administration of a single dose of 2000 mg/kg of crude tucumã pulp extract, no signs of toxicity or behavioral changes were observed. Repeated oral administration of crude tucumã pulp extract (200, 400, and 600 mg/kg) did not induce any sign of toxicity, and no mortality was recorded during the experiment. The authors did not observe signs of mortality or toxicity during the study. Thus, crude extract from tucumã pulp was classified as safe (category 5, OCDE guide) in which acute lethal toxicity exceeds 2000 mg/kg. Histopathological findings showed renal damage in male rats when higher doses (600 mg/kg) were administered, suggesting that low doses administered repeatedly in males are considered safer.

6. Technological potential of fruits of Amazonian palm trees

The harvest of fruits from Amazonian palm trees traditionally targets the supply of local free fairs and, generally, are not used by the food industry due to their seasonality [79]. Therefore, there is a great challenge in making these fruits more attractive for industrial use, and it is imperative to optimize the processing conditions of these fruits to present new application alternatives [80]. In this regard, the literature has promising research that uses fruits of Amazonian palm trees in food formulations (Table 3).

Rigoto et al. [81] investigated the effect of hydrolyzed collagen, cheese serum, and açai pulp contents on the characteristics of probiotic dairy beverages. Probiotic milk drinks were elaborated with different proportions of açai pulp (15, 22.5, and 30 %), cheese whey (20, 30 and 40 %), and hydrolyzed collagen (0.5, 1.0, and 1.5 %). Regarding the color of the beverages, the authors observed a more reddish and dark coloration in beverages with a higher proportion of açai pulp. The highest sensory acceptance was verified in formulations containing 22.5 % açai pulp, 30 % cheese whey, and 1.0 % hydrolyzed collagen. The authors concluded that açai pulp, cheese whey, and collagen could be used to elaborate dairy beverages with functional appeal and good acceptability of sensory attributes.

The influence of adding açai powder on the sensory attributes of chewable gums with and without sucrose was investigated by Silva et al. [82]. The formulations of chewable gums were added 10.4 g/100 g of açai powder. This inclusion allowed the removal of vegetable fats, used in traditional formulations, without affecting the texture of chewable gums. In addition, açai powder improved the color and flavor of the formulations without the need to use additive dyes and flavorings. The results of the sensory analysis indicated that açai gum without the inclusion of sucrose presented better results compared to açai gum with sucrose, especially when the flavor attribute and purchase intent were evaluated. Therefore, edible açai gum prepared without the inclusion of sucrose is a formulation with the potential for acceptability in the consumer market.

The effect of using açai extract powder as a natural antioxidant in pork hamburgers during refrigerated storage was investigated by Bellucci et al. [83]. For this, five treatments were performed: without antioxidants, with sodium erythorbate (500 mg/kg), and with açai extract (250, 500, and 750 mg/kg). All açai concentrations improved the antioxidant status of hamburgers. However, among the levels of açai extract addition, the concentration of 250 mg/kg caused minor color changes and granted a protective effect against lipid oxidation similar to the formulation with sodium erythorbate. The authors concluded that açai extract at a dose of 250 mg/kg can be used as a natural antioxidant instead of sodium erythorbate to preserve the quality of frozen pork hamburgers.

Ribeiro et al. [28] evaluated the effect of adding flour prepared with whole fruit of pupunha (pulp + peel) and another only with the pulp in gluten-free biscuit formulations; in both formulations, 40 % of pupunha flour was added. The two formulations showed low

moisture (4.9–6.2 %), high lipid (25.56–26.37 %), and total carbohydrates (59.10–61.84 %) contents, resulting in products with high total energy value (501.8–502.8 kcal/100 g). The biscuit with pupunha fruit flour made with whole fruit presented a total carotenoid content (18.10 mg/100g) higher than the flour formulation made only with the fruit pulp (10.23 mg/100g). The two biscuit formulations rendered good values of acceptability index (>70 %) and purchase intent (>71 %).

