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Review article

Tumbo, an Andean fruit: Uses, nutrition, processing, and biomolecules

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A R T I C L E I N F O

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A B S T R A C T

Tumbo fruit has potential for industrialization due to its nutritional and functional properties, but scientific knowledge of this species is still limited compared to other species of the same genus, *Passiflora*. This review compiles the latest scientific advances on Tumbo, which cover the food technological aspects of Tumbo fruit, its uses and its potential as a source of bioactives for different industries, especially food, pharmaceutical, and cosmetics. The products (nectar, jellies, jams, wines, others) and by-products of the processing of the Tumbo fruit have various nutritional, sensory, and composition attributes for developing new food and non-food products. The potential applications of the fruit and its derivatives are broad, such as cosmetics, drugs, functional foods, and additives; these applications are due to its technological properties and its content of bioactive molecules. The Tumbo biorefinery presents an important perspective, especially for its bioactivity of high biological value for different industries.

1. Introduction

The Tumbo (*Passiflora mollissima*) is a species native to Colombia, Ecuador, Panama, Venezuela and Peru [1]. Its fruit is highly appreciated for its flavor and nutritional properties, known as Tumbo Serrano in the central mountains of Peru [2]. The fruit is valued for its mucilage (commonly called pulp) [3] with very interesting sensory, nutritional [4], and functional [4] characteristics for the food industry, constituting the group of healthy foods with promising functional properties [5]. It can also be used as an ingredient in food products, providing bioactive compounds to increase functional properties, such as antioxidant capacity in whey-based drinks [6] and probiotic yogurt [7]. The peel and seeds of the tumbo fruit have been the subject of studies demonstrating their potential as an ingredient and additive for manufacturing food, cosmetics, and pharmaceutical products [8]. These characteristics give the Tumbo

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fruit good prospects for developing products with nutritional and functional properties that contribute to maintaining good health for consumers.

According to the studies available in the scientific literature on the composition and properties of Tumbo (fruit, leaves, and stems) have revealed good potential for the industry [6,9–11]. Residues from fruit processing are derived for farm animal feed; these residues contain bioactive compounds of interest to the industry, such as unsaturated/polyunsaturated fatty acids and phenolic compounds contained in the seeds [8]. The Tumbo peels can become a source for the production of pectins [11–13], phytoprostanes [14], phenolic compounds [14], among others [8,11]. The leaves and woody parts have proven to be a valuable source of flavonoids, many of them with important biological properties for the pharmaceutical and medicine industries [15]. Tumbo biomolecules have varied bioactive properties, such as anticancer activity [16], improved lipid digestion [12], antihyperglycemic [17], antidiabetic [18,19], production of functional foods [20], cosmetic products [21], pharmaceuticals [22], and others.

Many methods are available to extract bioactive compounds from the most diverse raw materials [23]. Emerging green methods have received particular attention due to their extraction efficiency and the fact that they are eco-friendly; these aspects are desirable to be incorporated into bioactive production processes. Among the most used are ultrasound-assisted extraction [24], microwaves [25], pulsed electric fields [26], and pressurized solvents (subcritical and supercritical fluids) [27]; These methods have been combined with other methods, to obtain greater efficiency and effectiveness in the extraction process [28–31]. Although these methods are available, the current reports on the extraction of bioactive biomolecules from Tumbo were more frequently performed using conventional methods, such as Soxhlet [32], infusion with boiling water [33]. There are other methods that have been used to obtain bioactives from Tumbo, such as pressurized-liquid extraction [34], pressurized hot water extraction [35], and dynamic headspace solid-phase microextraction (HS-SPME) [36]. In this context, the production of bioactives from Tumbo still has a broad perspective to be explored through more efficient, environmentally safe, and selective technologies to take advantage of the potential of this plant, seeking its integral use. On the other hand, when considering the implementation of new technologies in the extraction processes, it is necessary to consider the effect on the functional properties of the bioactive extracts.

The objective of this review article is to describe the main advances in scientific research on the Tumbo fruit in order to know its potential for the industry and to verify aspects that require attention from the scientific community. This objective can be achieved using an unrestricted search of scientific articles. Thus, using the scientific name of the fruit Tumbo, a search was carried out using the Google Scholar database. The main aspects investigated on the Tumbo fruit detailed in our manuscript are limited to the aspects of traditional uses, processing, active biomolecules, and technologies applied to obtain its bioactive components.

2. Botanical description and distribution

Fig. 1 shows the physical characteristics of the Tumbo plant that grows in the central highlands of Peru. Tumbo is the common name adopted throughout Peru's central highlands for the fruit of *P. mollissima* (Kunth) L.H. Bailey. This species is known by other synonymous scientific names: *Murucuja mollissima* (Kunth) Spreng., *M. mollissima* (Kunth) Spreng., *P. tomentosa* var. *mollissima* (Kunth) Triana & Planch., *P. tripartita* var. *mollissima* (Kunth) Holm-Niels. & P.M.Jørg., *Tacsonia mollissima* Kunth, and *T. mollissima* var. *glabrescens* Mast. [37]. The species belongs to the Passifloraceae family, and the genus *Passiflora* is categorized as a species of woody

Fig. 1. Flowers and fruits of Tumbo. Photo by Lobato Calderon.

climbing vine. This species naturally adapted to a variety of climate conditions and, thus, is cultivated in different countries, where they are known by other common names, such as banana passion fruit (New Zealand, Australia, and New Guinea), banana passion-flower, banana poka (Hawaii), bananadilla, curuba, sabanero blanco, maracujá banana, curuba (Latin American countries), parcha (Venezuela) and tacso (Colombia and Ecuador) (Colombia and Ecuador) [37].

