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Technological applications and color stability of carotenoids extracted from selected Amazonian fruits

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Abstract

In this review, we gathered information regarding the carotenoid composition of selected Amazonian fruits: peach palm (*Bactris gasipaes*), buriti (*Mauritia flexuosa*), tucumã (*Astrocaryum vulgare*), taperebá (*Spondias mombin*), and araçá-boi (*Eugenia stipitata*); and also discussed the stability of carotenoid extracts and their potential to be used as natural colorants in foods. Notwithstanding the claimed health benefits, information on technological approaches to the use of carotenoid extracts from Amazonian fruits as natural colorants or antioxidant are quite limited. These findings evidenced the need for more systematic studies assessing the stability of carotenoid extracts of Amazonian fruits and their application as natural food additives.

Keywords: natural pigments; bioactive compounds; color stability; carotenoid profiles; food additives.

Practical application: Carotenoids from Amazonian fruits have high technological potential as natural food additive.

1 Introduction

The scientific interest in investigating the composition and technological potential of bioactive compounds extracted from fruits has increased since high intake of fruits and vegetables has been associated with protective effects against various chronicle degenerative diseases, including prevention of cancer, coronary heart disease, inflammatory reactions, age-related diseases and other comorbidities (Griffiths et al., 2016; Coelho et al., 2019). Interestingly, Amazonian fruits have been the focus of intensive researches due to their high levels of bioactive compounds, especially carotenoids (Virgolin et al., 2017; Lima et al., 2020; Montero et al., 2020; Khouryieh, 2021).

Carotenoids are natural tetraterpenic pigments with lipophilic characteristics, comprising more than 750 compounds mainly responsible for the orange, yellow, and/or red color of plants, but can be also bioaccumulated in animals and synthesized by microorganisms and some arthropods such as hemipteran (aphids, adelgids, phylloxerids) (Dias et al., 2018; Rodriguez-Concepcion et al., 2018; Maoka, 2020). Carotenoids find application as healthy food ingredients and contribute to improving sensory characteristics of food products. Among the sensory attributes, color is known to impart the greatest influence on purchase decision, especially compared with taste and aroma, as it defines consumers' first impression of overall product quality (Martins et al., 2016; Stinco et al., 2019).

The industrial use of carotenoids as natural colorants still requires further attention. These compounds are unstable when exposed to light, oxygen, high temperatures, and acidic conditons, resulting in expressive discoloration of food products, reduced sensory quality, and, in some cases, decreased biological activity (Neri-Numa et al., 2017; Ribeiro & Veloso, 2021). Given these limitations, there is a constant need for effective strategies to increase the stability of carotenoids to be used as natural colorants (Rostamabadi et al., 2019; Dutta et al., 2021; Valerio et al., 2021).

In this review, information available in the current literature on the carotenoid composition of five Amazonian fruits, namely peach palm (*Bactris gasipaes* Kunth), buriti (*Mauritia flexuosa* L.f.), tucumã (*Astrocaryum vulgare* Mart.), taperebá (*Spondias mombin* L.), and araçá-boi (*Eugenia stipitata* McVaugh) were summarized, including specific aspects of the color stability of their carotenoid extracts for further application as natural food colorants.

2 Carotenoids: chemical definition and biological properties

Carotenoids are isoprenoid compounds with several conjugated double bonds in their chemical structures that confer high chemical reactivity and capacity to absorb light in the visible region of the electromagnetic spectrum, appearing as yellow, orange, or red to the human eye; however, there are also colorless carotenoids (phytoene and phytofluene) (Meléndez-Martínez et al., 2015; Sovová & Stateva, 2019). Carotenoids can be cyclic or acyclic structures and they can be classified into two groups: carotenes, which comprise chemical structures formed only by carbon and hydrogen atoms; and xanthophylls – oxygenated structures derived from carotenes (Figure 1A) (Rodriguez-Concepcion et al., 2018).

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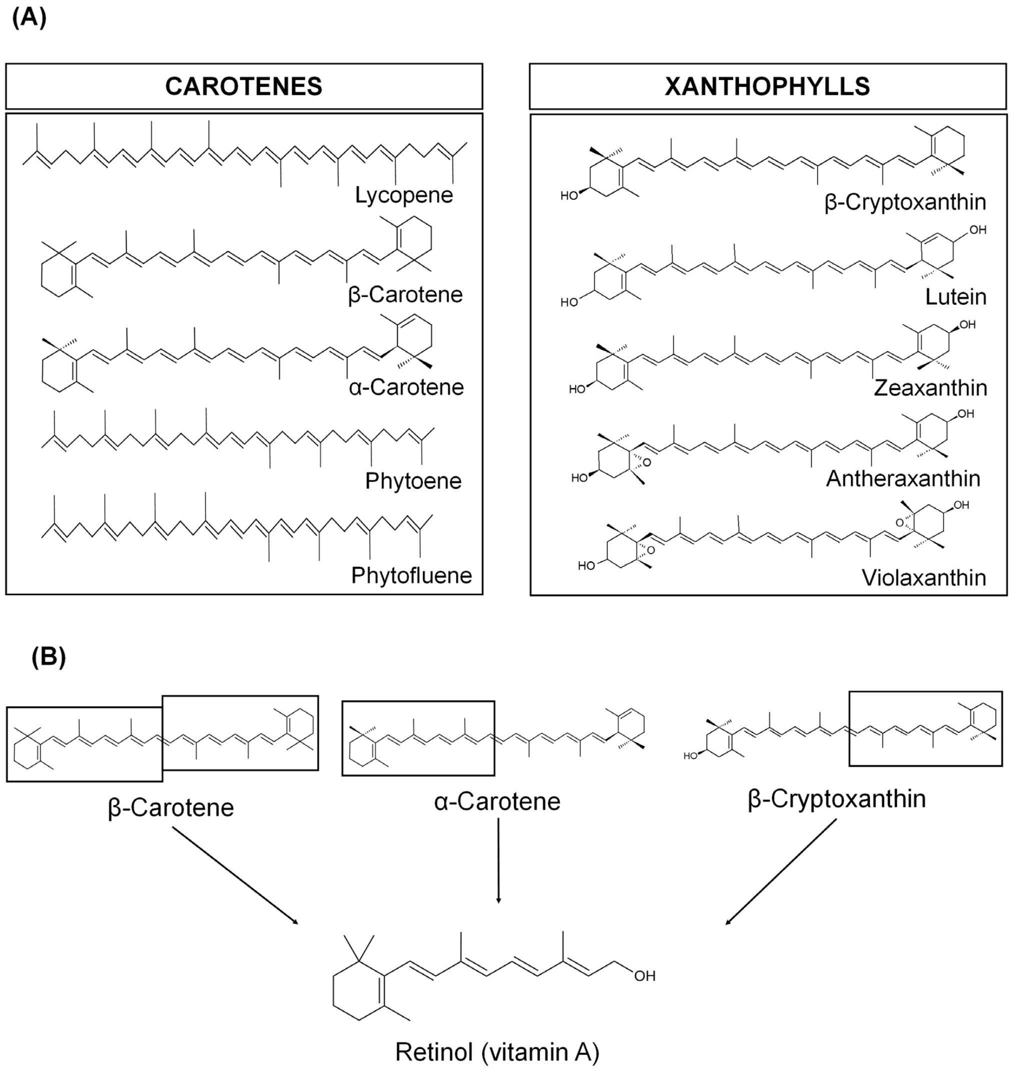

