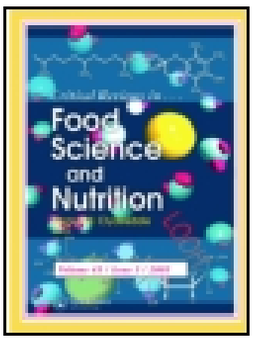

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Superfruits: Phytochemicals, antioxidant efficacies, and health effects – A comprehensive review

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ABSTRACT

The term "superfruit" has gained increasing usage and attention recently with the marketing strategy to promote the extraordinary health benefits of some exotic fruits, which may not have worldwide popularity. This has led to many studies with the identification and quantification of various groups of phytochemicals. This contribution discusses phytochemical compositions, antioxidant efficacies, and potential health benefits of the main superfruits such as açai, acerola, camu-camu, goji berry, jaboticaba, jambolão, maqui, noni, and pitanga. Novel product formulations, safety aspects, and future perspectives of these superfruits have also been covered. Research findings from the existing literature published within the last 10 years have been compiled and summarized. These superfruits having numerous phytochemicals (phenolic acids, flavonoids, proanthocyanidins, iridoids, coumarins, hydrolysable tannins, carotenoids, and anthocyanins) together with their corresponding antioxidant activities, have increasingly been utilized. Hence, these superfruits can be considered as a valuable source of functional foods due to the phytochemical compositions and their corresponding antioxidant activities. The phytochemicals from superfruits are bioaccessible and bioavailable in humans with promising health benefits. More well-designed human explorative studies are needed to validate the health benefits of these superfruits.

KEYWORDS

Superfruits; phytochemicals; antioxidant activities; health benefits; toxicity; future perspectives

Highlights

- Phytochemical profiles of selected superfruits are compared.
- The antioxidant efficacies of selected superfruits are discussed.
- Potential health benefits of selected superfruits are updated.
- Risks of toxicity and future perspectives of superfruits are presented.

Introduction

A diet rich in fruits and vegetables has shown to be beneficial for prevention of numerous non-communicable diseases as well as long term health (Shahidi and Ambigaipalan 2015). Fruits are generally consumed as sources of essential nutrients such as vitamins, minerals, and fiber as well as water. The health benefits and the nutritional composition of fruits from Europe and North America have been described in the literature, whereas those native to tropical countries, especially South America, have not been well studied (Rufino et al. 2010; Gironés-Vilaplana et al. 2014). These tropical fruits are growing wild with certain climate conditions in specific ecosystem, where they are cultivated on a small scale of which little is known about their benefits, and hence they are underutilized. These fruits are usually called "exotic fruits". The term "exotic" is defined as "being extraordinary and unexpected, which can be found only in certain parts of the world". This definition is suitable for exotic fruits, since they have the following characteristics: unusual shape, uncommon color, or flavor in comparison to what consumers are used to. These exotic fruits have shown to be highly relevant to small farmers' survival and might also help in the fight against undernutrition among indigenous communities (Sant' Ana 2011).

Globally, long term health is the key driver in new product development. Malnutrition and over-nutrition, with the high prevalence of numerous non-communicable diseases (NCDs) are driving demand for healthier foods. People are also seeking out new kinds of indulgence, driving demand for new exotic flavors and authentic regional products. The term "superfruit" has gained popularity and significant usage/attention in recent years as a term corresponding with the marketing strategy to promote the health benefits of these exotic fruits, which do not have worldwide popularity such as açai, acerola, camu-camu, goji berry, and blueberries, among others (Dembitsky et al. 2011; de Lima Yamaguchi et al. 2015). In addition, the biodiversity of fruits are attracting attention as the nutrients and non-nutrient bioactives within species can vary dramatically. Superfruits, consumed regionally are gaining popularity in the marketplace due to their nutritional and therapeutic values, but also because of their flavors and color varieties. The nutritional and therapeutic values are primarily due to the presence of numerous bioactive compounds with potential beneficial health effects (Rufino et al. 2010; Costa et al. 2013; Gironés-Vilaplana et al. 2014; de Lima Yamaguchi et al. 2015).

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The health benefits of superfruits have been instrumental in their success as ingredients for food companies and as a source of new flavors for consumers. The superfruits are deemed "super" by nutrition scientists as they are packed with extremely high levels of antioxidants, fibers, vitamins, minerals, and other nutrients that improve health. Hence, the importance of superfruits as a necessary part of the human diet and as cash crops is well-recognized (Dembitsky et al. 2011; de Lima Yamaguchi et al. 2015). Research on properties and characterization of superfruits is a promising field to be explored by food and nutritional scientists, where it can lead to numerous benefits to mankind, if managed in a sustainable and responsible manner (Clerici and Carvalho-Silva 2011; Sant'Ana 2011). The by-products (e.g., peel) of these underutilized superfruit species can also serve as potential raw material for production of new powdered agro-industrial ingredients. The powders of these fruits have been used in the beverage industry as supplements to improve the nutritional value of foodstuffs. Thus, powders obtained from the peel of these fruits can be a good source of industrial bioactive compounds (Schreckinger et al. 2010; Clerici and Carvalho-Silva 2011; Peixoto et al. 2016a).

The health benefits and potential applications of superfruits could be better exploited if more research is available (Sant'Ana 2011). This review discusses the phytochemical compositions, antioxidant efficacies, and potential health-promoting properties of selected superfruits. These tropical superfruits (açai, acerola, camu-camu, goji berry, jaboticaba, jambolão, maqui, noni, and pitanga) are discussed and their potential as functional or healthy foods is highlighted. It is intended that it generates interest among researchers in various scientific fields to study superfruits as functional foods or functional food ingredients, and hence, stimulating large-scale commercial cultivation.

Botanical characteristics of selected superfruits

Açai palm is the commonly used name for the specific species of palm tree known as *Euterpe oleracea* Martius. This fruit is native of South America and grows mainly in Brazil, Colombia, and in the Amazonian floodlands (Schauss et al. 2006). This palm tree produces an edible small purple-black berry, 10–12 mm in diameter, at maturity. The pulp of this fruit is largely consumed as food, and presents an unusual flavor similar to that of raspberry with a nutty taste (Gallori et al. 2004).

Malphigia emarginata is also known as acerola. It is grown widely in the Caribbean islands, parts of the United States, Japan, Taiwan, and Brazil. Acerola may exhibit different colors, depending upon degree of maturity and origin, usually from green to orange-red to dark reddish-purple. It is well-known for raw consumption, but some locals prefer to use it as hot and cold pressed juices, compotes, and jellies (Schreckinger et al. 2010).

Camu-camu (*Myrciaria dubia*) is one of the exotic fruits from the Amazon region (Colombia, Venezuela, Peru, and Brazil). It has a green color when unripe, but turns to a red-colored tonality upon ripening. The berry is globoid, with a strong acidic taste contributed by the citric acid flavor and a white gelatinous pulp. Camu-camu high in its ascorbic acid content and is often used to produce juice, jelly, and ice cream (Costa et al. 2013).

Lycium barbarum, also known as goji or wolf berry, can be found in most areas of China. Goji berry has been consumed as a common health food and as medicine in Asia for over 1,000 years. The fruit is fusiform with acute apex and pericarp of red to dark red. Goji berry is dried to yield the market herb, or the fresh fruit may be squeezed for juice production which is then concentrated to preserve it for future use in making various healthy beverages, such as wine and tea (Amagase and Farnsworth 2011).

Jaboticaba (*Myriciaria cauliflora*) is a grape-like fruit that is found extensively in the Southeast of South America. The berry has a globoid shape with one to four seeds (Costa et al. 2013). The fruit appears dark purple or black during ripening. It is also fragile and astringent, where the pulp is sweet with a white gelatinous flesh. This fruit is of great economic interest as it can be used in many forms (Clerici and Carvalho-Silva 2011). Moreover, the extraction procedure is of great importance for obtaining natural colorants where its high content of anthocyanins is an attractive feature (Rufino et al. 2010). However, it is highly perishable due to the high sugar and water content, associated with a rapid decay and fermentation, and a very short postharvest shelf-life.

Syzigium cumini, also known as jambolão or black plum or jamun, belongs to the Myrtaceae family. It is originated from Asia, especially India and Southeast Asia. The fruit is ovoid in shape with a purple to black color peel and the pulp has a grayish white color and contains a big purple seed. The juice of unripe jambolão is often used to prepare vinegar while the ripe fruit is used to produce preserves, squashes, and jellies. In folk medicine, this fruit has been used as anti-scorbutic, diuretic, and for the treatment of gastrointestinal diseases. Nevertheless, the main use of the jambolão fruit relates to its anti-diabetic features (Gordon et al. 2011).

Aristotelia chilensis, commonly known as maqui, grows well in the temperate forests of central to southern Chile and western Argentina. Maqui is a small purple or black color berry with four seeds. This fruit contains higher amount of pulp compared to other berries of this region, with an acidulous but fresh flavor (Schreckinger et al. 2010).

Noni fruit (*Morinda citrifolia* L.) is grenade-shaped and fleshy with lumpy marks on the surface. The fruit is semi-translucent and turn yellow as it ripens, and then to whitish grey, and finally to brown when it senesces. It contains small reddish-brown buds. The gelatinous pulp with a light dull yellow or whitish color is juicy with a bitter and strong rancid odor (Chan-Blanco et al. 2006). Currently, noni products, such as juices and encapsulated powders, are popular functional foods in Asia, Europe, and North America (Motshakeri and Ghazali 2015).

Finally, pitanga or Brazilian cherry (*Eugenia uniflora*) is a member of the Myrtaceae family. It is native to Brazil that is widely distributed in South American countries, such as Argentina, Paraguay, and Uruguay (Bicas et al. 2011). The fruit, which looks like a small pumpkin, is globoid and presents eight to ten longitudinal grooves (Celli et al. 2011). Its color ranges from red to purple, where the fruit has an exotic flavor, sweet, and sour taste. In Brazil, pitanga is economically important

since it has been used to produce juices, jellies, and fruit compotes (Bicas et al. 2011).

Phytochemicals in superfruits

As already mentioned, superfruits have exceptionally high nutrients, a wide range of bioactive phytochemicals (such as phenolic acids, flavonoids, phytoestrogens, and carotenoids, among others), and antioxidant activities (Schreckinger et al. 2010; Alezandro et al. 2013a; Costa et al. 2013; de Lima Yamaguchi et al. 2015). Phenolic compounds as phytochemicals in plants occur as soluble (aglycones, conjugated glycosides, and soluble esters) and insoluble-bound forms (Shahidi and Ambigaipalan 2015; Xiao 2017). Phenolics in the insoluble-bound form are covalently bound to cell wall structural components such as cellulose, hemicellulose, lignin, pectin, and certain proteins. This fraction is not extractable by organic solvents, being released after alkaline and acid or enzyme treatments. While alkaline hydrolysis breaks ester bonds, acid hydrolysis breaks glycosidic bonds, but generally leaves ester bonds intact (Acosta-Estrada et al. 2014; Xiao 2017). However, a large percentage of phytochemicals is still unknown and remains to be identified (Tomás-Barberán and Andrés-Lacueva 2012).

Different classes and levels of phenolic compounds have been studied for different superfruits and have been reported in some databases such as Phenol-Explorer and USDA (Pérez-Jiménez et al. 2010; USDA 2015a, b). Although there are some review articles reporting the nutritional and functional properties in relation to the phytochemicals (carotenoids, polyphenols, phenolic acids, flavonoids, anthocyanins, coumarins, and iridoids) of superfruits (Costa et al. 2013; de Lima Yamaguchi et al. 2015), detailed comparison among nine superfruits have not been reviewed yet.

Table 1 summarizes the reported phenolics such as total phenolics, flavonoids, anthocyanins, and proanthocyanidins as well as vitamin C in selected superfruits (açai, acerola, camu-camu, goji berry, jaboticaba, jambolão, maqui, noni, and pitanga). Açai, goji berry, noni, jaboticaba, and maqui are among the most studied superfruits in terms of the compositions of their phenolic compounds and corresponding antioxidant activities. Among the superfruits, açai and jambolão have the most diverse phenolic profiles. However, limited studies have been carried out on the detailed phenolic compositions of pitanga, jambolão, and acerola as well as their corresponding antioxidant activities.

Total phenolic contents of superfruits, expressed as mg of gallic acid equivalents (GAE)/100 g fresh weight (fw), are in the range of 113–1620 (Table 1). Camu-camu and maqui have the richest contents of total phenolics among nine superfruits reported. Different concentrations of anthocyanins and proanthocyanidins have been reported in superfruits, except goji berry. Moreover, camu-camu is the richest source of vitamin C

Table 1. Reported phenolics and vitamin C in selected superfruits.

Super fruits	Total phenolics[a]	Flavonoids[b]	Anthocyanins[b]	Proanthocyanidins	Vitamin C[b]
Açai	529	91.3	111	nr	84
Acerola	113	9.6	18.9	115[c]	83.2[d]
Camu-camu	1196	20.1	42.2	345–744[e]	1882
Goji berry	268	36.1–54.7[f]	nr	nr	48.9[g]
Jaboticaba	333	147	58.1	65.1–539[h]	238
Jambolão	170	70.9	93.3	186[i]	112
Maqui	1110–1620[j]	215[k]	7.3–12.5[l]	0.4–0.5[m]	nr
Noni	748–770	67.7–228[n]	138[o]	2.25[p]	53.2–76.2[q]
Pitanga	434–800[r]	nr	3.0[s]	45–165[t]	0.09–0.13[u]

C3GE, cyanidin-3-glycoside equivalents; D3GE, delphinidin-3-glucoside equivalents; dw, dry weight; ECE, epicatechin equivalents; fw, fresh weight; GAE, gallic acid equivalents; nr, not reported; QE, quercetin equivalents; QTE, quebracho tannin equivalents; RE, rutin equivalents.

