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Anatomical Study of Passion Fruit Aril Structure and Juice Quality in Different Aril Parts

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Passion fruit has edible arils with a complicated structure. Each aril has three different membranes; an external membrane, an internal membrane with a fimbriate structure at the basal area, and a transparent membrane that completely envelops the seed. It was reported that juice quality, including organic acid and sugar contents, varied depending on the extraction method. So, organic acid and sugar are potentially localized inside the aril. In this study, using three cultivars (purple passion fruit, yellow passion fruit, and 'Summer Queen', a hybrid variety between the two), juice qualities of different aril parts were determined. The aril was separated into three parts, that is, the outer pulp (OP), the distal part of the inner pulp (DIP), and the basal part of the inner pulp (BIP). The OP included the external membrane and the juice held by this membrane. The DIP surrounding the seed and the BIP was a fimbriate structure attached to the internal membrane. In all varieties, titratable acidity (TA) and citric acid content at DIP were higher than those at OP and BIP, although there were some differences among the varieties. Malic acid content did not vary among the parts. Total soluble solid content (TSS) at BIP was the highest among the parts, and glucose, sucrose, and fructose contents at DIP were lower than those at BIP. Purple passion fruit had a high juice content at OP and the yellow cultivar had high juice content at DIP, while the hybrid between the two showed intermediate characteristics. Organic acid and sugar were localized inside the aril in the passion fruit cultivars; the citric acid content and TA at DIP were higher than those at OP and BIP, and TSS at BIP was higher than those at DIP and OP. Therefore, adjusting the juice extraction intensity may be needed depending on the required juice quality.

Key Words: citric acid, juice sack, malic acid, *Passiflora edulis*, sugar content.

Introduction

Passiflora has about 400 species, and 50–60 species bear edible fruit (Martin and Nakasone, 1970). Among them, purple passion fruit (*P. edulis*), yellow passion fruit (*P. edulis* f. *flavicarpa*), and hybrids between the two are referred to as passion fruit in a narrow definition that is used in this paper. Passion fruit is now widely cultivated in tropical and subtropical areas, although the main production area is still South America, where passion fruit originated. Purple passion fruit has lower acidity than the yellow variety (Beal and Farlow, 1984) and is suitable for fresh consumption, while the hybrid varieties show intermediate characteristics. Passion fruit is used for both processing and fresh consumption. Recently, fresh consumption has been increasing, but processing is still important in Brazil (Ferraz and Lot, 2007; Meletti, 2011). The passion fruit juice volume imported into European countries is the second largest after pineapple among tropical fruit and has been increasing (CBI, 2021a). The juice mainly comes from Peru, Ecuador, and Vietnam, and the price has been relatively high (CBI, 2021b).

Passion fruit has a hard pericarp of 3–6 mm containing seeds attached by a funiculus to the endocarp and surrounded by an edible aril. The aril contains a large amount of juice with high organic acid and sugar contents. The aril has three different membranes; an external membrane, an internal membrane with a fimbriate structure at the basal area, and a transparent membrane which completely envelops the seed (Florez et al., 2003; Fig. 1). To extract juice, at first the fruit must be halved and after that arils with seeds must be separated from the pericarp using a pressing machine such as a

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roller juice extractor. Then, seeds are removed to obtain juice using a screw-press or centrifugal refiner. The seeds are fragile and if they break, an oil that gives a rancid taste to the juice is released (Casimir et al., 1981), so the extraction process must be done carefully. To increase juice yield without breaking the seeds, a pectinolytic enzyme has also been used (Florez et al., 2003; Lipitoa and Robertson, 1977).