Figure 1. (A) Major carotenes and xanthophylls found in foods. (B) Conversion of provitamin A carotenoids to retinol (vitamin A).

Carotenoids are biosynthesized by photosynthetic organisms as well as by some non-photosynthetic prokaryotes and fungi (Pérez-Gálvez et al., 2020). In photosynthetic organisms, carotenoids have several functions beyond its attractiveness: these compounds play an important role in photosynthesis, act as accessory pigments for photoprotection, prevent overexcitation of chlorophyll reaction centers, promote heat dissipation, and act as natural antioxidants, inhibiting or delaying lipid peroxidation (Cazzaniga et al., 2016). The role of carotenoids (and their derivatives) as pigments in fruits, vegetables and derived food products has high impact on the marketability and appearance of these products and also on consumers' choices, as well as ample evidence that these compounds have demonstrated health-promoting properties, as elegantly discussed in details by Meléndez-Martínez (2019).

To date, more than 750 carotenoids have been identified in nature, of which about 50 are part of the human diet and 10 to 15 are found in measurable concentrations in the body. The main bioavailable dietary carotenoids found in human fluids and tissues are lycopene, α-carotene, β-carotene, lutein, β-cryptoxanthin, and zeaxanthin, but also the colorless carotenoids phytoene, and phytofluene, which have recently attracted more attention of the scientific community (Kiokias et al., 2016; Pietro et al., 2016; Meléndez-Martínez, 2019).

The frequent intake of dietary carotenoids have been associated with the reduced risk to develop chronic degenerative diseases such as cardiovascular diseases, macular degeneration, cataracts, inflammation, and also the development of several types of cancer, including prostate, breast, lung, and bowel cancer (Eggersdorfer & Wyss, 2018; Rivera-Madrid et al., 2020). Regarding cancer, once manifested, it triggers the oxidation of biomolecules by inducing a state of oxidative stress due to the overproduction of reactive oxygen and nitrogen species, leading to cell aging and promoting the development of chronicle degenerative diseases. In these cases, the action of dietary (exogenous) antioxidants, such as carotenoids, is of utmost importance because it helps to protect cells from the oxidative damage caused by reactive species (Rowles & Erdman, 2020).

However, in addition to the antioxidant action, other possible mechanisms for the health benefits of carotenoids have been postulated, such as pro-oxidant mechanisms, enhancement of gap junctional intercellular communication, modulation of signaling pathways, and absorption of visible light, which may work synergistically (Meléndez-Martínez, 2019).

In addition to their coloring and antioxidant properties, some carotenoids are also precursors of retinol (vitamin A), which is essential for immune and reproductive functions as well as for the prevention of vision problems (cataract and age-related macular degeneration) (Arunkumar et al., 2020). Some examples of carotenoids with provitamin A activity commonly found in foods are α-carotene, β-carotene, and β-cryptoxanthin (Figure 1B), being β-carotene the carotenoid with the highest conversion efficiency, as each β-carotene molecule can be enzymatically cleaved into two molecules of retinol (Eggersdorfer & Wyss, 2018; Meléndez-Martínez, 2019; Hermanns et al., 2020).

3 Carotenoid composition in the selected Amazonian fruits

The Amazonia biome is distributed in an extensive area comprised by nine countries in South America: Brazil (which houses ≈ 60% of total area), Peru, Bolivia, French Guiana, Suriname, Guyana, Venezuela, Colombia and Ecuador. The Brazilian Amazonia is predominantly covered by dense tropical rainforest under warm, humid climate and constant, heavy rainfall. This biome houses a broad variety of native and exotic fruit-producing plants, described as promising sources of bioactive compounds and micronutrients (Anunciação et al., 2019; Matos et al., 2019).

Although Amazonian fruits have been little explored commercially, they hold great agroindustrial potential for the development of healthy products with high contents of bioactive compounds, such as phenolic compounds, ascorbic acid and carotenoids (Montero et al., 2020). It becomes clear each day more that an extensive effort must be supported by government policies with the help of the scientific community to stimulate the conscious prospection of Amazonia's biodiversity for the sustainable production of health-promoting foods. However, the lack of knowledge about Amazonian fruits impairs sustainable agricultural production and conservation, increasing the need for further research to unravel their chemical composition followed by investigations regarding the stability of bioactive compounds for future application in the food industry.

