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Review

Phytochemistry and health benefits of jaboticaba, an emerging fruit crop from Brazil

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ABSTRACT

Many edible dark-colored fruits, rich in anthocyanins, are thought to be important for human health. Jaboticaba (*Myrciaria cauliflora* (Mart.) O. Berg) fruit, native to Brazil, is a pleasant-tasting, dark-colored fruit, and a rich source of a wide variety of phenolic compounds, including flavonoids, anthocyanins, tannins, phenolic acids, as well as less well-known polyphenols like depsides. These dietary phenolics and polyphenols are important natural products, most of them having human health benefits, such as treating or preventing chronic obstructive pulmonary disease, diabetes, cancer, cardiovascular diseases, and stroke. In the past decade, there has been an increase in the number of publications about jaboticaba. This review will discuss the morphology, taxonomy, nutritional composition, and use of the edible parts of jaboticaba (*i.e.* peel and pulp). In addition, an exhaustive survey of this fruit's secondary products, including volatiles, anthocyanins, and other phenolics, is included, and related to the ethnobotanical use of this plant in Brazil and implications of these compounds to human health. Optimization of extraction, focusing on bioactive constituents from this fruit, will be discussed, and prospects and challenges of future jaboticaba studies are pointed out.

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1. Introduction

Natural dietary phenolics, such as flavonoids, anthocyanins, tannins, and other polyphenolics, are thought to be important for human health (Crozier, Jaganath, & Clifford, 2009). There is much epidemiological evidence that diets rich in edible dark-colored fruits can reduce the incidence of cardiovascular diseases, diabetes, cancer, and stroke (Crozier et al., 2009). These protective effects are attributed, in part, to phenolic secondary metabolites, especially the anthocyanins. So, these edible dark-colored fruits, such as blueberry, grapes, pomegranate and jaboticaba, have been called "super fruits", especially in the food industry. Recently, there has been a global trend toward the use of natural phenolics as antioxidants and functional ingredients due to their perceived safety and prevalence in nature (Akter, Oh, Eun, & Ahmed, 2011; Crozier et al., 2009; Tomás-Barberán & Andrés-Lacueva, 2012).

The interest in edible tropical fruits has been increasing in developed countries due to their potential health benefits (Clerici & Carvalho-Silva, 2011; Oliveira, Yamada, Fagg, & Brandão, 2012). Jaboticaba, known as the "Brazilian grape tree", is native to Brazil (Fig. 1); these fruits have a sweet pleasant taste with a little acidity. They are consumed *in natura* or used to prepare juice, jams, liquors, and wines (Wu, Dastmalchi, Long, & Kennelly, 2012). Similar to other dark-colored fruits, jaboticaba is also an important source of traditional nutrients, ingredients and phytochemicals, like polyphenols. These compounds, such as the depsides and anthocyanins, possess well-described biological properties including strong antioxidant and anti-inflammatory, anti-diabetic, and anti-obesity properties and have the potential to treat chronic obstructive pulmonary disease (COPD) (Wu et al., 2012). Therefore, these fruits have attracted considerable attention and an increase in the number of publications has been reported in the past few years. From the SciFinder database statistics, there were 20 publications concerning jaboticaba reported from 2011 to 2013, and this number is more than the sum total from the previous 10 years. Jaboticaba, an emerging functional fruit, may play an important role in the food and nutritional supplement industry in the near future (Costa, Garcia-Diaz, Jimenez, & Silva, 2013).

Fig. 1. Photograph of jaboticaba. The dark-colored fruits of jaboticaba are distinctive since they grow directly from the branches of the tree, as suggested by its Latin species name *M. cauliflora* (photographed by Adam Negrin).

In this review we focused on the traditional and on the modern uses of the edible parts of jaboticaba (*i.e.* peel and pulp). It is an exhaustive survey of this fruit's secondary products. Most of them are polar or semipolar metabolites, including volatiles, anthocyanins, flavonoids, gallo-/ellagi-tannins, depsides, and other phenolics. We will further discuss the medicinal activity of jaboticaba fruit metabolites, especially for their potent antioxidant and anti-inflammatory activities, and their potential to treat COPD. We will relate this medical research to the ethnobotanical use of this plant in Brazil, and discuss the implications of these compounds to human health. Optimization of extraction, focusing on bioactive constituents from this fruit will also be examined. Finally, prospects and challenges of future jaboticaba studies are described.

2. Morphology and taxonomy

Jaboticaba [*Myrciaria cauliflora* (Mart.) O. Berg], or *jabuticaba*, *jabuticaba assú* in local language, belongs to the family Myrtaceae. The flowers are borne directly on the trunks and branches of the tree (the specific epithet *cauliflora* reflects this unusual flower habit), and fruits mature rapidly within 40–60 days. They are 2.0–3.5 cm in diameter and round when mature, with a pericarp color ranging from red to dark-purple and black. The pulp is white, containing 1–4 seeds. There is another species which is similar to jaboticaba, *Myrciaria jaboticaba* (Vell.) O. Berg or *jabuticaba sabará* in local language. Both *M. cauliflora* and *M. jaboticaba* produce edible fruits. *M. cauliflora* is a small tree, 3–6 m tall with smooth gray bark. Its leaves are typically 2–6 cm long, with finely reticulate veins (Lorenzi, Bacher, Lacerda, & Sartori, 2000). In contrast, *M. jaboticaba*, known as "great jaboticaba" is 6–9 m tall, with bicolored leaves ca. 2–4 cm long (Lorenzi et al., 2000). In general, both these two fruits are called jaboticaba and this review is focused on the reports and publications about these species. Although there are several species of jaboticaba distributed with the genus *Myrciaria*, the *M. cauliflora* is the most widespread species in Brazil (Lima, Mélo, & Lima, 2002).

Table 1 summarizes other species related to jaboticaba native to Brazil or Mesoamerica. All of them are *Myciaria* species that produce edible fruits. *Myrciaria vexator* McVaugh (syn: *Eugenia palmarum* Standl. & L.O. Williams ex P.H. Allen) is another species closely related to jaboticaba and called "false jaboticaba". This fruit is bigger and darker, has a thicker shell, and is considered less palatable than jaboticaba fruit. *Myrciaria aureana* is a green fruit which lacks anthocyanins in its peel and is called "white jaboticaba". Similarly, the yellow fruit, *Myrciaria glazioviana*, is called "yellow jaboticaba" (Table 1). Although our group recently reported marker compounds distinguishing jaboticaba and false jaboticaba (Wu et al., 2013), there were no other publications studying the difference among other jaboticaba relatives.

3. Nutritional composition of jaboticaba

Fresh edible fruits have a wide variety of so-called classic nutrients, such as carbohydrates, salts, minerals, amino acids, and vitamins, and although some of these are present in low concentrations in a given fruit, they may have significant impact on human health. The nutritional composition of jaboticaba fruits is shown in Table 2. Among *Myrciaria* edible fruits, such as *Myrciaria dubia* and *M. glazioviana*, *M. cauliflora* fruits are an especially good source of minerals such as calcium, iron, and especially potassium and phosphorus, containing up to 34.6 and 13.2 mg in 100 g fresh fruits, respectively

Table 1
Some edible *Myrciaria* fruits from South America (Lorenzi et al., 2000).