The quality of primary juice extracted using a scraper blade and that of secondary juice extracted using an enzyme after the primary juice extraction varied and the primary juice had higher total soluble solid (TSS) and titratable acid (TA) contents (Lipitoa and Robertson, 1977). Some farmers and researchers reported that strong pressing increases the acid content in juice, although there is no scientific report on this subject. Some consumers also find that the acidity is higher when chewing the pulp and seeds compared to without chewing. Therefore, organic acid and sugar may be localized inside the aril. The required juice quality depends on the intended use after juice extraction, so information on the organic acid and sugar contents of different parts of the aril is essential to establish an appropriate juice extraction method. In this study, using three cultivars (purple passion fruit, yellow passion fruit, and 'Summer Queen', a hybrid variety between the two), juice qualities of different parts of the aril were determined.

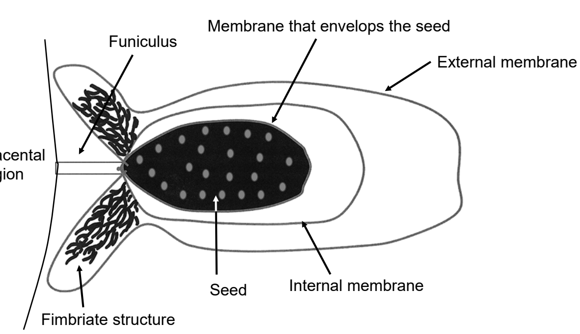

Fig. 1. Morphology of the passion fruit aril.

Materials and Methods

Purple passion fruit, yellow passion fruit, and a hybrid between the two, 'Summer Queen', were grown in a greenhouse at Kyoto University (35.0°N, 135.8°E). Five fruits harvested from each variety were used for experiments. The plants were grown in a trained hedge as described by Kondo and Higuchi (2011). To retain fruit on vines and prevent them from dropping to the ground, each fruit peduncle was tied to the vine with thread, and mature fruits that abscised from the vine were harvested. Fruits harvested from August 25 to September 19, 2011 were used. Following the method of Kondo and Higuchi (2011), the fruits were stored at 25°C for 10 days, and after that fruit was weighed. After weighing, fruit was longitudinally cut into three sections without cutting the juice sack. Using two of the three pieces, juice weight, titratable acidity (TA), and total soluble solid (TSS) were measured by the same methods described by Kondo and Higuchi (2011). Juice weight of whole fruit was calculated by multiplying the measured juice weight by 1.5, and after that juice content (%) was calculated by dividing juice weight by fruit weight. The number of seeds in three sections was also counted.

Every juice sack was removed from the peel of the remaining piece by cutting the funiculus using tweezers (Fig. 2A). The external membrane was removed easily by pulling the funiculus and the upper end of juice sack using tweezers (Fig. 2B). The external membrane and the juice held by the external membrane are dubbed as the outer pulp (OP), and the rest are dubbed as the inner pulp in this paper. The OPs were gathered and thoroughly squeezed by hand with a polyethylene cloth. The distal part of the inner pulp (DIP), including the structure and surrounding seeds, was pale yellow. The basal part of inner pulp (BIP), which was dubbed the fimbriate structure by Florez et al. (2003), was dark yellow. DIP and BIP were separated using scissors. The seed and DIP were easily separated by pushing the seed using tweezers (Fig. 2C). The DIPs and BIPs were

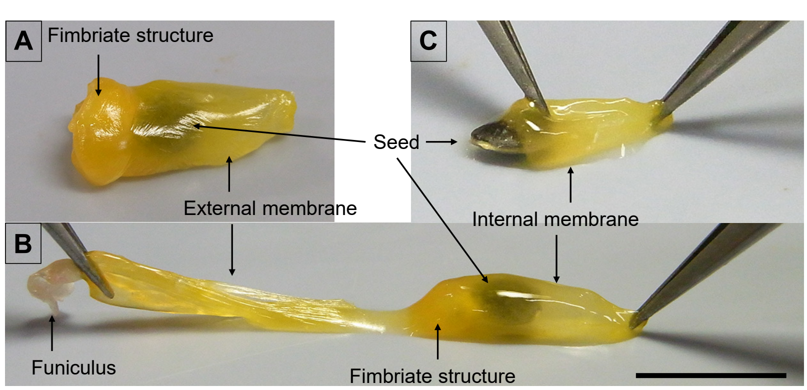

Fig. 2. Appearance of the passion fruit aril; an aril removed from the pericarp (A), the external membrane was removed from the internal membrane (B), a seed removed from the aril (C). Bar represents 1 cm.

