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Review Article

Functional compounds in tropical fruit processing by-products and intrinsic factors affecting their composition: A review

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ABSTRACT

Tropical fruits, highly demanded in the food industry, generate a considerable amount of waste during processing. These traditionally discarded by-products, such as peels, seeds and pomace, are rich in bioactive compounds, natural molecules that have beneficial properties for human health, as they participate in various metabolic processes in the organism. Among the most prominent compounds are flavonoids, carotenoids, phenolic compounds, tannins and vitamin C. Beyond their health benefits, these compounds have significant industrial value and are widely used in the textile, pharmaceutical, cosmetic, biotechnological and food fields, in the latter especially as preservatives, additives, colorants and others. This review explores the main bioactive compounds found in fruit by-products, highlighting their functional relevance and analyzing the intrinsic or fruit-derived factors that influence the composition of these compounds, such as the type of by-product (peels, seeds, bagasse, pomace), the variety of fruit, and the state of maturity at the time of processing. In addition, the extraction methods used to obtain these compounds are addressed, differentiating between conventional techniques, such as solvent extraction, and emerging methods, such as ultrasound-assisted extraction and supercritical fluid extraction, which offer advantages in terms of efficiency and sustainability. The diversity of bioactive compounds and their potential application in various industries highlight the importance of ongoing research in this field. It is necessary to further study the factors that influence the composition of these compounds, as well as the development of more efficient and sustainable extraction methods. These advances will not only add value to food industry waste, but will also contribute to the development of natural products with health benefits.

1. Introduction

Tropical fruits are one of the most important crops worldwide (Villacís-Chiriboga et al., 2020), and have been part of the group of basic products since 1970, due to advances in transport, trade agreements and changes in consumer preferences. Tropical fruits represent 3 % of world agricultural food products, positioning them as the third most valuable group within the fruit sector, due to their high export price per unit (Cádiz et al., 2020). They can be classified according to the extent of their cultivation, volume of production and market, in main and secondary (among which are the wild ones). The main ones include mango (*Mangifera indica* L.), pineapple (*Ananas comosus* L. Merr), avocado (*Persea americana* Mill.), papaya (*Carica papaya* L.) and banana (*Musa paradisiaca* L.), among others. Secondary fruits include guava (*Psidium guajava* L.), tamarind (*Tamarindus indica* L.), açai (*Euterpe oleracea* Mart.), passion fruit (*Passiflora edulis* Sims), pomegranate (*Punica granatum* L.), coconut (*Cocos nucifera* Linn.), acerola (*Malpighia emarginata* D.C.), noni (*Morinda citrifolia* L.), camu-camu (*Myrciaria dubia* McVaugh), dragon fruit (*Hylocereus* spp.), mangosteen (*Garcinia mangostana* L.), among others.

These fruits are consumed fresh and in products such as juices, sauces, jams, chutneys, ready-to-use peeled fruit, ice creams and others. Their industrial processing generates significant amounts of food by-products, such as trimmings, peels, pomace, seeds, and leaves, which normally have no additional food use (Vilas et al., 2024). The by-product fraction can reach approximately up to 60 % of the whole fruit (J. F. Ayala et al., 2011), which implies enormous losses and waste, being an environmental problem that requires adequate management (Trigo et al., 2020). However, the efficient management of these wastes faces significant challenges, such as the lack of effective technologies to manage large volumes of biomass, the lack of suitable processing methods, and the high costs associated with their treatment (Sharma

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et al., 2016).

The use of by-products or waste from the tropical fruit industry is an alternative that allows the implementation of an industrial circular economy, which leads to an increase in profitability and environmental sustainability (Routray and Orsat, 2019), ultimately giving rise to a greater diversity of products. The use of such waste has been taking place for decades, mainly for animal feed (Cádiz et al., 2020; Clemente et al., 2015), and in some cases its potential as an alternative source of energy production (biogas, bioethanol or biohydrogen) has been explored (Domínguez-Bocanegra et al., 2015). In particular, papaya and pineapple peels have been used for the production of methane through anaerobic digestion (Romero et al., 2020; Arifan et al., 2022); melon, pineapple and mango waste, for the production of bioethanol using a non-conventional yeast *Wickerhamomyces* sp. (Zanivan et al., 2022) and cashew nut shells for biomethane production (Nikiema et al., 2020). However, in recent years, the use of these by-products has focused on the formulation of products intended for human consumption (Durán-Aranguren et al., 2023), due to their great nutritional quality derived from the high content of bioactive compounds (Sood and Saini, 2022), which provide significant antioxidant and antimicrobial properties (Peschel et al., 2006; O'Shea et al., 2012; Trigo et al., 2020; Sayago-Ayerdi et al., 2021; Belmonte et al., 2022), preventing them from leaving the food supply chain (Thorsen et al., 2022).

Bioactive compounds are present in all anatomical parts of the fruit (Lachowicz et al., 2019) and the composition of these compounds varies between different fractions, often being significantly higher in the so-called inedible parts of the fruit (Banerjee et al., 2017). Bioactive compounds obtained from tropical fruit residues can act through several pathways in the human body, including interacting with proteins, DNA and other biological molecules. These processes stop oxidation, which inactivates free radicals and increases the potential to modify the composition and metabolic activity of the intestinal microbiota (Ajikumar et al., 2008; El-Hadary and Ramadan, 2019; Azizan et al., 2020). This results in health benefits by reducing the risk of diseases (Gil-Chávez et al., 2013), among which diabetes, cancer and cardiovascular diseases stand out (Şahin et al., 2018; Dobrinčić et al., 2020; Pavlović et al., 2020; Pirozzi et al., 2020), thus contributing to the revalorization of underutilized waste or by-products.