Species	Other names	Fruit diameter (cm)	Fruit color
Myrciaria cauliflora (Mart.) O. Berg	Brazilian grape; jaboticaba paulista (ponhema, assu)	2.0–3.5	Dark-purple
Myrciaria jaboticaba (Vell.) O. Berg	Jaboticaba murta; jaboticaba sabara	2.0–3.0	Dark-purple
Myrciaria vexator McVaugh	False jaboticaba; blue grape	2.5–4.0	Dark-purple, black
Myrciaria dubia (Kunth) McVaugh	Camu camu; caçari	2.5–3.0	Red
Myrciaria grandifolia Mattos	Jaboticaba grauda; jaboticatuba	1.5–2.5	Dark-purple
Myrciaria phitrantha (Kiaersh.) Mattos	Jaboticaba costada; jaboticaba brancavinho	1.5–2.5	Red to purple
Myrciaria trunciflora O. Berg	Jaboticaba de cabinho; jaboticaba café	1.8–2.5	Dark-purple
Myrciaria oblongata Mattos	Jaboticaba azeda; jabuticaba-ácida	2.5–3.0	Dark-purple
Myrciaria coronata Mattos	Jaboticaba coroada; jaboticaba-de-coroa	2.5–3.5	Purple with
Myrciaria floribunda (H. West ex Willd.) O. Berg	Rumberry, camboim	0.4–0.8	Green to red
Myrciaria aureana Mattos	White jaboticaba; jabuticaba-branca	1.0–2.5	Green
Myrciaria glazioviana (Kiaersk.) G.M. Barroso ex Sobral	Cabeludinha, cabeluda; peludinha yellow jaboticaba	2.0–3.0	Yellow
Myrciaria tenella (DC.) O. Berg	Camboim, cambuí, cambuim, camboí	1.0–1.5	Scarlet

(Lorenzi et al., 2000). Jaboticaba also contains significant levels of certain amino acids like tryptophan and lysine. Vitamins B1 and B2 are found as minor constituents in this fruit. Ascorbic acid (vitamin C), an important water-soluble antioxidant nutrient, was found at levels up to 238 mg in 100 g fresh fruits (Rufino, Alves, Fernandes, & Brito, 2011). In additional to the classical nutrients, total anthocyanins in 100 g fresh jaboticaba have been reported to be 58.1–315 mg (Rufino et al., 2011; Terci, 2004), and total polyphenols and carotenoids in 100 g fresh jaboticaba were found to be 440 and 0.32 mg, respectively (Rufino et al., 2010, 2011).

4. Phytochemical composition of jaboticaba

Jaboticaba was reported to contain volatiles, anthocyanins, flavonoids, gallotannins and ellagitannins, depsides, and other phenolic compounds (Einbond, Reynertson, Luo, Basile, & Kennelly, 2004; Plagemann, Krings, Berger, & Marostica, 2012; Reynertson et al., 2006; Wu et al., 2012). Most of these studies focused on the fruits, especially the peels. Thirty-two phenolic compounds have previously been isolated or detected from jaboticaba fruits (Figs. 2–4). Anthocyanins were the major constituents in fresh jaboticaba fruits and at present most of the literature has focused mainly on these pigments (Leite-Legatti et al., 2012; Santos, Veggi, & Meireles, 2010; Veggi, Santos, & Meireles, 2011). Recently, our group has tried to isolate and identify other constituents from this fruit, such as depsides, gallotannins, ellagitannins and other phenolic compounds (Reynertson et al., 2006; Wu et al., 2012).

Table 2
Nutritional composition of per 100 g jaboticaba fruits [a].

Caloric and nutritional composition	Values
Calories	45.7–51.7 units
Water	87.1 g
Protein	0.11–0.32 g
Fat	<0.01 g
Carbohydrate	12.58 g
Ash	0.2 g
Calcium	6.3–7.6 mg
Phosphorus	9.2–34.6 mg
Iron	0.49–0.87 mg
Potassium	13.2 mg
Vitamin B1	0.04 mg
Vitamin B2	0.09 mg
Niacin	1.3 mg
Fiber	0.08 mg
Riboflavin	0.02 mg
Tryptophan	1.0 mg
Lysine	7.0 mg
Ascorbic acid	17.7–238 mg
Total anthocyanins	58.1–315 mg
Total phenolics	460.9 mg
Total carotenoids	0.32 mg

[a] Source from Lorenzi et al. (2000), Morton (1987), Rufino et al. (2011), Rufino et al. (2010) and Assis et al. (2009).

4.1. Volatiles

Volatiles play a role in producing the flavor of the fruits, and their investigation is important to ensure processing procedures that result in a high quality of aroma in the final products. In 2006, Apel, Sobral, Zuanazzi, and Henriques (2006) studied the essential oil composition of jaboticaba leaves for the first time, and reported that spathulenol and caryophyllene oxide were two major oils from jaboticaba leaves. In 2012, the composition of volatiles of jaboticaba fruits was explored by Plagemann et al. (2012). A total of 45 volatile compounds were identified (Table 3), of which 23 imparted a sensory impression at the sniff-port of the GC-olfactometry. Terpenes and alcohols, as well as organic acids (such as dodecanoic/tetradecanoic/hexadecanoic acids and cinnamic acid), were the most abundant volatiles or semi-volatile of the fruits identified. Terpenes in particular are thought to contribute significantly to the flavor of jaboticaba fruits (Plagemann et al., 2012).

A study of the variation of essential oils in jaboticaba during its maturation indicated that some minor terpenoid volatiles changed significantly during the fruit's maturation (Fortes et al., 2011). Some of the jaboticaba monoterpenes (α/β-pinene, α-terpineol, and linalool (*E*)-β-ocimene) increased while some sesquiterpenes (amorpha-4,7(11)-diene, δ-cadinene, δ-amorphene, and α-cadinene) decreased from green to ripe stages. However, the major terpenoid volatiles showed no significant changes during these stages (Fortes et al., 2011). Duarte et al. (2010) also studied the volatile compounds in jaboticaba and other tropical fruit wines by GC–MS and reported that two isoamyl alcohols, 2-methyl-1-butanol and 3-methyl-1-butanol, were the most abundant compounds identified in jaboticaba spirit (Duarte, Amorim, Lago, Dias, & Schwan, 2011).

4.2. Anthocyanins

Anthocyanins are a class of flavonoids with powerful antioxidant properties; they are widely dispersed throughout the plant kingdom, being particularly evident in dark-colored fruits, such as blueberry, cranberry and pomegranate, and in some flower tissues where they are responsible for red, purple, or blue colors (Crozier et al., 2009). Jaboticaba fruits are known as one of the richest Brazilian sources of anthocyanins. Commonly found in Brazilian markets, fresh jaboticaba fruits are widely consumed, and their popularity has been compared to that of grapes in the United States (Leite-Legatti et al., 2012).

Up to now, there are five anthocyanins which have been isolated and identified from jaboticaba fruits (Fig. 2). Most of these pigments exist in the fruit's peel. Peonidin (**1**) and peonidin-3-*O*-glucoside (**2**) were first purified and separated by using thin-layer chromatography (TLC) in 1972 (Trevisan, Bobbio, & Bobbio, 1972), and until

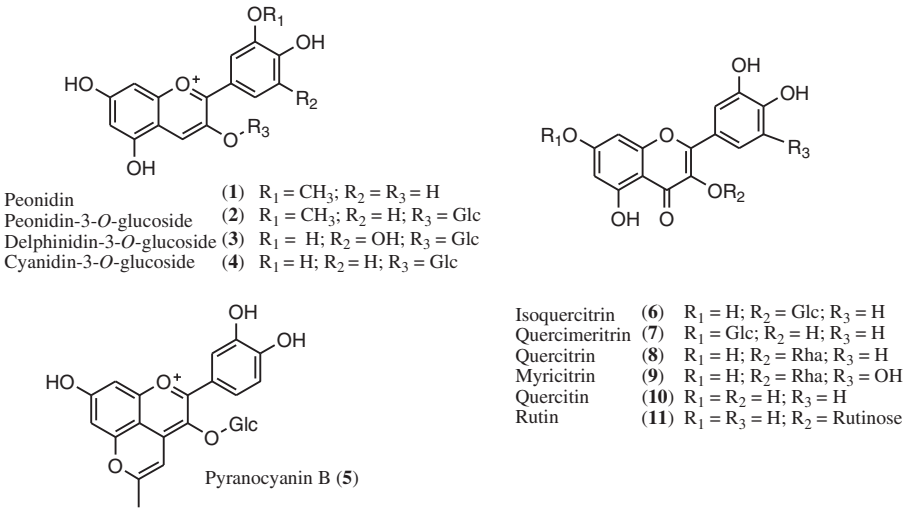


Fig. 2. Anthocyanins and flavonoids reported from jaboticaba (Reynertson et al., 2006; Trevisan et al., 1972; Wu et al., 2012).