The Tumbo is a climbing plant (Fig. 1), requiring for its cultivation support structure; its fruits are oblong to round, green when unripe (Fig. 1) and yellow to cream-colored when ripe (Fig. 2A); its pulp is aromatic and gelatinous, and of an orange color (Fig. 2B) that is strongly attached to the seeds (Fig. 2C) [38].

3. Traditional uses

Tumbo is a fruit (Fig. 2A) that stands out for its acidity. It was used by pre-Hispanic cultures in Peru [39]. Tumbo and species of the same genus were used and still are used for applications in medicine; the fruit and other parts of the plant are used [11,19,40–43]. To Tumbo is attributed several medicinal properties; in the literature, various preparations are described for the treatment of various diseases [44–46]. Tumbo juice is used for food preparations and is traditionally used to treat liver disorders; these characteristics allow the Tumbo fruit to be classified as a medicinal food [47]. Traditional uses of Tumbo also include culinary and cosmetic uses; some preparations are described in the literature [45]. Other traditional uses of Tumbo in the high Andean populations of Peru are little known, and this knowledge is limited to the inhabitants of these communities.

4. Tumbo fruit processing

The products and by-products derived from the processing of the Tumbo fruit have particular technological, sensory, nutritional, and functional characteristics that characterize it [48–53]. Tumbo mucilage, commonly referred to as pulp, is firmly attached to the seeds (Fig. 2A) and is characterized by its vitamin C content of 77 mg/100 g [52] and carotenoids of 16 mg/100 g of dry pulp [53]. Tumbo pulp can be used as an alternative natural source of vitamin C and other bioactives for the preparation of food products, but first, the process must be designed and optimized, taking into account that vitamin C is a thermolabile compound; therefore, special attention should be paid to unit operations that involve heat treatments with temperatures above 60 °C [52]. Fresh pulp is highly perishable; alternatively, it can be subjected to dehydration for preservation using appropriate techniques that prevent the degradation of bioactive compounds, such as freeze-drying [54] and spray-drying [53,55]. Other bioactive compounds in the Tumbo pulp are the polyphenols and flavonoids, which are the object of attention because they confer functional properties to food products [51]. The use of the nutritional and functional properties of Tumbo mucilage in the formulation of new food and non-food products must consider an adequate design of the transformation process and optimization of the process, which allows for maintaining the properties of the raw material in the final manufactured product.

Recently, various applications of Tumbo pulp have been reported in food processing, such as yogurt [51], functional beverages [50], nectar [49], and jam [48]. In general, Tumbo fresh pulp is used to prepare products, but alternatively, spray-dried can be used,

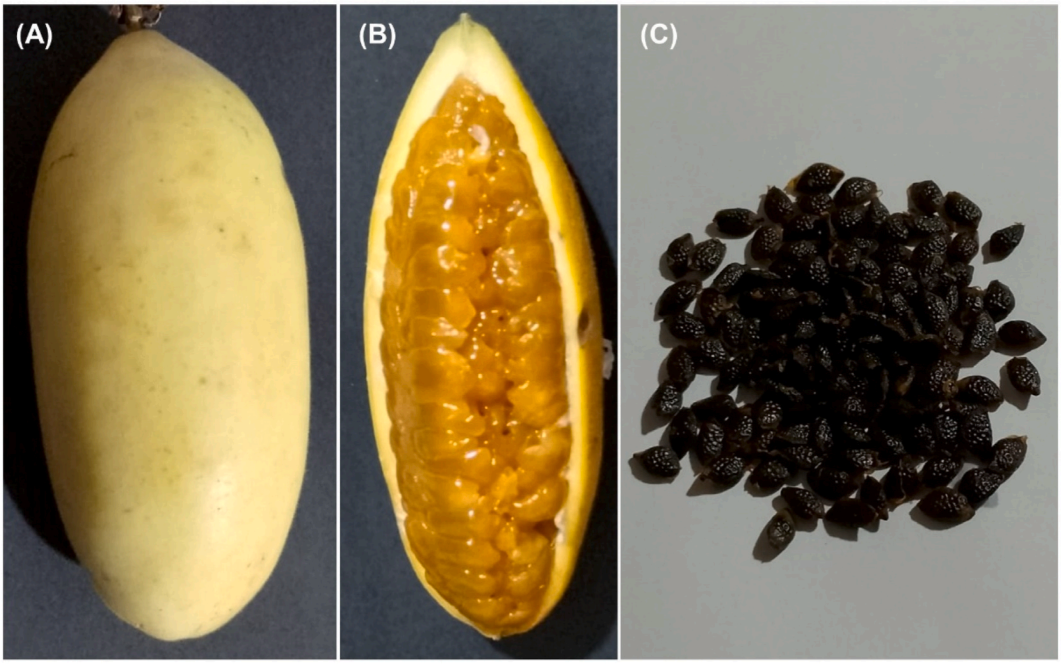

Fig. 2. Tumbo fruit (A), longitudinal cut of the fruit (B), and seeds (C). Photo by Lobato Calderon.