Table 1 focused to summarize the major carotenoids found in peach palm, buriti, tucumã, taperebá, and araçá-boi. In general, the fruit peels presented the highest contents of the main carotenoids identified in the selected Amazonian fruits, being β-carotene de major compound in peach palm, buriti and tucumã, while β-cryptoxanthin was the major in taperebá and araçá-boi (Table 1). All the contents of the individual carotenoids in Table 1 were used to classify the fruits in low (0-1 μg/g), moderate (1-5 μg/g), high (5-20 μg/g) and very high sources (≥ 20 μg/g), according to Britton & Khachik (2009), and discussed along the text.

3.1 Peach palm

Peach palm fruits are small drupes weighing between 0.5 and 25 g and measuring between 2 and 7 cm-diameter. The epicarp is fibrous, and the mesocarp varies from starchy to oily. At the full ripe stage, the fruit peels become yellow, orange, red, or some species keep them green, and may or may not contain seeds (Bezerra & Silva, 2016; Santos et al., 2020). Peach palm is mainly found in the Brazilian Amazonia, but also commonly found in Peru, Colombia e Ecuador (Adin et al., 2004; Silva et al., 2019a). In the Brazilian Amazonia, peach palm fruits are typically cooked in salty water before consumption and they are valued for their characteristic flavor and high energetic value (≈ 391 kcal 100 g^{-1}) (Melo et al., 2017). The fruits are mainly composed of lipids, carbohydrates (starch), as well as vitamin C, selenium, and zinc and very high levels of carotenoids (Basto et al., 2016; Rojas-Garbanzo et al., 2016). In the fruit pulp, Basto et al. (2016) identified β-carotene and α-carotene, which have provitamin A activity, whereas Rosso & Mercadante (2007) detected β-carotene, followed by δ-carotene and γ-carotene as the major carotenoids. Recently, Chisté et al. (2021) reported a total of 16 carotenoids in cooked peach palm fruits of orange variety and 20 carotenoids in the yellow variety, being β-carotene the major carotenoid in both types. In the peels of peach palm fruits, Matos et al. (2019) identified β-carotene, δ-carotene, and γ-carotene as the major carotenoids and reported almost 11 times higher total carotenoid contents in the peel than in the pulp. (Table 1). Interestingly, γ-carotene is a rare provitamin A carotenoid found in fruits and it was reported at high concentrations in both peel and pulp of peach palm fruits, classifying them as very high sources of γ-carotene, in addition to also β-carotene and δ-carotene (Table 1). Overall, given its chemical composition, peach palm fruit has high biological and health potential, associated with antioxidant activity (Jatunov et al., 2010; Quesada et al., 2011).

3.2 Buriti

M. flexuosa is distributed throughout Amazonia and popularly known as buriti, miriti, and muriti, depending on the region. The fruits are elongated oval-shaped drupes measuring 4 to 7 cm-length, 3 to 5 cm -diameter, and 25 to 40 g-weight. Buriti has a brown–reddish epicarp (shell), a fleshy, intense orange colored mesocarp (pulp), an endocarp (seed coat), and an endosperm (seed) (Pereira-Freire et al., 2016). The oily pulp is the most consumed part of the fruit, which is rich in iron, calcium, and fibers and widely used by local population for the production of ice cream, candy, and jelly. Buriti pulp is predominantly composed by lipids and carbohydrates, with total energetic values varying from 93 to 230 kcal 100.g^{-1}, depending on growing location (Cândido & Silva, 2017; Sandri et al., 2017; Nascimento-Silva et al., 2020). The oil fraction in the pulp is composed by high percentage of oleic acid (C18:1) (89.81%) and palmitic acid (C16:0) (10.16%) (Pereira et al., 2018). Regarding the bioactive compounds, buriti pulp exhibits a remarkable composition presenting tocopherols, ascorbic acid, very high contents of carotenoids; and, as stated by Rosso & Mercadante (2007), Freitas et al. (2018) and Cruz et al. (2020) currently, it has the highest β-carotene contents in nature. In addition, γ-carotene, was also reported at high contents in the pulp of

Table 1. Carotenoid composition of peach palm (*Bactris gasipaes*), buriti (*Mauritia flexuosa*), tucumã (*Astrocaryum vulgare*), taperebá (*Spondias mombin*), and araçá-boi (*Eugenia stipitata*).