gathered separately and thoroughly squeezed by hand with a polyethylene cloth. The series of operations to obtain the juices were carried out at 4°C to minimize the effect of evaporation during the procedure. The juices were weighed, and the number of seeds was counted to calculate the juice weight per seed. TA and TSS were measured by the same methods described by Kondo and Higuchi (2011). The juices were stored at −20°C until the sugar and organic acid contents were analyzed as described below. Using F-kit (Sucrose/D-Glucose/D-Fructose; J.K. International Inc., Tokyo, Japan), sucrose, glucose, and fructose contents were measured. The juice was centrifuged at 15,000 × g for 5 min, and the supernatant was diluted 200-fold and filtered through a 0.2 μm mesh filter. The citric and malic acid contents of the supernatant were measured using a high-performance liquid chromatography unit and a UV-VIS detector (LC-10, and SPD-10AV; Shimadzu, Kyoto, Japan) with 0.005 N H_2SO_4 as the mobile phase, a detector wavelength of 210 nm, a column (ROA-Organic Acid H+; Phenomenex, CA, USA) temperature of 55°C, and a flow rate of 0.5 $mL \cdot min^{-1}$.

The data obtained from three different parts were subjected to two-way ANOVA (part × variety). The whole pulp data were subjected to ANOVA. Significant differences ($P < 0.05$) between treatments were determined by Tukey's test. The whole fruit data were analyzed by Tukey's test.

Results and Discussion

For juice weight per seed there were interactions between the juice part and cultivar. The OP juice was heavier in purple passion fruit, while the weights of those of OP, BIP, and DIP were about 42, and 31, and 27% respectively (Table 1). DIP was heavier in yellow passion fruit, and those of OP, BIP, and DIP were about 26, and 33, and 41%, respectively. Summer Queen, the hybrid variety between the two, showed intermediate characteristics, while the juice weights of the three parts were almost the same. Lipitoa and Robertson (1977) and Florez et al. (2003) reported that juice weights extracted using a scraper blade and using an enzyme after scraper blade extraction were around 70% and 30%, respectively, in yellow passion fruit, although it is difficult to compare these results with our results because the membrane structure was likely disrupted by a scraper blade. The weight of the three parts combined in terms of juice per seed was lower in purple passion fruit (Table 2). The number of seeds was lower in purple passion fruit and higher in yellow passion fruit. As a

Table 1. The juice qualities of the outer pulp, basal part of the inner pulp and distal part of the inner pulp in purple passion fruit, yellow passion fruit, and a hybrid of the two, 'Summer Queen'.

Variety	Part	Juice weight per seed (mg)	TA (%)	Citric acid (%)	Malic acid (%)	TSS	Gulcose (%)	Sucrose (%)	Fructose (%)
Purple passion fruit	Outer pulp	40.1 a	0.56 b	0.59 b	0.30 a	15.0 b	6.0 a	1.2 a	5.2 a
	Basal part of inner pulp	29.1 b	0.63 b	0.63 b	0.26 a	15.8 a	5.9 a	1.9 a	5.3 a
	Distal part of inner pulp	25.4 b	1.86 a	1.95 a	0.25 a	15.2 b	5.5 b	0.9 b	5.0 a
Hybrid (Summer Queen)	Outer pulp	48.7 a	1.65 b	1.47 b	0.20 a	17.5 b	5.7 a	3.1 b	5.3 ab
	Basal part of inner pulp	44.8 a	1.61 b	1.54 b	0.19 a	18.1 a	5.9 a	3.8 a	5.6 a
	Distal part of inner pulp	47.4 a	4.03 a	4.42 a	0.18 a	17.1 b	5.1 b	1.9 c	4.8 b
Yellow passion fruit	Outer pulp	41.3 c	2.05 c	2.11 c	0.58 a	16.8 b	6.1 a	1.5 a	6.8 a
	Basal part of inner pulp	50.7 b	2.89 b	2.82 b	0.49 a	17.6 a	5.8 a	1.4 a	6.4 a
	Distal part of inner pulp	63.9 a	5.43 a	5.56 a	0.57 a	16.6 b	4.3 b	0.9 b	4.7 b
Variety 〔V〕		**	**	**	**	**	n.s.	**	**
Part 〔P〕		n.s.	**	**	n.s.	**	**	**	**
〔V〕 × 〔P〕 interaction		**	**	**	n.s.	n.s.	n.s.	**	**