Table 1
Bioactive compounds and extraction methods of Tumbo and species of the same genus.

Compounds	Source	Extraction methods	References
Volatile compounds (terpenes, alcoholics, esters, ketones and phenolic acids) Total phenolic (691.90 mg GAE/g extract) Tannin (313.81 mg GAE/g extract)	Pulp from *P. leschenaultii* DC.	Soxhlet method with petroleum ether, chloroform, acetone, and methanol	[19]
Protocatechuic acid Ferulic acid Vanillic acid Epicatechin *p*-coumaric acid Cinnamic acid Eriodictyol Quercetin-3-glucoside	Pulp from *P. subpeltata*	Soxhlet method with petroleum ether, chloroform, acetone, and methanol	[56]
Apigenin-6-C-α-l-rhamnopyranosyl-(1 → 2)-(6″-O-acetyl)-β-D-glucopyranoside Luteolin-6-C-α-L-rhamnopyranosyl-(1 → 2)-(6″-O-acetyl)-β-D-glucopyranoside Isovitexin Isoorientin Isovitexin-2″-O-rhamnoside Isoorientin-2″-O-rhamnoside	Leaves from *P. bogotensis*	Extraction by infusion with distilled water	[57]
Orsellinic acid-2-O-β-glucoside (epi)catechin glucoside Glucosyringic acid Procyanidin dimer Procyanidin trimer Quercetin-glucoside Luteolin-glucoside Quercetin 3-O-(6″-acetyl-glucoside) Apigenin-8-C-glucoside (Vitexin) Luteolin 3-O-acetyl-glucoside Myricetin-3-O-(6″-galloyl)-glycoside Apigenin 7-(6″-O-acetyl)-glucoside	Peels from *P. ligularis*	Pressurized hot water extraction	[35]
(epi)catechin glucoside isomer Protocatechualdehyde acid Catechin (epi)catechin glucoside isomer Epicatechin Cyanidin glucoside Quercetin 3-O-(6″ malonyl-glucoside)-7-O-glucoside Luteolin-rhamnosyl-glucoside Quercetin glucoside Luteolin glucoside Luteolin-3-glucosyl-rhamnoside Quercetin 3-O-(6″acetyl-glucoside) Phloretin glucoside Artemitin	Peels from *P. edulis*	Pressurized hot water extraction	[35]
Luteolin-(7-O-glucopyranosyl)-8-C-glucoside (Lucenin) Apigenin dihexoside Luteolin–(6-C-pentosyl)-8-C-β-D-glucoside Luteolin-6-C-glucoside (Orientin/isoorientin) Luteolin-rhamnosyl-glucoside Ellagic acid 7 Apigenin-8-C-β-D-glucoside (Vitexin) Luteolin-rutinoside 6-C-Fucosylluteolin isomer Apigenin rhamnosyl-glucoside 6-C-Fucosylluteolin isomer	Peels from *P. edulis* flavicarpa	Pressurized hot water extraction	[35]
(epi)catechin-(epi)gallocatechin (epic)catechin glucoside Procyanidin dimer Catechin (epi)catechin glucoside isomer 6 Myricetin Apigenin 7-neohesperidoside-4-glucoside Isoorientin-7-rutinoside Luteolin-(7-O-glucopyranosil)-8-C-glucoside (Lucenin) Luteolin-6-C-glucoside ((iso)orientin) Luteolin-rhamnosyl-glucoside Quercetin rutinoside Ellagic acid Luteolin rhamonsyl glucoside	Peels from *P. mollissima*	Pressurized hot water extraction	[35]

(*continued on next page*)

Table 1 (*continued*)