2004 there were no further anthocyanins reported from this fruit. In 2004, our group reported that cyanidin-3-*O*-glucoside (**4**) was detected in the MeOH extract of jaboticaba fruits (Einbond et al., 2004). Terci (2004) also reported delphinidin-3-*O*-glucoside (**3**) in this fruit. In addition, as an important source of anthocyanins, jaboticaba was reported to have 58.1–315 mg anthocyanins in 100 g of fresh fruit by using spectrophotometry or other methods (Rufino et al., 2011; Santos & Meireles, 2009; Terci, 2004). In 2006, some other anthocyanins, delphinidin-3-*O*-glucoside (**3**), cyanidin-3-*O*-glucoside (**4**) and pyranocyanin B (**5**), were also isolated and identified from another MeOH extract of jaboticaba fruits (Fig. 2) (Reynertson et al., 2006). Additional publications have reported the detection or isolation of anthocyanins from jaboticaba fruits (Leite-Legatti et al., 2012; Santos et al., 2010; Veggi et al., 2011; Wu et al., 2012). Delphinidin-3-*O*-glucoside (**3**) and cyanidin-3-*O*-glucoside (**4**) are two major anthocyanins reported in jaboticaba fruits, as further confirmed by the Meireles group using TLC (Santos et al., 2010) and our group using LC-TOF-MS (Wu et al., 2012). Dry jaboticaba whole fruit (100 g) was found to contain up to 433 mg cyanidin-3-*O*-glucoside (**4**) and 81 mg delphinidin-3-*O*-glucoside (Reynertson et al., 2006). Leite-Legatti separated the fruit prior to extraction, and found that the dark-colored dry peel contained several times more anthocyanins (about 4.5–7.8 times) than the whole fruits reported by Reynertson et al. (2006); the exact amounts of cyanidin-3-*O*-glucoside and delphinidin-3-*O*-glucoside reported by Leite-Legatti were 1963.57 and 634.75 mg 100 g^{-1} d.w. respectively (Leite-Legatti et al., 2012). Therefore, products that want to maximize the levels of anthocyanins should use the peels.

4.3. Other flavonoids

Besides anthocyanins, other common C_6–C_3–C_6 flavonoids have importance as functional dietary supplements. In 2006, isoquercitrin (**6**), quercimeritrin (**7**), quercitrin (**8**), myricitrin (**9**), quercitin (**10**), and rutin (**11**) were identified from *M. cauliflora* for the first time (Reynertson et al., 2006). All of these compounds, except rutin (**11**), were confirmed by using detailed LC-TOF-MS analysis and co-injection experiments in 2012 (Wu et al., 2012). All of these compounds were flavonol structures and most of them were found with sugars (Fig. 3). In addition, the amount of quercitin (**10**) was up to 11.57 mg per 10 g fresh jaboticaba fruit extract (0.11%), and the amount of flavonoids was found in the order quercitin (**10**) > isoquercitrin (**6**) > quercitrin (**8**) > myricitrin (**9**) > quercimeritrin (**7**) (Wu et al., 2012).

4.4. Tannins

Gallic acid (**12**) is the most common phenolic constituent, which can be found widely as complex sugar esters of gallotannins in many fruits, such as grapes, strawberries and pomegranates. Tannins, including gallotannins and ellagitannins, are important dietary sources in jaboticaba. Gallic acid (**12**) and ellagic acid (**22**) were identified from this fruit for the first time in 2006 (Reynertson et al., 2006). In her review of edible tropical fruits, Morton (1987) reported that jaboticaba contains tannins, but provides no citation. Recently, gallotannins and ellagitannins from jaboticaba were reported, including free ellagic acid (0.06 ± 0.003 g) and total ellagic acid (3.11 ± 0.19 g) per kg of fresh jaboticaba fruits (Abe, Lajolo, & Genovese, 2012). The levels of tannins reported in jaboticaba are significantly higher than the other Myrtaceae fruits, such as cambuci, guava, camu-camu, surinam cherry, and grumixama (Abe et al., 2012); therefore, jaboticaba is a promising source of ellagic acid derivatives in the diet. Our 2012 report on jaboticaba found seven gallotannins (**13**–**19**), together with two ellagic acid derivatives (**20** and **21**), detected for the first time in jaboticaba fruit MeOH extract (Wu et al., 2012). Their structures were tentatively determined by detailed analysis of their mass spectral fragmentation patterns (Wu et al., 2012). Also, our group has recently isolated and identified two ellagitannins, iso-oenothein C (**23**) and oenothein C (**24**), from jaboticaba fruits for the first time (Wu et al., 2013). Interestingly, both of these compounds exist as an inseparable equilibrium mixture of α and β forms in solution (methanol-d_4), as there are two distinct patterns of proton resonances (1:1) for the sugar and phenolic moieties in their ^{1}H NMR spectra (Omar, Li, Yuan, & Seeram, 2012; Wu et al., 2013).

4.5. Depsides and other phenolics

Depsides, such as 2-*O*-(3,4-dihydroxybenzoyl)-2,4,6-trihydroxyphenylacetic acid (**25**) and jaboticabin (**26**) in Fig. 4, originally found in lichens, are a unique kind of phenolic compound composed of some monocyclic aromatic groups linked by the ester bonds. Recently, this class of compound has been found in higher plants, such as *Inga laurina* (Lokvam, Clausen, Grapov, Coley, & Kursar, 2007), *Origanum dictamnus* (Chatzopoulou et al., 2010), and also in the Traditional Chinese Medicine (TCM) Dan-Shen, in a freeze-dried injectable formulation (Jiang et al., 2011). Depsides have antibiotic, anti-HIV, antiproliferative, and potent nonsteroidal anti-inflammatory activities (Reynertson et al., 2006). Depsides were not previously

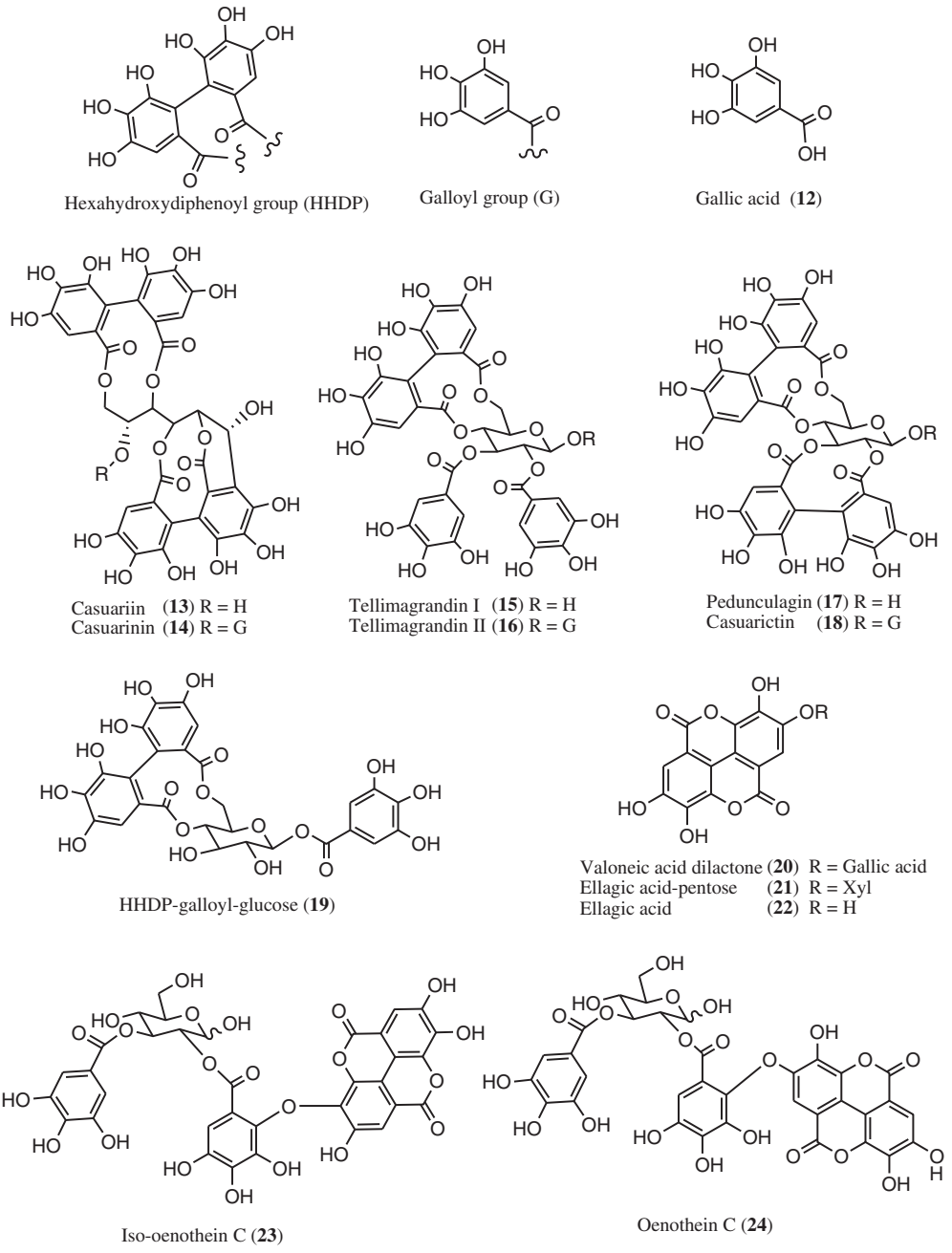
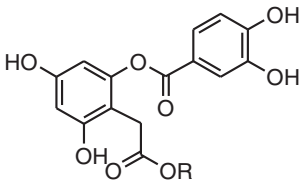