Fruit (species)	Fruit part	Analytical method	Carotenoids	Individual carotenoid content	Classification of individual carotenoid sources*	Sum of the identified carotenoids	Retinol activity equivalents (RAE)	Reference
Peach palm (*Bactris gasipaes*) 	Pulp	HPLC-DAD-MS/MS	All-*trans*-β-carotene	55.51 µg g^{-1}	Very high	197.66 µg g^{-1} (wet basis)	7.45 µg RAE g^{-1}	Rosso & Mercadante (2007)
			All-*trans*-δ-carotene	45.77 µg g^{-1}	Very high			
			All-*trans*-γ-carotene	35.43 µg g^{-1}	Very high			
			cis-γ-Carotene	28.35 µg g^{-1}	Very high			
			All-*trans*-α-carotene	1.78 µg g^{-1}	Moderate			
			All-*trans*-β-cryptoxanthin	0.12 µg g^{-1}	Low			
			9-*cis*-Lycopene	8.44 µg g^{-1}	High			
			cis-δ-Carotene 1	5.22 µg g^{-1}	High			
			13-*cis*-β-Carotene	4.02 µg g^{-1}	Moderate			
			cis-γ-Carotene 1	3.25 µg g^{-1}	Moderate			
			cis-γ-Carotene 2	2.26 µg g^{-1}	Moderate			
			9-*cis*-β-Carotene	2.21 µg g^{-1}	Moderate			
			cis-γ-Carotene 3	2.11 µg g^{-1}	Moderate			
			cis-δ-Carotene 2	2.09 µg g^{-1}	Moderate			
			cis-δ-Carotene 3	0.86 µg g^{-1}	Low			
			cis-γ-Carotene 5	0.13 µg g^{-1}	Low			
			15-*cis*-β-Carotene	0.08 µg g^{-1}	Low			
			5,8-Epoxy-β-carotene	0.03 µg g^{-1}	Low			
	Pulp	HPLC-DAD	All-*trans*-lutein	1.7 µg g^{-1}	Moderate	134.8 µg g^{-1} (dry basis)	NR	Basto et al. (2016)
			All-*trans*-zeaxanthin	1.3 µg g^{-1}	Moderate			
			All-*trans*-β-cryptoxanthin	0.7 µg g^{-1}	Low			
			All-*trans*-α-carotene	2.9 µg g^{-1}	Moderate			
			All-*trans*-β-carotene	53.8 µg g^{-1}	Very high			
			13-*cis*-β-Carotene	2.3 µg g^{-1}	Moderate			
			9-*cis*-β-Carotene	5.4 µg g^{-1}	High			
	Peel	HPLC-DAD-MS/MS	All-*trans*-β-carotene	73 µg g^{-1}	Very high	150 µg g^{-1} (wet basis)	8.5 µg RAE g^{-1}	Matos et al. (2019)
			All-*trans*-δ-carotene	17.4 µg g^{-1}	High			
			cis-γ-Carotene	18.0 µg g^{-1}	High			
			All-*trans*-γ-carotene	41.0 µg g^{-1}	Very high			
Buriti (Mauritia flexuosa) 	Pulp	HPLC-DAD-MS/MS	All-*trans*-β-carotene	372.32 µg g^{-1}	Very high	513.87 µg g^{-1} (wet basis)	36.40 µg RAE g^{-1}	Rosso & Mercadante (2007)
			13-*cis*-β-Carotene	59.23 µg g^{-1}	Very high			
			9-*cis*-β-Carotene	18.57 µg g^{-1}	High			
			All-*trans*-γ-carotene	14.76 µg g^{-1}	High			
			cis-γ-Carotene 3	9.88 µg g^{-1}	High			
			15-*cis*-β-Carotene	8.87 µg g^{-1}	High			
			5,8-Epoxy-β-carotene	7.44 µg g^{-1}	High			
			cis-δ-Carotene 1	5.46 µg g^{-1}	High			
			cis-δ-Carotene 2	3.67 µg g^{-1}	Moderate			
			All-*trans*-α-carotene	3.23 µg g^{-1}	Moderate			
			cis-δ-Carotene 3	2.42 µg g^{-1}	Moderate			
			cis-γ-Carotene 2	2.33 µg g^{-1}	Moderate			
			All-*trans*-δ-carotene	2.09 µg g^{-1}	Moderate			
			All-*trans*-α-cryptoxanthin	1.28 µg g^{-1}	Moderate			
			Di-*cis*-α-carotene	1.25 µg g^{-1}	Moderate			
			5,6-Epoxy-β-carotene	0.41 µg g^{-1}	Low			
			Phytoene	0.34 µg g^{-1}	Low			
			Di-*cis*-β-carotene 2	0.11 µg g^{-1}	Low			
			5,6-Epoxy-β-cryptoxanthin	0.10 µg g^{-1}	Low			
			All-*trans*-ζ-carotene	0.08 µg g^{-1}	Low			
			All-*trans*-lutein	0.03 µg g^{-1}	Low			
	Pulp oil	HPLC-DAD	All-*trans*-β-carotene	295.24 µg g^{-1}	Very high	540.81 µg g^{-1} (dry basis)	NR	Santos et al. (2015)
			cis-β-Carotene	165.65 µg g^{-1}	Very high			
			All-*trans*-α-carotene	19.20 µg g^{-1}	High			
			cis-α-Carotene	1.8 µg g^{-1}	Moderate			
			All-*trans*-γ-carotene	3.45 µg g^{-1}	Moderate			
			cis-γ-Carotene	1.82 µg g^{-1}	Moderate			
			5,8-Epoxy-β-carotene	4.38 µg g^{-1}	Moderate			
			cis-Lutein	16.28 µg g^{-1}	High			
			All-*trans*-lutein	32.12 µg g^{-1}	Very high			
			All-*trans*-luteoxanthin	2.68 µg g^{-1}	Moderate			

*Classification of individual carotenoid sources suggested by Britton & Khachik (2009): low (0-1 µg/g), moderate (1-5 µg/g), high (5-20 µg/g) and very high sources (≥ 20 µg/g). NR: not reported.

Table 1. Continued...