Current literature reviews on bioactive compounds in tropical fruit by-products focus on composition and their application as ingredients in food products (Khan et al., 2024; Chel et al., 2022; Oliveira et al., 2022; Marcillo et al., 2021a; Maqsood et al., 2020). This review stands out by its comprehensive approach, analyzing not only the presence of bioactive compounds in tropical fruit by-products, but also the intrinsic factors that affect their composition, such as the type of by-product, the fruit variety and its maturity stage, aspects rarely explored in previous reviews. It emphasizes on the valorization of agro-industrial waste within a circular economy approach, promoting its use in the development of functional and sustainable products.

2. Bioactive compounds present in tropical fruit by-products

Tropical fruit by-products are a significant source of bioactive compounds, which stand out mainly for their content of polyphenols or phenolic compounds, including flavonoids, phenolic acids and tannins. Also, carotenoids and ascorbic acid or vitamin C, among others (Marcillo et al., 2021a), have been classified as potential sources of antioxidants and contribute to improving health (Kumar et al., 2017). Table 1 presents information on the bioactive compounds extracted from different tropical fruit residues, highlighting the extraction method and the amount of each compound. The analyzed residues come from different parts of the fruits, such as peels, seeds, pomace, flavedo and albedo, and correspond to strawberry, raspberry, acerola, guava, melon, avocado, mango, passion fruit, lemon, papaya, plum, pineapple, watermelon, cashew, seriguela and noni.

Table 1
Bioactive compounds in the by-products of tropical fruits.

Bioactive compounds	Residues	Quantity	References
Phenolic compounds	Strawberry waste	7157 ± 160 μg GAE/100 g 5761 ± 12 μg GAE/100 g	Vázquez et al. (2020)
	Raspberry waste	19405 ± 377 μg GAE/100 g 49644 ± 760 μg GAE/100 g	
	Acerola pomace	444.01 ± 45.99 mg GAE/100 g 419.35 ± 7.4 mg GAE/100 g	Carvalho et al. (2021)
	Guava pomace	160.33 ± 5.77 mg GAE/100 g 172.56 ± 15.13 mg GAE/100 g	
	Acerola waste	106.8 ± 5.5 mg GAE/100 g	Poletto et al. (2021)
	Melon peels	296.03 ± 7.75 mg GAE/100 g	Gómez et al. (2021)
	Hass avocado peel	190 ± 3 mg GAE/g dry extract	Rojas et al. (2022)
	Hass avocado seed	60 ± 2 mg GAE/g dry extract	
	Mango peels	2931 ± 175–5149 ± 154 mg GAE/100 g 22.57 ± 0.38 mg GAE/100 g	Marcillo et al. (2021b) Zahid et al. (2022)
	Cashew bagasse	293 ± 2.84–265 ± 3.88 mg GAE/100 g	Cruz et al. (2022)
	Lemon Flavedo	2.89 ± 0.27 mg GAE/100 g	Rosa et al. (2023)
	Lemon Albedo	2.42 ± 0.26 mg GAE/100 g	
	Passion Fruit Peels	2.07 ± 0.05 mg GAE/g	Vitor et al. (2022)
	Pomegranate Peel	25.92 ± 0.13 mg GAE/g 40.55 ± 0.23 mg GAE/g 42.92 ± 0.65 mg GAE/g	Kupnik et al. (2022)
	Sweet apple peel	1043 ± 224 mg GAE/L	Tlais et al. (2023)
	Papaya peel	2.79 ± 0.12 mg GAE/g	Zhou et al. (2023)
	Papaya seed	2.80 ± 0.11 mg GAE/g	
	Plum waste	10.24 ± 0.37 mg GAE/100 g	Xiang et al. (2023)
	Purple passion fruit seeds	112.81 ± 13 mg GAE/100 g	da Costa et al. (2023)
	Sweet apple peel	770.18 ± 6.13 mg GAE/100 g	
	Watermelon rind	7.07 ± 0.86 μg GAE/mg 15.10 ± 0.58 μg GAE/mg	Yusoff et al. (2023)
	Noni seeds	12.48 ± 0.23 mg GAE/100 g	Dzah et al. (2024)
	Lemon pomace	1.47 ± 0.08 μg GAE/mg 1.18 ± 0.04 μg GAE/mg	Iervese et al. (2024)
	Seriguela peel	2563.30 ± 331.60 mg GAE/100 g	Cangussu et al. (2024)
	Seriguela seeds	991.18 ± 52.33 mg GAE/100 g	
Flavonoids	Acerola pomace	213.38 ± 35.8 mg QE/100 g 207.82 ± 21.09 mg QE/100 g	Carvalho et al. (2021)

(continued on next page)

Table 1 (*continued*)

