Camu-camu—*Myrciaria dubia* (Kunth) McVaugh

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Chapter Outline

CULTIVAR ORIGIN AND BOTANICAL ASPECTS

Myrciaria dubia (Kunth) McVaugh "camu-camu" is a typical native fruit shrub found in the tropical rainforests of the Amazon. Natural populations of this species grow in dense areas exposed to substantial flooding (complete submergence for four to five months) on the banks of rivers, streams, lakes and swamps of Guyana, Venezuela (Casiquiare Oreda, Pargueni, Caura, and Orinoco), Colombia (Putumayo and Inirida), Ecuador, Brazil (Maçangana, Urupa, Javari, Madeira, and Black), and Bolivia (Villachica, 1996; Lim, 2012). The greatest concentration of natural populations and source of genetic variability, however, is found in the Loreto region of the Peruvian Amazon, specifically along the basins of the Amazon, Putumayo, Napo, Curaray, Tigre, Marañon, Yavari, Ucayali, Itaya, Nanay, Tahuayo, Pintuyacu, Ampiyacu, Apacayu, Manati, Orozam, and Curaray rivers (Villachica, 1996; Peters and Vasquez, 1987; Rodrigues et al., 2001).

Camu-camu can adapt very well to different edaphoclimatic conditions. Populations can be found in the well-drained loamy oxisols and clay-rich floodplains of the Amazon River as well as in the sandy soils of black water rivers that are nutrient poor (Lim, 2012). In addition to its preferred habitat, it can thrive in land soils, acid soils, low fertility soils, and poor drainage soils (Villachica, 1996) that are present in land forms such as lowlands, riversides, low and high restinga, and others (Penn, 2006). This habitat flexibility has enabled the expansion of *M. dubia* cultivation to other macroregions such as the highlands and coast of Peru where increased production is essential to meet the growing regional, national, and global demand for fruit pulp and other products derived from this species.

Camu-camu is approximately 4−8 m in height that branches from the base to form several secondary stems, which in turn branch out as an open vessel. The trunk (~ 14 cm in basal diameter) and branches are glabrous, cylindrical, smooth, and the bark is light or reddish brown, which peels off naturally in periods of drought (Peters and Vasquez, 1987; Imán et al., 2011). The shrub is deeply rooted and the roots contain numerous absorbing hairs. The leaves are opposed, single, petiolar, elliptical or lanceolate of 3−12 cm in length and 1.5−4.5 cm in width, with an acuminated apex and rounded base, provided with a central vein with 18−20 pairs of lateral veins. The petiole is cylindrical with a length of 3−9 mm and width of 1−2 mm. The inflorescences are axillary with 1−12 (generally four) subsesiles and hermaphrodite flowers arranged in two pairs on the axis. The rounded ciliated bracts and bracteoles are persistent. The calyx is approximately 2 mm long and 2 mm wide and includes 4 sepals with apex broadly and the hypanthium is prolonged and circumscissile at the summit of the ovary and falls with the calyx as a unit after anthesis (Landrum and Kawasaki, 1997). The corolla has four white ovate petals of 3−4 mm long with a ciliated margin. The ovary is inferior with a simple style that is

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FIGURE 1 *Myrciaria dubia* "camu-camu" fruit.

10−11 mm long and the androecium has 125 stamens of 6−10 mm in length and anthers of 0.5−0.7 mm length. Although camu-camu flowers are hermaphroditic, inbreeding is largely prevented by the lack of synchrony between the development of the gynoecium and androecium, leading to facultative allogamy (Villachica, 1996; Peters and Vasquez, 1987; Imán et al., 2011). The fruit is globular (Fig. 1), 1.0−4.0 cm in diameter and their weight averages 8.4 g. The shiny peel can be pink to deep red or even black when completely ripe, with a slightly pinkish pulp (Villachica, 1996; Peters and Vasquez, 1987; Imán et al., 2011). The seeds are kidney-shaped to ellipsoid, flattened bilaterally and are exalbuminous (reserve materials are accumulated within the cotyledons). A fruit contains one to four seeds with an average length of 13.5 ± 1.6 mm and width of 4.8 ± 0.6 mm. The average fresh seed weight is 440 ± 170 mg. The elongated seed coats are brown, thin, and covered with spiny-celled villi (Uchiyama et al., 1996; Medina et al., 2014).