Fig. 3. Gallotannins and its derivatives reported from jaboticaba (Wu et al., 2012, 2013).

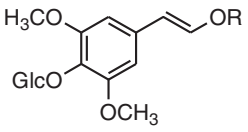
reported in the Myrtaceae family until 2006. In 2006, Reynertson et al. (2006) reported that one new depside, jaboticabin (**26**), together with another known depside, 2-*O*-(3,4-dihydroxybenzoyl)-2,4,6-trihydroxyphenylacetic acid (**25**) (Fig. 4), was isolated and identified from jaboticaba fruits. These two compounds exhibited antiradical activity in DPPH assay and cytotoxicity against HT29 and HCT116 colon cancer cells and significantly inhibited chemokine interleukin (IL)-8 productions before and after cigarette smoke treatment of cells (Reynertson et al., 2006).

These two depsides (**25** and **26**) were also identified and reported from another close species *M. vexator* (false jaboticaba) in 2012 (Dastmalchi, Flores, Wu, Ma, & Dabo, 2012). Besides *Myrciaria* fruits, **25** and **26** were also isolated and identified from kiwi (Wurms & Cooney, 2006), cranberry (Turner et al., 2007), and chokeberry fruits (Li et al., 2012). Jaboticabin, together with its derivatives, exists in many important edible fruits, and was also reported to exhibit potent antioxidant activity. However, these depsides were shown to be minor constituents in the fruit extract and sometimes could not be detected in jaboticaba commercial products, such as juice, jam, and wine (Wu et al., 2012). Therefore, in order to have more of this compound for *in vivo* testing and for use as authentic standard compound, the total synthesis of this compound was undertaken by our group. In summary, jaboticabin was synthesized from commercially available phloroglucinol and 3,4-dihydroxybenzoic acid in nine linear steps (Wu et al., 2013).

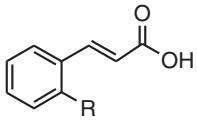
Other common phenolic compounds, such as hydroxycinnamates were isolated and reported from jaboticaba fruits as well (Fig. 4). For example, cinnamic acid (**29**) and *O*-coumaric acid (**30**), as well as protocatechuic acid (**31**) and methyl protocatechuic acid (**32**) were identified (Reynertson et al., 2006); syringin-3-*O*-glucoside (**27**) and syringin (**28**) were determined and reported from fresh jaboticaba MeOH extract more recently (Wu et al., 2012).



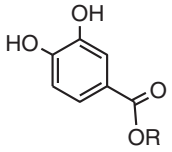
2-O-(3,4-dihydroxybenzoyl)-2,4,6-trihydroxyphenylacetic acid (**25**) R = H
Jaboticabin (**26**) R = CH_3



Syringin-3-*O*-glucoside (**27**) R = Glc
Syringin (**28**) R = H



Cinnamic acid (**29**) R = H
O-coumaric acid (**30**) R = OH



Protocatechuic acid (**31**) R = H
Methyl protocatechuic acid (**32**) R = Me

Fig. 4. Depsides and other phenolic compounds reported from jaboticaba (Reynertson et al., 2006; Wu et al., 2012).

Table 3
Major volatile and semi-volatile compounds detected from jaboticaba fruits or wine.

Volatile compound	RI[a]	Column	Reference	Volatile compound	RI[a]	Column	Reference
α-Pinene	<1000	CP-Wax[b]	Plagemann et al. (2012)	α-Caryophyllene	1637	CP-Wax	Plagemann et al. (2012)
β-Pinene	<1100	CP-Wax	Plagemann et al. (2012)	Cubenol	1645	CBP-5	Fortes et al. (2011)
β-Myrcene	<1000	CBP-5[c]	Fortes et al. (2011)	β-Eudesmol	1654	CBP-5	Fortes et al. (2011)
(*Z*)-β-ocimene	1035	CBP-5	Fortes et al. (2011)	α-Eudesmol	1658	CBP-5	Fortes et al. (2011)
Limonene	1186	CP-Wax	Plagemann et al. (2012)	Diethyl succinate[e]	1672	VF-Wax	Duarte et al. (2010)
α-Terpineol	1191	CBP-5	Fortes et al. (2011)	Germacrene D	1676	CP-Wax	Plagemann et al. (2012)
1,8-Cineole	1192	CP-Wax	Plagemann et al. (2012)	α-Selinene	1686	CP-Wax	Plagemann et al. (2012)
3-Methyl-1-butanol	1204	CP-Wax	Plagemann et al. (2012)	α-Muurolene	1698	CP-Wax	Plagemann et al. (2012)
(*E*)-β-Ocimene	1244	CP-Wax	Plagemann et al. (2012)	δ-Cadinene	1729	CP-Wax	Plagemann et al. (2012)
Ethyl lactate[e]	1338	VF-Wax[d]	Duarte et al. (2010)	2-Phenylpropan-2-ol	1739	CP-Wax	Plagemann et al. (2012)
δ-Elemene	1338	CBP-5	Fortes et al. (2011)	Methyl dodecanoate	1785	CP-Wax	Plagemann et al. (2012)
Hexanol	1352	CP-Wax	Plagemann et al. (2012)	α-Calacorene	1878	CP-Wax	Plagemann et al. (2012)
β-Bourbonene	1374	DB_5[e]	Apel et al. (2006)	2-Phenylethanol	1882	CP-Wax	Plagemann et al. (2012)
β-Elemene	1384	CP-Wax	Plagemann et al. (2012)	Palustrol	1889	CP-Wax	Plagemann et al. (2012)
(*E*)-3-Hexen-1-ol	1377	CP-Wax	Plagemann et al. (2012)	Benzothiazole	1926	CP-Wax	Plagemann et al. (2012)
Acetic acid	1422	CP-Wax	Plagemann et al. (2012)	Caryophyllene oxide	1938	CP-Wax	Plagemann et al. (2012)
Allo-aromadendrene	1451	DB_5	Apel et al. (2006)	Dodecanol	1963	CP-Wax	Plagemann et al. (2012)
α-Humuleno	1455	CBP-5	Fortes et al. (2011)	(E)-Methyl cinnamate	2052	CP-Wax	Plagemann et al. (2012)
γ-Muurolene	1472	DB_5	Apel et al. (2006)	Ledol	2035	CP-Wax	Plagemann et al. (2012)
α-Copaene	1472	CP-Wax	Plagemann et al. (2012)	Octanoic acid[e]	2057	VF-Wax	Duarte et al. (2010)
Amorpha-4,7(11)-diene	1477	CBP-5	Fortes et al. (2011)	10-epi-Eudesmol	2084	CP-Wax	Plagemann et al. (2012)
δ-Selinene	1492	CBP-5	Fortes et al. (2011)	Spathulenol	2092	CP-Wax	Plagemann et al. (2012)
Bicyclogermacrene	1498	CBP-5	Fortes et al. (2011)	Nonanoic acid	2157	CP-Wax	Plagemann et al. (2012)
δ-Amorphene	1503	CBP-5	Fortes et al. (2011)	τ-Cadinol	2149	CP-Wax	Plagemann et al. (2012)
α-Cadinene	1541	CBP-5	Fortes et al. (2011)	τ-Muurolol	2166	CP-Wax	Plagemann et al. (2012)
Linalool	1544	CP-Wax	Plagemann et al. (2012)	α-Bisabolol	2174	CP-Wax	Plagemann et al. (2012)
Elemol	1552	CBP-5	Fortes et al. (2011)	α-Cadinol	2202	CP-Wax	Plagemann et al. (2012)
Methyl 2-furoate	1554	CP-Wax	Plagemann et al. (2012)	α-Selin-11-en-4-ol	2226	CP-Wax	Plagemann et al. (2012)
(*E*)-Nerolidol	1557	DB_5	Apel et al. (2006)	Decanoic acid	2263	CP-Wax	Plagemann et al. (2012)
β-Caryophyllene	1570	CP-Wax	Plagemann et al. (2012)	Hexadecanol	2373	CP-Wax	Plagemann et al. (2012)
Caryophyllene oxide I	1573	DB_5	Apel et al. (2006)	Mono-ethyl succinate[e]	2377	VF-Wax	Duarte et al. (2010)
Globulol	1586	CBP-5	Fortes et al. (2011)	Benzophenone	2419	CP-Wax	Plagemann et al. (2012)
Humulene oxide I	1594	DB_5	Apel et al. (2006)	Dodecanoic acid	2476	CP-Wax	Plagemann et al. (2012)
Humulene epoxide II	1600	DB_5	Apel et al. (2006)	Phytol	>2500	CP-Wax	Plagemann et al. (2012)
5-Epi-7-epi-α-eudesmol	1604	CBP-5	Fortes et al. (2011)	Tetradecanoic acid	>2500	CP-Wax	Plagemann et al. (2012)
Aromadendrene	1614	CP-Wax	Plagemann et al. (2012)	Cinnamic acid	>2500	CP-Wax	Plagemann et al. (2012)
γ-Eudesmol	1637	CBP-5	Fortes et al. (2011)	Hexadecanoic acid	>2500	CP-Wax	Plagemann et al. (2012)