Fruit (species)	Fruit part	Analytical method	Carotenoids	Individual carotenoid content	Classification of individual carotenoid sources*	Sum of the identified carotenoids	Retinol activity equivalents (RAE)	Reference
Tucumã (*Astrocaryum vulgare*) 	Pulp	HPLC-DAD-MS/MS	All-*trans*-β-carotene	47.36 μg g^{-1}	Very high	62.65 μg g^{-1} (wet basis)	4.25 μg RAE g^{-1}	Rosso & Mercadante (2007)
			All-*trans*-α-carotene	1.68 μg g^{-1}	Moderate			
			All-*trans*-β-cryptoxanthin	1.64 μg g^{-1}	Moderate			
			13-*cis*-β-Carotene	1.60 μg g^{-1}	Moderate			
			All-*trans*-α-cryptoxanthin	1.30 μg g^{-1}	Moderate			
			Zeinoxanthin	1.02 μg g^{-1}	Moderate			
			All-*trans*-lutein	0.79 μg g^{-1}	Low			
			cis-γ-Carotene 3	0.89 μg g^{-1}	Low			
			Unidentified compound	0.82 μg g^{-1}	Low			
			15-*cis*-β-Carotene	0.80 μg g^{-1}	Low			
			5,8-Epoxy-β-carotene	0.76 μg g^{-1}	Low			
			cis-β-Zeacarotene	0.65 μg g^{-1}	Low			
			All-*trans*-δ-carotene	0.60 μg g^{-1}	Low			
			All-*trans*-β-zeacarotene	0.52 μg g^{-1}	Low			
			Mixture	0.44 μg g^{-1}	Low			
			All-*trans*-γ-carotene	0.36 μg g^{-1}	Low			
			All-*trans*-neoxanthin	0.35 μg g^{-1}	Low			
			cis-Violaxanthin	0.26 μg g^{-1}	Low			
			cis-Neoxanthin	0.24 μg g^{-1}	Low			
			All-*trans*-zeaxanthin	0.18 μg g^{-1}	Low			
			All-*trans*-ζ-carotene	0.16 μg g^{-1}	Low			
			cis-Lutein	0.14 μg g^{-1}	Low			
				0.04 μg g^{-1}	Low			
	Peel	HPLC-DAD-MS/MS	All-*trans*-β-carotene	78.0 μg g^{-1}	Very high	115.0 μg g^{-1} (wet basis)	7.9 μg RAE g^{-1}	Matos et al. (2019)
			All-*trans*-δ-carotene	3.0 μg g^{-1}	Moderate			
			cis-γ-Carotene	8.0 μg g^{-1}	High			
			All-*trans*-γ-carotene	26.0 μg g^{-1}	Very high			
Taperebá (*Spondias mombin*) 	Pulp	HPLC-DAD-MS/MS	All-*trans*-β-cryptoxanthin	6.5 μg g^{-1}	High	23.9 μg g^{-1} (wet basis)	0.67 μg RAE g^{-1}	Costa & Mercadante (2018)
			All-*trans*-zeinoxanthin	3.5 μg g^{-1}	Moderate			
			All-*trans*-β-carotene	2.3 μg g^{-1}	Moderate			
			All-*trans*-α-carotene	2.4 μg g^{-1}	Moderate			
			All-*trans*-lutein	1.2 μg g^{-1}	Moderate			
			All-*trans*-zeaxanthin	0.5 μg g^{-1}	Low			
			All-*trans*-β-cryptoxanthin myristate	2.3 μg g^{-1}	Moderate			
			All-*trans*-lutein-3-*O*-myristate	1.3 μg g^{-1}	Moderate			
			All-*trans*-β-cryptoxanthin palmitate	1.4 μg g^{-1}	Moderate			
			All-*trans*-lutein dimyristate	1.1 μg g^{-1}	Moderate			
			All-*trans*-zeinoxanthin stearate	1.8 μg g^{-1}	Moderate			
	Pulp	HPLC-DAD	All-*trans*-β-cryptoxanthin	17.08 μg g^{-1}	High	48.69 μg g^{-1} (wet basis)	1.11 μg RAE g^{-1}	Tiburski et al. (2011)
			All-*trans*-lutein	6.34 μg g^{-1}	High			
			All-*trans*-zeinoxanthin	5.47 μg g^{-1}	High			
			All-*trans*-α-carotene	3.40 μg g^{-1}	Moderate			
			All-*trans*-β-carotene	3.14 μg g^{-1}	Moderate			

*Classification of individual carotenoid sources suggested by Britton & Khachik (2009): low (0-1 μg/g), moderate (1-5 μg/g), high (5-20 μg/g) and very high sources (≥ 20 μg/g). NR: not reported.

Table 1. Continued...

Fruit (species)	Fruit part	Analytical method	Carotenoids	Individual carotenoid content	Classification of individual carotenoid sources*	Sum of the identified carotenoids	Retinol activity equivalents (RAE)	Reference
Araçá-boi (*Eugenia stipitata*) 	Pulp	HPLC-DAD	All-*trans*-β-carotene	2.10 μg g^{-1}	Moderate	8.78 μg g^{-1} (wet basis)	0.31 μg RAE g^{-1}	Berni et al. (2019)
			All-*trans*-α-carotene	0.65 μg g^{-1}	Low			
			All-*trans*-β-cryptoxanthin	2.44 μg g^{-1}	Moderate			
			9-*cis*-β-Carotene	0.18 μg g^{-1}	Low			
			13-*cis*-β-Carotene	0.16 μg g^{-1}	Low			
			15-*cis*-β-Carotene	0.11 μg g^{-1}	Low			
			All-*trans*-violaxanthin	1.04 μg g^{-1}	Moderate			
			All-*trans*-lutein	1.60 μg g^{-1}	Moderate			
			All-*trans*-zeaxanthin	0.55 μg g^{-1}	Low			
	Pulp	HPLC-DAD-MS/MS	All-*trans*-α-carotene	0.31 μg g^{-1}	Low	8.06 μg g^{-1} (wet basis)	NR	Garzón et al. (2012)
			All-*trans*-zeinoxanthin	0.25 μg g^{-1}	Low			
			All-*trans*-zeinoxanthin myristate	0.38 μg g^{-1}	Low			
			All-*trans*-zeinoxanthin palmitate	0.54 μg g^{-1}	Low			
			All-*trans*-β-carotene	0.44 μg g^{-1}	Low			
			All-*trans*-β-cryptoxanthin	0.47 μg g^{-1}	Low			
			All-*trans*-β-cryptoxanthin myristate	0.43 μg g^{-1}	Low			
			All-*trans*-β-cryptoxanthin palmitate	0.92 μg g^{-1}	Low			
			All-*trans*-lutein	1.54 μg g^{-1}	Moderate			
			All-*trans*-anhydrolutein	0.63 μg g^{-1}	Low			
			All-*trans*-lutein dimyristate	0.47 μg g^{-1}	Low			
			All-*trans*-lutein myristate palmitate	0.99 μg g^{-1}	Low			
			All-*trans*-lutein dipalmitate	0.91 μg g^{-1}	Low			
			All-*trans*-zeaxanthin	0.17 μg g^{-1}	Low			
	Peel	HPLC-DAD-MS/MS	All-*trans*-α-carotene	0.96 μg g^{-1}	Low	24.84 μg g^{-1} (wet basis)	NR	Garzón et al. (2012)
			All-*trans*-zeinoxanthin	0.81 μg g^{-1}	Low			
			All-*trans*-zeinoxanthin myristate	1.03 μg g^{-1}	Moderate			
			All-*trans*-zeinoxanthin palmitate	1.87 μg g^{-1}	Moderate			
			All-*trans*-β-carotene	1.43 μg g^{-1}	Moderate			
			All-*trans*-β-cryptoxanthin	1.42 μg g^{-1}	Moderate			
			All-*trans*-β-cryptoxanthin myristate	0.77 μg g^{-1}	Low			
			All-*trans*-β-cryptoxanthin palmitate	1.53 μg g^{-1}	Moderate			
			All-*trans*-lutein	7.56 μg g^{-1}	High			
			All-*trans*-anhydrolutein	1.36 μg g^{-1}	Moderate			
			All-*trans*-lutein dimyristate	1.01 μg g^{-1}	Moderate			
			All-*trans*-lutein myristate palmitate	2.35 μg g^{-1}	Moderate			
			All-*trans*-lutein dipalmitate	2.56 μg g^{-1}	Moderate			
			All-*trans*-zeaxanthin	1.14 μg g^{-1}	Moderate			