HARVEST SEASON AND ESTIMATED ANNUAL PRODUCTION

Natural and cultivated populations are harvested between September and April. The estimated annual fruit production of camu-camu is highly variable in both natural and cultivated populations. For example, in Sahua Lake, a natural population located in the floodplain of the Ucayali river, Peters and Vasquez (1987) estimated that fruit production ranged between 9.5 and 12.7 t/ha per year. Recently, however, the Minister of Agriculture and the Agrarian Regional Direction of Loreto estimated that natural and cultivated populations in the Loreto Region fruit production ranged between 1.5 and 8 t/ha per year, with an average of 3 t/ha per year (Defilippi, 2011; Dirección Regional Agraria Loreto, 2010). This high variability is due to the high density of seedlings per hectare in some areas, which can be as dense as ten thousand (Peters and Vasquez, 1987). In addition, investigations have consistently shown that fruit production is highly and positively correlated (r values from 0.97 to 0.99) with the trunk basal diameter (Peters and Vasquez, 1987). In the Loreto region, there are 7820 ha of cultivated populations with an estimated fruit production of 5.7 to 12.7 t/ha per year (Defilippi, 2011). This variability is attributed to several factors, such as the use of unselected seeds obtained directly from natural populations (94% of cultivated areas) and only a small fraction of cultivated areas have been planted with improved seeds provided by the Instituto Nacional de Innovación Agraria (INIA). This improved seed is an amalgamation of populations MD-014-INIA and MD-015-INIA that were obtained by a genetic improvement program conducted by INIA during the past 10 years. These populations are characterized by increased fruit production of >15 t/ha per year with high L-ascorbic acid (vitamin C) content of more than 2.0 g per 100 g of fruit pulp (Imán et al., 2011).

FRUIT PHYSIOLOGY AND BIOCHEMISTRY

The development of camu-camu fruits from flowering to ripening takes a period of approximately 14−15 weeks (Bardales et al., 2008; Neves et al., 2015). After anthesis, the fruits show a sigmoidal growth curve, characterized by an initial period (until 60 days after anthesis) of rapid growth rate (~683 mg/day). In the second period, the growth rate decreases and the fruit reaches its final full size (~81 days after anthesis). Finally, ripening takes place, which is characterized by a slight decrease in weight and change in the fruit color from green to red and finally purple. Such changes are intended to reflect the onset of fruit ripening and senescence. The fruit exhibits nonclimacteric patterns both in respiration rate and ethylene production. In the first, because fruits are characterized by the absence of a respiratory peak and a decrease in respiration rate levels (below 100 mg CO_2/kg per h) throughout development (Bardales et al., 2008; Neves et al., 2015; Gonzáles et al., 2013). Looking at ethylene production, the fruits exhibit a low and a steady-state production of this gaseous signal molecule during development and ripening (Bardales et al., 2008; Neves et al., 2015).

In contrast to ethylene production, other biochemical components exhibit significant concentration variation during fruit development, such as total sugars, reducing sugars, soluble pectin, total flavonols, cyanidin-3-glucoside, and vitamin C (Neves et al., 2015; Alves et al., 2002; Chirinos et al., 2010). Vitamin C concentration, however, decreases in the last step of ripening (Neves et al., 2015). The biochemical components that exhibit decreases in concentrations are starch and total pectin. The decrease in total pectin is due to depolymerization and subsequent solubilization by catalytic activity of pectin methyl esterase and polygalacturonase (Neves et al., 2015; Alves et al., 2002).

Also, our research group has conducted several biochemical and molecular studies related to vitamin C metabolism in camu-camu. First, we have demonstrated the capability for vitamin C biosynthesis of leaves, pulp, and peel through the D-mannose/L-galactose pathway, because we detected mRNAs of the six key genes (GDP-D-mannose pyrophosphorylase [GMP]), GDP-D-mannose-3′,5′-epimerase, GDP-L-galactose phosphorylase, L-galactose-1-phosphate phosphatase, L-galactose dehydrogenase [GDH], and L-galactono-1-4-lactone dehydrogenase (GLDH)] and catalytic activities of the corresponding enzymes (GMP, GDH, and GLDH) (Castro et al., 2015). In addition, with next-generation sequencing, de novo assembly, and transcriptome annotation of the fruits we identified five metabolic pathways for vitamin C biosynthesis: animal-like pathway, myo-inositol pathway, L-gulose pathway, D-mannose/L-galactose pathway, and uronic acid pathway. We also identified transcripts coding enzymes involved in the ascorbate-glutathione cycle, polyphenol biosynthesis, starch and pectin metabolism, and several other metabolic pathways (Castro et al., 2015).