Mesquita et al. [84] evaluated the bioaccessibility of pupunha carotenoids in mayonnaise and lyophilized pulp. Pupunha carotenoids were extracted via ultrasound in sunflower oil (solid-liquid ratio of 1:6 for 5 min). Then, 38.70 % of the oil-added pupunha carotenoids were incorporated into an aqueous phase to obtain mayonnaise. The authors determined that the carotenoid content incorporated in the micelles after digestion was 11 times higher for the mayonnaise than for the lyophilized fruit and associated this result with better protection that emulsified carotenoids have against degradation and stability during digestion. When evaluated sensorially, the mayonnaise containing pupunha carotenoids achieved good acceptance (grades up to 8, category: liked it very much, purchase intent: 4.56, category: probably would buy) and yellowish color similar to commercial mayonnaise.

Pinzón-Zárate et al. [26] also used pupunha in elaborating on meat products. In this study, the analysis of color parameters in Frankfurt sausages was performed with partial replacement of nitrites with added oily extract of pupunha residues (exocarp and mesocarp). The maximum amount of nitrite added in the formulations was 200 mg/kg and 100 mg/kg minimum. The oily extracts were added with maximum levels of 97 ml/kg and 9 ml/kg minimum. The authors indicated that the formulations with extract addition were not similar to commercial sausages concerning luminosity and coordinate a*. When evaluating the coordinate b* (related to the yellowing) and chroma (C), the authors observed that the formulations added 9 and 19 ml of the oily extract are statistically equal to commercial sausage products. At the same time, the maximum extract addition (97 ml/kg) was similar to the hue (*h*) of the standard formulation.

The fruits contemplated in this review are excellent sources of natural pigments that can be applied for food use since they can balance color loss during food processing and storage and thus can substitute artificial dyes [85]. Despite the remarkable composition of pigments of Amazonian fruits, industries can only use them to extract pigments after selecting extraction methods to provide a higher yield. Additionally, it is necessary to have adequate control of the factors that reduce the stability of these pigments [86].

With the evaluation of the contemplated studies, it was possible to observe that the fruits of Amazonian palm trees can be widely used in different formulations, such as bakery, dairy, and meat. Various forms of induction of new products include adding pulp, pulp flours, or fruit peel and oily extracts. In general, the insertion of fruits from Amazonian palm trees in food formulations improved the nutritional and sensory composition of the products studied.

Among the Amazonian fruits already studied, tucumã has been little explored, and its applications are still scarce and challenging. In the literature, some studies have addressed possible alternatives for inserting tucumã in food, for example, in preparing mayonnaise, salad dressing, and pastes [80,87,88].

7. Final considerations

The data collected on the fruits of Amazonian palm trees made it possible to verify that açai (*Euterpe oleracea*), pupunha (*Bactris gasipaes*), buriti (*Mauritia flexuosa*), and tucumã (*Astrocaryum aculeatum*) are excellent sources of bioactive compounds, which have potential action in the prevention of chronic diseases. It is worth noting that the use of these fruits, as mentioned earlier in food formulations, still progresses timidly. Many studies are still necessary to understand the relationship between the inclusion of fruits and the nutritional and technological properties of different formulations. Further research is needed to explore the potential of Amazonian fruits, focusing on their economic importance for regional producers and their bioactive and nutritional potential.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Isabelly Silva Amorim: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Danyelly Silva Amorim:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Helena Teixeira Godoy:** Writing – original draft, Visualization, Validation, Supervision, Formal analysis. **Lilian Regina Barros Mariutti:** Writing – original draft, Visualization, Validation, Supervision, Resources, Funding acquisition, Formal analysis. **Renan Campos Chisté:** Writing – original draft, Visualization, Validation, Supervision, Formal analysis. **Rosinelson da Silva Pena:** Writing – original draft, Visualization, Validation, Supervision, Formal analysis. **Stanislau Bogusz Junior:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Formal analysis, Conceptualization. **Josiane Freitas Chim:** Writing – original draft, Visualization, Validation, Supervision, Project administration, Formal analysis.

Declaration of competing interest

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

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