Note: Where possible for comparision among superfruits, data were re-calculated from dry weight to fresh weight [moisture content: açai (83.8%), acerola, (91.7%), camu-camu (89.7%), goji berry (10.34%), jaboticaba (90.7%), jambolão (85%), maqui (95%), noni (86.5%), and pitanga (81.2%).

[a]Data are expressed as mg of GAE/100 g fw (Rufino et al. 2010; Donno et al. 2015; Ruhomally et al. 2015).

[b]Data are expressed as mg/100 g fw (Rufino et al. 2010).

[c]Data are expressed as mg of QTE/100 g fw (Nóbrega et al. 2015).

[d]Data are expressed as mg/100 g fw (Nóbrega et al. 2015).

[e]Range (minimum – maximum) values expressed as mg QTE/100 g fw (Fujita et al. 2013; de Azevêdo et al. 2014).

[f]Range (minimum – maximum) values expressed as mg RE/g fw, determined from 8 Chinese goji berries (Zhang et al. 2016).

[g]Data are expressed as mg/100 g fw (Donno et al. 2015).

[h]Range (minimum – maximum) values expressed as mg QTE/100 g fw, determined from two species (Sabará and Paulista) of jabuticaba from Brazil (Alezandro et al. 2013a).

[i]Data are expressed as mg QTE/100 g fw (Borges et al. 2016).

[j]Range (minimum – maximum) values expressed as mg GAE/100 g fw, determined from maqui from four different regions during two consecutive growing seasons in Chile (Fredes et al. 2014).

[k]Data are expressed as mg QE/100 g fw, determined from maqui from Chile (Rodríguez et al. 2016).

[l]Range (minimum – maximum) values expressed as g C3GE/kg fw, determined from maqui from four different regions during two consecutive growing seasons in Chile (Fredes et al. 2014).

[m]Data are expressed as % ECE, determined from maqui from Chile (Schreckinger et al. 2010).

[n]Data are expressed as μg QE/100 g fw (Ruhomally et al. 2015).

[o]Data are expressed as mg D3GE/100 g fw (Brauch et al. 2016).

[p]Data are expressed as mg RE/g fw (Kumar et al. 2014).

[q]Data are expressed as mg/100 g fw (Ruhomally et al. 2015).

[r]Range (minimum – maximum) values expressed as mg GAE/100 g fw, determined from orange, red, and purple Brazilian pitanga (Denardin et al. 2015).

[s]Data are expressed as g C3GE/kg fw, determined from purple Brazillian pitanga (Borges et al. 2016).

[t]Range (minimum – maximum) values expressed as mg QTE/100 g fw, determined from red and purple Brazillian pitanga (Borges et al. 2016).

[u]Data are expressed as mg/100 g fw (Denardin et al. 2015).

(1882 mg /100 g fw) among the nine superfurits listed in Table 1, followed by jaboticaba (238 mg /100 g fw) and jambolão (112 mg /100 g fw). Camu-camu is also considered to be the richest natural source of vitamin C in Brazilian superfruits (Langley et al. 2015). No vitamin C has been reported in maqui.

Flavonols, such as isorhamnetin, quercetin, kaempferol, rutin, and myricetin, have been reported in all superfruits. Meanwhile, flavan-3-ols, such as epicatechin and catechin, have been reported in all major superfruits, such as maqui, goji berry, camu-camu, jaboticaba, and acerola, except in açai. Flavononols, such as orientin, scoparin, isovitexin, taxifolin, and isoorientin, have been reported only in açai. Similarly, flavones, such as apigenin, chrysoeriol, and luteolin and their derivatives, have been reported only in açai (Table 2).

Two classes of phenolic acids, namely hydroxycinnamic acids (caffeic, chlorogenic, cinnamic, *trans*-cinnamic, *o*-coumaric, *p*-coumaric, ferulic, caffeoylquinic, *p*-coumaroylquinic, sinapic, and *trans*-*p*-coumaric acids) and hydroxybenzoic acids (gallic, *p*-hydroxybenzoic, 3,4-dihydroxybenzoic, *p*-hydroxyphenylacetic, protocatechuic, syringic, and vanillic acids) have been reported in superfruits (Table 2). Although phenolic acids have not been well characterized in most superfruits, ellagic acid is present in all superfruits, but not in noni and açai. Meanwhile, gallic acid is present in superfruits, except in camu-camu and pitanga.

Ellagitannins, such as sanguiin H-10 isomers and sanguiin H-6, have been reported only in jaboticaba. Procyanidins, such as procyanidin A2, B1, and procyanidin dimer and trimer, have been reported only in açai, acerola, and jaboticaba. Numerous anthocyanins, such as cyanidin, peonidin, pelargonidin, delphinidin, malvidin, and petunidin as well as their derivatives have been detected in most major superfruits, except in noni and goji berry (Table 2).

Coumarins, such as scopoletin, nonioside B, and C, have been reported only in goji berry and noni. Iridoids (such as deacetylasperulosidic and asperulosidic acids) and anthroquinones (such as lucidin) have been detected only in noni fruit. Terpenes, especially monoterpenes, such as phellandrene, sabinene, and γ-terpinene, have been reported only in goji berry (Table 2). Numerous carotenoids and their derivatives have also been reported in selected superfruits, except for noni and jaboticaba (Table 3). The structures of the representative phytochemicals reported in certain superfruits are shown in Fig. 1. The types and contents of phytochemicals available in the existing literature in the nine selected superfruits are discussed below.

Açai

Numerous phytochemicals have been identified in açai, of which they are mainly flavonoids (31%), followed by phenolic acids (23%), lignoids (11%), and anthocyanins (9%). Other classes include fatty acids, quinones, terpenes, and norisoprenoids (de Lima Yamaguchi et al. 2015). Açai has a wide range of phytochemicals such as anthocyanins, flavanones, flavanonols, flavone-*C*-glycosides, flavones, dehydroflavonols, flavonols, phenolic acids, and procyanidins with antioxidant properties among all superfruits (Table 2). Among the listed phytochemicals, cyanidin-3-*O*-rutinoside (anthocyanins), taxifolin deoxyhexose isomer 1 (flavanones), orientin (flavanonols), luteolin-8-*C*-glucoside (flavone-*C*-glycosides), luteolin deoxyhexosyl-hexoside (flavones), dihydrokaempferol hexoside (dehydroflavonols), kaempferol deoxylhexosyl-hexoside (flavonols), 4-hydroxybenzoic acid (phenolic acids), and procyanidin trimers (procyanidins) are present in highest quantities in their respective groups. Traces of taxifolin deoxyhexose and homoorientin methyl-derivative are also present in açai (Gallori et al. 2004). Chin et al. (2008) identified 22 phytochemicals in açai, including lignans, simple benzenoids, flavonoids, monoterpenoids, and norisoprenoids. With respect to carotenoids, 12 carotenoids and their derivatives are reported in açai, of which all-*trans*-lutein is the major one, followed by all-*trans*-β-carotene and all-*trans*-α-carotene (Table 3) (da Silva et al. 2014).

Acerola

To the best of our knowledge, limited phytochemicals (anthocyanins, flavan-3-ols, flavonols, phenolic acids, and procyanidins) have been reported in acerola, where the most abundant group is anthocyanins (Table 2). Acerola has the highest content and the most diverse carotenoid profile among superfruits (Table 3). The most abundant ones are β-carotene, β-cryptoxanthin, and lutein (de Rosso and Mercandante 2005; Mezadri et al. 2005). Carotenoid contents in acerola genotypes harvested at three ripening stages ranged from 3.2 to 406 mg/kg (Lima et al. 2005).

Camu-camu

Anthocyanins, ellagitannins, flavanones, flavonols, and phenolic acids have been reported in camu-camu (Table 2). Catechin is the most abundant flavonols, while ellagic acid is the most abundant phenolic acid detected in camu-camu. Flavanones (such as eriodictyol and naringenin) and ellagitannins [such as castalagin and di-hexahydroxydiphenoyl (HHDP)] glucose, have only been reported in camu-camu among superfruits listed in Table 2. Zanatta and Mercadante (2007) reported 14 carotenoids and their derivatives in camu-camu, of which all-*trans*-lutein (160 μg/100 g fw) is the predominant one, followed by β-carotene (72.8 μg/100 g fw), zeaxanthin (22.9 μg/100 g fw), and luteoxanthin (21.5 μg/100 g fw) (Table 3).

Goji berry

Goji berry is unique in its combination and overall content of phytochemicals. It contains a wide range of phytochemicals including flavan-3-ols, flavonols, monoterpenes, phenolic acids, coumarin, and phenolic amides (Table 2). Recently, three new dimers of phenolic amides, named lyciumamides A, B, and C, together with two monomers, *N*-*E*-coumaroyl tyramine and *N*-*E*-feruloyl tyramine, were isolated from goji berry for the first time (Gao et al. 2015). A new *N*-feruloyl tyramine dimer (Figure 2) was identified as the most abundant polyphenol in goji berry, together with some known phenolics, including caffeic acid, *p*-coumaric acid, rutin, scopoletin, *N*-*trans*-feruloyl tyramine, and *N*-*cis*-feruloyl tyramine (Forino et al. 2016). *N*-feruloyl tyramine dimmer has demonstrated better bioactivities

Table 2. Reported phytochemicals in selected superfruits.

Superfruit	Types of phenolic compounds		Unit	Content	References
Açai	Anthocyanins	Cyanidin-3-*O*-glucoside	mg/100 g dw	425–927	Pacheco-Palencia et al. 2009; da Silva et al. 2014; Garzón et al. 2017
		Cyanidin-3-*O*-galactoside		18	
		Cyanidin-3-*O*-rutinoside		1255–2195	
		Cyanidin-3-rhamnoside		3	
		Cyanidin-3-*O*-glucoside-5-*O*-rhamnoside		12.6	
		Cyanidin-3,5-hexose pentose		1.43	
		Malvidin-3-*O*-glucoside		0.8	
		Pelargonidin-3-glucoside		1.7	
		Pelargonidin-3-rutinoside		2.8	
		Peonidin-3-rutinoside		3.6	
	Flavanones	Taxifolin deoxyhexose isomer 1		2.8	
		Taxifolin deoxyhexose isomer 2		1.3	
		Taxifolin		1.2	
	Flavanonols	Apigenin-di-glucoside	mg/kg	8.13	Pacheco-Palencia et al. 2009
		Isovitexin		10.6	
		Isovitexin derivative		3.7	
		Isoorientin		34.8	
		Luteolin-di-glucoside		7.3	
		Orientin		53.1	
		Scoparin		5.8	
		Taxifolin derivative		7.9	
		Taxifolin deoxyhexose		7.9	
		Taxifolin hexoside		13.3	
	Flavone-C-glycosides	Luteolin-6-*C*-glucoside	mg/L	17.4	Pacheco-Palencia et al. 2009; Garzón et al. 2017
		Luteolin-8-*C*-glucoside		24.2	
		Apigenin-6-*C*-glucoside		4.2	
		Apigenin-6-*C*-glucosyl-8-arabinoside		5.1	
		Apigenin-6,8-di-*C*-glucoside		5.1	
		Total flavone-C-glycosides		56.0	
	Flavones	Isovitexin	mg/100 g dw	12.0	da Silva et al. 2014; Garzón et al. 2017
		Homoorientin		9.9	
		Luteolin		0.9	
		Luteolin deoxyhexosyl-hexoside		37.6	
		Dihydroluteolin deoxyhexosyl-hexoside		12.7	
		Chrysoeriol		0.5	
		Chrysoeriol deoxyhexosyl-hexoside		22.5	
		Orientin		15.0	
		Scoparin		0.6	
		Vitexin		9.8	
		Apigenin hexoside		13.2	
		Apigenin dihexoside		11.1	
		Apigenin deoxyhexosyl hexoside		25.4	
	Dehydroflavonols	Dihydrokaempferol isomer 1		0.3	
		Dihydrokaempferol isomer 2		0.5	
		Dihydrokaempferol hexoside		66.4	
		Dihydrokaempferol acetyl-hexoside		2.8	
	Flavonols	Kaempferol deoxyhexosyl-hexoside		7.2	
		Quercetin-3-*O*-galactoside		2.3	
		Quercetin-3-*O*-glucoside		0.5	
		Quercetin-3-*O*-arabinoside		0.6	
	Phenolic acids	3-*O*-Caffeoylquinic acid	mg/100 g dw	0.38	Inada et al. 2015; Garzón et al. 2017
		5-*O*-Caffeoylquinic acid		1.36	
		5-*O*-*p*-Coumaroylquinic acid		0.13	
		trans-Cinnamic acid[a]		0.03	
		m-Coumaric acid[a]		0.4	
		p-Coumaric acid[b]		4.6	
		5-*O*-Caffeoyl quinic acid		4.3	
		p-Coumaric acid hexoside		1.0	
		Caffeic acid		1.9	
		Feruloyl sinapic acid isomer 1		1.3	
		Feruloyl hydroxypyruvic acid		1.4	
		Caffeoyl shikimic acid isomer 1		1.7	
		Feruloyl sinapic acid isomer 2		0.8	
		Caffeoyl shikimic acid isomer 2		5.4	
		Feruloyl derivative		2.3	
		Ferulic acid		17[b], 4.6[c]	
		Gallic acid		4.4[a]	
		Gallic acid hexoside		1.7	
		p-Hydroxybenzoic acid		7.74	
		4-Hydroxybenzoic acid		3.4[a]	
		4-Hydroxybenzoic acid		20[b], 34[c]	