Bioactive compounds	Residues	Quantity	References
	Guava pomace	44.45 ± 4.00 mg QE/100 g 22.26 ± 0.20 mg QE/100 g	
	Mango peels	502 ± 23.2–779 ± 11.9 mg QE/100 g	Marcillo et al. (2021b)
	Watermelon peel	4.97 ± 0.29 μg RE/g 6.16 ± 0.09 μg RE/g	Yusoff et al. (2023)
	Papaya peel Papaya seed	1.25 ± 0.05 mg QE/g 0.16 ± 0.01 mg QE/g	Zhou et al. (2023)
	Seriguela skin	80.50 ± 3.56 mg QCE/100 g	Cangussu et al. (2024)
	Seriguela seeds	28.96 ± 0.48 mg QCE/100 g	
	Lemon pomace	0.47 ± 0.02 mg CE/mL 0.33 ± 0.02 mg CE/mL	Iervese et al. (2024)
Anthocyanins	Strawberry waste	0.49 ± 0.03 mg/100 g 2.83 ± 0.03 mg/100 g	Vázquez et al. (2020)
	Raspberry waste	0.18 ± 0.02 mg/100 g 1.28 ± 0.06 mg/100 g	
	Pineapple peel	208 mg/g	Luan et al. (2023)
	Plum waste	68.95 ± 1.03 μg/g	Xiang et al. (2023)
Tanins	Cashew bagasse	299 ± 3.09–288 ± 4.50 mg TA/100 g	Cruz et al. (2022)
	Papaya peel Papaya seed	1.88 ± 0.06 mg CE/g 0.19 ± 0.01 mg CE/g	Zhou et al. (2023)
	Seriguela skin	1849.29 ± 333.29 mg TAE/100 g	Cangussu et al. (2024)
	Seriguela seeds	718.50 ± 98.65 mg TAE/100 g	
Carotenoids	Cashew fibers	0.29 mg/100g 0.38 mg/100g	Servent et al. (2020)
	Mango shells	4.53 ± 0.03–5.69 ± 0.20 mg/100g	Marcillo et al. (2021a)
	Cashew pseudofruit	134.41 ± 1.40 μg/g 165.47 ± 1.79 μg/g	Coelho et al. (2022).
	Cashew bagasse	1.71 ± 0.28–4.72 ± 0.60 μg/100g	Cruz et al. (2022)
	Pineapple shells	71 pg/mL	Luan et al. (2023)
	Seriguela seeds	991.18 ± 52.33 mg GAE/100 g	
Ascorbic acid	Cashew bagasse	88 ± 3.81–204 ± 4.26 mg/100g	Cruz et al. (2022)
	Noni seeds	1.79 ± 0.11 mg/g	Dzah et al. (2024)

2.1. Polyphenols or phenolic compounds

In tropical fruit by-products, phenolic compounds or polyphenols (characterized by having at least one phenol group and an aromatic ring that is attached to a hydroxyl group) are found in greater quantities, including phenolic acids, flavonoids and tannins (J. Ayala et al., 2011; Belmonte et al., 2022; López et al., 2021; Pereira, 2018). Among the residues with high polyphenol content, citrus residues (Rosa et al., 2023; Vitor et al., 2022), mango peels (Marcillo et al., 2021a; Zahid et al., 2022), seriguela (Cangussu et al., 2024), passion fruit (da Costa et al., 2023), acerola (Poletto et al., 2021), avocado (Rojas et al., 2022), among others, stand out. Among the residues analyzed, avocado peel had the highest content of these compounds, followed by mango and seriguela peel, indicating that the polyphenol content is higher in the peel than in the seed (Table 1).

2.1.1. Phenolic acids

The term "phenolic acids" mainly describes phenolic compounds that have a carboxylic acid group. They are secondary metabolites produced by plants and found in the plant cell wall (Mandal et al., 2010). They are found in a variety of plant-based foods (seeds, fruit peels, and vegetable leaves). They are usually present bound forms, such as amides, esters, or glucosides, and are rarely in free form (Pereira et al., 2009). They are characterized by being the main polyphenols, which are effortlessly absorbed in the intestine (Kumar and Goel, 2019) and have great antioxidant activity, providing health benefits, significantly reducing the risk of many diseases related to oxidative stress (cancers, diabetes, and cardiovascular diseases) (Sehrawat et al., 2022).

In the food industry, they have been used to improve the organoleptic (flavor, astringency, and hardness), nutritional, and antioxidant properties of foods (Shahidi and Naczk, 2003). They have also been recognized as antimicrobial compounds due to their ability to be metabolized by microorganisms, thus providing an alternative as a preservative (Faustino et al., 2019), which reduces the use of chemicals harmful to the environment. The application of these compounds in high concentrations in food matrices is limited, because unpleasant changes are generated in their sensory properties, promoting the encapsulation or immobilization of said compounds with a view to improving their functionality (Gutiérrez et al., 2018).

The most common phenolic acid in these residues is gallic acid, which has a high antioxidant, anti-inflammatory and neuroprotective capacity due to its ability to neutralize free radicals (Frešer et al., 2021; Xu et al., 2021). It is primarily present in guava waste (4.69 ± 0.01 μg/g) (Carvalho et al., 2021), mango peels (28.6 ± 2.22–28.6 ± 2.22 mg/100g) (Marcillo et al., 2021a), and papaya peels (0.33 ± 0.20 μg/g) (Khan et al., 2021). Chlorogenic acid is another phenolic acid that protects cells from free radical damage and, at the same time, exhibits antimicrobial activity against various bacteria, especially Gram-positive bacteria (Chaves and Esquivel, 2019; X. Guo et al., 2019). It is present in acerola and guava waste (42.54 ± 0.05 μg/g and 6.89 ± 0.28 μg/g, respectively) (Carvalho et al., 2021). Likewise, ferulic acid shows high antioxidant properties related to its phenolic core and an unsaturated side chain that forms resonance-stabilized structures (Celebioglu and Uyar, 2020; Gu et al., 2021). It is commonly found in papaya peels and seeds (0.3 ± 0.16 mg/100g and 3.86 ± 0.53 mg/100g respectively) (Khan et al., 2021) and in lemon pomace (25.45 ± 1.36 mg/100g) (Iervese et al., 2024).

2.1.2. Flavonoids

Flavonoids are low molecular weight polyphenolic phytochemicals secreted as a secondary metabolite of plants (Donadio et al., 2021). They are responsible for color, fragrance and flavor characteristics and are considered the most abundant pigments along with chlorophyll and carotenoids (Rodríguez et al., 2020). The main sources of these compounds are fruits, vegetables, seeds and flowers. Although they are also found in beer, wine, green tea and agro-industrial waste derived from the same primary sources (Stefanello et al., 2018).