CHEMICAL AND NUTRITIONAL COMPOSITIONS

Pioneering work on chemical and nutritional compositions of camu-camu fruits were performed in the early 1990s by Zapata and Dufour (1993). Further investigations have allowed us to understand, more exhaustively, the various chemical and nutritional components that are contained within this native fruit plant of the Amazon. The chemical and nutritional compositions of camu-camu fruits are shown in Table 1. These fruits are composed of carbohydrate, proteins, lipids, ash, and several other chemical constituents. It is also a good source of essential amino acids and fatty acids, as well as vitamin C, B-complex vitamins, and vitamin A. This fruit, however, is very interesting especially for their exceptional high content of vitamin C (0.96−2.99 g/100 g), which is approximately 60 times higher than that of orange juice (Villachica, 1996; Alves et al., 2002; Castro et al., 2015; Castro et al., 2015; Zapata and Dufour, 1993; Rodrigues and Marx, 2006). Additionally, it contains several minerals such as potassium, phosphate, sulfate, calcium, magnesium, chloride, sodium, copper, cobalt, iron, and selenium.

HEALTH-PROMOTING PHYTOCHEMICALS

In the Loreto region of Peru, camu-camu is widely used in folk medicine for the treatment of diseases such as asthma, atherosclerosis, cataracts, depression, flu, gingivitis, glaucoma, hepatitis, infertility, migraine, osteoporosis, Parkinson's disease, and malaria (Rengifo, 2009). These traditional uses are in agreement with recent investigations showing that camu-camu is a significant source of various bioactive phytochemicals with demonstrated beneficial properties for health (Table 2) (da Silva et al., 2012; Nascimento et al., 2013; Azevêdo et al., 2015; Zanatta and Mercadante, 2007; Kaneshima et al., 2016). For example, Inoue et al. (2008) demonstrated that camu-camu fruits provide powerful antioxidant and antiinflammatory properties in comparison to vitamin C tablets. Similarly, findings of Yazawa et al. (2011) suggest that camu-camu seed extract is a potentially useful material as a source of betulinic acid and as a functional food for the prevention of immune-related diseases. Also, the active compound 1-methylmalate, present in the juice of camu-camu, was found to have hepatoprotective activity, as evidenced by significantly suppressing D-galactosamine induced liver injury in rats (Akachi et al., 2010). In addition, ethanol extract of fruits exhibited antiplasmodial activity with the ferriprotoporphyrin inhibition test with $IC_{50} = 1$ μg/mL (Ruiz et al., 2011). The ethanolic and aqueous extract from the cortex of camu-camu have also demonstrated antiplasmodial activity against the chloroquine resistant strain

TABLE 1 Chemical and Nutritional Compositions of Camu-Camu Fruit Pulp (per 100 g)

Components	Contents in pulp	
	Fresh	Freeze-dried
Moisture (g)	94.1–94.4	
Carbohydrate (g)	3.5–4.7	47.00 ± 0.00
Monosaccharides (g)	0.87–1.77	
Citric acid cycle intermediates (g)	2.48–2.90	
Protein (g)	0.4–0.5	6.65 ± 0.14
Lipids (g)	0.2–0.3	0.98 ± 0.07
Ash (g)	0.2–0.3	3.67 ± 0.21
Fiber (g)	0.1–0.6	19.23 ± 0.00
Total sugars (%)	1.28–1.48	
Starch (%)	0.34–0.44	
Total pectin (%)	0.11–0.21	
Total soluble solids (°Brix)	5.5–6.8	
Total titrable acidity (%)	2.63–2.86	
pH	2.51–2.54	2.61 ± 0.02
Energy (cal)	17–20.9	
Essential Aminoacids		
Phenylalanine (mg)	22–43	128
Threonine (mg)	28–36	124
Valine (mg)	16.8–31.6	176
Leucine (mg)	13.2–28.9	219
Isoleucine (mg)		124
Lysine (mg)		196
Histidine (mg)		110
Methionine (mg)		58
Essential Fatty Acids[a]		
C18:3ω6 (α-Linolenic acid)	16	
C18:2ω6 (Linoleic acid)	9.7	
Vitamins		
Vitamin C (g)	0.96–2.99	20.31 ± 0.04
Niacin (μg)	62	
Riboflavin (μg)	40	
Thiamine (μg)	10	
Vitamin A value (RE/100 g)	14.2–24.5	
Vitamin B12 (μg)		0.34
Minerals		
K (mg)	60–144.1	796.99 ± 43.94
PO_4 (mg)	25.6–29.5	
SO_4 (mg)	13.2–16.3	