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Table 2. (*Continued*)

Superfruit	Types of phenolic compounds		Unit	Content	References
		3,4-Dihydroxybenzoic acid		4.5[b], 1.1[c]	
		Hydroxyferuloyl quinic acid		0.7	
		Protocatechuic acid		6.15	
		Protocatechuic acid hexoside		0.9	
		Syringic acid		13.8	
		Vanillic acid		19.5	
		Sinapoyl rhamnose		1.4	
		Sinapoyl hexose		1.0	
		4-Hydroxyphenylacetic acid		2.6[a]	
		3,4-Dihydroxyphenylacetic acid		5.9[c]	
	Procyanidins	(+)-Catechin	mg/100 g dw	5.1	Pacheco-Palencia et al. 2009; Garzón et al. 2017
		(-)-Epicatechin		1.1	
		Procyanidin dimers		18.8	
		Procyanidin trimers		34.4	
		Procyanidin dimer 1		4.4	
		Procyanidin dimer 2		4.9	
		Procyanidin trimer 1		5.7	
		Procyanidin trimer 2		5.4	
Acerola	Anthocyanins	Cyanidin-3-rhamnoside	mg/100 g dw	270	de Rosso et al. 2008
		Pelargonidin-3-rhamnoside		125	
		Total anthocyanins		395	
	Flavan-3-ols	(-)-Epigallocatechin gallate	mg/L	0.53–1.4[d]	Mezadri et al. 2008
		(-)-Epicatechin		1.38[d]	
	Flavonols	Rutin		0.6–3.01[d]	
	Phenolic acids	Chlorogenic acid		0.16–0.48[d]	
	Procyanidins	Procyanidin B1		1.03–8.53[d]	
		Furfural		0.15[d]	
Camu-camu	Anthocyanins	Cyanidin-3-glucoside	mg/100 g dw	22.4	Chirinos et al. 2010; Abe et al. 2012; Fracassetti et al. 2013; de Azevêdo et al. 2014
		Cyanidin-3-*O*-glucoside		19.6	
		Delphinidin-3-glucoside		2.2	
	Ellagitannins	Castalagin		12.7	
		Di-HHDP-glucose		3.4	
	Flavanones	Eriodictyol		0.6	
		Naringenin		11.4	
	Flavonols	Catechin		48.2	
		Myricetin		1.0	
		Myricetin-3-*O*-hexoside		0.6	
		Myricetin-3-*O*-pentoside		1.5	
		Quercetin		6.4	
		Quercetin-3-*O*-hexoside		tr	
		Quercetin-3-*O*-pentoside		0.05	
	Phenolic acids	Ellagic acid		18.9	
		Ellagic acid deoxyhexoside		2.8	
		Ellagic acid pentoside		5.6	
		Ellagic acid derivative		7.0	
		Ellagic acid derivative		3.6	
		Ellagic acid derivative		9.0	
		Ellagic acid derivative		1.1	
		Ellagic acid derivative		3.6	
		Syringic acid		7.0	
Goji berry	Flavan-3-ols[d]	Catechin	mg/100 g fw	119	Inbaraj et al. 2010; Wang et al. 2010; Donno et al. 2015 2016; Forino et al. 2016; Zhang et al. 2016
		Epicatechin		229	
	Flavonols[e]	Isorhamnetin-3-*O*-rutinoside		72.1	
		Hyperoside		116	
		Kaempferol		15.3–93.6	
		Kaempferol-3-*O*-rutinoside		97.7	
		Myricetin		16.9–117	
		Quercetin		65.3–370	
		Quercetin-3-*O*-rhamno-di-hexoside		435–1065	
		Quercetin-3-*O*-rutinoside		159–629	
		Quercetin-di-(rhamno)-hexoside		117	
		Quercetin-rhamno-di-hexoside		435	
		Quercetin-diglycoside		66	
	Monoterpenes[d]	Phellandrene		216	
		Sabinene		56.7	
		γ-Terpinene		83.5	
	Phenolic acids[f]	Caffeic acid		111	
		Chlorogenic acid		113	
		p-Coumaric acid		111	
		Ferulic acid		126	
		Gallic acid		15.3	
		Caffeoylquinic acid		0.34	

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Table 2. (*Continued*)

Superfruit	Types of phenolic compounds		Unit	Content	References
		Dicaffeoylquinic acid		250	
		Vanillic acid		68.4	
	Coumarin[f]	Scopoletin	mg/100 g dw	0.80	Gao et al. 2015; Forino et al. 2016
	Phenolic amides[f]	*N-trans*-Feruloyl-tyramine		0.37	
		N-cis-Feruloyl tyramine		0.23	
		N-Feruloyl tyramine dimer		1.69	
Jaboticaba	Anthocyanins	Cyanidin	mg/100 g dw	58–123	Abe et al. 2012; Inada et al. 2015; Morales et al. 2016
		Cyanidin-3-*O*-glucoside		280	
		Cyanidin-*O*-glycosyl-*O*-acetylpentoside		0.04	
		Delphinidin		7.1–23.5	
		Delphinidin-3-*O*-glucoside		48	
		Monomeric anthocyanins		1515	
	Flavan-3-ols	(+)-Catechin	mg/g dw	0.13	Gurak et al. 2014; Morales et al. 2016
		(-)-Epicatechin		0.06	
		(-)-Epicatechin gallate		0.08	
		bis-HHDP-glucose		1.3	
		Valoneic acid dilactone isomer		2.4	
		Digalloyl glucose		1.3	
		HHDP-galloyl-glucose isomer		2.8	
		HHDP-digalloyl-glucose		1.1	
		Total flavan-3-ols		5.04	
	Proanthocyanidins	Condensed tannins		9.7	
	Flavonols	Myricetin	mg/100 g dw	0.2[a], 0.4[b]	Abe et al. 2012; Gurak et al. 2014; Inada et al. 2015
		Myricitrin		3.5[a]	
		Rutin		7.1[a]	
		Quercetin-3-*O*-rhamnoside		0.17	
		Quercetin derivatives		2.0–2.1	
	Ellagitannins	Ellagic acid	mg EAE/100 g dw	9.4	Alezandro et al. 2013a
		Sanguiin H-10 isomer (1)		1.6	
		Sanguiin H-10 isomer (2)		4.8	
		Sanguiin H-10 isomer (3)		5.4	
		Lambertianin C without ellagic acid		1.8	
		Sanguiin H-6 isomer (1)		1.8	
		Sanguiin H-6 isomer (2)		6.6	
		Sanguiin H-6 isomer (4)		2.8	
		Sanguiin H-6 isomer (6)		2.6	
		Unknown ellagitannin		2.2	
	Phenolic acids	Benzoic acid	mg/100 g dw	0.15	Abe et al. 2012; Alezandro et al. 2013a; Gurak et al. 2014; Inada et al. 2015
		m-Coumaric acid		0.3[b]	
		trans-Cinnamic acid		1.4[c]	
		Ellagic acid		34[a], 40[b]	
		Gallic acid		7.9[a], 135[b]	
		Ellagic acid		119[c]	
		Gallic acid		63[c]	
		3,4-Dihydroxybenzoic acid		4.4[b]	
		Free ellagic acid		19–40	
		Total ellagic acid		5050–9566	
	Procyanidins	Procyanidin A2	mg/g dw	0.12	Gurak et al. 2014
	Tannins	Total tannins	g TAE/kg dw	11.6–315[g]	Abe et al. 2012
Jambolão	Anthocyanins	Cyanidin	mg/100 g dw	16	Faria et al. 2011; Borges et al. 2016; de Carvalho Tavares et al. 2016; Singh et al. 2016
		Cyanidin-3,5-diglucoside		29	
		Cyanidin-3-*O*-glucoside		1.3	
		Delphinidin		20.2	
		Delphinidin-3,5-diglucoside		256	
		Delphinidin-3,5-*O*-diglucoside		2.6	
		Delphinidin-3-*O*-glucoside		7	
		Malvidin-3-*O*-glucoside		0.08	
		Malvidin-3,5-*O*-diglucoside		1.54	
		Peonidin-3,5-diglucoside		75	
		Petunidin-3,5-diglucoside		245	
		Petunidin-3,5-*O*-diglucoside		2.35	
		Delphinidin acetyl-diglucoside	mg C3GE/100 g	0.3	Faria et al. 2011
		Petunidin-3-glucoside		1.7	
		Malvidin-3-glucoside		0.8	
	Flavonols	Myricetin	mg/kg fw	61	Borges et al. 2016; de Carvalho Tavares et al. 2016; Singh et al. 2016
		Myricetin-3-*O*-glucuronide		0.32	
		Myricetin-3-*O*-galactoside		0.1	
		Myricetin-3-*O*-glucoside		1.3	
		Myricetin-3-*O*-rhamnoside		0.46	
		Myricetin-3-*O*-pentoside		0.5	
		Laricitrin-3-*O*-galactoside		0.22	
		Laricitrin-3-*O*-glucoside		0.25	

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Table 2. (*Continued*)

Superfruit	Types of phenolic compounds		Unit	Content	References
		Syringetin-3-*O*-galactoside		0.77	
		Syringetin-3-*O*-glucoside		0.4	
		Quercetin		14.9	
	Flavanonols	Dihydroquercetin-dihexoside isomer 1	mg/kg fw	0.04	de Carvalho Tavares et al. 2016
		Methyl-dihydroquercetin-dihexoside		0.9	
		Dihydromyricetin-dihexoside isomer 1		0.7	
		Dihydromyricetin-dihexoside isomer 2		0.6	
		Dihydromyricetin-dihexoside isomer 3		0.03	
		Dihydromyricetin-dihexoside isomer 4		1.15	
		Dihydromyricetin-dihexoside isomer 5		0.5	
		Dihydromyricetin-dihexoside isomer 6		1.1	
		Methyl-dihydromyricetin dihexoside isomer 1		0.03	
		Methyl-dihydromyricetin dihexoside isomer 2		0.23	
		Methyl-dihydromyricetin dihexoside isomer 4		0.67	
		Methyl-dihydromyricetin dihexoside isomer 5		0.18	
		Methyl-dihydromyricetin dihexoside isomer 6		0.2	
	Monomeric flavan-3-ols	Catechin	mg CE/kg fw	0.06	
		Epicatechin		0.04	
		Gallocatechin		1.09	
		Epigallocatechin		0.03	
		Epicatechin-3-*O*-gallate		0.001	
		Catechin-3-*O*-gallate		0.001	
		Epigallocatechin-3-*O*-gallate		0.03	
		Gallocatechin-3-*O*-gallate		0.01	
	Proanthocyanidins	Total proanthocyanidins		23.72	
	Hydrolysable tannins	Free gallic acid	mg EAE/kg fw	8.2	
		Free ellagic acid		2.4	
		Ellagic acid pentoside		0.76	
	Gallotannins	Galloyl glucose	mg GAE/kg fw	55	
		Digalloyl-glucose + trigalloyl-glucose isomer 2		29.4	
		Trigalloyl glucose isomer 3		3.6	
		Trigalloyl glucose isomer 4		16.6	
		Tetragalloyl glucose isomer 1		5.0	
		Tetragalloyl glucose isomer 2		24.5	
		Pentagalloyl glucose isomer 1		3.4	
		Pentagalloyl glucose isomer 2		12.0	
		Pentagalloyl glucose isomer 3		25.2	
		Hexagalloyl glucose isomer 1		1.86	
		Hexagalloyl glucose isomer 2		1.82	
		Total gallotannins		178.4	
	Ellagitannins	Vescalagin	mg CasE/kg fw	26.6	
		Castalagin		8.2	
		Di-HHDP-glucose isomer 1		15.3	
		Di-HHDP-glucose isomer 2		10.4	
		Galloyl-di-HHDP-glucose isomer 1		20.0	
		Trisgalloyl-HHDP-glucose isomer 1		14.0	
		Trisgalloyl-HHDP-glucose isomer 2		11.0	
		Total ellagitannins		105.5	
	Phenolic acids	Caffeic acid	g/kg dw	65.6	Borges et al. 2016; Singh et al. 2016
		Ellagic acid		0.94	
		Gallic acid		41.4	
		Sinapic acid		21.3	
Maqui	Anthocyanins	Cyanidin-3-*O*-glucoside-5-*O*-rhamnoside	mg D3GE/100 g dw	0.52	Rojo et al. 2012; Fredes et al. 2014; Brauch et al. 2016; Schreckinger et al. 2010
		Cyanidin-3-*O*-sambubioside		2.36–8.6	
		Cyanidin-3,5-*O*-diglucoside		4.3	
		Cyanidin-3-*O*-sambubioside-5-*O*-glucoside		18.7	
		Cyanidin-3-*O*-glucoside		8.6	
		Delphinidin-3-*O*-glucoside		7.1–17.1	
		Delphinidin-3-*O*-sambubioside		2.2–14.2	
		Delphinidin-3,5-*O*-diglucoside		23.7	
		Delphinidin-3-*O*-sambubioside-5-*O*-glucoside		16.7–46.4	
		Total anthocyanins		138	
		Delphinidin-3-*O*-glucoside-5-*O*-glucoside	g/kg dw	6.4–8.7[h]	Brauch et al. 2017
		Total delphinidins		10.5–12.0[h]	
		Total cyanidins		2.3–2.6[h]	
		Total diglycosides		10.6–12.5[h]	
		Total monoglycosides		2.17–2.24[h]	
	Flavan-3-ols	Catechin[i]	mg/100 g dw	55.5	Gironés-Vilaplana et al. 2012a, 2012b, 2013; Brauch et al. 2016
	Flavonols	Myricetin[i]		1.3	
		Myricetin-3-*O*-galloylglucoside		1.22	
		Myricetin-3-*O*-galactoside		1.46	