Flavonoids are considered natural antioxidants for their ability to eliminate free radicals and inhibit their formation. As well as the chelation of metal ions to inhibit lipid peroxidation (Chamira and Preethi, 2014). Due to these characteristics, they have a wide variety of physiological functions in the human body, such as anti-inflammatory, anticancer, cardioprotective, antimicrobial and antiviral (Dias et al., 2021). In the food field, their use as preservatives focuses on the prevention of lipid oxidation and the inhibition of microbial growth. They are also used for the protection of vitamins and enzymes, as additives in human dietary supplements and animal feed, flavorings and colorings (e.g., anthocyanins) (Ruiz et al., 2017). In tropical fruit residues, flavonoids are mainly found in mango peels (Marcillo et al., 2021a), acerola pomace and guava (Carvalho et al., 2021; Rezende et al., 2018), with the first two having the highest amount of flavanoids (Table 1).

Anthocyanins are part of the flavonoid family, which constitute one of the largest groups of water-soluble pigments in the plant kingdom. They are responsible for giving color to flowers and fruits (Santos and González, 2019) and are widely distributed in fruits, vegetables and cereals with reddish tones. They are generally used as natural coloring agents replacing synthetic ones (Albuquerque et al., 2020). Epidemiological studies, in vitro trials and dietary intervention have supported the possibility that they play multiple roles as antivirals, antioxidants and anti-inflammatories, and promoters of intestinal health (Gull et al., 2022). Anthocyanins have also proven to have great potential as substitutes for antibiotics, but their use is limited due to their unstable structure and low bioavailability (Guo and Shahidi, 2024). Their stability is affected by external factors such as pH, temperature, light, solvent, oxygen, enzymes, other flavonoids, proteins and metal ions (Fang, 2014). These compounds are found mainly in tropical fruits waste with red, purple and blue peels, such as strawberries and raspberries (Vázquez et al., 2020) and plums (Xiang et al., 2023).

2.1.3. Tannins

Tannins are categorized within water-soluble polyphenols that differ in terms of solubility and site of accumulation in the plant (Petchidurai et al., 2019). They are classified into three different chemical structures: hydrolysable tannins, flavonoid-based tannins and phlorotannins. Hydrolysable tannins are derived from simple phenolic acids and carbohydrates, where hydroxyl groups are partially or completely esterified with phenolic groups. Flavonoid-based tannins are synthesized through flavins and catechins, which are well known for their antioxidant properties. For their part, phlorotannins are characteristic of brown algae (*Phaeophyceae*), they are composed of phloroglucinol units linked by carbon-carbon bonds. Phlorotannins present a wide range of biological activities, including antioxidant, anti-inflammatory, antiviral and anticancer properties (Lopes et al., 2012).

The astringency of most foods is attributed to their tannin content (Dheeraj and Mishra, 2023), which occurs when salivary proteins precipitate mainly as a result of the formation of insoluble complexes between proteins and tannins (astringent polyphenolic compounds) (Tezotto et al., 2018). This process depends on the average degree of polymerization and the compound; the higher the degree of tannins, the greater their affinity to bind to salivary proteins and cause astringency (Soares et al., 2020). Some tropical fruit waste with high tannin content includes Cashew nut pomace (Cruz et al., 2022), papaya peel and seed (Zhou et al., 2023), as well as seriguela skin and seed (Cangussu et al., 2024). Among them, the seriguela skin stands out for having the highest concentration of this compound (Table 1).

2.2. Carotenoids

Carotenoids are considered precursors of vitamin A (Meléndez, 2019; Meléndez et al., 2023), and are responsible for the yellow, orange, and red colors in fruits (Meléndez et al., 2023). β-carotene, α-carotene, β-cryptoxanthin, lycopene, lutein, and zeaxanthin are the carotenoids most frequently found in foods and represent the greatest benefits to human health (Beltrán et al., 2015). They participate in important biological actions that contribute to reducing the risk of diseases such as cancer, cardiovascular, skin, bone, eye, and metabolic diseases, and are beneficial for cognitive development (Meléndez, 2019).

They are widely used in the food, supplement, and pharmaceutical industries for their coloring and nutraceutical properties. They exhibit stronger antioxidant properties than other pigments, are considered prooxidants, and enhancers of communication between junctional cells, but they degrade rapidly when exposed to light, oxygen, moisture and heat during processing and storage, causing undesirable changes and reduced bioactivity (Meléndez et al., 2023). Among the changes that occur are color loss and the production of unpleasant flavors and aromatic compounds, which reduce consumer acceptability and shorten the shelf life of the final product (Vieira et al., 2020).

The intensity of the yellow, orange or red color of the fruit peel depends largely on the composition and concentration of the colored carotenoids (Ma et al., 2013; Luan et al., 2024). The color of the peel is an important characteristic of appearance, which is an indicator of fruit ripeness and quality, directly affecting consumer preference. Fruit waste such as cashew, seriguela and mango present shades ranging from yellow to orange, being great representatives of these compounds (Cangussu et al., 2024; Coelho et al., 2022; Cruz et al., 2022; Marcillo et al., 2021a). Among them, cashew waste stands out for their high content of carotenoids, with a higher concentration in the pomace compared to the pseudofruit, whose shades vary from yellow to red (Table 1).

2.3. Ascorbic acid

Ascorbic acid is commonly known as vitamin C and is one of the basic and necessary compounds for the proper functioning of the human body. It contributes to many processes, such as the strengthening and sealing blood vessels, the regulation of microbial absorption by leukocytes, the reduction of cholesterol levels, and is involved in skin rejuvenation and acceleration of wound healing (Gęgotek and Skrzydlewska, 2023).

It is considered an important water-soluble antioxidant due to its great capacity to donate electrons. It has a protective effect on cellular oxidation, is capable of reducing the number of free radicals produced during metabolic processes, and stimulates iron absorption. It is thermolabile and easily oxidized in the air. It is bioavailable in fruits, vegetables, juices, and fortified foods (Ramírez and Quiles, 2005). The waste of citrus, cashew, guava, acerola and passion fruit seeds contain ascorbic acid (Barros et al., 2017; Carvalho et al., 2021, Cruz et al., 2022). Table 1 shows the high content of these compounds in uncommon waste such as noni seeds and cashew bagasse.