[a] Retention index.
[b] CP-Wax 52 CB column (Varian, Darmstadt, Germany).
[c] CBP-5 (Shimadzu) fused silica capillary column.
[d] Factor Four VF-Wax_{MS} Varian column.
[e] A fused silica capillary column with DB-5 polarity.

5. Health benefit properties of jaboticaba

5.1. General overview of jaboticaba's health benefit

Jaboticaba is very popular in Brazil, and has been used as a folk medicine for a long time. Traditionally, an astringent decoction of its sun-dried peel has been used as the treatment for diarrhea, as well as respiratory problems such as hemotypsis, asthma, and chronic inflammation of the tonsils (Morton, 1987). Its bark is commonly used against diarrhea and other disorders based on its astringency (Souza-Moreira et al., 2011). The bark and leaves are used to treat diarrhea by the local people in a semi-arid Brazilian region (de Albuquerque et al., 2007). Recently, there has been an increase in publications about this fruit's diverse biological activities, and the major studies are summarized in Tables 4 and 5.

5.2. Antioxidant and radical scavenger capacity

For human health, antioxidant or radical scavenger capacity is considered to be an important activity of polyphenol-rich fruits, especially anthocyanin-rich edible fruits. Some fruits, most notably blueberries, have been dubbed "superfruits" due to their high antioxidant capacity. There are two major types of antioxidant assays: one is based on hydrogen atom transfer reactions, such as oxygen radical absorbance capacity (ORAC) and total radical trapping antioxidant parameter (TRAP) assays, and the other one is based on electron transfer, such as Trolox equivalence antioxidant capacity (TEAC), 2,2-di(4-tertoctylpheny)-1-picrylhydrazyl (DPPH), and 2,2′-azinobis (3-ethylbenzothiazo-line-6-sulfonate) (ABTS) assays (Huang, Ou, & Prior, 2005). There are sixteen studies in the literature that report the strong radical scavenging activity of jaboticaba (Table 4). Abe et al. (2012) reported that the methanol/water (70:30, v/v) extract of jaboticaba showed 62 ± 6 mmol Trolox eq. kg^{-1}. Reynertson, Yang, Jiang, Basile, and Kennelly (2008) reported that the IC_{50} value of methanolic extract of jaboticaba was 19.4 ± 0.28 mg mL^{-1} in DPPH assay, which was the strongest antioxidant activity compared with the other edible Myrtaceae fruits. Einbond et al. (2004) also reported that its methanolic extract had a 6.2 ± 0.7 mg mL^{-1} IC_{50} in the same assays.

The three publications mentioned above only used one antioxidant assay, and there are other references which reported results using two antioxidant assays. For example, Haminiuk et al. (2011) reported that the ethanolic extract had an EC_{50} value of 47.04 ± 0.50 μg mL^{-1} based on the DPPH assay, and 97.51 ± 0.61% based on the β-carotene-linoleic acid assay. Wu et al. (2012) reported that the DPPH• value of fresh jaboticaba fruit extract was higher than those of the commercial juice and jam; however, the $ABTS^{\bullet+}$ value of the juice is stronger than those of fruit extracts and jam products.

Antioxidants used in the food industry often refer to substances that can inhibit fatty acid autoxidation, and most of the antioxidant assays are carried out in a controlled manner in a homogeneous solution with an artificial oxidant or radical precursor added to initiate the reaction (Huang et al., 2005). However, in reality, oxidation occurs without an added radical initiator or oxidant, but rather it is initiated by light, metal ions, or heat during food processing or storage. In order to comprehensively study different aspects of antioxidants, validated and specific assays are needed, and several common antioxidant assays are necessary for comparison if the results are to be extended to real food systems (Huang et al., 2005).

There are some jaboticaba publications that use three or even four assays to confirm the fruit's antioxidant activity. Assis et al. (2009) reported the antioxidant capacity of jaboticaba and nine other exotic fruits from Brazil in three different assays (HOCl scavenger, ABTS, and DPPH). Rufino et al. (2010) have reported the antioxidant capacities of jaboticaba together with 17 other fresh and dry fruits using four different methods (ABTS, DPPH, FRAP, and β-carotene bleaching).

Table 4
Antioxidant activity/radical scavenger capacity of jaboticaba.