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Table 2. (*Continued*)

Superfruit	Types of phenolic compounds		Unit	Content	References
		Myricetin-3-*O*-glucoside		0.84	
		Quercetin[i]		1.13	
		Quercetin-3-*O*-rutinoside		2.4	
		Quercetin-3-*O*-glucoside		0.84	
		Quercetin-3-*O*-galactoside		2.36	
		Quercetin-3-*O*-xyloside		0.45	
		Quercetin-3-*O*-arabinoside		0.95	
		Quercetin-3-*O*-rhamnoside		2.41	
		Rutin hydrate		7.1[i], 0.53[j]	
	Phenolic acids	3-Caffeoylquinic acid		0.35	
		4-Caffeoylquinic acid		0.37	
		5-*O*-Caffeoylquinic acid		1.07	
		Ellagic acid		176[i], 19.9[j]	
		Gallic acid		7.4[i], 17.1[j]	
		Protocatechuic acid[j]		1.5	
		p-Coumaric acid[j]		0.5	
	Ellagic acid derivatives	Granatin B		6.35	
		Ellagic acid hexoside		0.73	
		Ellagic acid rhamnoside		3.73	
Noni	Anthroquinones	Lucidin	mg/100 g dw	2.06	Potterat et al. 2007; Deng et al. 2010; Basar and Westendorf 2011; West et al. 2011
	Coumarin	5,15-Dimethylmorindol		0.5–26	
		(2E, 4Z, 7Z)-Decatrienoic acid		15–492	
		Scopoletin		5.7–13.8	
		Nonioside B		4420	
		Nonioside C		42.4	
	Flavonols	Kaempferol-3-*O*-rutinoside		2.06	
		Quercetin-3-*O*-rutinoside-7-pentoside		0.13	
		Quercetin-3-*O*-rutinoside		0.98	
		Quercetin		1.6	
		Rutin		258	
	Iridoids	Deacetylasperulosidic acid		138–944	
		Asperulosidic acid		39–298	
Pitanga	Anthocyanins	Cyanidin	mg/100 g dw	1.94	Celli et al. 2011; Borges et al. 2016
		Cyanidin-3-*O*-glucoside		31[m], 1690[n]	
	Flavonols	Myricetin		0.07	
		Myricetin-3-*O*-hexoside		130[m], 132[n]	
		Myricetin-3-*O*-pentoside		22.4[m], 25.2[n]	
		Myricetin-3-*O*-rhamnoside		226[m], 279[n]	
		Myricetin deoxyhexoside-gallate		9.9[m], 7.9[n]	
		Quercetin[k]		0.1	
		Quercetin[l]		0.16	
		Quercetin-3-*O*-hexoside		116[m], 375[n]	
		Quercetin-3-*O*-pentoside		28[m], 62[n]	
		Quercetin-3-*O*-rhamnoside		135[m], 285[n]	
	Phenolic acids	Ellagic acid		0.6	
		p-Coumaric acid		0.05	
		Protocatechuic acid		0.02	

C3RE, cyanidin-3-rutinoside equivalents; CasE, caastalagin equivalents; CE, catechin equivalents; dw, dry weight; EAE, ellagic acid equivalents; fw, fresh weight; GAE, gallic acid equivalents; HHDP, hexahydroxydiphenoyl; TAE, tannic acid equivalents; tr, trace.
[a]Phenolic compounds of açai determined from soluble phenolic extracts (Inada et al. 2015).
[b]Phenolic compounds of açai determined from alkaline hydrolysis (Inada et al. 2015).
[c]Phenolic compounds of açai determined from acidic hydrolysis (Inada et al. 2015).
[d]Phenolic compounds determined from goji berry from Alzate di Momo (Italy).
[e]Range (minimum – maximum) values expressed as μg/g fw determined from 8 Chinese goji berries (Zhang et al. 2016).
[f]Values determined from the ethyl acetate extract of dried goji berry.
[g]Range (minimum – maximum) values determined from jabuticaba at five different ripening stages from green until fully ripe.
[h]Range (minimum – maximum) values determined from two maqui clones (Morena and Luna Nueva).
[i]Free flavonoids and phenolic acids.
[j]Bound flavonoids and phenolic acids.
[k]Values determined from red pitanga from Brazil.
[l]Values determined from purple pitanga from Brazil.
[m]Values determined from red pitanga (mature stage) from Brazil.
[n]Values determined from purple pitanga (mature stage) from Brazil.

when compared to the monomers, *N*-cis-feruloyl tyramine and *N*-trans-tyramine tyramine. Hence, more studies on the bioactivities of *N*-feruloyl tyramine dimers are needed (Forino et al. 2016). A recent study conducted by Benchennouf et al. (2017) identified various phenolic acid derivatives and flavonoids in Greek goji berry. The phenolic acids identified were esters of hydrocinnamic and dihydroxybenzoic acids with quinic acid. Coumaric, isoferulic, and caffeic acids as well as their derivatives were the dominant phenolic acids. Some of the phenolic acids that were identified are dihydroisoferulic acid derivatives such as isoferuloyl quinic acid, dihydrocoumaroyl-quinic acid, feruloylquinic acid ester, coumaroyl caffeic acid, caffeoyl-caffeic

Table 3. Reported carotenoids and their derivatives in selected superfruits.

Superfruit	Carotenoids	Unit	Content	References
Açai	9-*cis*-Neoxanthin	μg/100 g fw	13.2	da Silva et al. 2014
	13-*cis*-Violaxanthin		6.5	
	cis-Lutein		12.6	
	9-*cis*-Violaxanthin		5.5	
	all-*trans*-Lutein		293	
	all-*trans*-Zeaxanthin		5.4	
	all-*trans*-Zeinoxanthin		7.7	
	15-*cis*-β-Carotene		9.2	
	13-*cis*-β-Carotene		15.8	
	all-*trans*-α-Carotene		60.2	
	all-*trans*-β-Carotene		266	
	9-*cis*-β-Carotene		37.8	
	Total carotenoids		737	
	Vitamin A	μg RAE/100 g fw	27.8	
Acerola	Neoxanthin	μg/100 g fw	1.8–5.1[a]	de Rosso and Mercadante 2005; Mezadri et al. 2005
	Violaxanthin		0.2–2.9[a]	
	Luteoxanthin		0.6–3.6[a]	
	Lutein		70.7–101[a]	
	Zeaxanthin		0.1–0.2[a]	
	5,6,5′,6′-diepoxy-β-Cryptoxanthin		0.1–1.4[a]	
	5,6-epoxy-β-Cryptoxanthin		0–0.2[a]	
	5,8-epoxy-β-Cryptoxanthin		1.3–3.7[a]	
	Zeinoxanthin		0.1–1.9[a]	
	β-Cryptoxanthin		16.3–49.5[a]	
	5,6,5′,6′-diepoxy-β-Carotene		1.0–2.4[a]	
	5,8-epoxy-β-Carotene		3.3–6.7[a]	
	α-Carotene		7.8–24.2[a]	
	β-Carotene		265–617[a]	
	Total carotenoids		371–884[a]	
	Neochrome	μg/100 g fw	13.4[b]	Mezadri et al. 2005
	Auroxanthin		21.8[b]	
	Antheraxanthin		21.8[b]	
	Mutatoxanthin		8.3[b]	
	β-Cryptoxanthin		108[b]	
	cis-β-Carotene		61.3[b]	
	Total carotenoids		1397[b]	
	Vitamin A	μg RAE/100 g fw	145[b]	
Camu-camu	Neoxanthin	μg/100 g fw	3.9[d]	Zanatta and Mercadante 2007
	cis-Neoxanthin		2.1[d]	
	Violaxanthin[c]		12.0[d]	
	Luteoxanthin		21.5[d]	
	Flavoxanthin		9.4[d]	
	5,6-epoxy-Lutein		2.1[d]	
	5,8-epoxy-Zeaxanthin		9.2[d]	
	5,6-epoxy-Zeaxanthin		12.9[d]	
	all-*trans*-Lutein		160[d]	
	Zeaxanthin		22.9[d]	
	Sintaxanthin		1.1[d]	
	β-Cryptoxanthin[c]		9.9[d]	
	5,8-epoxy-β-Carotene		3.6[d]	
	β-Carotene		72.8[d]	
	Total carotenoids		355[d]	
	Vitamin A	RAE/100 g	14.2[d]	
Goji berry	Neoxanthin	μg/g fw	6.1[e]	Imbaraj et al. 2008; Zhang et al. 2016
	9′-*cis*-Zeaxanthin		30.4[e]	
	13′-*cis*-Zeaxanthin		10.5[e]	
	15′-*cis*-Zeaxanthin		12.3[e]	
	all-*trans*-Zeaxanthin		420[e]	
	all-*trans*-β-Cryptoxanthin		18.6[e]	
	9′-*cis*-β-Cryptoxanthin		1.8[e]	
	13′-*cis*-β-Carotene		7.2[e]	
	all-*trans*-β-Carotene		15.4[e]	
	9′-*cis*-β-Carotene		7.1[e]	
	Zeaxanthin monopalmitate		45.2[e]	
	β-Cryptoxanthin monopalmitate		14.8[e]	
	Zeaxanthin dipalmitate		135[e]	
	Total carotenoids		400–11300	

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Table 3. (*Continued*)

Superfruit	Carotenoids	Unit	Content	References
Jambolão	*cis*-Neoxanthin	μg/100 g fw	0.6	Rufino et al. 2010; Faria et al. 2011
	cis-Lutein		2.0	
	all-*trans*-Lutein		39.0	
	all-*trans*-Zeaxanthin		1.7	
	Phytoene		5.6	
	all-*trans*-β-Cryptoxanthin		0.3	
	Phytofluene		2.9	
	15-*cis*-β-Carotene		3.1	
	13-*cis*-β-Carotene		3.8	
	all-*trans*-α-Carotene		2.7	
	all-*trans*-β-Carotene		22.7	
	9-*cis*-β-Carotene		4.9	
	Total carotenoids		510	
Pitanga	β-Cryptoxanthin	μg/g fw	16–34	Bagetti et al. 2011
	Lycopene		151–166	
	β-Carotene		2.9–5.1	
	all-*cis*-Violaxanthin		2.3	Porcu and Rodriguez-Amaya 2008
	all-*cis*-Lutein		1.2	
	all-*cis*-Rubixanthin		9.4	
	cis-Rubixanthin		5.3	
	all-*cis*-β-Cryptoxanthin		11.8	
	all-*cis*-Lycopene		71.1	
	13-*cis*-Lycopene		5.0	
	all-*cis*-γ-Carotene		3.8	
	all-*cis*-β-Carotene		3.2	
	Total carotenoids		3.04–5.86	

fw, fresh weight; RAE, retinol activity equivalents.
[a]Range (minimum – maximum) values determined from acerola harvested during two consecutive growing seasons (2003 and 2004) in Brazil.
[b]Values determined from full-coloured ripe acerola from Itajai, Brazil.
[c]All-*trans* and *cis*-isomers.
[d]Values determined from camu-camu harvested in Iguape, Brazil.
[e]Values determined from saponified carotenoids extracted from goji berry.

acid, protocatechoyl-quinic acid, and dimethylcaffeoyl quinic acid. Among the flavonoids identified, quercetin 3-*O*-hexose coumaric ester and quercetin 3-*O*-hexose-*O*-hexose-*O*-rhamnose, have recently been reported for the first time in goji berry (Benchennouf et al. 2017).

Goji berry is also rich in polysaccharides (comprising 5–8% of the dried fruit), scopoletin (6-methoxy-7-hydroxycoumarin), the glucosylated precursor, vitamin C analog 2-*O*-β-d-glucopyranosyl-L-ascorbic acid, carotenoids (such as zeaxanthin and β-carotene), betaine, cerebroside, β-sitosterol, flavonoids, amino acids, minerals, and vitamins (especially vitamins B and C) (Potterat 2010; Amagase and Farnsworth 2011; Cheng et al. 2015). Polysaccharides are the most important functional constituents in goji berry (Amagase and Farnsworth 2011; Cheng et al. 2015). Goji polysaccharides which are highly branched glycopeptide, contain 18 amino acids. The main chains of the glycan backbones of goji polysaccharides is either alpha-(1–>6)-D-glucans or alpha-(1–>4)-D polygalacturonans; these have been reviewed and reported by Potterat (2010).