When analyzing the tropical fruit waste, it is observed that mango, acerola, seriguela and cashew nuts have the highest concentrations of bioactive compounds, standing out for their richness in phenolic compounds, flavonoids, tannins and carotenoids. The high concentration of these compounds suggests a great potential for their valorization in the food, pharmaceutical and cosmetic industries, contributing to the development of functional and sustainable products. In addition, the optimization of extraction methods could further improve the recovery and utilization of these residues, strengthening the circular economy and the reduction of agro-industrial waste.

3. Extraction methods of bioactive compounds

Extraction is essential for the recovery of bioactive compounds, for which conventional techniques have been developed (e.g., Soxhlet extraction, maceration and hydro-distillation) and extended to an industrial scale, but have generated environmental problems due to CO_2 emissions and the use of dangerous chemical solutions. Therefore, in recent years alternative techniques have been used, such as ultrasound-assisted extraction, ohmic extraction, pulsed electric fields, high pressures, supercritical fluid extraction and others, seeking high yields and recovery effectiveness. This results in shorter extraction times and less environmental damage, tending towards green and environmentally friendly extraction techniques (Vânia and Ramin, 2018; Zhang et al., 2018).

Table 2 shows comparison of techniques used for the extraction of different bioactive compounds from tropical fruit waste. Phenolic compounds, flavonoids, anthocyanins and carotenoids are analyzed using various extraction methods.

Most of the bioactive compounds from tropical fruits are extracted by conventional methods, including maceration, digestion, percolation, decoction, hydrodistillation, and Soxhlet extraction, which usually require a large volume of chemical solvents (acetone, methanol, ethanol, and others). Despite being low-cost techniques, they exhibit long extraction times, low extraction efficiency and degradation of the compounds due to increased temperature. As a result, other extraction

Table 2
Comparison of techniques used for the extraction of bioactive compounds in tropical fruit by-products.

Bioactive compounds	Residues	Extraction methods[a]	Quantity	References
Phenolic compounds	Strawberry waste	EES	7.157 ± 0.160 mg GAE/100 g	Vázquez et al. (2020)
		OES	5.761 ± 0.012 mg GAE/100 g	
	Raspberry waste	EES	19.405 ± 0.377 mg GAE/100 g	
		OES	49.644 ± 0.760 mg GAE/100 g	
	Acerola pomace	ECS - A	444.01 ± 45.99 mg GAE/100 g	Carvalho et al. (2021)
		ECS - US	419.35 ± 7.4 mg GAE/100 g	
	Guava pomace	ECS - A	160.33 ± 5.77 mg GAE/100 g	
		ECS - US	172.56 ± 15.13 mg GAE/100 g	
	Mango peels	OES - A	2931 ± 175–5149 ± 154 mg GAE/100 g	Marcillo et al. (2021a)
		ECS	22.57 ± 0.38 mg GAE/100 g	Zahid et al. (2022)
	Pomegranate peel	ECS - US	25.92 ± 0.13 mg GAE/g	Kupnik et al. (2022)
		ECS - SE	40.55 ± 0.23 mg GAE/g	
		ECS - CM	42.92 ± 0.65 mg GAE/g	
	Watermelon rind	ECS - CM	0.00707 ± 0.00086 mg GAE/mg	Yusoff et al. (2023)
		ECS - US	0.01510 ± 0.00058 mg GAE/mg	
	Lemon pomace	ECS - CM	0.00147 ± 0.08 mg GAE/mg	Iervese et al. (2024)
		ECS - US	0.00118 ± 0.04 mg GAE/mg	
Flavonoids	Acerola pomace	ECS- A	213.38 ± 35.8 mg QE/100 g	Carvalho et al. (2021)
		ECS - US	207.82 ± 21.09 mg QE/100 g	
	Guava pomace	ECS- A	44.45 ± 4.00 mg QE/100 g	
		ECS - US	22.26 ± 0.20 mg QE/100 g	
	Watermelon rind	ECS- M	0.00497 ± 0.00029 mg RE/g	Yusoff et al. (2023)
		ECS - US	0.00616 ± 0.0009 mg RE/g	
	Lemon pomace	ECS- M	0.47 ± 0.02 mg CE/mL	Iervese et al. (2024)
		ECS - US	0.33 ± 0.02 mg CE/mL	
Anthocyanins	Strawberry waste	EES	0.49 ± 0.03 mg/100 g	Vázquez et al. (2020)
		OSE	2.83 ± 0.03 mg/100 g	
	Raspberry waste	EES	0.18 ± 0.02 mg/100 g	
		OSE	1.28 ± 0.06 mg/100 g	
Carotenoids	Cashew fibers	M	0.29 mg/100g	Servent et al. (2020)
		M – ET	0.38 mg/100g	
	Cashew pseudofruit	ECS– M	0.13441 ± 0.00140 mg/g	Coelho et al. (2022).
		ECS- US	0.16547 ± 0.00179 mg/g	

[a] ECS: Extraction with chemical solvents; A: Agitation; OSE: Organic solvent extraction; EES: Extraction with eutectic solvent; US: Ultrasound; M: Maceration; ET: Enzyme treatment; SE: Soxlet.

methodologies have been investigated that are more sustainable, faster, more reliable, energy efficient and environmentally friendly (Kaderides et al., 2019). Within these emerging methodologies, ultrasound is the most frequently used, as it is more cost-effective (Kupnik et al., 2022).