*Classification of individual carotenoid sources suggested by Britton & Khachik (2009): low (0-1 μg/g), moderate (1-5 μg/g), high (5-20 μg/g) and very high sources (≥ 20 μg/g). NR: not reported.

buriti (high source) (Rosso & Mercadante, 2007). Due to the chemical composition of buriti, its fruits have been investigated regarding its high antioxidant, antibacterial, antimutagenic, and healing activities (Rosso & Mercadante, 2007; Santos et al., 2015; Freitas et al., 2018; Pereira-Freire et al., 2018; Cruz et al., 2020).

3.3 Tucumã

The genus *Astrocaryum* is also distributed throughout Amazonia. Two species of the genus *Astrocaryum* occur in northern Brazil, *A. aculeatum* G.Mey. in Pará and *A. vulgare* in Amazonas State (Chiste & Fernandes, 2016). The fruits are smooth ovoid drupes, about 5-6 cm in diameter and 70-75 g in weight, consisting of endocarp, endosperm, and edible epicarp (peel) and mesocarp (pulp), which range in color from yellow to dark orange and red (Matos et al., 2019). Lipids, along with carbohydrates and fibers are the main fruit constituents. The pulp is used to extract oil with anti-inflammatory and antioxidant properties (Baldissera et al., 2017; Cabral et al., 2020). Oil extracts show great potential for the use in food industry and biodiesel production (Rosso & Mercadante, 2007; Santos et al., 2015; Costa et al., 2016). Tucumã pulp has high total energetic value (247 kcal 100 g^{-1}) and contains high levels of fatty acids, mainly oleic (C18:1), linoleic (C18:2), and palmitic (C16:0) acids, in addition to vitamin B2, vitamin C, catechin, quercetin, and carotenoids (Serra et al., 2019; Cunha Jr et al., 2020; Ferreira et al., 2021). The fruit was found to contain 21 different types of carotenoids, being β-carotene the major one (very high source) (Table 1). Matos et al. (2019), reported that tucumã peel and pulp had total carotenoid levels of 18.06 and 8.39 mg 100 g^{-1}, respectively, and the fruit peel was classified as a very high source of β-carotene and γ-carotene.

3.4 Taperebá

S. mombin is a small deciduous tree widespread over Amazonia whose fruit is popularly known as taperebá in the Amazonia and cajá, cajá verdadeiro, and cajá-miri in other regions of Brazil (Silva et al., 2009; Neiens et al., 2017). The fruit is an ellipsoid-shaped drupe about 4 cm long with a thin yellow peel and translucent to yellow pulp (Neiens et al., 2017). The pulp contains about 90% moisture and is acidic, with a pH of 2.63 (Carvalho et al., 2017). Taperebá is rich in potassium, phenolic compounds, and carotenoids, such as β-cryptoxanthin as the major compound (high source), zeinoxanthin, β-carotene, α-carotene, lutein, and zeaxanthin (Table 1) (Neiens et al., 2017; Costa & Mercadante, 2018). The fruit's flavor, aroma, and high carotenoid content are characteristics that capture the interest of consumers and the food industry (Silvino et al., 2017; Pelais et al., 2020). Although taperebá is highly appreciated, few studies have investigated the biological properties of the pulp. Aniceto et al. (2021) reported a high antioxidant capacity for the pulp of taperebá through different *in vitro* assays, suggesting that carotenoids had high contribution, among the bioactive compounds in the pulp composition. Tiburski et al. (2011), indicated an efficient antioxidant effect for taperebá fruit (17.47 mmol $TEAC.g^{-1}$), and they reported a content of total carotenoids of 4869.5 $\mu g.100g^{-1}$ pulp, being β-cryptoxanthin (1708.5 μg. 100 g-1) the major compound.

3.5 Araçá-boi

Araçá-boi is a fruit tree native to the equatorial region of the Amazonia. It is popularly known in the Brazilian Amazonia as arazá, marmelo, and Amazon guava. The fruit weighs 30-80 g, measures 12 cm in diameter, and has a thin yellow epicarp, white pulp, soft texture, and highly acidic taste taste (pH around 2.5) (Baldini et al., 2017). Araçá-boi contains 83% moisture, high contents of sugars, fibers, and ascorbic acid (Avila-Sosa et al., 2019). Because of its sensory properties and composition, araçá-boi is widely used to produce juice, nectar, ice cream, jam, and syrup (Araújo et al., 2019). Few studies have investigated the bioactive compounds composition of araçá-boi fruit, and the carotenoid profile of its pulp and peel was reported to be mainly composed by lutein, which the fruit peel can be considered a high source, β-carotene, β-cryptoxanthin, violaxanthin, and zeaxanthin (Table 1). The peel of araçá-boi fruit was reported to contain higher total carotenoid contents (24.84 $\mu g.g^{-1}$) than the pulp (8.06 $\mu g.g^{-1}$), and regarding the antioxidant capacity, the peel extract was five time more efficient than the pulp (Garzón et al., 2012). In another study, Berni et al. (2019) showed that the pulp of araçá-boi fruit (8.78 $\mu g.g^{-1}$ of total carotenoids) presented lower antioxidant capacity in comparison to other tropical fruits, such as acerola (*Malpighia emarginata*) and cambuití (*Sageretia elegans*). Notwithstanding the few available studies, araçá-boi fruits are widely used in folk medicine to treat intestinal diseases, bladder disorders, and common cold.