Compounds	Source	Extraction methods	References
Luteolin-dihexoside Luteolin-7-gentiobioside Vitexin-2″-rhamnoside Luteolin-rhamnosyl-glucoside Apigenin-8-C-β-D-glucoside (Vitexin) Diosmitin rutinoside			
Principal volatile compounds (of 51 volatiles identified): Hexyl butanoate Hexyl hexanoate Ethyl hexanoate	Juice from *P. edulis* Sims	Dynamic headspace solid-phase microextraction (HS-SPME)	[36]
Principal volatile compounds (of 24 volatiles identified): Methyl hexanoate (E)-methyl-2-hexenoate Methyl benzoate	Juice from *P. edulis* Sims f. *flavicarpa* Yellow	Dynamic headspace solid-phase microextraction (HS-SPME)	[36]
Principal volatile compounds (of 21 volatiles identified): (Z)-β-ocimene Hexyl butanoate Hexyl hexanoate	Juice from *P. mollissima* banana	Dynamic headspace solid-phase microextraction (HS-SPME)	[36]
The major phenolic compounds: Proanthocyanidin dimers C-glycosylated luteolin The content of the major carotenoids: Lutein β-carotene	*P. tenuifila* fruit	Solvent extraction with and without ultrasound assistance	[58]
Flavonoids: Isoorientin Orientin Vitexin Swertisin 4′-Methoxyluteolin-8-C-6″- acetylglucopyranoside	Leaves from *P. tripartita* var. *mollissima*	Extraction by infusion with boiling water	[33]
Flavonoids: Isoorientin Isovitexin	Leaves from *P. bogotensis*	Extraction by infusion with boiling water	[33]
Orientin Vitexin-2″-O-rhamnoside Isovitexin	Leaves from *P. alata*	Extraction by infusion with boiling water	[33]
Vitexin-2″-O-xiloside Vitexin	Leaves from *P. quadrangularis*	Extraction by infusion with boiling water	[33]
2-Methylpropyl acetate Butyl acetate Hexanal (Z)-3-Hexenal 1,8-Cineole Hexyl acetate (Z)-3-Hexenyl acetate 1-Hexanol (Z)-3-Hexen-1-ol Butyl hexanoate + hexyl butanoate Furanoid *trans*-linalool oxide Methional Furanoid *cis*-linalool oxide Linalool α-Terpineol 3-Sulfanylhexyl acetate 4-Hydroxy-2,5-dimethyl-3(2H)-furanone δ-Dodecalactone	Pulp from *P. mollissima* (Kunth) L. H. Bailey	Solvent extraction (n-pentane/ethyl ether) with stirring	[32]
Phenolics acid Flavonoids Stilbenoids Fatty acids Terpenoids	Seeds from *P. mollissima* (Kunth) L. H. Bailey	Pressurized liquid extraction	[34]

which adequately preserves its nutritional and functional properties [53]. The incorporation of Tumbo pulp in food products, fresh or dehydrated, must consider an adequate proportion with the other ingredients, mainly due to its acidity (0.64 %) and pH (3.2) [49], which can strongly contribute to the sensory attributes of the manufactured product. Due to its pH and acidity characteristics, Tumbo pulp can be used to formulate dairy foods with low pH, such as yogurt. Adding Tumbo pulp in a concentration of 50 mg/mL in preparing a probiotic yogurt gave it highly acceptable sensory attributes evaluated by 200 consumer panelists of this type of yogurt [51]. The Tumbo pulp contributed to the functional properties of the yogurt, increasing its antioxidant capacity, probably due to the presence of phenolic compounds, flavonoids, and carotenoids; likewise, it had no adverse effect on the probiotic cells (lactic acid bacteria), observing an adequate concentration for a probiotic yogurt [51]. In other applications, the pulp was used to make a functional beverage with lactose-free whey, showing attractive sensory and nutritional properties [50]. The Tumbo pulp was combined with the pulp of the *Mammea americana* fruit to make a jam with acceptable sensory attributes [48]. When the pulp was used to make nectar with honey, it was observed that the best dilution was one part pulp to five parts water; its vitamin C content was 9.9 mg/mL of nectar [49]. The use of Tumbo pulp in manufacturing dairy food products and new products has an interesting perspective due to this fruit's particular sensory, nutritional, and functional properties [8].

The industrialization of the fruit of Tumbo would bring with it a considerable production of residues, constituted mainly by the peel (32 % of the weight of the fruit) and seeds (9 % of the weight of the fruit), both by-products represent a good source of bioactive molecules, for the functional food, pharmaceutical, cosmetic and medicine industries [8]. In subsequent sections, the potential of the by-products of the Tumbo fruit will be described in greater detail.

5. Promising bioactives and extraction methods

Tumbo is a promising secondary metabolite and macronutrient source with various bioactives (Table 1). Tumbo compounds are extracted from leaves, stems, flowers, and fruits. The fruit (Fig. 2) has been specially studied due to its importance for the food industry, and its processing generates abundant residues consisting of seeds and peels [8]. Tumbo seeds are a good source of lipid compounds and phenolic compounds. The total phenolic (FT) content observed in defatted seeds was approximately 30 mg FT for each gram of defatted seed. A total of 61 phenolic compounds were found present in the seeds, compounds belonging to the families of phenolic acid, phenolic acid derivative, flavonoid, stilbenoid, and others [34]. The lipid fraction of Tumbo seeds is made up of saturated, unsaturated, and polyunsaturated fatty acids, probably coming from acylglycerides molecules. Other lipid molecules, such as phytosterols, tocopherol, and other terpenoids, are dispersed in the lipid fraction of the seeds [34].

Tumbo peels from the food industry have a high content of total phenolic compounds (approx. 30 mg for each gram of dry extract) and a larger number of these compounds (20 phenolics, shown in Table 1) as compared to other species of the same genus [35]. The phenolic content and profile of Tumbo peels represent an excellent alternative source of antioxidants for the formulation of functional products by several industries [35]. The use of these residues for the production of valuable bioactive is an alternative that promotes an environmentally responsible food industry, contributing to the comprehensive use of raw materials and therefore reducing environmental polluting residues [59–61].