Inbaraj et al. (2008) reported 13 carotenoids in goji berry, among which all-*trans*-zeaxanthin (420 μg/g fw) predominated (Table 3). Five carotenoids, including lutein, neoxanthin, β-cryptoxanthin, β-carotene, and zeaxanthin, have been reported in goji berry extract (Zhang et al. 2016). Results showed that zeaxanthin was the predominant carotenoid, with levels of 17.1-9306 μg/g fw, followed by β-cryptoxanthin (8.6–740 μg/g fw), β-carotene (18.8–343 μg/g fw), neoxanthin (3.3–265 μg/g fw), and lutein (10.5–79.6 μg/g fw). In another study carried out by Wang et al. (2010), all-*trans*-zeaxanthin and its *cis* isomers constituted the largest portion (1403 μg/g), followed by neoxanthin and β-cryptoxanthin fraction (72.1 μg/g) and β-carotene fraction (35.9 μg/g).

Jaboticaba

Numerous phenolics (anthocyanins, flavan-3-ols, proanthocyanidins, flavonols, ellagitannins, phenolic acids, procyanidins, and tannins) have been reported in jaboticaba (Table 2). Anthocyanins (such as cyanidin, cyanidin-3-*O*-glucoside, and monomeric anthocyanins), phenolic acids (such as gallic acid and ellagic acid), and total tannins were among the phenolics found in high concentrations. Among the flavan-3-ols detected, valoneic acid dilactone isomer and HHDP-galloyl-glucose isomer were the main compounds. These flavan-3-ols have been identified and reported in jaboticaba pulp for the first time (Morales et al. 2016). Ellagitannins and their derivatives have also been reported for the first time in jaboticaba pulp (Alezandro et al. 2013a). The sanguiin H-6 isomer 2 and sanguiin H-10 isomers 2 and 3 are the highest ellagitannins found in jaboticaba (Table 2).

Jambolão

Among superfruits, jambolão has the second most diverse phytochemical profiles. A total of 74 phenolic compounds has recently been characterized in the edible part of jambolão (de Carvalho Tavares et al. 2016). These include anthocyanins (mainly cyanidin, delphinidin, malvidin, and petunidin), flavonols (mainly myricetin, laricitrin, and syringetin glycosides),

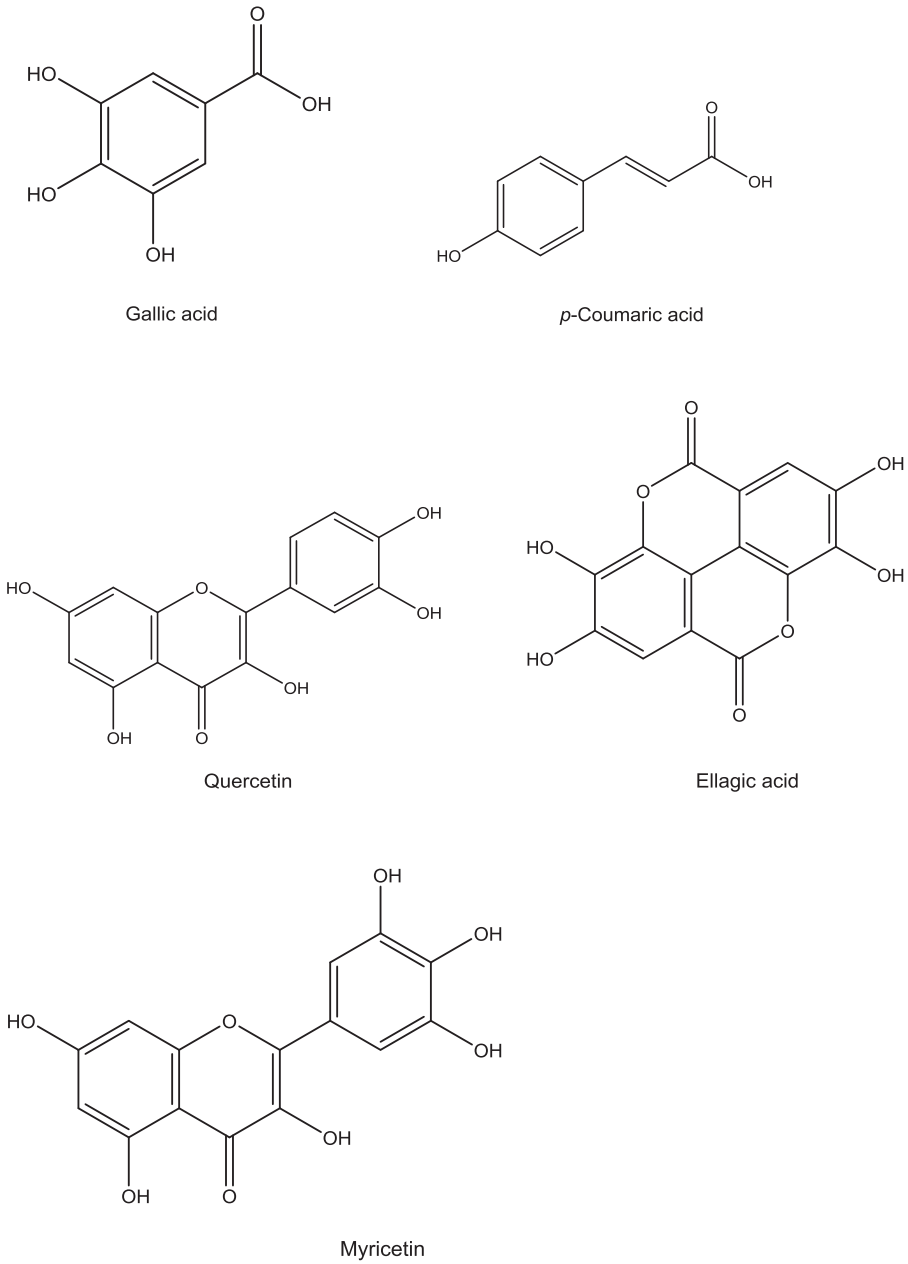
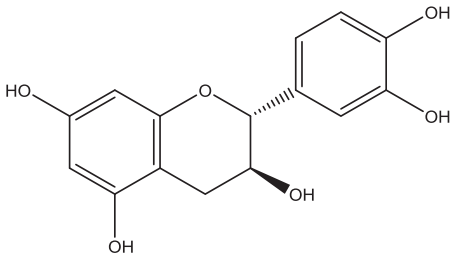


Figure 1. Structures of the representative phytochemicals (anthocyanins, flavonoids, and phenolic acids) reported in superfruits.

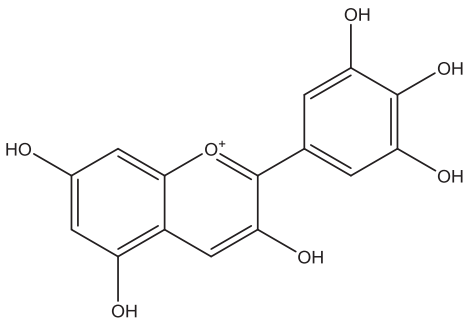
flavanonols (mainly dihexosides of dihydromyricetin and its methylated derivatives), monomeric flavan-3-ols (mainly gallocatechin), gallotannins, and ellagitannins, together with some proanthocyanidins, hydrolysable tannins, and phenolic acids (Table 2). With the exception of most gallotannins, the rest of the hydrolysable tannins were reported for the first time in jambolão. Ellagitannins (such as vescalagin, castalagin, and the two isomers of di-HHDP glucose) accounted for important levels in the pulp of jambolão. However, hydroxycinnamic acid derivatives were not reported in the edible parts of jambolão (de Carvalho Tavares et al. 2016).

Thirty-seven phenolic compounds have also been identified in jambolão by Gordon et al. (2011). These compounds were classified as gallotannins, ellagitannins, flavonols, and flavanonols. For example, digalloylglucose, trigalloylglucose, tetragalloylglucose, pentagalloylglucose, hexagalloylglucose, methyldihydromyricetin dihexoside, galloylmethylmyricetin hexoside, methylmyricetin hexoside, methylmyricetin pentoside, methylmyricetin glucuronide, dimethylmyricetin hexoside, acylated myricetin deoxyhexoside, dimethylmyricetin pentoside, acylated methylmyricetin deoxyhexoside, and acylated galloylmyricetin deoxyhexoside were among the identified compounds. All flavanonols in jambolão occur as dihexosides (Gordon et al. 2011). In another study, hydrolysable and condensed tannins in jambolão were characterized using nuclear magnetic resonance (NMR), matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF-MS), and high-performance liquid chromatography (HPLC) analyses (Zhang and Lin 2009). To the best of our knowledge, flavones, flavanones, and flavanonols have not yet been reported in jambolão.

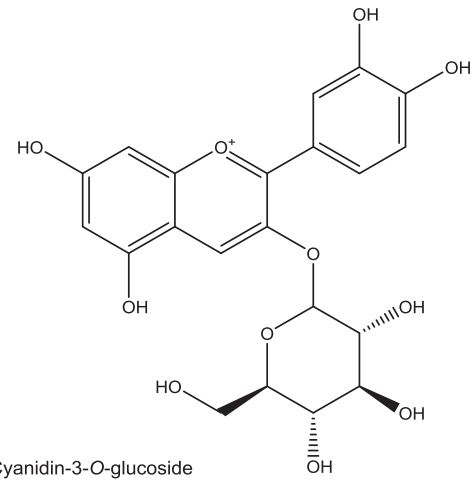
With respect to carotenoids and their derivatives, 12 compounds have been reported in jambolão by Faria et al. (2011), among which all-*trans*-lutein (39.0 μg/100 g fw) is the predominant one followed by all-*trans*-β-carotene (22.7 μg/100 g fw) (Table 3).



(+)-Catechin



Cyanidin

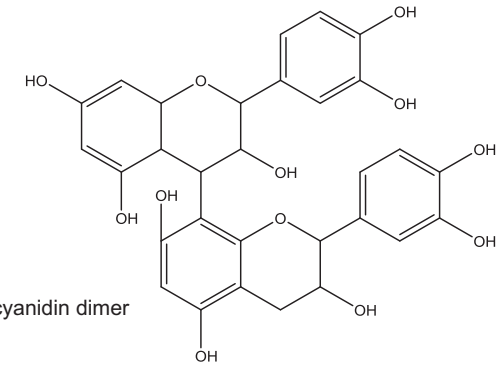


Cyanidin-3-*O*-glucoside

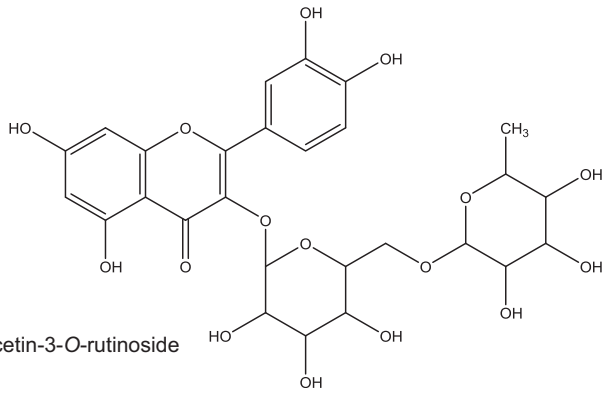
Figure 1. (Contiued)

Maqui

Various phytochemicals such as anthocyanins, flavan-3-ols, flavonols, phenolic acids, and ellagic acid derivatives have been reported in maqui. Numerous anthocyanins have been characterized in maqui, of which delphinidin-3-*O*-sambubioside-5-*O*-glucoside, delphinidin-3,5-*O*-diglucoside, cyanidin-3-*O*-sambubioside-5-*O*-glucoside, delphinidin-3-*O*-glucoside, and delphinidin-3-*O*-sambubioside are the most abundant ones (Table 2). The glycosylation pattern of the aglycones of maqui anthocyanins was recently studied by Brauch et al. (2017), using high-performance liquid chromatography – diode array detector – electrospray ionization interface – mass spectrometry (HPLC-DAD-ESI-MS) and two dimensional (2D)-NMR spectroscopy. For the first time, 2D-NMR spectroscopic data demonstrated that the major maqui anthocyanins were delphinidin 3-*O*-(2”-*O*-*β*-xylopyranosyl-*β*-glucopyranoside)-5-*O*-*β*-glucopyranoside and delphinidin 3-*O*-*β*-glucopyranoside-5-*O*-*β*-glucopyranoside. Among these pigments, delphinidin 3-*O*-*β*-glucopyranoside-5-*O*-*β*-glucopyranoside was the most



Procyanidin dimer



Quercetin-3-*O*-rutinoside

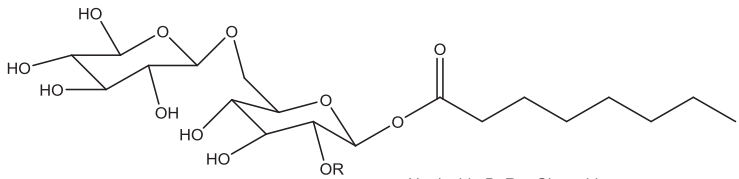
Figure 1. (Contiued)

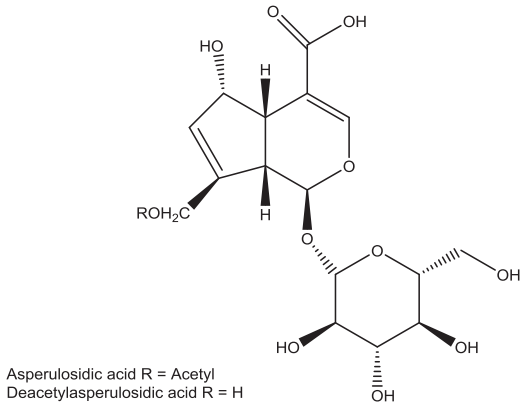
abundant anthocyanin in maqui clones named Luna Nueva (59% of total anthocyanins) and Morena (50% of total anthocyanins). The relative proportions of diglycosylated anthocyanins (84% of total anthocyanins) in both maqui clones exceeded those of monosubstituted anthocyanins (16%). However, no carotenoids or their derivatives have been reported in maqui.