Source	Assay	Results	Reference
Peel extract	ORAC	25,514.24 ± 3037 μM TE g^{-1}	Leite-Legatti et al. (2012)
Peel extract	DPPH	45.35 ± 0.50 μg mL^{-1}	Leite-Legatti et al. (2012)
Peel extract	ABTS	9458 ± 97 μM TEAC g^{-1}	Leite-Legatti et al. (2012)
Ethanolic extract	DPPH	47.04 ± 1.66 μg mL^{-1}	Haminiuk et al. (2011)
Ethanolic extract	β-Carotene-linoleic acid	97.51 ± 0.61%	Haminiuk et al. (2011)
Methanol/water extract	DPPH	62 ± 6 mmol Trolox eq. kg^{-1}	Abe et al. (2012)
Fruit extract	DPPH	0.282 ± 0.009 mg mL^{-1}	Wu et al. (2012)
Juice	DPPH	0.453 ± 0.000 mg mL^{-1}	Wu et al. (2012)
Jam	DPPH	0.618 ± 0.023 mg mL^{-1}	Wu et al. (2012)
Fruit extract	ABTS	220 μmol/g dry sample (20 min)	Wu et al. (2012)
Juice	ABTS	480 μmol/g dry sample (20 min)	Wu et al. (2012)
Jam	ABTS	60 μmol/g dry sample (20 min)	Wu et al. (2012)
Freeze-dried peel	*In vitro* TEAC	1.7 times compared to the control	Leite et al. (2011)
Freeze-dried peel	*In vitro* ORAC	1.3 times compared to the control	Leite et al. (2011)
Fruit extract	TNB oxidation by HOCl	18% inhibition (both 10 and 50 mL fruit samples)	Assis et al. (2009)
Fruit extract	ABTS	30% (10 mL) and 95 (50 mL) inhibition	Assis et al. (2009)
Fruit extract	DPPH	10% (10 mL) and 32% (50 mL) inhibition	Assis et al. (2009)
Fruit extract	DPPH	19.4 ± 0.28 mg mL^{-1}	Reynertson et al. (2008)
Methanol extract	DPPH	35 mg mL^{-1}	Reynertson, Basile, and Kennelly (2004)
Methanol extract	DPPH	6.2 ± 0.7 mg mL^{-1}	Einbond et al. (2004)
Cyanidin 3-*O*-glucoside	ABTS	3.75 mmol/g dry sample (20 min)	Dastmalchi et al. (2012)
Seed extract	ORAC-PGR	15 ± 1 mM	Romero et al. (2010)
Pulp extract	ORAC-PGR	5 ± 1 mM	Romero et al. (2010)
Ripe fruits	DPPH	36,300 μmol Trolox eq./100 g dw	Alezandro et al. (2010)
Green unripe fruits	DPPH	91,310 μmol Trolox eq./100 g dw	Alezandro et al. (2010)
Peels	β-Carotene	Combined UAE + ABE process resulted highest antioxidant extracts	Santos et al. (2010)
Fresh and dry aqueous-organic fruit extracts	ABTS/DPPH/FRAP/β-Carotene bleaching	1472 (g/g DPPH); 37.5 μM Trolox/g (ABTS); 87.9 μM Fe_2SO_4/g (FRAP); 90.7% O.I. (β-carotene bleaching)	Rufino et al. (2010)
Methanol/water extract	DPPH	k_2: 17.23 and 3.11 L/mol g s	Rufino et al. (2011)
2-*O*-(3,4-dihydroxy-benzoyl) [a](**25**)	DPPH	61.8 μM	Reynertson et al. (2006)
Jaboticabin (**26**)	DPPH	51.4 μM	Reynertson et al. (2006)

[a] 2-*O*-(3,4-dihydroxy-benzoyl)-2,4,6-trihy-droxyphenylacetic acid.

Table 5
Other biological activities of jaboticaba.

Activity	Source	Assay	Cell line/bacterium	Results	Reference
Treatment of COPD (anti-inflammatory mechanism)	2-O-(3,4-Dihydroxy-benzoyl)-2,4, 6-trihy-droxyphenylacetic acid (**25**)	*In vitro* SAE		Inhibited IL-8 by 74.9% in untreated and 70.3% in CSE treated cells	Reynertson et al. (2006)
	Jaboticabin (**26**)	*In vitro* SAE		Inhibited IL-8 by 81.3% in untreated and 47.3% in CSE treated cells	Reynertson et al. (2006)
	Ellagic acid (**22**)	*In vitro* SAE		Significantly inhibited MMP-1 expression in CSE-induced SAE cells	Dastmalchi et al. (2012)
Antiproliferative	Delphinidin 3-*O*-glucoside (**3**)	*In vitro*	SAE	Not detected in SAE cells and 96% in CSE treated cells	Reynertson et al. (2006)
	Cyanidin 3-*O*-glucoside (**4**)	*In vitro*	SAE	Inhibited IL-8 by 65.3% in untreated and 36.4% in CSE treated cells	Reynertson et al. (2006)
	Non-polar extract	SRB	U251 and others	13.8–144.0 μg mL^{-1}	Leite-Legatti et al. (2012)
	Polar extract	SRB	U251 and others	1.9–181.2 μg mL^{-1}	Leite-Legatti et al. (2012)
Cytotoxicity	2-*O*-(3,4-Dihydroxy-benzoyl)-2,4, 6-trihy-droxyphenylacetic acid (**23**)	MTT	HCT116	30 μM	Reynertson et al. (2006)
	Jaboticabin (**24**)	MTT	HT29	65 μM	Reynertson et al. (2006)
Anti-cancer	Anthocyanins	*In vivo*		Reduce oxidative DNA damage	Santos et al. (2010)
Antimutagenic	Jaboticaba peel (JP)	*In vivo*	mice bone marrow cells	No mutagenic effects	Leite-Legatti et al. (2012)
Antibacterial	Ethanolic extract	*In vivo*	*K. pneumoniae*	Slight inhibitory	Haminiuk et al. (2011)
	Leaf extract	*In vivo*	Oral bacteria	Effective	Macedo-Costa et al. (2008)
	Leaf extract	*In vivo*	*Candida* species	Effective	Souza-Moreira et al. (2010)
	Leaf extract	*In vivo*	*Staphylococcus aureus* and others	Active	de Oliveira et al. (2011)
Antidiarrheal	Fruit and leaf extracts	*In vitro*/*in vivo*	SIRC CCL 60/mice	Show some antidiarrheal activity	Souza-Moreira et al. (2011)
Anti-obesity	Freeze-dried peel	*In vivo*	High-fat diet rats	Increase HDL-cholesterol	Lenquiste et al. (2012)
Insulin resistance	Freeze-dried peel	*In vivo*	Obese rats	Improve insulin resistance 47–57%	Lenquiste et al. (2012)
Antidiabetes	Fruit extract	*In vivo*	Obese rats	Significantly inhibit α-amylase and α-glycosidase	Alezandro et al. (2010)
	Anthocyanins	*In vitro*/*in vivo*		Effective in inhibiting α-glucosidase/maltase activity	Santos et al. (2010)
Protective effect against hepatic damage	Anthocyanins	*In vivo*	Rats	Effective in liver protection from hepatotoxicity induced by BHP	Santos et al. (2010)
Protective effect against collagen degradation	Anthocyanins	*In vitro*		Inhibit elastase acting as a protection	Santos et al. (2010)
Cell regeneration properties	Anthocyanins	*In vitro*	Endothelial cells	Induce active phagocytosis and intense cell regeneration	Santos et al. (2010)
Benefit in cognitive performance	Anthocyanins	*In vivo*	Mice	Increase cognitive performance and protect brain function	Santos et al. (2010)