4 Potential of the selected Amazonian fruits for the application as natural colorants

Sight is one of the most important senses influencing food acceptance. Colorful foods, for instance, can be highly attractive to consumers. Due to this fact, a wide variety of artificial and natural coloring agents is used in the food industry. Carotenoids, a major class of natural colorants, are important not only for their color properties but also for their biological activity. The compounds' capacity to promote health benefits has further stimulated their use in the food industry (Martins et al., 2016; Mesquita et al., 2017).

There has been much discussion about the negative health and environmental impacts associated with the intense use of artificial coloring to increase food attractiveness. Consumers' awareness of the risks of artificial colorant consumption (e.g., cytotoxicity, genotoxicity, hyperactivity, and anxiety) has increased the demand for natural coloring agents (Doguc et al., 2015; Rodriguez-Amaya, 2016).

Amazonian fruits are well known for their bioactive potential, stemming from their carotenoid contents (Anunciação et al., 2019). Peach palm is currently the most studied Amazonian fruit, with high potential to be incorporated in food formulations (Martínez-Girón et al., 2017; Pires et al., 2019b; Costa et al., 2022). Buriti is still underexploited, while tucumã, taperebá, and araçá-boi remains still unexploited, despite their high promising content of natural pigments (Aniceto et al., 2017; Avila-Sosa et al., 2019; Pires et al., 2019a).

Pinzón-Zárate et al. (2015) investigated the effect of adding the oily residue of peach palm extract to Frankfurt sausages through instrumental color (CIELAB space) evaluation lightness (L^*), reddish ($+a^*$) and yellowish ($+b^*$) color coordinates, color saturation (C^*, chroma) and hue angle ($h°$). Sausages prepared using oily residue had higher lightness (L^*) (75.54 to 8.95), b^* (8.39 to 20.34), chroma (C^*) (10.17 to 0.85), and hue ($h°$) (55.76 to 76.38) and lower a^* (5.73 to 2.73) than the control ($L^* = 69.00$, $b^* = 11.00$, $C^* = 11.37$, $h° = 76.38$, $a^* = 2.73$). The authors concluded that natural colorants from the oily residue of peach palm extract are a viable alternative to reduce the use of nitrites in meat products.

Martínez-Girón et al. (2017) added different concentrations of peach palm peel flour (2.5, 5.0, 7.5, and 10%) to cakes to replace tartrazine. Addition of 10% peach palm peel flour increased total carotenoid content, darkening index (from 88.2 to 118.1), and a^* value (from 8.5 to 17.5) while decreasing L^* (from 60.9 to 44.1), b^* (from 42.2 to 20.1), and $h°$ (from 78.6 to 49.0) compared with the control. The results suggest that peach palm peel flour can be used as a natural colorant in bakery products to replace the artificial dye tartrazine.

Mesquita et al. (2020) found that the use of peach palm carotenoids as colorant in mayonnaise positively influenced color perception. Control mayonnaise had a whitish color, whereas mayonnaise prepared with carotenoid extract had a more yellowish color, similar to that of commercial mayonnaise. The carotenoid-added mayonnaise formulation scored a mean of 8.0 in color, aroma, flavor, texture, and overall acceptance. These findings are promising, as color is crucial for mayonnaise acceptance. Therefore, this study presented an excellent alternative for the incorporation of carotenoids in new food formulations, providing promising options for developing functional products with more bioaccessible fat-soluble bioactive compounds.

Buriti carotenoids have also been investigated for use as natural food colorants. Best et al. (2020) used freeze-dried buriti pulp as a colorant in a milk-based beverage, resulting in increased lightness (L^*) and yellowish color (b^*). The study concluded that buriti carotenoids are a natural option for improving the sensory properties of milk-based beverages.

Bovi et al. (2017) added buriti to isotonic beverages as a partial replacer of Sunset Yellow. Redness was not influenced by buriti addition. Although only 25% of Sunset Yellow was replaced, the color of buriti-enriched beverages remained stable for up to 38 days of storage.

5 Stability of carotenoids from the selected Amazonian fruits

Color instability in food systems is a common industrial issue to be overcome when natural colorants are considered, including carotenoids. The stability of carotenoids is influenced by intrinsic structural characteristics of carotenoids (carotene or xanthophyll, esterified or non-esterified, *E* or *Z* configuration) and the food matrix (fruit, leaf, root, or juice). Carotenoids are mainly subject to oxidation, which leads to changes in color. Because of their sensitivity to acidic pH and heat, carotenoids may undergo isomerization ($E \to Z$), resulting in color loss. Carotenoid degradation is further stimulated by the rupture of cell's structure, inadequate storage conditions of food products, processing, packaging material, permeability and exposure to light and oxygen (Rodriguez-Amaya, 2015).

Fruit peeling and enzymatic or non-enzymatic oxidative degradation during processing and storage are known to result in carotenoid loss. Non-enzymatic oxidation (autoxidation) is followed by isomerization, and both *Z* and *E* isomers can be oxidized. The oxidative process is characterized by epoxidation, followed by cleavage into apocarotenal and hydroxylation. Subsequent fragmentations result in volatile compounds with low molecular weight. Direct cleavage of the polyene chain and modifications of cleavage products may also occur, resulting in a wide range of volatile products. The volatile compounds formed after carotenoid degradation are colorless and might impart off-flavors in food and beverages (Rodriguez-Amaya, 2019).