Tumbo leaves are a source of flavonoids of interest to the pharmaceutical and cosmetic industry [33]. Table 1 shows the main flavonoids identified in the leaves of Tumbo and other species of the same genus. Isoorientin was common in extracts from the leaves of Tumbo and *P. bogotensis*, and this compound has promising applications due to its various pharmacological properties that allow for the improvement of different metabolic complications, such as hyperglycemia, hyperlipidemia, and insulin resistance [62].

Tumbo pulp presents attractive sensory and nutritional characteristics for preparing various food products. The pulp stands out for its orange color, acidity, and aroma. These characteristics are due to the presence of carotenoids [51], vitamin C, and volatile components [32,36]. The bioactive components of the pulp can be transferred to processed food products by directly adding the pulp during processing to a formulation of the food product previously established [51]. Due to the importance of vitamin C for health and the content of this component in Tumbo pulp, it can be used as an indicator of the shelf life and quality of fresh, processed pulp and derived products [52]. With a suitable formulation and processing of foods derived from pulp, it is possible to obtain probiotic food products with good bioactive properties and stability during storage [51]. Another group of bioactive compounds present in Tumbo pulp are phenolic compounds; this group of compounds is made up of a large number of phytochemicals, each one with specific biological properties. One of these bioactive properties frequently reported and of interest in food products is the antioxidant capacity, generally attributed to phenolic compounds [17,51]. Alternatively, the bioactive components of Tumbo mucilage can be preserved using processing techniques such as spray-drying with a microencapsulating agent [55] and freeze-drying [63]; both methods allow the preservation of bioactive compounds in the storage period, for subsequent applications.

Tumbo bioactive compounds have different chemical characteristics: apolar, low polarity, and polar (Table 1). Various extraction techniques are used to analyze these compounds and extract them for subsequent applications (food, pharmaceutical, medicinal and cosmetic), such as conventional extraction with organic solvents, pressurized liquids with hot water, pressurized fluids, ultrasound extraction, etc. The extraction techniques used to recover Tumbo bioactive are detailed in the following subsections.

5.1. Conventional extraction

Conventional extraction with organic solvents (petroleum ether, chloroform, acetone, methanol, others) is generally performed for analytical purposes, frequently using methods such as Soxhlet [19,56] or Bligh Dyer [64]. Other methods, such as infusion with boiling water [33,57] and cold extraction with constant stirring [32], were used for the extraction of bioactive from the leaves [33,57], fruits [19,56], seeds [34] of Tumbo and other *Passiflora* species. The extraction conditions for Soxhlet and Bligh Dyer are standardized to be used as analytical methods to quantify total lipids, widely used in food analysis laboratories and reported in scientific publications. Other techniques, such as hot water infusion and solid-liquid extraction with shaking, were used under conditions and extraction parameters that allowed the obtaining of various chemical compounds from the Tumbo. Still, it would be convenient to optimize these methods to maximize the extraction yield of the most valuable components of Tumbo and by-products.

5.2. Pressurized hot water extraction

PHWE stands for pressurized hot water extraction method. This method is used to recover chemical compounds from different raw materials. Bioactive recovery using PHWE involves studying the parameters of pressure, temperature, and extraction time. Other parameters that can influence the extraction with this method are the particle size, solvent/sample ratio, type of cosolvent, and the use of incompressible material mixed with the sample to avoid compaction of the bed (sand, glass beads, others). Recently, the PHWE method was used to recover bioactive from the shells of *Passiflora* species, obtaining a good recovery of valuable bioactive for the food industry; the operating conditions of the extraction method were optimized, focusing on the variables temperature, pressure, and extraction time, using a mixture of solvents (water/ethanol/formic acid, 94/5/1, vol%) [35].

5.3. *Ultrasound-assisted extraction*

The application of ultrasound in the extraction processes has intensified the recovery of bioactive from various raw materials [24, 65]. Properly adjusting the frequency and ultrasonic power allows it to control the size, diameter, and production of bubbles during the cavitation phenomenon [65]. This phenomenon is responsible for increasing the extraction yields of secondary metabolites from different types of raw materials due to the damage to the cellular tissue caused by the collapse of the cavitation bubbles, which allows for improving the penetration of the solvent into the interior of the raw material matrix improving the extraction of chemical components [65]. Ultrasonic extraction and agitation were recently combined for the extraction of phenolic compounds from the fruit of *P. tenuifila*, using a mixture of methanol/water (70/30, v/v) as a solvent, with an extraction time of 60 min [58]. Other technologies have been combined with ultrasound to enhance the extraction of bioactive components, such as vacuum distillation [29] and supercritical fluids [66]. The use of ultrasound in combination with other technologies, especially green technologies, is currently under investigation to improve the efficiency of the extraction processes of valuable bioactive components for the natural products industry; in this scenario, Tumbo represents a good source of bioactive (Table 1) that can be explored with these technologies.