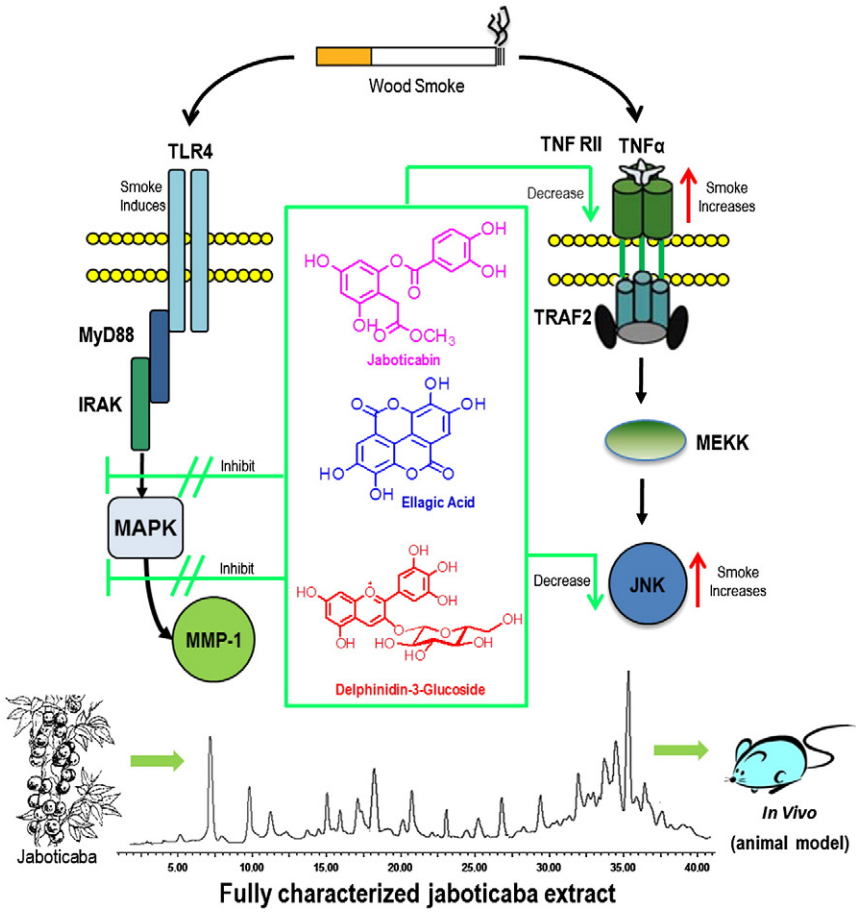


Fig. 5. The relationship between jaboticaba polyphenols (delphinidin-3-*O*-glucoside (**3**), elligic acid (**22**) and jaboticabin (**24**)) and the chronic obstructive pulmonary disease (COPD) (Barnes, Shapiro, & Pauwels, 2003; MacNee, 2000). Wood and cigarette smoke can induce human toll-like receptor 4 (TLR4) and further activates the mitogen-activated protein kinase (MAPK) and matrix metalloproteinase-1 (MMP-1) enzymes. Also, wood and cigarette smoke can increase tumor necrosis factor (TNF) and TNF receptor-associated factor 2 (TRAF2) expression, which will increase jun N-terminal kinases (JNKs). These three polyphenols can either inhibit MAPK and TNF enzymes, or reduce TRAF2 and JNKs. Both of these pathways are important for the treatment of COPD.

Recently, Leite-Legatti et al. (2012) also reported that jaboticaba peel showed strong antioxidant potential at three different assays: 25,514.24 ± 3037 μM TE g^{-1} (ORAC), 45.35 ± 0.50 μg mL^{-1} (DPPH), and 9458 ± 97 μM TEAC g^{-1} (ABTS) (Table 4).

As for *in vivo* antioxidant model, Leite et al. (2011) reported that the antioxidant potential of rat plasma increased 1.7 times after oral treatment with 1 and 2% freeze-dried jaboticaba peel, as measured by the TEAC assay, and 1.3 times by ORAC assay. Therefore, consumption of jaboticaba peel increased the antioxidant capacity of the blood *in vivo*.

There have been only five anthocyanins detected or isolated from jaboticaba, which are fewer from other dark-colored fruits, such as blueberry and grapes. However, the total anthocyanin level for jaboticaba has been reported up to 315 mg in 100 g fruits, and the total phenolic was 460.9 mg (Table 2). When compared with blueberry, it was reported to contain 200–350 mg (total anthocyanin) and 350–490 mg in 100 g fresh fruits (total phenolic) (Yuan et al., 2011). As the main antioxidant constituents reported in pomegranate juice are hydrolyzable tannins (Gil, Tomás-Barberán, Hess-Pierce, Holcroft, & Kader, 2000) we believe the potent antioxidant capacity of jaboticaba may also be due to the presence of large quantities of ellagic acid and ellagitannins in jaboticaba fruits (Wu et al., 2012).

5.3. Treatment of COPD and anti-inflammatory activity

Table 5 summarizes the other biological activities of jaboticaba. Our work on jaboticaba has focused on examining its potential for the treatment of COPD, a complex lung disease characterized by irreversible airflow obstruction due to chronic inflammation. We reported that the new depside, jaboticabin (**26**) decreases IL-8 production in small airway epithelial (SAE) cells treated with cigarette smoke extract (CSE) by 47.3% and decreased production 81.3% in untreated SAE cells. Also, a known depside (**25**) inhibited IL-8 production by 70.3% in treated SAE cells and inhibited by 74.9% in untreated SAE cells. Similar activity of anthocyanins **3** and **4** were found in the same experiment (Reynertson et al., 2006). The ability of these depsides to decrease IL-8 production suggested an important anti-inflammatory action of these compounds. COPD includes chronic obstructive bronchiolitis and emphysema. These diseases are considered steroid-resistant, and it has been noted that nonsteroidal anti-inflammatories targeting chemokine pathways are needed as new therapies (Reynertson et al., 2006). Our group demonstrated that jaboticaba depsides and anthocyanins can reduce inflammation caused by exposure to cigarette smoke and hypothesized that there may be a novel therapeutic role for these compounds in the treatment of COPD (Fig. 5). Therefore, a patent based on the constituents from jaboticaba (anthocyanins and depsides) for the treatment of COPD was applied and is held (D'Armiento, Reynertson, Kennelly, & Wallace, 2007). Using jaboticabin (**26**) that we have successfully synthesized in the laboratory (Wu et al., 2013), we will further explore the depside's biological activity in animal experiments in the near future. Analogues of jaboticabin are being made to explore structure–activity relationships.

Recently, Dastmalchi et al. (2012) also reported that the edible *M. vexator* fruit, known as blue grape or false jaboticaba, has potential for the treatment of COPD due to the presence of jaboticabin; in addition,

its most abundant compound, ellagic acid (**22**) was found to inhibit cigarette smoke extract induced MMP-1 expression *in vitro*. As ellagic acid was also detected from jaboticaba, this fruit and its related dark-colored species are promising emerging functional foods for smokers trying to decrease the impact of lung damage due to cigarette smoke exposure (Fig. 5). However, the fruits of false jaboticaba are not as widely consumed, and are generally considered less pleasant tasting than jaboticaba.

5.4. Antimicrobial and antidiarrheal

Most of the previous studies about the antimicrobial activity of jaboticaba were focused on its leaf extracts. From 2008 to 2010, both Macedo-Costa et al. (2008) and Souza-Moreira, Moreira, Sacramento, and Pietro (2010) studied the antimicrobial of jaboticaba leaf extracts. The strong *in vitro* bactericidal activity of jaboticaba leaf extract against oral biofilm bacteria indicated that this plant can be used as an economic alternative to control odontological diseases (Macedo-Costa et al., 2008). Souza-Moreira et al. (2010) found that a polar jaboticaba leaf extract showed great activity against *Candida* species, such as *Candida tropicalis* and *Candida albicans*. de Oliveira et al. (2011) also supported the antiseptic activity of jaboticaba leaf extracts. It was reported that jaboticaba leaf extracts showed effects against *Staphylococcus aureus* and some other species by using agar diffusion method, which suggests these extracts may be useful in skin infections, especially in the treatment of candidiasis (de Oliveira et al., 2011). In the same year, Haminiuk et al. (2011) reported the antimicrobial activity of ethanolic extracts of seven fruits including jaboticaba from Brazilian Atlantic Forest, and it was found that only jaboticaba fruits showed a slight inhibitory effect on the Gram-positive bacterium (*Klebsiella pneumoniae*), but no effect was observed in the tests on *Escherichia coli* and *S. aureus*. As for antidiarrheal activity, Souza-Moreira reported that jaboticaba fruit and leaf extracts showed some activity against *Enterococcus faecalis*, *E. coli*, *Salmonella* spp., and *Shigella* spp., but have no effect on gastrointestinal motility (Souza-Moreira et al., 2011).

5.5. Benefits in controlling obesity, insulin resistance, and diabetes

Type 2 diabetes (T2D) is a disease which can be characterized by insulin resistance and pancreatic beta cell dysfunction, and leads to macro- and microvasular complications (Sancho & Pastore, 2012). According to some studies, anthocyanins may prevent type 2 diabetes and obesity (Sancho & Pastore, 2012; Santos & Meireles, 2009). Recently, jaboticaba fruits, which have high concentrations of anthocyanins in their peel, have been shown to have potential benefits on the treatment of obesity and insulin resistance in experimental animals (Alezandro, Lajolo, & Genovese, 2010; Lenquiste, Batista, Marineli, Dragano, & Moróstica, 2012). Recently, Lenquiste et al. (2012) reported that the consumption of 1, 2, and 4% of freeze-dried jaboticaba peel can reduce serum insulin (47, 57 and 52%) and HOMA-IR (40, 54 and 48%) in obese rats. Also, the consumption of 2% of freeze-dried jaboticaba peel was shown to increase HDL-cholesterol levels at 41.65% when compared to HF control, which supported that freeze-dried jaboticaba peels have the ability to increase HDL-cholesterol and improve insulin resistance. Jaboticaba has significant inhibitory activity against α-amylase and α-glucosidase activities (Alezandro et al., 2010). Interestingly, iso-oenothein C (**23**) was reported in 2012 as a new compound isolated from jamun (*Eugenia jambolana*, Myrtaceae) seeds, and showed strong α-glucosidase inhibitory activity with IC_{50} = 8.2 μM. Oenothein C (**24**) also showed a moderate inhibitory activity in the same assay (Omar et al., 2012). The isolation of these two ellagitannins (**23** and **24**) from jaboticaba indicated that this edible fruit may also have α-glucosidase inhibitory activity (Wu et al., 2013).