(Continued)

TABLE 1 (Continued)

Components	Contents in pulp	
	Fresh	Freeze-dried
Ca (mg)	6.2–15.7	22.12 ± 2.54
Mg (mg)	4.7–12.4	33.47 ± 1.30
Cl (mg)	6.6–11.6	
Na (mg)	2.7–11.1	
Co (mg)	0.6–2.4	
Cu (μg)	200–800	0.84 ± 0.03
Fe (μg)	180–665	2.23 ± 0.12
Zn (μg)	120–472	1.26 ± 0.07
Al (μg)	210–300	
Mn (μg)	140–211	1.29 ± 0.08
B (μg)	50	
Br (μg)	17–26.8	
Cr (μg)	8.8–19.9	
Mo (μg)	2.3–6.2	
Se (μg)	0.33–0.52	

[a]*Percentage in total lipids.*

TABLE 2 Extracts and Bioactive Phytochemicals of Camu-Camu and Its Demonstrate Health-Promoting Properties

Components	Part of plant	Health-promoting properties	Reference
Extracts			
Methanolic, freeze dried	Seed, pulp, peel	Antimicrobial, antidiabetic	Myoda et al. (2010), Fujita et al. (2013)
Aqueous and ethanolic	Pulp, peel, cortex	Antiplasmodial	Ruiz et al. (2011), Gutierrez et al. (2008)
Aqueous	Fruit juice, pulp	Antioxidant, antiinflammatory, antigenotoxic, antiobesity	da Silva et al. (2012), Nascimento et al. (2013), Inoue et al. (2008)
Aqueous and acetonic	Seed, peel	Neuroprotective	Azevêdo et al. (2015)
Bioactive Phytochemical			
Polyphenols	Pulp, peel	Antioxidant, antidiabetic, antimicrobial, cellular regeneration	Fracassetti et al. (2013), Fujita et al. (2013)
Carotenoids	Peel	Antioxidant	Zanatta and Mercadante (2007)
Ellagic acid and derivatives	Leaves	Aldose reductase inhibitor	Ueda et al. (2004)
1-methylmalate	Fruit juice	Hepatoprotective	Akachi et al. (2010)
C-glycosidic ellagitannins	Peel, seed	Antioxidant	Kaneshima et al. (2016)
Betulinic acid	Seed	Antiinflammatory	Yazawa et al. (2011)

FCR3 of *Plasmodium falciparum* with IC_{50} of 6 and 3 μg/mL, respectively (Gutierrez et al., 2008). Finally, Japanese research groups showed that the leaves contain aldose reductase inhibitors (Ueda et al., 2004), and the extract of camu-camu juice residue (seeds and peel) exhibit antimicrobial activity against *Staphylococcus aureus* (Myoda et al., 2010).

SENSORY CHARACTERISTICS

The high content of L-ascorbic acid and phenolic acid compounds makes the fruit very sour, affecting their palatability and making direct consumption of fruits nearly impossible. According to several researchers, the palatability index (total soluble solids: titratable acidity ratio) of camu-camu fruit is extremely low, ranging from 1.60 to 2.75. For comparison, the desired ratio is between 12 and 24 in plums and above 16 in apples (Vangdal, 1985). This ratio is an important qualitative attribute, because it indicates the relative contributions of the compounds responsible for sweetness and acidity, and therefore provides an indication of the fruit flavor (Prasanna et al., 2007). Despite the abundant information on the health benefits of the fruits, the juice has high sensory rejection (Vidigal et al., 2011). Due to its high L-ascorbic acid content, however, the pulp and juice are used to provide nutritional enrichment in soft drinks, juices, jams, icecream, concentrates, nectars, isotonic beverages, and yogurt (Rodrigues et al., 2001; Rodrigues et al., 2004). These preparations, particularly yogurt drinks, have high sensory acceptability, providing the population with a more nutritious and functional food option (Rodrigues and Marx, 2006; Aguiar and do Amaral, 2015).