5.4. *Pressurized liquid extraction*

The pressurized liquid extraction (PLE) method can use organic solvents (methanol, acetone, and others) and GRAS (Generally recognized as safe) solvents. This method allows extractions of apolar, low polarity, and apolar chemical components selectively using solvents of different polarities [34]. The variables that control the PLE process are temperature, pressure, mass flow of the solvent, and type of solvent, among others [27]. In a recent study, fractions of compounds of different polarities were extracted from Tumbo seeds. The process was carried out in two stages, first extracting low-polarity or apolar compounds with low-polarity organic solvents (n-heptane, cyclohexane, n-hexane, and (+)-limonene) and in a second stage, polar compounds were extracted using an ethanol/ethyl acetate mixture [34]. Different fractions of extracts can be obtained from raw material using solvents in a suitable polarity gradient. For this purpose, toxic organic solvents are usually used. Alternatively, supercritical carbon dioxide is used to obtain low polarity or apolar bioactive fractions from raw materials. Subsequently, GRAS solvents (ethanol, water, and ethanol/water mixture) can be used

Table 2
Biomolecules and their potential applications of Tumbo and other *Passiflora* species.

Molecules	Source	Application	References
Phenolics compounds	*P. mollissima* seeds	Antiproliferative activity of human colon cancer cells	[16]
Phenolics compounds	*P. edulis*. f. edulis seeds	Enrich particles with bioactive	[69]
Pectin	*P. tripartita* var. *mollissima* fruit epicarp.	Modulation of lipid digestion	[12]
Lipids compounds	*Passiflora* spp. seeds	Preparation of functional nanoemulsions for dermatological products.	[22]
Phenolic compounds (free and bound)	*P. molíssima* pulp	Potential use as an antihyperglycemic agent	[17]
Lipidic compounds	*P. tripartita* var. *mollisima* seed oil	Use as an excipient for nanoemulsions	[70]
Phenolic compounds	*P. tripartita* var. *molíssima* juice	Functional foods	[20]
Phenolic compounds	*P. tripartita* var. *mollisima* fruit pulp	Alpha-amylase and alpha-glucosidase inhibitory activity	[18]
–	*P. molíssima* fruit pulp	Antimicrobial ingredient for dentifrice.	[71]
Phenolics Flavonoids	*P. molíssima* fruit pulp	Hepatoprotective effect	[72]
Phytoprostanes Phenolic Compounds	*P. tripartita* var. *mollisima* Fruit Shell	Bioactive compounds for pharmaceutical and cosmetic products.	[14]
Alpha-hydroxy acids	*P. mollissima* seeds	Exfoliating formulation.	[21]
Unsaturated fatty acids	*Passiflora* spp. seeds	Induces the proliferation of keratinocytes.	[22]
Phenolic compounds (daidzein, epicatechin and artepillin C, others) Volatile compounds (terpenes, alcoholics, esters, ketones and phenolic acids)	*P. leschenaultii DC.* Fruits pulp	Anti-radical and anti-diabetic properties	[19]
–	*P. foetida* L. leaves	Analgesic and anti-inflammatory activity.	[73]
Flavonoids	*P. cincinnata* Mast. leaves and stems	Antinociceptive and anti-inflammatory activities.	[74]
Dietary fiber Phenolics compounds	*P. edulis* L., cv. Flovicarpa peel, pulp and seeds.	Food enrichment. Antioxidant properties.	[75]
–	*P. tripartita* var. mollisima fruit pulp.	Pulp with low glycemic load (GL).	[76]
Flavonoids and Phenolics compounds	*P. mollissima* Seed	Antiproliferative activity of tumor cells.	[68]

under subcritical conditions to obtain fractions of polar compounds. Adding GRAS solvents to the supercritical extraction process with CO_2 as a polarity modifier makes it possible to obtain polar components remaining from the supercritical extraction process [27,67].

6. Potential uses of bioactive from Tumbo fruit

Several studies have found the bioactive potentialities of the Tumbo fruit (Table 2); however, most of them have been performed only *in vitro* assays. The most recent studies indicate that the seed extract obtained through extraction with pressurized fluids inhibits the growth and proliferation of CAL 27 oral cancer cells (100 μg/mL at 72 h) and HT-29 colon cancer cells (IC_{50} 39 ± 2 μg/mL and 62 ± 3 μg/mL at 48 and 72 h, respectively) [16,68]. The ethanolic extract of the Tumbo fruit showed antibacterial activity against *Streptococcus sanguinis*, *Streptococcus oralis*, and *Streptococcus mutans* [40]. Likewise, it showed a highly toxic effect in the embryonic development of fertilized eggs of *Tetrapygus niger* [40].

The Tumbo fruit has a low glycemic index (GI) [76]. For this reason, it is advisable to incorporate it into the diet to reduce the consumption of high-GI foods and increase the intake of low-GI foods to improve the control of type 2 diabetes mellitus [77]. Additionally, the aqueous extract of Tumbo fruit inhibited the α-amylase and α-glycosidase enzymes [18]. Their inhibition in carbohydrate digestion can significantly reduce the rise in postprandial blood glucose. Therefore, it may be an important strategy for glycemic control in people with type 2 diabetes [78].