Ultrasound-assisted extraction allows to increase extraction performance due to the formation of microscopic bubbles that release large amounts of energy (Briones et al., 2015). It uses acoustic-mechanical waves to generate high shear, turbulence (Shirsath et al., 2017), and cavitation, causing several effects in the liquid, such as shock waves and high-velocity liquid jets (Sharma et al., 2023). It is widely used in the extraction of volatile compounds due to the mechanical effect generated by acoustic cavitation, which causes the release of intracellular products by breaking the cell wall, thus increasing the extraction of volatile substances (Zamanipoor et al., 2020). This effect can be evidenced in the carotenoid content of the cashew pseudofruit (Coelho et al., 2022), in the phenolic compounds of guava residues (Carvalho et al., 2021) and watermelon (Yusoff et al., 2023). However, the flavonoid content in acerola, guava (Carvalho et al., 2021) and lemon (Iervese et al., 2024) residues decreased, which may be due to the extraction time, since high exposure to sonication increases the temperature and consequently the material to be extracted degrades (Qiu et al., 2020).

The use of deep eutectic solvents allowed for increased extraction of phenolic compounds (Vázquez et al., 2020), as they have much lower melting points compared to the individual components of the food matrix, which gives them high thermal stability and biodegradability (Cao et al., 2022, 2024; Płotka-Wasylka et al., 2021). However, it should not be applicable for anthocyanins, as the recovery of this compound is not efficient with respect to the traditional method using acetone.

Gas-expanded liquids are a novel extraction technique, using a liquid solvent that acts as the main solvent and a compressible gas to assist in the extraction (Strieder et al., 2024), making it an environmentally friendly method, resulting in a solvent with higher extraction power, even at low temperatures (Abderrezag et al., 2022; Herrero et al., 2017; Zabot et al., 2021). By using this technique, the yield of obtaining phenolic compounds was increased compared to conventional methods in acerola waste (106.8 ± 5.5 mg GAE/100 g) (Poletto et al., 2021).

Another technique is pressure-driven membranes, which are an alternative to high temperature treatments because they avoid damaging the functional characteristics of the products (di Corcia et al., 2022). Among these membrane processes is cross-flow microfiltration, which allows the separation of particles with very small diameters (Khan et al., 2023), where the important thing is the retentivity, since the bioactive compounds accumulate there (di Corcia et al., 2020; di Corcia et al., 2022). This technique has been applied in conjunction with enzymatic liquefaction in cashew fiber extract, allowing to multiply the carotenoid content, reducing energy costs and increasing the production volume (Servent et al., 2020).

These characteristics have allowed alternative methodologies to awaken the interest of researchers as future application prospects, as they are more efficient due to high yields for the recovery of bioactive compounds (Vidal et al., 2024). However, the choice of the appropriate method depends on factors such as the type of bioactive compound, the plant matrix and the available resources. The industrial implementation of these emerging techniques requires a careful evaluation of the costs, since the investment in equipment may be higher, the reduction in operating costs and processing times may compensate this investment. Likewise, industrial-scale implementation is feasible, but may require technical adaptations in the case of ultrasound, deep eutectic solvents and gas-expanded liquids (Enríquez et al., 2023; Khan et al., 2024; Wong et al., 2020).

4. Factors affecting the content of bioactive compounds in tropical fruit by-products

The composition of bioactive compounds from tropical fruit by-products is influenced by extrinsic factors such as climate, soil type and geographical location (Ahmed et al., 2020; Vignesh et al., 2024), and intrinsic or fruit-derived factors such as type of by-product (peel, pomace or seed), plant variety and fruit maturity at harvest (Fig. 1) (Ceccarelli et al., 2021; Lolletti et al., 2021; Marcillo et al., 2021a).

4.1. By-product type

The peel, seed and pomace of the fruits have different compositions of bioactive compounds. In the outermost parts of the fruits (peels), there is usually a higher content of bioactive compounds due to the differences in the composition of their cell wall (Resende et al., 2019; Cangussu et al., 2021). The high levels of bioactive compounds present in the fruit peel act as a defensive barrier, helping to protect and preserve the internal parts and seeds against possible threats from insects and microorganisms (Jayarathne et al., 2024).

The peel is the barrier between the fruit and the environment. It is exposed to different environmental factors (sunlight, insect bites, temperature, wind and others) that cause stress in plants, which induces the secondary metabolism of bioactive compounds, mainly for defense purposes, thus increasing the levels of these metabolites, among which phenolic compounds stand out (Ashraf et al., 2018; Dzah et al., 2024). Likewise, flavonoids and anthocyanins are significantly higher in the peel than in the seeds, which is attributed to the accumulation of pigments in this part of the fruit (Jayarathne et al., 2024).

Seeds are vital structures that contain the reserves needed for the germination of a new plant. They contain bioactive compounds, mainly phenolic compounds, which help protect the embryo (Samtiya et al., 2021). In seeds, the accumulation of these compounds is related to protection against abiotic and biotic stress during their development and germination (Jeon et al., 2022), and the expenditure of the compounds in these processes decreases their composition.

The pomace consists of a mixture of shell and seed residues, characterized by a distinctive chemical composition that distinguishes it from the shell and seed individually. The bioactive compounds from the pomace, such as flavonoids, carotenoids and polyphenols, act as an immune system for the plant, protecting it from various threats and ensuring its survival (How and Nyam, 2024).

The levels of phenolic compounds, anthocyanins, flavonoids, tannins and ascorbic acid in different parts of the fruit can fluctuate in response to environmental factors such as drought, temperature variations, pollution, ultraviolet light and pathogen attacks, which significantly influence the synthesis and accumulation of bioactive compounds (Altaf et al., 2024).

For instance, the peel of papaya and seriguela have higher flavonoid content than the seeds of both fruits (Table 1). Also, phenolic compounds are higher in the peel of purple passion fruit, seriguela, and Hass avocado (Rojas et al., 2022; da Costa et al., 2023; Zhou et al., 2023), which is associated with their antioxidant effect mainly attributed to the chelating potential conferred by the chemical structure of phenolic compounds (Prietsch et al., 2014).