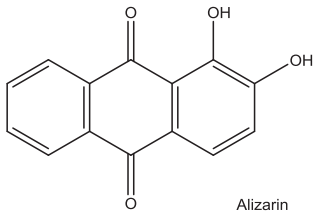
Noni

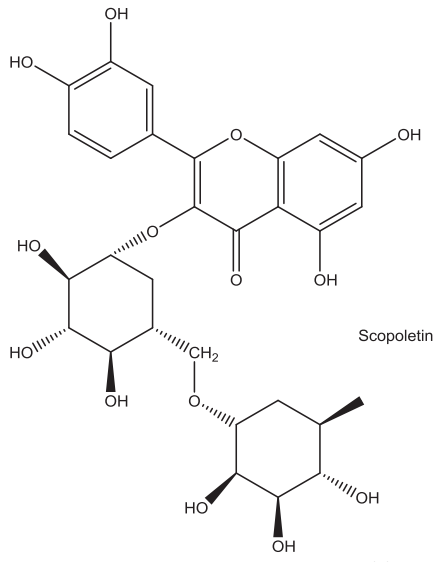
In addition to the information provided in Table 2, various metabolites have been reported in noni including a number of anthraquinones and anthraquinone glycosides, fatty acids and their derivatives, iridoids and iridoid glycosides, lignans, neolignans, flavonol glycosides, phenylpropanoids, and saccharides, as well as volatile constituents such as monoterpenes, short chain fatty acids, and fatty acid esters (Kamiya et al. 2004; Pawlus and Kinghorn 2007; Motshakeri and Ghazali 2015). In addition, noni also contains proxeronine, which is converted to xeronine by the enzyme proxeroninase in the body. It was hypothesized that xeronine is able to modify the molecular structure of proteins, allowing the proteins to function properly with appropriate conformation (Wang et al. 2002). Moreover, phenolic compounds that serve as the major group of functional phytochemicals in noni juice include damnacanthal, scopoletin, morindone, alizarin, aucubin, nordamnacanthal, rubiadin, rubiadin-1-methyl ether, and other anthraquinone glycosides that have been identified in noni. The structures of most of these phytochemicals have already been reviewed and published (Pawlus and Kinghorn 2007).

In addition, four characteristic compounds, namely scopoletin, rutin, quercetin, and 5,15-dimethylmorindol (5,15-DMM)









(a) Noni

Figure 2. Structures of the unique phytochemicals reported in (a) noni (b) goji berry (c) açai, and (d) acerola.

have been reported in all noni fruits and commercial juices originating from different regions of the world. They can be used as a reference for authentication of noni fruit raw materials and commercial noni products (Deng et al. 2010). These compounds that have been identified by spectroscopic analysis are 3,3‘-bisdemethylpinoresinol, americanol A, americanin A, americanoic acid A, morindolin, and isoprincepin, of which compounds americanoic acid A and morindolin are considered to be novel (Kamiya et al. 2004). Carotenoids and their derivatives have not been reported in noni fruit.

Pitanga

Several anthocyanins, flavonols, and phenolic acids have been identified and characterized in red and purple pitanga varieties (Table 2) (Celli et al. 2011; Borges et al. 2016). These include

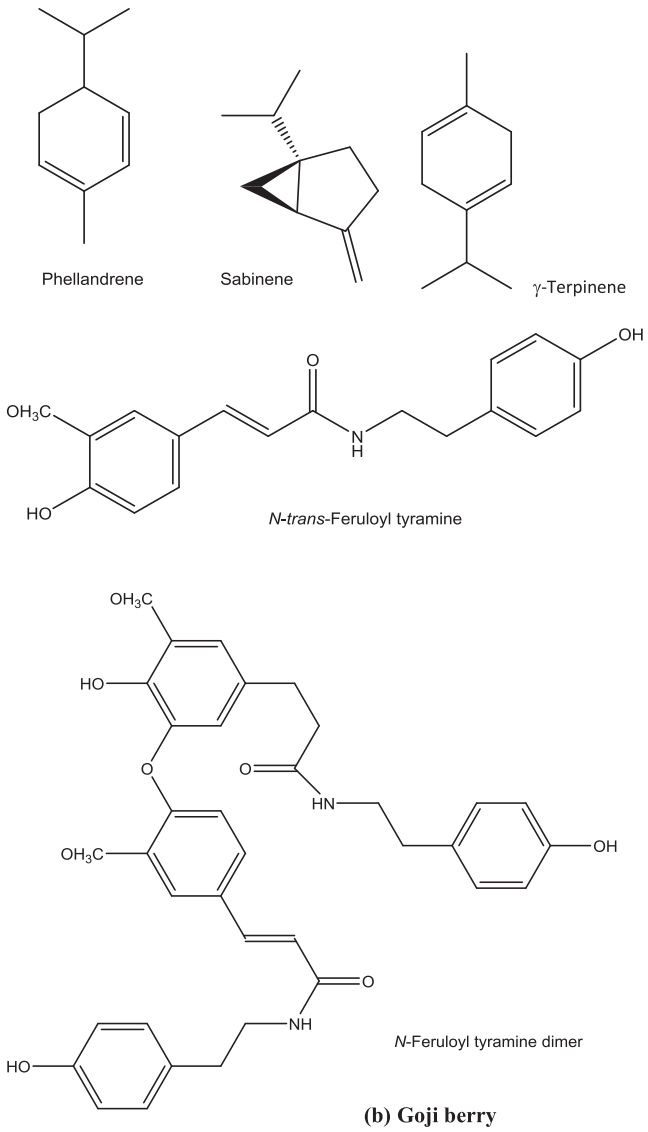


Figure 2. (Continued)

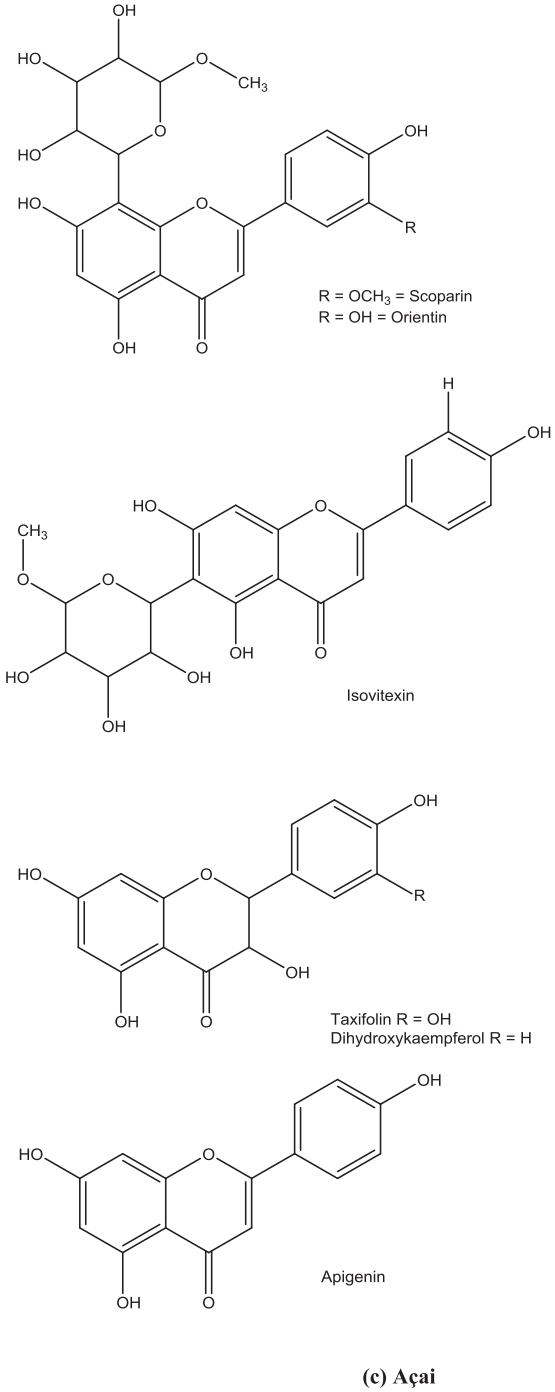


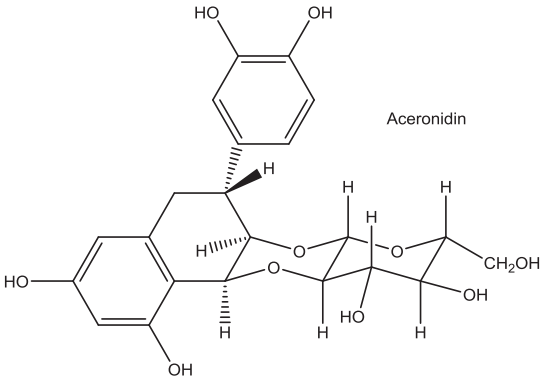
Figure 2. (Continued)

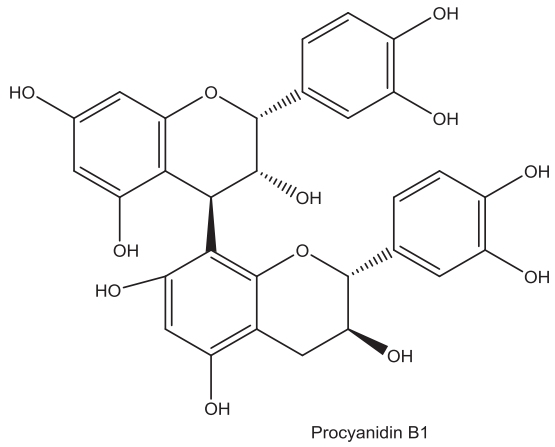
cyanidin-3-*O*-glucoside, myricetin-3-*O*-hexoside, myricetin-3-*O*-pentoside, myricetin-3-*O*-rhamnoside, quercetin-3-*O*-hexoside, quercetin-3-*O*-pentoside, quercetin-3-*O*-rhamnoside, myricetin deoxyhexoside-gallate, and ellagic acid. Kawaguchi et al. (2007) have isolated a novel flavonoid, leucocyanidin-3-*O*-β-D-glucoside, commonly known as aceronidin, from acerola puree. Aceronidin has shown antioxidant activity, with the inhibitory effect on α-glucosidase and α-amylase enzymes. The inhibition of these two sugar digestive enzymes would help to slow down the carbohydrate digestion. The antioxidant activity of aceronidin was compared with some well-known phenolic compounds, such as taxifolin, catechin, isoquercitrin, and quercitrin which have a similar structure. The 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavening activity of aceronidin was shown to be stronger than α-tocopherol, but comparable to taxifolin, catechin, isoquercitrin, and quercitrin (Kawaguchi et al. 2007). These results demonstrate that aceronidin could serve as a potent antioxidant with potential value as a functional compound ingredient.

With respect to carotenoids and their derivatives, 12 compounds have been reported in pitanga (Porcu and Rodriguez-Amaya 2008; Bagetti et al. 2011), among which lycopene (151–166 μg/g fw) is the predominant carotenoid (Table 3).

Antioxidant efficacies of superfruits

Reported antioxidant activities in selected superfruits are given in Table 4. A number of methods have been used to determine the antioxidant activities of selected superfruits. These include ferric reducing antioxidant power (FRAP), oxygen radical absorbance capacity (ORAC), 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid) (ABTS), cupric ion reducing





(d) Acerola

Figure 2. (Continued)

antioxidant capacity (CUPRAC), and DPPH radical scavenging activity. Superfruits are rich sources of antioxidant polyphenols. The antioxidant activities of different superfruits vary widely based on the assay type. In another words, different assays follow different mechanism of actions and hence may afford different antioxidant activity trends among superfurits. This suggests the need to perform more than one type of antioxidant activity measurement to consider the various mechanisms of antioxidant action and limitations of each assay (Shahidi and Ambigaipalan 2015). Due to different units used for the same assay, it may not be wise to rank superfurits for their antioxidant efficacy (Table 4).