Several studies of characterization and identification of compounds of Tumbo fruit were carried out. Through techniques such as high-performance liquid chromatography (HPLC), gas chromatography-olfactometry (GC-O), gas chromatography coupled to a mass spectrometer (GC-MS), liquid chromatography coupled to a mass spectrometer (HPLC-ESI-MS) it was possible to identify biomolecules with important biological properties [17,34,79–81]. Ballesteros-Vivas et al. [34] mainly identified phenolic acids, flavonols, flavanones, and other flavonoid derivatives, including proanthocyanidins, in the polar fraction of seed extracts (Fig. 3). Also were identified compounds such as proanthocyanidins, (epi)-afzelechin glycosides, carotenoids, benzophenones, and (epi)catechin [17,80]. These bioactive compounds give it a high nutraceutical potential as food and input for manufacturing other products [80].

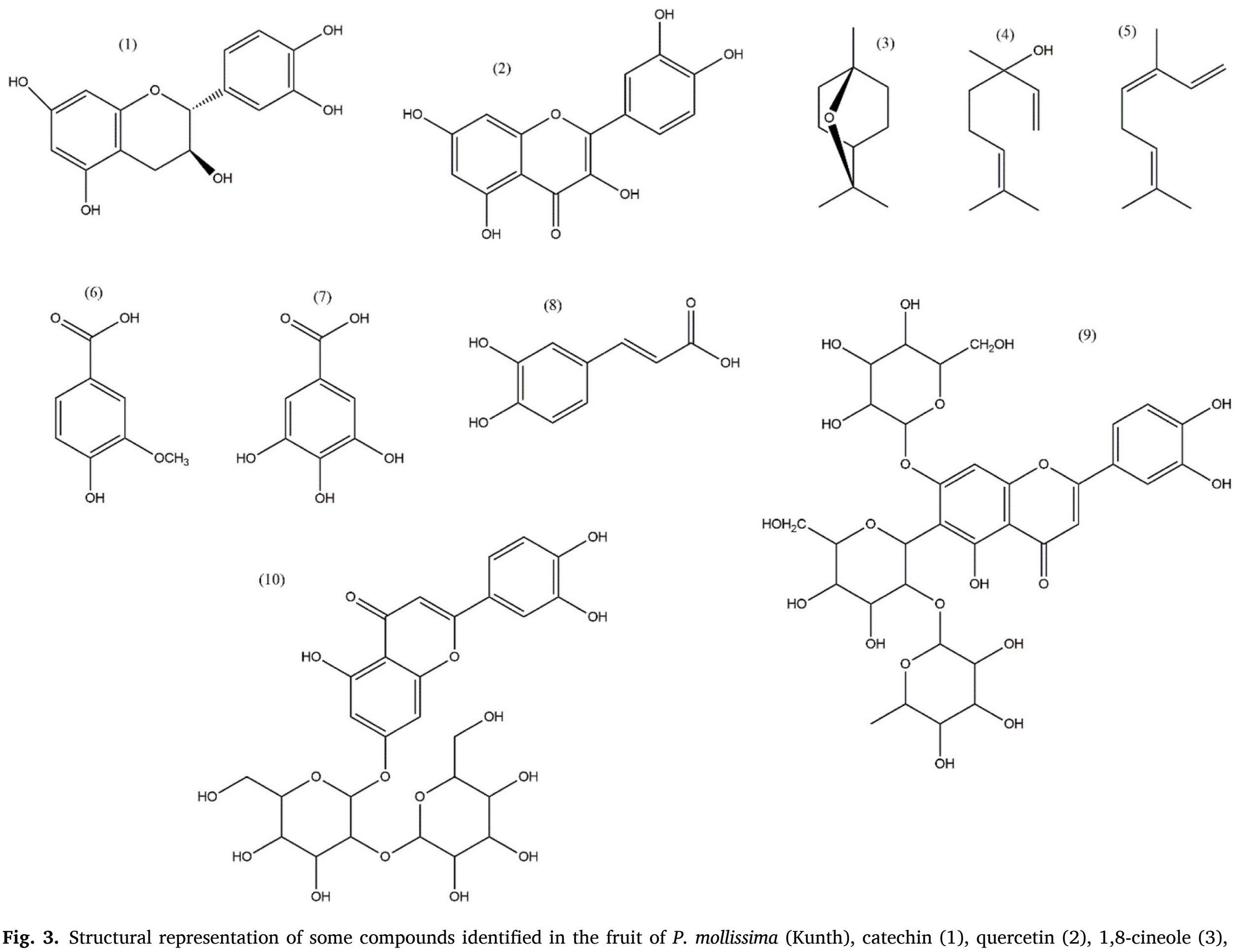

Fig. 3. Structural representation of some compounds identified in the fruit of *P. mollissima* (Kunth), catechin (1), quercetin (2), 1,8-cineole (3), linalool (4), *cis*-β-ocimene (5), vanillic acid (6), Gallic acid (7), Caffeic acid (8), luteolin-7-*O*-sophoroside (9), and luteolin-7-*O*-hexoside-6-*C*-(2-rhamnosyl) hexoside (10) [34]; [17]; [14].