4.2. Variety

Within the same species of plants, different varieties can be found, which differ in size, color, shape, genotype and, above all, adaptation to

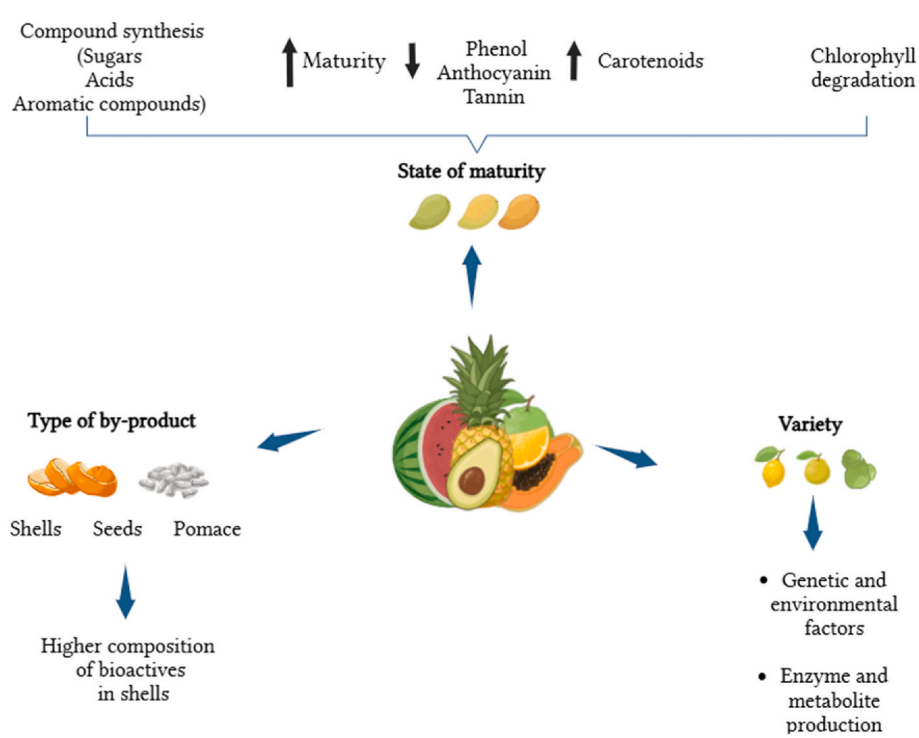

Fig. 1. Intrinsic factors affecting the content of bioactive compounds in fruit by-products.

different climates (Muhie, 2023). Variety is a factor that influences the composition of bioactive compounds (Ceccarelli et al., 2021; Sahie et al., 2023), due to a complex interaction of genetic and environmental factors (Peron et al., 2024). These characteristics confer biochemical properties to the fruit, influencing the production and accumulation of bioactive compounds (Ghahremani et al., 2023).

Each variety has a characteristic set of genes that code for the production of specific enzymes and secondary metabolites. These genetic differences translate into variations in the concentration and type of bioactive compounds present in the fruit (Sheidai et al., 2024). The genes code for enzymes that catalyze reactions in metabolic pathways leading to the synthesis of bioactive compounds. Variations in these genes can alter the speed and efficiency of these pathways, affecting the composition of the compounds produced (Kashyap et al., 2022).

The dynamic interactions between multiple hormones, transcription factors and genetic modifications establish the complex regulatory network that controls the expression levels of genes related to the composition of bioactive compounds. Also, interactions between genotype and environment have a pronounced effect on fruit carotenoids, anthocyanins, and phenolic compounds (Palmieri et al., 2017; Kim et al., 2024).

Particularly, the Aliança variety papaya has higher phenolic contents in peels (8.9 mg GAE/g) and seeds (4.7 mg GAE/g) than the Formosa variety (8.0 and 4.3 mg GAE/g for peels and seeds, respectively). Likewise, the flavonoid content is higher in the Aliança variety than in Formosa (2.3 and 2.5 mg CE/g respectively) (Vinha et al., 2024) (Table 1). Similar to papaya varieties, the bioactive composition of bagasse from different cashew varieties was evaluated, reporting differences in the compositions of carotenoids, tannins and phenolic compounds, which are attributed to their genetic differences (Cruz et al., 2022).

4.3. Maturity stage

The maturity stage of the fruit is an important factor when evaluating bioactive compounds (Ceccarelli et al., 2021; Khan et al., 2021). Fruit ripening is a complex process, which involves several physiological, biochemical and molecular mechanisms (Bhatla and Lal, 2023). As the fruit matures, the phenolic, anthocyanin and tannin content decreases, which may be associated with the biosynthesis processes and color changes that occur in the fruit (López et al., 2019; de Souza Silva et al., 2020; Gadelha et al., 2024).

During maturity, the synthesis of sugars, acids, aromatic compounds (Altaf et al., 2024) and the degradation of chlorophyll occur, and as a result of these biological reactions, free radicals are generated, which are counteracted by bioactive compounds, thus minimizing the content of the latter (Dzah, 2014; Martínez et al., 2017). Senescence in fruits affects their metabolic integrity, due to physiological disorders that eventually weaken antioxidant defense systems, making fruits vulnerable to oxidative stress induced by free radicals and depletion of antioxidant compounds (Zheng et al., 2016).

With maturation there is a greater probability of genetic errors induced by reactive oxygen species that can hinder the adequate synthesis of bioactive compounds. Also, with the degradation of components of the cellular structure such as pectin, other compartmentalized biomolecules and enzymes are exposed to the internal cellular environment, which inhibits the specialized biosynthesis of antioxidant compounds and enzymes, causing a reduction in the levels of phenolic compounds. Furthermore, as maturity-related loss of cellular integrity occurs, plant parts experience a loss of water and nutrients that are crucial for biosynthetic mechanisms. This phenomenon also negatively affects the biosynthesis of bioactive compounds of interest (Idris et al., 2023; Dzah et al., 2024).