Carotenoids have an important structural characteristic that influences their stability under high-temperature conditions. These phytochemicals have highly unsaturated structures; thus, they are sensitive to degradation reactions caused by heat treatment, which may vary according to temperature. Isomerization of *E*-carotenoids to *Z*-isomers modifies its biological activities and color, but not to the same extent as oxidation. In several foods, enzymatic carotenoid degradation can be more damaging than thermal decomposition or non-enzymatic oxidation (Valerio et al., 2021).

The stability of carotenoids in food products depends on several factors, including storage conditions of raw materials, product stability, sensory characteristics, and chemical composition of extracts (Bajoub et al., 2015). Franklin & Nascimento (2020) found that cooked peach palm (4,710.00 $\mu g.\ g^{-1}$) had a higher carotenoid content than raw peach palm (3,769.25 $\mu g.\ g^{-1}$). This finding demonstrates that cooking may facilitate carotenoid extraction from plant materials. On the other hand, cooking may also alter compound stability, resulting in color loss (Franklin & Nascimento, 2020).

Pelais et al. (2020) assessed the total carotenoid content of taperebá pulp subjected to freezing (30.3 $\mu g\ g^{-1}$) and taperebá nectar subjected to pasteurization and refrigeration (14.2 and 12.4 $\mu g\ g^{-1}$ at 0 and 31 days of storage, respectively). The results showed that heat treatment and storage conditions affected carotene content. It seems that the lower carotenoid content of nectar was due to pasteurization, as heating prior to refrigeration can lead to instability. Given the scarcity of research on taperebá fruit, it was not possible to discuss the findings of the referred study. Similar reports used different methods, precluding comparative analysis; transformation of results to the same unit afforded large discrepancies (Pelais et al., 2020).

Ferreira (2011) investigated the effects of time and pressure conditions of high hydrostatic pressure (HHP) treatment on the content and isomerization of taperebá pulp carotenoids using response surface methodology. The major carotenoids were found to be β-carotene, α-carotene, β-cryptoxanthin, and lutein. Concentrations of all *trans*-carotenoids did not differ significantly between treated and control samples, although there was a decreasing trend with HHP treatment. The authors recognized that the isomerization study was hampered by the low concentrations of *Z*-isomers, explained by the fact that *Z*-carotenoids undergo oxidation during formation. *Z*-Isomer concentrations were significantly higher in HHP-treated taperebá pulps than in untreated pulp, except for β-carotene content, which did not differ between samples. The findings showed that treatment of taperebá pulp at 157-441 MPa for 3 to 17 min causes isomerization. The effects of HHP on carotenoids differ according to the nature/integrity of the food matrix, intensity of treatment, and type of carotenoid. The stability of carotenoids in foods subjected to HHP depends on pressure–time conditions (Ferreira, 2011).

Ribeiro et al. (2020) produced carotenoid-rich microcapsules by atomization of oil-in-water buriti emulsions stabilized with soy protein isolate and high-methoxyl pectin. The authors observed that the sample with the lowest maltodextrin content (0.75 $g\ g^{-1}$) had the lowest L^* value (76.93), that is, a more intense color. This sample also had the highest chroma value (85.90), whereas the sample containing 1.25 $g\ g^{-1}$ maltodextrin had the lowest chroma value (80.94). The findings showed that the higher the maltodextrin content, the lower the color saturation of buriti oil microcapsules. Microcapsules were shown to be promising alternatives to enhance the carotenoid content and color properties of foods. Encapsulation efficiency and retention of carotenoids and buriti oil were significantly influenced ($p \leq 0.05$) by maltodextrin content. The highest encapsulation efficiencies (63.75% for carotenoids and 65.70% for buriti oil) and retention of carotenoids (53.31%) and buriti oil (56.38%) were observed in samples containing 1.25 $g\ g^{-1}$ maltodextrin. Maltodextrin probably acted as a barrier at the microcapsule surface, thereby minimizing oil and carotenoid loss. Such results demonstrate that high concentrations of drying agents can contribute to the production of highly effective encapsulation matrices for bioactive compound protection (Ribeiro et al., 2020).

Although several studies have confirmed the beneficial effects of ultrasound treatment on the extraction and protection of bioactive compounds from fruit juices, few have investigated the use of this emerging technology in Amazonian fruits. Carvalho et al. (2020) assessed the influence of high-energy ultrasound on the physicochemical properties of buriti juice. Ultrasound energy density was positively correlated with processing temperature, so that acoustic cavitation energy was dissipated in the form of heat. Under ultrasound treatment at 1.8 $kJ\ cm^{-3}$, buriti juice did not reach 45 °C, whereas, at 3.6 kJ cm^{-3}, juice reached 70 °C after 10 min. Ultrasound energy significantly influenced ($p < 0.05$) the color parameters of buriti juice: L^* and b^* values increased with energy density. This result is associated with the higher carotenoid concentration of samples, given that ultrasound treatment promotes intracellular extraction of these compounds. In general, color changes in buriti juice treated with ultrasound might be associated with oxidation of bioactive compounds and the consequent production of other compounds with different colors (Ordóñez-Santos et al., 2017; Silva et al., 2019b; Carvalho et al., 2020).

6 Conclusions and future perspectives

This review summarized the main chemical characteristics and composition of carotenoids of the selected Amazonian fruits (peach palm, buriti, tucumã, taperebá, and araçá-boi) and the factors that affect their stability, bioactive properties and potential as natural food colorants. Notwithstanding the information provided, this review highlights the need of further and systematic researches on these underexploited Amazonian fruits as sources of carotenoid extracts with promising potential to be used as natural colorants in food formulations, particularly in lipid-rich formulations, given the lipophilic characteristic of carotenoids.

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