Conde-Martínez et al. [32] identified linalool, hexyl acetate, 1,8-cineole, and butyl acetate as the main aromatic compounds in the Tumbo fruit. Other relevant odors due to their contribution to the overall aroma were 2-methyl propyl acetate, (Z)-3-hexen-1-ol, and (Z)-3-hexenyl acetate. Linalool is an aromatic monoterpene compound widely found in essential oils and commonly used in perfumery, cosmetics, and household cleaning products [82]. Linalool also has anti-cancer, antimicrobial, neuroprotective, anxiolytic, antidepressant, anti-stress, and hepatoprotective properties [83]. Different pharmacological properties have been documented for 1, 8-cineole, such as anti-inflammatory, antioxidant mainly through regulation of nuclear factor kappa B (NF-kB) and erythroid nuclear factor 2-related factor 2 (Nrf2), in the treatment of respiratory and cardiovascular diseases [84]. Compounds derived from luteolin predominate in the Tumbo fruit [79]. Luteolin is a flavonoid found in many plants, herbs, and fruits. This compound is an anti-cancer agent for lung, breast, glioblastoma, prostate, colon, and pancreatic cancer [85]. The most abundant volatile compound identified in the Tumbo fruit was *cis*-β-ocimene. This terpene is responsible for more than 55 % of the volatile compound profile, which probably contributes to the citrus aroma of the fruit. *Cis*-β-ocimene has a variety of uses as a flavoring, food supplement fragrance, and as a base for pharmaceuticals, stabilizers, surfactants, and emulsifiers [81]. This compound also has a cytotoxic effect against *Leishmania amazonenses* [86].

The residue assessment study of the Tumbo fruit shows they are a source of phytoprostanes and phenolic compounds (including derivatives of cinnamoyl acid, flavonoid-O-glucoside, flavonoid-C-glucosides), which may be a good alternative for many companies that can take advantage of their vegetable residues [14].

The Tumbo fruit has a high concentration of phenolic compounds such as flavonoids and terpenes (carotenoids), and several authors have reported their nutritional potential and high antioxidant capacity [80,72,87–90]. Foods with antioxidant capacity are of great interest because they can help protect the human body against damage from reactive oxygen species (ROS). ROS in physiological concentrations is necessary for normal cell function. Still, in imbalance, they are capable of damaging biomolecules such as nucleic acids, lipids, proteins, polyunsaturated fatty acids, and carbohydrates and can cause DNA damage and lead to mutations [91,92]. Therefore, some product prototypes were already developed using Tumbo fruit, such as toothpaste, which had an antibacterial effect against seven microbial strains [71], cream gel with antioxidant properties and sun protection factor [93], and exfoliating cosmetics [21]. Also, Tumbo extract microencapsulation can be used as a functional ingredient in the food industry [80].

7. Future trends and perspectives

The Tumbo is a promising species from the central highlands of Peru. It stands out for its nutritional value [4] and bioactive components (Tables 1 and 2). The available studies of Tumbo and species of the same genus [94] show that it is a raw material that can be fully processed, being able to take advantage of leaves [74], branches/stems [74], fruits [58], seeds [68], shells [75,95], and pulp [76]. Despite the potential of Tumbo, only a few products have currently been developed based on this raw material, such as dermatological products [21,93], microencapsulated bioactive [80], toothpaste [71], beverages [49,50], and others food products [48, 51]. The development of other products, especially pharmaceutical and cosmetic products, is pending due to the diversity of bioactive components of high biological value found in Tumbo.

The implementation of a biorefinery in Tumbo is a promising perspective for industries due to the integral use of raw materials, which would allow the valorization of by-products that currently do not have a commercial value but represent an expense for companies due to costs of environmental management, which depends on the legal framework of each country [96]. Although the implementation of a biorefinery could increase the commercial value of the by-products and products, its implementation by a single company will require a substantial investment in a great diversity of technologies, which would be limited depending on the level of development of each country and the size of each company [96,97]. Alternatively, one could think of a collaborative biorefinery, that is, a company could process the raw material to market a type of product, apply the necessary care to preserve the quality of the by-products, using technologies that allow obtaining by-products that will later become raw material for the manufacture of other products by other companies.

8. Conclusions

The Tumbo fruit (*P. mollisima*) is a food rich in macronutrients, micronutrients, and bioactive compounds. Likewise, the leaves, seeds, and peels are a by-product of fruit processing, which contain bioactive components of high biological value for applications in medicine, cosmetics, and food. Despite the promising characteristics of Tumbo for the industry, scientific studies are still limited. Our review of the available literature shows that Tumbo biomolecules could be used for the treatment of degenerative and metabolic diseases. Tumbo biomolecules of high biological value require more refined technologies for safe production with good extraction yield and environmental responsibility. The implementation of emerging and green technologies for the processing of Tumbo and its biomolecules is a current challenge; aspects such as the sustainability of the Tumbo biorefinery and the applications of its products and by-products require special attention.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Larry Oscar Chañi-Paucar: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Perfecto Chagua-Rodríguez:** Formal analysis, Data curation, Conceptualization. **Walter Javier Cuadrado-Campó:** Writing – original draft, Data curation, Conceptualization. **Godofredo Román Lobato Calderón:** Writing – original draft, Data curation, Conceptualization. **Julio Cesar Maceda Santivañez:** Writing – original draft, Data curation, Conceptualization. **Célio Fernando Figueiredo Angolini:** Writing – original draft, Data curation, Conceptualization. **Maria Angela A. Meireles:** Writing – review & editing, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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