Health benefits of superfruits

Various human intervention and animal studies have evaluated the potential health benefits of selected superfruits. Health benefits of açai (Heinrich et al. 2011; de Lima Yamaguchi et al. 2015), camu-camu (Langley et al. 2015), goji berry (Amagase and Farnsworth 2011; Tang et al. 2012; Cheng et al. 2015; Ulbricht et al. 2015), and noni (Pawlus and Kinghorn 2007; Brown 2012; Motshakeri and Ghazali 2015) have been reviewed. Results of the *in vitro* experiments of crude extracts from superfruits are not provided in this review, but well-designed animal and human studies are included. The health benefits of açai, acerola, goji berry, jambolão, maqui, and noni are detailed below. Limited information is available in the literature for the remaining superfruits (camu-camu, jaboticaba, and pitanga). The health promoting properties and mechanism

Table 4. Reported antioxidant activities in selected superfruits.

Superfruit	DPPH[a] EC_{50} (g/g DPPH)	ABTS[a] μmol TE/g	FRAP[a] μmol Fe_2SO_4/g	β-Carotene bleaching[a] % OI	ORAC
Açai	598	64.5	220	76.1	33.6[b]
Acerola	49.2	953	1996	nr	34.6–85.4[c]
Camu-camu	42.6	1237	2502	nr	34.7[d]
Goji berry	35.9–85.5[e]	47.8–95.6[e]	17.4–21.1[f]	nr	2950[g]
Jaboticaba	138	317	635	90.6	2400[h]
Jambolão	938	125	173	88.4	1640[i]
Maqui	5.4–17.6[j]	8.35[k]	149–201[l]	nr	23–39[g]
Noni	25[m]	nr	11.2–11.9[n]	nr	11[g]
Pitanga	37[o]	nr	81.6[p]	nr	nr

ABTS, 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid; DPPH, 2,2-diphenyl-1-picrylhydrazyl; EC_{50} half maximal inhibitory concentration; nr, not reported; FRAP, ferric-reducing antioxidant power; fw, fresh weight; OI, oxygen inhibition; ORAC, oxygen radical absorbance capacity; TE, trolox equivalents.

Note: Where possible for comparision among superfruits, data were re-calculated from dry weight to fresh weight [moisture content: açai (83.8%), acerola, (91.7%), camu-camu (89.7%), goji berry (10.34%), jaboticaba (90.7%), jambolão (85%), maqui (95%), noni (86.5%), and pitanga (81.2%).

[a]Data obtained from Rufino et al. (2010), unless specified.

[b]Data are expressed as mmol TE/100 g fw (Inada et al. 2015).

[c]Range (minimum – maximum) values expressed as mmol/kg fw, determined from acerola (Mezadri et al. 2008).

[d]Data are expressed as μmol TE/100 g fw (Fracassetti et al. 2013).

[e]Range (minimum – maximum) values expressed as μM TE/g fw, determined from 8 Chinese goji berries (Zhang et al. 2016).

[f]Range (minimum – maximum) values expressed as mmol Fe^{2+}/kg (Donno et al. 2015 2016).

[g]Data are expressed as μmol TE/100 g fw (both hydrophilic and lipophilic ORAC activities) (USDA 2010).

[h]Data are expressed as mM TE/100 g fw (Morales et al. 2016).

[i]Data are expressed as mol TE/100 g fw (Faria et al. 2011).

[j]Range (minimum – maximum) values expressed as EC_{50} (mg/fw that bleached 50% of DPPH solution) (Fredes et al. 2014).

[k]Data are expressed as mmol TE/g fw (Schreckinger et al. 2010).

[l]Range (minimum – maximum) values expressed as mmol Fe^{2+}/kg fw, determined from maqui from four different regions during two consecutive growing seasons in Chile (Fredes et al. 2014).

[m]Data are expressed as IC_{50} (mg/mL) (Gironés-Vilaplana et al. 2014).

[n]Data are expressed as mM Fe^{2+}/g fw (Kumar et al. 2014).

[o]Data are expressed as IC_{50} (mg/L) determined from purple Brazilian pitanga (Denardin et al. 2015).

[p]Data are expressed as μmol iron(II) sulphate heptahydrate/g fw, determined from purple Brazilian pitanga (Denardin et al. 2015).

Table 5. Health promoting properties and mechanisms of actions demonstrated by selected superfruits determined in human and animal studies.

Health effects	Super fruits/bioactives	Study design	Results/mechanisms	References
Cardio-protective	Açai (flavonoids)	Randomized, controlled, high-fat challenge, double-blind, crossover, and acute intervention trial	Improved vascular function with postprandial increase in FMD and enhanced antioxidant capacity.	Alqurashi et al. 2016
	Maqui (anthocyanins)	Male Wistar rats	Reduced lipid peroxidation and enhanced antioxidant defence.	Céspedes et al. 2008
	Pitanga	Hypertensive rats	β-Adrenergic induced hypotension in the hearts.	Consolini and Sarubbio 2002
Antioxidative	Açai (anthocyanins)	Randomized, double-blind, placebo-controlled, and crossover study	Reduced lipid peroxidation and increased serum antioxidant capacity.	Jensen et al. 2008
	Açai (anthocyanins)	Acute four-way crossover clinical trial	Enhanced plasma antioxidant capacity.	Mertens-Talcott et al. 2008
	Açai	Lung damaged mice	Reduced oxidative and inflammatory reactions of cigarettes and enhanced functions of plasma antioxidant enzymes protect against emphysema.	de Moura et al. 2011, 2012
	Camu-camu (vitamin C)	Randomized, double-blind, and placebo-controlled trial	Reduced oxidative stress and inflammatory biomarkers among smokers.	Inoue et al. 2008
Cancer preventive effect	Açai	Genotoxic-induced DNA damage rats	Inhibited genotoxicity.	Ribeiro et al. 2010
		Colon cancer-induced rats	Reduced colon cancer cells proliferation.	Fragoso et al. 2013
	Açai (anthocyanins and carotenoids)	Colon cancer-induced rats	Reduced carcinogen-induced genotoxicity in peripheral blood cells, increased hepatic glutathione, and attenuated initiation phase of colon carcinogenesis.	Romualdo et al. 2015
	Noni (scopoletin)	Randomized, double-blind, and placebo-controlled trial	Prevents fatigue and pain as well as maintaining physical function.	Issell et al. 2009
	Noni	Carcinogenic rats	Reduced serum cytokines and IL-5, enhanced serum antioxidant capacity, and inhibition of tumour progression.	Stoner et al. 2010
Lipid-lowering effect	Açai	Randomized and open label pilot study	Reduced fasting glucose, insulin, TC, LDL, and TC/HDL ratio as well as postprandial increase in plasma glucose.	Udani et al. 2011
	Goji berry (glycoconjugated polysaccharides and amino acids)	Hyperlipidemic rabbits	Improved lipid profiles (increased HDL) and improved glucose control.	Luo et al. 2004
	Camu-camu	Obesity-induced rats	Improved blood lipid profiles (LDL, TC, and TAG) with reduced blood glucose and insulin levels.	Nascimento et al. 2013
Anti-diabetic	Goji (glycoconjugated polysaccharides)	Randomized and controlled trial	Reduced lipid peroxidation, enhanced plasma antioxidant status, and improved immunological functions. Improved red blood cell fragility and abnormality.	Li et al. 2000
	Noni	Diabetic rats	Reduced blood sugar levels and improved glucose metabolism and insulin sensitivity.	Nerurkar et al. 2012
		Diabetic rats	Reduced blood sugar, glycosylated hemoglobin (HbA1c), LDL, and TAG levels, and improved insulin sensitivity.	Lee et al. 2012
	Jaboticaba	Diabetic rats	Increased plasma antioxidant capacity and endogenous antioxidant enzymes.	Alezandro et al. 2013b
	Maqui (anthocyanins)	High fat diet obese diabetic mice	Enhanced insulin sensitivity and glucose metabolism and decreased fasting blood glucose.	Rojo et al. 2012
	Açai	Streptozotocin-induced diabetic rats	Reduced lipid peroxidation while enhancing antioxidant enzymes in the liver.	Guerra et al. 2011
Immune-stimulating effect	Goji berry (glycoconjugated polysaccharides)	Randomized, double-blind, and placebo-controlled trial	Increased post-vaccination serum influenza-specific IgG levels and enhances immune system.	Vidal et al. 2012
Weight maintenance	Goji berry	Randomized, double-blind, and placebo-controlled trial	Increase metabolic rate/energy expenditure.	Amagase and Nance 2011
Eye health	Goji berry	Single-blinded, paralleled, and placebo-controlled intervention trial	Increased fasting plasma zeaxanthin concentration which helps to maintain visual acuity.	Cheng et al. 2005
		Randomized, double-blind, and placebo-controlled trial	Protects from hypopigmentation and soft drusen accumulation in the macula of elderly subjects. Increased plasma antioxidant levels.	Bucheli et al. 2011

(*Continued on next page*)

Table 5. (*Continued*)

Health effects	Super fruits/bioactives	Study design	Results/mechanisms	References
Pain relieving	Noni	Randomized, double-blind, and placebo-controlled trial	Improved pain and bleeding scores with no reduction in menstrual pain.	Fletcher et al. 2013
	Açai	Open-label clinical pilot study	Reduced lipid peroxidation with increased antioxidant status. Improved in pain and range of motion.	Jensen et al. 2011
Ergogenic effect/exercise performance	Goji berry (polysaccharides)	Oxidative stressed rats	Prolonged exercise endurance and reduced lipid peroxidation while enhancing endogenous antioxidant enzyme levels.	Shan et al. 2011
Osteoporosis prevention	Noni	Pilot health survey	Increased bone reconstruction.	Langford et al. 2004
Gastric ulcer healing effect	Noni (scopoletin)	Single-dose, randomized, open-label, and 2-period crossover study	Enhanced the absorption of ranitidine and reduced formation of acute gastric lesions.	Mahattanadul et al. 2011; Nima et al. 2012
Memory enhancing effect	Noni (rutin and scopoletin)	Scopolamine induced memory impairment mice model	Inhibition of acetylcholinesterase activity and the enhancement of the cerebral circulation.	Pachauri et al. 2012
Neuro-protective effect	Açai (anthocyanins)	*Caenorhabditis elegans* model organism	Improved chemosensory response, attenuated neuronal protein oxidation as well as stress resistance, and hence, neurotoxicity.	Peixoto et al. 2016a
Hepato-protective effect	Camu-camu	Galactosamine-induced liver injured rats	Protected against liver injury by increasing liver enzymes.	Akachi et al. 2010
Anti-aging effect	Açai (anthocyanins)	*C. elegans* model organism	Modulate the development of age-related markers, protection against oxidative stress.	Peixoto et al. 2016b

FMD, flow-mediated dilatation; HDL, high density lipoprotein; IgG, immunoglobulinG; IL, interleukin; LDL, low density lipoprotein; TC, total cholesterol; TAG, triacylglycerols.

of actions demonstrated by selected superfruits determined in human and animal studies are also summarized in Table 5.

Açai

Açai has shown to have numerous phytochemicals, especially phenolic compounds, which have been associated with antioxidant, anti-inflammatory, antiproliferative, cancer-preventive, lipid-lowering, and cardioprotective properties, as summarized in Table 5. A prospective study was conducted among 40 healthy young female adults consuming 200 g of açai pulp/day for 1 month (Pala et al. 2017). Their results demonstrated that consumption of açai did not affect body weight, blood pressure, glucose, insulin resistance, total cholesterol, low-density lipoprotein (LDL) cholesterol, and high-density lipoprotein (HDL) cholesterol, triacylglycerol (TAG), and apolipoprotein B (apo B) among the study subjects, while increasing the concentration of apolipoprotein AI (apo AI). In fact, consumption of açai increased the HDL levels of the subjects. However, the metabolism of unesterified cholesterol, phospholipids, and TAG was not affected. Moreover, açai consumption reduced the oxidative biomarkers such as the reactive oxygen species (ROS), oxidized LDL, and malondialdehyde (MDA), while enhancing the action of antioxidative enzyme and paraoxonase 1. In short, the plasma total antioxidant capacity was increased. Improvement of the antioxidant defenses was demonstrated by açai consumption where açai could have a preventive effect against atherosclerosis (Pala et al. 2017). A nutritional intervention study was conducted by Barbosa et al. (2016) using 35 healthy young female adults consuming 200 g of açai pulp/day for 4 weeks. Their results demonstrated that açai pulp consumption enhanced catalase activity, total antioxidant status, and reduced the amount of ROS. Furthermore, it lowered serum concentration of protein carbonyl and increased total serum sulfhydryl groups, enhancing the endogenous antioxidant defense of the subjects.

Camu-camu

A randomized and double-blind placebo-controlled trial was conducted to investigate the effect of camu-camu on the health-related biomarkers among smokers (Inoue et al. 2008). Results demonstrated that camu-camu has great potential in reducing oxidative stress and inflammatory biomarkers (urinary 8-hydroxydesoxyguanosine, a robust biomarker of *in vivo* oxidative stress) among the smokers. Some health benefits of camu-camu are given in Table 5.

Goji berry

A randomized, double-blind, and placebo-controlled trial was conducted to investigate the effect of goji berry on exercise-induced adrenal steroid in humans (Amagase and Nance 2011). Results demonstrated that goji berry demonstrated significant reductions in feelings of tiredness after exercise in the human subjects tested. This shows that goji berry may attenuate stress-related reactivity and facilitate adaptation to physical stressors during exercise (Amagase and Nance 2011). Some health promoting properties and mechanism of actions demonstrated by goji berry are shown in Table 5.