5.6. Cytotoxic/antiproliferative/anticancer activities

In 2006, we reported that 2-*O*-(3,4-dihydroxy-benzoyl)-2,4,6-trihy-droxy-phenylacetic acid (**25**) and jaboticabin (**26**) have moderate cytotoxic effects on the HCT116 and HT29 colon cell lines, and that their IC_{50} values were 30 μM and 65 μM, respectively. Delphinidin 3-glucoside (**3**) also showed strong cytotoxicity against both HCT116 and SW480 cell lines (IC_{50}s: 12 and 20 μM, respectively). However, cyanidin 3-glucoside (**4**) showed only slight cytotoxicity (IC_{50} at the 100 μM range) which is consistent with the published literature (Reynertson et al., 2006). Leite-Legatti et al. (2012) also studied the antiproliferative effects of jaboticaba peel on 11 different tumor cell lines, and concluded that the polar extract of jaboticaba peels showed strongest antiproliferative activity on a leukemia (K-562) cell line (GC_{50}: 1.9 μg mL^{-1}), and its non-polar extract showed the most activity against a prostate (PC-3) cancer cell line (GC_{50}: 13.8 μg mL^{-1}). The authors also carried out a micronucleus test indicating that the polar jaboticaba-peel extract induced no DNA damage and showed no cytotoxic effects on murine bone marrow cells and caused no mutagenic effects. This was the first report of the antimutagenic activity of jaboticaba *in vitro* (Leite-Legatti et al., 2012).

6. Processing of jaboticaba

6.1. Stability and changes in the quality of jaboticaba during storage

Jaboticaba fruits are consumed in the forms of juices, jams, liqueurs, distillates, wine, and ice cream, as an alternative to prevent post-harvesting losses. Therefore, the stability and changes in the quality during storage become important. This fruit spoils easily, leading to rapid changes in appearance arising from the loss of water, physiological and microbiological deterioration, and pulp fermentation (Donadio, 2000). Recently, some publications concerning the changes in the quality of jaboticaba fruit or its commercial products were reported (da Silva Agostini et al., 2009; Alves da Silva, de Faria, Tonon, Dornelas Mota, & Pinto, 2008; Chiarelli, Nogueira, & Venturini Filho, 2005; Fortes et al., 2011; Teixeira, Durigan, Santos, Hojo, & Cunha Júnior, 2010). da Silva Agostini et al. (2009) evaluated the physicochemical effects of different storage conditions (room temperature and refrigeration) for jaboticaba cv. 'Paulista', and it was found that PVC film and polyethylene were efficient in reducing mass loss. Also, refrigeration was important for the post-harvest maintenance of jaboticaba as fruits could remain edible for up to 12 days, *versus* 8 days at room temperature. In 2010, Teixeira et al. (2010) studied the effect of controlled atmosphere (CA) with varying concentrations of oxygen during cold storage of jaboticaba fruits. It was found that the total anthocyanin content decreased 40.4% during CA storage, and was not affected by oxygen concentration. Chiarelli et al. (2005) also reported that during jaboticaba fermentation, maceration time did not interfere with alcohol level, total sulfur dioxide content, nor the pH value; however, the color and yield did show a positive correlation to maceration time.

6.2. Optimization of the extraction of bioactive constituents

Recently, some studies focused on the optimization of bioactive compound extraction, including anthocyanins, from jaboticaba peels (Cavalcanti, Veggi, & Meireles, 2011; Santos, Albuquerque, & Meireles, 2011; Santos & Meireles, 2011; Santos, Veggi, & Meireles, 2012; Santos et al., 2010). It was reported that bioactive compounds from Brazilian jaboticaba peels were more effectively extracted by high-pressure carbon dioxide assisted extraction (HPCDAE) (Santos & Meireles, 2011) and pressurized liquid extraction (PLE) with certain optimum conditions (Santos et al., 2012), as well as by using supercritical fluid extraction (SFE) (Cavalcanti et al., 2011) and a

homemade pressurized solvent extraction system (Santos et al., 2011). In 2005, Montes, Vicario, Raymundo, Fett, and Heredia (2005) also utilized tristimulus colorimetry (monitored at 535 nm) to optimize the extraction of anthocyanins from jaboticaba peels, and the yield of anthocyanins correlated significantly (ANOVA) with lightness (L^*) ($p < 0.05$; $r = -0.85$) and chroma (C^*_{ab}) ($p < 0.05$; $r = 0.84$). In addition, the type of acid used and solvent/water ratio ($p < 0.05$) play an important role, and ethanol acidified with HCl but with pH > 2 would be the best option to obtain a pigment with the highest C^*_{ab} and h_{ab} values, and the lowest L^* values. Sato and Cunha (2009) reported that the particle size of pulp may be important to the rheological properties of jaboticaba processing.

In order to protect ingredients that are sensitive to light, oxygen, and free radical degradation, spray-drying microencapsulation technology is often used in the food industry. By simultaneous optimization of different carrier agents and temperatures for the production of jaboticaba extracts by spray-drying microencapsulation, they determined that at 180 °C, the use of the excipients maltodextrin and gum arabic achieved more homogeneous particles for spray dry microencapsulation (Silva, Stringheta, Teófilo, & de Oliveira, 2013).

6.3. Optimization of fermentation conditions

The fermentation conditions (temperature and sugar content, aka °Brix) for producing jaboticaba spirit were optimized by using the response surface methodology (RSM); 20 °C and 22 °Bx were found to be the optimal conditions to produce jaboticaba distillate (Duarte et al., 2011). Also, chemical changes during jaboticaba fermentation were evaluated by ^{1}H NMR spectroscopy and chemometric analyses, and it was found that alcohols, organic acids, pH, and titratable acidity can influence the extraction and stability of anthocyanins and color properties (Fortes, Naves, Ferri, & Santos, 2012).

7. Future prospects and challenges

Although some publications related to jaboticaba have been reported recently, the challenge still remains to study its secondary metabolites, since there are only a handful of publications concerning its chemical constituents (Reynertson et al., 2006; Wu et al., 2012). There is no phytochemical report on the other tissues of this plant, and these tissues could be further exploited, in order to isolate and identify the various biologically-active constituents responsible for its activity.

More research is needed to relate the chemical constituents of jaboticaba with certain biological activities, to obtain a better understanding of their molecular targets and mechanisms of action. There is a dearth of human studies with jaboticaba and more are needed in the future, in particular randomized controlled trials, in order to confirm the potential health-related properties that the fruit has shown in *in vitro* and in animal studies.

Outside of Brazil, jaboticaba is not widely consumed or recognized due to the issue of spoilage during transportation. For this healthful fruit to be consumed worldwide, enhancement of storage methods, maximization of color retention by anthocyanins, and extension of shelf life need to be further researched (Wu et al., 2012). Due to its generally acknowledged pleasant taste profile, as well as its unique phytochemical and bioactivity profiles, jaboticaba is poised to be an important newly recognized functional fruit (Abe et al., 2012). However, up to now there is no study focusing on the selection, breeding, and the use of genomic tools for the improvement of this crop and its bioactive properties. Also, there are few publications about the morphology and phylogeny of jaboticaba and its related fruits. We believe these fields of inquiry will be important future research trends.

8. Conclusions

This review has summarized the relevant literature concerning the chemical constituents, biological activities, and processing of jaboticaba in the last ten years. Jaboticaba fruits, rich in certain anthocyanins, phenolic acids, and flavonoids, have high antioxidant activity in addition to other important biological activities, such as antimicrobial, antidiabetes, and benefits in controlling obesity and COPD. Thus, this dark-colored fruit can be used to enhance the bioactive compounds in food products and to treat or prevent various human diseases.

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