HARVEST AND POSTHARVEST CONSERVATION

In the nonfloodable regions, harvesting is carried out manually, once or twice per week, according to the stage of production (Rodrigues et al., 2001). In natural populations, harvesting is also carried out manually, but canoes are used to move easily during the harvesting process, because at harvest time plants are submerged and it is possible to harvest only those that are above the water surface (Villachica, 1996; Alves et al., 2002). As the camu-camu fruits are nonclimacteric (Neves et al., 2015; Gonzáles et al., 2013), they are harvested in the three stages of ripening (i.e., green-unripe, half-ripe, and full-ripe fruit) approximately 70−100 days after anthesis (Peters and Vasquez, 1987; Imán et al., 2011). The fruits are marketed in the three stages of maturation alone or in combination, but ripe fruits in good condition usually have greater demand and higher costs. The green-unripe fruits, at their maximum size, are also harvested to be used for vitamin C obtention (Rodrigues et al., 2001).

A significant proportion of fruits, however, are lost by several factors before they can be sold. For example, the mechanical damage during harvest and the increase in metabolic activity by unsuitable conditions during transport and storage. In conjunction, these factors influence the shortening of the shelf life of fruits. In addition, production areas are remote from the consumption cities and commonly the only means of transport is fluvial. Consequently, during the past 15 years some technological approaches have been evaluated and developed to reduce costs associated with packaging, storage, and transportation.

Currently, there are five postharvest conservation approaches that focus on the dehydration processes of juice and fruit pulp for camu-camu: (1) hot air drying (Dib et al., 2003; da Silva et al., 2005; Fracassetti et al., 2013), (2) spouted bed drying (Fujita et al., 2013), (3) reverse osmosis (Rodrigues et al., 2004), (4) osmotic evaporation (Souza et al., 2013), and (5) freeze drying (Fujita et al., 2013; Silva et al., 2006; da Silva et al., 2006). However, these dehydration technological approaches differ significantly in the quality and quantity of the bioactive compounds present in the dehydrated material. For example, the hot air drying and spouted bed drying show a decrease from 45% to 64% of vitamin C. In contrast, reverse osmosis (7.6%−18.4% losses of vitamin C) and osmotic evaporation (2.1%−4.4% losses of vitamin C) processes can concentrate camu-camu juice up to about 4-fold without damaging the nutritional potential of the raw material (Rodrigues et al., 2004). Also, the concentration of camu-camu juice by the coupling of reverse osmosis and osmotic evaporation processes proved to be an interesting alternative to the concentration of thermosensitive juices, reaching concentration levels up to 7 times for camu-camu juice's bioactive compounds (Souza et al., 2013). On the other hand, freeze drying is the best approach for bioactive compounds preservation in fruit pulp of camu-camu (Fujita et al., 2013). Its impact is minimal because the samples remain at a temperature below the freezing point during the process of sublimation, which tends to better preserve food quality. However, the expensive equipment, high energy costs, and long drying times are disadvantages which limits the application of these techniques (Ratti, 2001).

POTENTIAL INDUSTRIAL APPLICATION

Frozen fruit pulp is being exported to Japan, Asia, Europe, and the United States, where it is utilized as the main added value product for pharmaceutical and cosmetics industry, as well as for the food industry. In the food industry it is commonly used for mixed drinks to increase the vitamin C content. In Latin American countries, camu-camu is used at a small scale in the food, cosmetic, and pharmaceutical industry. In the first, the pulp is used to produce mainly juice, nectar, jam, icecream, candy, yogurt, cereal bars, and alcoholic drinks (Aguiar and do Amaral, 2015; Ayala-Zavala et al., 2011; Bustamante et al., 2000; Maeda and Andrade, 2003; Peuckert et al., 2010). In the cosmetic industry, it is used in shampoo (Bustamante et al., 2000), and a pilot study showed promise as a sunscreen in lotion and gel (Inocente-Camones et al., 2014). Finally, frequently after freeze-drying of the pulp, it is used to produce tablets and capsules as a source of natural vitamin C. Also, it is used for the elaboration of nutraceutical concentrates mixed with other fruits, honey from bees, or resinous substances such as copaiba and propolis (Santa Natura-Productos Naturales, 2016). To support the growing demand for industrial use of camu-camu, however, it is important to increase cultivation areas, because demand currently outweighs supply.

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