Jambolão

In an extensive review, Baliga et al. (2011) reported that jambolão exhibits several pharmacological properties, including antibacterial, antifungal, antiviral, anti-diarrheal, anti-allergic, antipyretic, antineoplasic, anti-inflammatory, chemopreventive, radioprotective, gastroprotective, hepatoprotective, free radical scavenging, cardioprotective, hypolipidemic, and hypoglycemic, determined using *in vitro* studies.

Maqui

The blood glucose lowering effect of maqui formulation has been studied in obese diabetic mice, demonstrating that oral administration of anthocyanin-rich maqui formulation improved hyperglycemia and insulin resistance. The insulin-stimulated glucose uptake in muscle cells and the activity of glucose-6-phosphatase in liver cells was down-regulated. These results suggest that maqui formulation, which is anti-diabetic, may be due to an improved glucose metabolism in both skeletal muscle and liver mediated by hormone insulin (Rojo et al. 2012). Recently, it has been shown that the bioactive delphinidin-3,5-diglucoside from maqui juice contributes to the restoration of tear secretion in a rat dry eye model by reducing the formation of ROS, suggesting that maqui juice could be of great use to prevent dry eyes and photoreceptor cell death induced by light (Nakamura et al. 2014; Osorio et al. 2016). Some other health benefits of maqui are given in Table 5.

Further studies should be carried out using well-designed intervention studies or clinical trials to determine the health-promoting properties of these superfruits, especially for acerola, camu-camu, jaboticaba, jambolão, maqui, and pitanga. Long term prospective epidemiological and clinical trials should also carried out among people whose principle diet includes superfruits (Latin America especially Brazil, Chile, Peru, and Argentina) and populations with high prevalence of coronary heart disease (CHD), obesity, and type 2 diabetes. Studies on the safety and toxicological properties of these superfruits especially açai are also required (Heinrich et al. 2011).

Bioavailability of superfruits

Phytochemicals, such as polyphenols, are extensively metabolized after consumption. Thus, the bioavailability of polyphenols from superfruits should be considered when evaluating their potential health benefits (Chiou et al. 2014). Further, polyphenol metabolites may also serve as useful biomarkers of intake of superfruits, even though the bioavailability of polyphenols from various natural foods has shown to be rather low (Shahidi and Ambigaipalan 2015). Lucas-Gonzalez et al. (2016) determined the effect of *in vitro* gastrointestinal (GI) digestion (oral, gastric, and intestinal phases) on the recovery and bioaccessibility indices, the stability of phenolic compounds, and the changes in antioxidant activity of maqui from Chile. The bioaccessibility of total phenolics and flavonoids of maqui after gastric digestion was 113 and 103%, respectively, while their bioaccessibility after intestinal digestion was 78.2 and 14.10%, respectively (Lucas-Gonzalez et al. 2016). Twelve phenolic compounds, including quercetin and quercetin-derivatives (eight compounds), myricetin and myricetin-derivatives (three compounds), and ellagic acid were detected in maqui. The concentration of all phenolic compounds decreased after oral and intestinal digestion, especially the anthocyanins which were most affected. However, the concentration of all phenolic compounds increased slightly after gastric digestion. Thus, it is postulated that flavonoids, including anthocyanins released after gastric digestion may be bioavailable and hence, exerting antioxidant activity in the small intestine. Meanwhile, GI digestion reduced the scavenging capacities of maqui for 89.9 and 84.2%, as determined using DPPH and ABTS assays, respectively, as well as a reducing power of 74.1%. Furthermore, the metal ion chelating activity of maqui was increased (127%) after the intestinal digestion (Lucas-Gonzalez et al. 2016).

A clinical trial demonstrated that zeaxanthin had high bioavailability after daily oral consumption of moderate amount of goji berry, which significantly increases the fasting plasma zeaxanthin level (Cheng et al. 2005). This result is quite similar to another clinical trial which demonstrated that daily consumption of a milk-based formulation of goji berry increased plasma zeaxanthin level and total antioxidant capacity which demonstrated hypopigmentation and soft drusen accumulation in the macula region of the eyes (Bucheli et al. 2011).

A short term four-way crossover clinical trial with açai pulp and clarified açai juice was conducted by Mertens-Talcott et al. (2008) to determine the absorption of anthocyanins upon consumption. Pharmacokinetic analysis of total anthocyanins quantified as cyanidin-3-*O*-glucoside demonstrated C_{max} values of 2321 and 1138 ng/L at t_{max} times of 2.2 and 2.0 hours, and area under the curve (AUC) values of 8568 and 3314 ng h/L for açai pulp and juice, respectively. This shows that anthocyanins from açai are bioavailable in healthy individuals upon consuming moderate levels of açai juice and pulp. In this connection, dose volume was identified as a predictor of the relative oral bioavailability for both açai pulp and juice. More importantly, plasma antioxidant capacity of the study subjects was significantly enhanced after consuming açai pulp and juice (Mertens-Talcott et al. 2008). Increment in plasma antioxidant capacity of up to 2- and 3-fold for açai juice and pulp, respectively, were observed individually which indicates the *in vivo* antioxidant potential of açai. However, the antioxidant capacity in urine, generation of ROS, and uric acid concentration in plasma were not significantly affected by the supplementation of açai pulp and juice (Mertens-Talcott et al. 2008). Henning et al. (2014) determined the effect of *in vitro* GI digestion of goji and açai dietary supplements on their antioxidant capacities *in vivo* and simulated digestion conditions. Results demonstrated that the *in vitro* simulation of GI digestion in mouth, stomach, and small intestine did not adversely affect the antioxidant capacity of açai dietary supplements. However, the *in vivo* antioxidant capacity of goji dietary supplements was lowered after GI digestion in mouth, stomach, and small intestine, even though the effect was not significant (Henning et al. 2014).

Insufficient information on the behavior of phytochemicals in the GI tract and factors that influence the bioavailability of these phytochemicals remain a big challenge in determining the role of individual health promoting components in natural foods. In fact, bioavailability is influenced by bioaccessibility, which is defined as the relative amounts of nutrients or phytochemicals "released" in the GI tract after food digestion, and therefore available for absorption into the body (Mandalari et al. 2013). *In vitro* GI tract digestion model has shown to be helpful to investigate the effect of food matrix and enzymes on polyphenol bioaccessibility even though the model cannot directly mimic the *in vivo* conditions in humans. Furthermore, studies on bioaccessibility using *in vitro* models have shown to be well-correlated with the results from human studies and animal models (Ting et al. 2015). More research should be carried out to determine the metabolites of bioactive compounds from superfruits, especially acerola, jambolão, noni, and pitanga, after urinary

excretion coupled with appropriate cellular models in order to obtain better qualitative results that correlate well with human clinical trials. These data are essential for demonstrating the true biological relevance of these compounds in the context of nutrition and human health (Chiou et al. 2014; Chang et al. 2016).

Risk of toxicity

The safety of superfruit consumption as a functional food requires full consideration. Exposure to irregular food components may pose allergenic or chemical toxicity risks (FDA 2012). Thus, the safety concerns of several superfruits and their associated components have been raised. Further studies into the safety and toxicological properties of these superfruits are urgently needed since the number of studies related to this aspect is still scarce. However, limited information on the quality of various products made from these superfruits is available *via* the internet (Heinrich et al. 2011). This remains to be an area where research gaps need to be addressed. Risks of toxicity for some superfruits (açai, goji berry, and noni) are detailed below.

Açai

Warning letters to various online and manufacturing companies have been issued by the Food and Drug Administration (FDA), regarding several açai products available in the market (Heinrich et al. 2011; FDA 2012). Recently, açai has shown to be contaminated with the parasite *Trypanosoma cruzi* which is responsible for chagaś disease. Hence, mandatory food safety surveillance of the açai products is required for marketing and sale to consumers. Other than that, limited information about toxicological properties of açai has been reported in humans (Menaa 2014).

Goji berry

Goji berry has traditionally been used as a functional food and as a complementary medicine for over 2500 years with limited toxicological symptoms reported in the literature or in traditional Asian herbal medicine textbooks (Amagase and Farnsworth 2011). However, there are studies reported the possible interactions between warfarin and goji polysaccharides, indicating a potential risk of goji polysaccharides-drug and goji-drug interaction (Leung et al. 2008; Rivera et al. 2012). It has been suggested that clinicians should question patients about their use of herbal therapies such as goji polysaccharides and document such use in their medical records before prescribing drugs such as warfarin (Rivera et al. 2012). Future research to determine the dose-response and dose-toxicity relationships of goji polysaccharides should be carried out in both animal and human studies.

Noni

Results from various animal and human studies demonstrated no toxicity symptoms after consuming noni. Additionally, various studies on the use of noni as a food have also been provided in the literature. In general, noni is considered safe for consumption (Pawlus and Kinghorn 2007). Issell et al. (2005) conducted a phase-I clinical trial to determine the toxicity symptoms among cancer patients after consuming 2–10 g of freeze-dried noni. Results demonstrated that there was no reported toxicity, significant pain relief ability, an improvement in fatigue, and physical functioning among the cancer patients (Issell et al. 2005). Subsequently, phase-II efficacy trial was carried out to determine a maximum dose of noni that can be tolerated in cancer patients (Issell et al. 2009). Results demonstrated that three or four capsules taken four times daily (6–8 g) can be recommended. In this relation, scopoletin, the main bioactive compound of noni extract, is bioavailable in blood and urine after noni consumption and can be used as a biomarker for pharmacokinetics study of noni in cancer patients (Issell et al. 2009).

Future perspectives of superfruits

In recent years, consumption of superfruits has increased rapidly due to their demonstrated health benefits (Costa et al. 2013; de Lima Yamaguchi et al. 2015; Lucas-Gonzalez et al. 2016). With the advancement in food processing technologies, a wide variety of superfruits and their combinations are now available in supermarkets, indicating their increased popularity. New functional beverages made from numerous superfruits are convenient and healthy, supported by various innovative marketing strategies (Gironés-Vilaplana et al. 2013). New formulations utilize the additive effect of superfruit mixtures in beverages available in the market with the claim of "boost fruit-flavored beverages". The health benefits of the superfruit beverages are to reenergize the tired mind and soul, as well as promoting good health (Osorio et al. 2016). In this case, Gironés-Vilaplana et al. (2012a 2012b 2013) formulated new isotonic drinks with lemon juice, maqui, açai, and blackthorn. These researchers have studied the quality parameters such as color, minerals, phytochemicals, antioxidant capacity, and biological activities (*in vitro* α-glucosidase and lipase inhibitory effects) of these new isotonic drinks compared to the commercially available isotonic drinks. As a result, new isotonic beverages were found to be more effective than commercial isotonic drinks in terms of their antioxidant capacity, vitamins, minerals, and biological activities, while possessing good sensory properties in terms of color and other relevant parameters (Gironés-Vilaplana et al. 2012a 2012b 2013).

In general, consumers tend to choose healthier and more natural and refreshing fruit-based drinks and juices (Osorio et al. 2016). However, such developments are not evenly spread due to factors such as consumer resistance, legislative barriers, ethical variations, cost effectiveness, and technological issues (Sun-Waterhouse 2011). Independent scientific substantiation of the nutrition labelling and health claims of superfruits should be made since there are various human and animal studies which demonstrate their phytochemicals and health benefits (Table 5) as well as toxicity issues. Appropriate nutrition labelling for superfruits-based food and their products will help consumers in choosing a healthy diet. Nutrition claims, such as disease risk reduction claims, and other function claims can be made since these two claims are of relevance to functional foods/components. Panel of experts appointed by regulatory agencies, such as the European Food Safety Authority

should review the health claims for superfruits using significant scientific agreement standard.

Complementary research is also needed to enhance the potential functionalities of the by-products of these superfruits in future, where such by-products have shown to contain numerous phytochemicals that may be beneficial to human health. To the best of our knowledge, studies have only been conducted on the by-products (peel) of acerola, camu-camu, and açai (de Azevêdo et al. 2014; de Lima Yamaguchi et al. 2015; Nóbrega et al. 2015). These aspects should be examined to identify other possible value-added uses for human nutrition and health, in addition to minimizing the cost of waste management for the agrobusiness industry. Utilization of by-products as raw material for developing functional foods and nutraceuticals such as ready-to-eat snacks, breakfast cereals, or other food products may also help to improve the quality of life by preventing the occurrence of diseases and promoting the health of human beings (Chang et al. 2016). The scientific community and consumers expect more exciting results on superfruit-based products in the coming years.

Conclusions

A number of superfruits having exceptional nutrients and high contents of phytochemicals (particularly phenolic acids and flavonoids) with associated antioxidant activities have been increasingly utilized. The compiled results indicated that many of their bioactive compounds remain to be fully identified and characterized (phenolic acids, flavonoids, and anthocyanins), especially for maqui, acerola, camu-camu, pitanga, and jambolão. Therefore, superfruits can be considered as valuable sources of functional food ingredients based on their phytochemical composition and related antioxidant activity as presented in this review. The phenolic compounds of superfruits are bioaccessible and bioavailable in humans with some demonstrated health benefits, including antioxidant, anti-inflammatory, prebiotic, anti-microbial, chemopreventive, and hypocholesterolaemic activities. Additional well-designed human intervention studies and clinical trials are needed to validate the health benefits of superfruits.

Conflict of interests

The authors have declared no conflict of interests.

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