On the other hand, carotenoids increase with fruit ripening, as color changes occur during this process. These changes typically begin with the degradation of chlorophyll, which results in the appearance of several darker pigments, accompanied by an increase in these bioactive compounds (Ma et al., 2023).

The extraction procedure varies according to the type of by-product; however, for the same by-product at different stages of maturation, the same extraction process is used. Therefore, according to Table 1, the phenolic content in purple passion fruit seeds decreases with the ripening of the fruit, where the decrease is 2.89 mg GAE/100g of sample (da Costa et al., 2023), in noni seeds the content decreased by 1.68 mg GAE/g of sample (Dzah et al., 2024) and in Hass avocado peel is 157.76 mg GAE/100g of sample (Alkaltham et al., 2021).

In addition to the aforementioned intrinsic factors, it is important to note that bioactive compounds are susceptible to various degradation mechanisms during storage and processing, which can affect their stability and functionality. Exposure to oxygen and high temperatures during processing can reduce the efficacy of these compounds, generating undesirable degradation products. Due to their high reactivity, compounds such as ascorbic acid, phenols and flavonoids undergo changes in their structure when reacting with oxygen. Likewise, elevated temperatures can induce thermal degradation of sensitive compounds, such as anthocyanins and some polyphenols, affecting their stability and biological activity (Elgamal et al., 2023; Mieszczakowska et al., 2021; Song et al., 2022).

Besides, variations in pH can destabilize bioactive compounds, leading to degradation or loss of functionality and bioactivity. Another key factor is exposure to light, especially ultraviolet radiation, which can trigger photochemical reactions that alter the structure and properties of the compounds, affecting their stability, as occurs with phenolic compounds in the presence of oxygen and light. On the other hand, high humidity levels can favor hydrolytic reactions and microbial growth, compromising the integrity and quality of these compounds. Increased water activity can accelerate their deterioration through oxidation and affect the dynamics of enzymatic reactions (Sepúlveda and Zapata, 2019; de Benedictis et al., 2023; García et al., 2025; Wang et al., 2025).

In order to improve the stability of bioactive compounds, which is affected by each of the above factors, microencapsulation (particles 1–1000 μm) and nanoencapsulation (particles <1000 nm) techniques have been applied (Hasan et al., 2024; Noore et al., 2021; Zabot et al., 2022). These techniques provide advantages such as protection against environmental degradation, controlled release and ease of handling in solid or liquid products. Nanoencapsulation offers advantages over microencapsulation in terms of increased solubility, improved absorption and targeted release in biological systems, especially for polyphenols and carotenoids (Chowdhury et al., 2024; Hasan et al., 2024; Matra et al., 2024). However, its disadvantages include higher production costs and greater complexity in industrial scale-up (Martins et al., 2022; Phupaboon et al., 2024). Despite their differences, both techniques represent promising strategies to improve the efficacy and stability of bioactive compounds, broadening their application in different sectors.

5. Conclusions and future perspectives

Tropical fruit by-products have a high content of bioactive compounds that give them a high nutritional value. However, they are often underused in the food field, so it is essential to investigate their application in this sector, to generate and develop new food products with excellent nutritional quality that contribute to improving and maintaining health.

The use of tropical fruit by-products contributes to improving the circular economy by using low-cost waste, thereby revaluing these by-products. Therefore, it is recommended to develop effective strategies to maximize their use and conduct a life cycle analysis to assess the environmental impact and economic benefits of the derived products.

The type of fruit by-product, the variety and the state of maturity are influential factors in the composition of bioactive compounds. These can be extracted by different methods, with green technologies being the ones used in the long term and on a large scale, due to their great environmental benefits, balancing their high costs with the benefits they provide.

The valorization of tropical fruit by-products in the formulation of functional foods represents a key strategy to take advantage of their high content of bioactive compounds and respond to the growing demand for products with health benefits. Future research should focus on the development of technologies that allow the efficient incorporation of these compounds into foods without compromising their stability and bioavailability. To this end, it is essential to optimize extraction and purification methods, as well as to explore strategies such as microencapsulation and nanotechnology, which can improve the protection, release and absorption of bioactive compounds in the organism. In addition, it is essential to conduct studies on interactions between bioactive compounds and the food matrix, their stability during processing and storage, as well as their impact on the functionality of the final product. Scientific validation of their beneficial effects through clinical studies and bioavailability tests will strengthen their acceptance in the market and facilitate their integration into value-added products.

From a regulatory perspective, the use of by-products in functional foods must align with regulatory frameworks and food safety policies, ensuring compliance with the standards established by bodies such as the European Food Safety Authority (EFSA), the U.S. Food and Drug Administration (FDA) and the Food Code (Codex Alimentarius). It is necessary to promote the development of specific regulations that facilitate the approval and marketing of these products, guaranteeing their safety and functionality without generating excessive regulatory barriers.

In conclusion, the future of the valorization of by-products in functional foods depends on the combination of scientific advances in extraction, formulation and stability, together with the evolution of regulatory frameworks that facilitate their commercialization and guarantee their safety and efficacy.

CRediT authorship contribution statement

María Romero-Martínez: Conceptualization, Methodology, Writing – original draft, Visualization, Writing – review & editing. **Ricardo Andrade-Pizarro:** Methodology, Writing – review & editing, Visualization. **Claudia De Paula:** Writing – review & editing, Visualization, All authors have read and agree with the published version of the manuscript.

Declaration of Competing Interest

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

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Data availability

Data will be made available on request.

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