**, and n.s. indicate significant defferences at $P < 0.01$, and not significant, respectively.
Within variety, different small letters indicate significant differences between part by Tukey's test at $P < 0.05$ (n = 5).

Table 2. The qualities of fruit and juice extracted from whole pulp of purple passion fruit, yellow passion fruit, and a hybrid between the two, 'Summer Queen'.

Variety	Fruit weight (g)	Juice weight (g)	Seed number	Juice weight per seed (mg)	TA (%)	TSS	Sugar/acid ratio
Purple passion fruit	30.8 c	11.4 c	124 c	94 b	0.9 c	15.3 b	16.7 a
Hybrid (Summer Queen)	81.5 b	30.6 b	219 b	141 a	2.4 b	17.5 a	7.4 b
Yellow passion fruit	116.2 a	48.9 a	314 a	156 a	3.6 a	17.0 a	4.9 c

Different letters within columns indicate statistical significance by Tukey's test at $P < 0.05$ (n = 5).

result, the juice weight per fruit was higher in yellow passion fruit and lower in purple passion fruit. Although it is known that the juice weight per fruit is higher in yellow passion fruit (Morton, 1987), the juice weights of each different aril part have not been reported. In lychee (Paull and Duarte, 2011) and durian (Aziz and Jalil, 2019), which also have edible arils, it has been reported that the aril weight differs among cultivars, although the weights of different aril parts were not reported. There are several fruits that have edible arils such as lychee, durian, mangosteen, and pomegranate, but none of them retain a large amount of juice in complex membrane structures as in passion fruit; therefore, there are no reports on the amount of juice or weight of each aril part.

TA at DIP was the highest among the parts in all varieties, although there was an interaction between each part and variety. In all varieties, citric acid contents were the highest at DIP and malic acid contents did not differ among the parts. In all parts, TA, citric and malic acid were the highest in yellow passion fruit. It is well known that the acid content is higher in yellow passion fruit and lower in purple passion fruit, while hybrids generally have intermediate characteristics (Beal and Farlow, 1984; Morton, 1987). In this study, it was shown that the high acid content in yellow passion fruit was due to the high acid content in each part of the aril and high juice content of the DIP, which had the highest acid content. TSS at BIP was the highest among the parts in all varieties (Table 1). Glucose and sucrose contents at DIP were the lowest among the parts in all varieties. In yellow passion fruit and Summer Queen, fructose contents at DIP were the lowest, while in purple passion fruit there was no statistical difference among the parts. TSS of whole fruit in purple passion fruit was the lowest among the varieties (Table 2). Lipitoa and Robertson (1977) reported that the TA and TSS of the primary juice extracted using a scraper blade in close contact with a screen with a 1.5 mm diameter hole were higher than those of secondary juice extracted from pulp and seeds remaining on the screen using a pectinolytic enzyme. Florez et al. (2003) also reported similar results from informal sensorial tests. The previous and current results differ, but it is difficult to compare them because the membrane structure may have been disrupted during the process of primary juice extraction with a scraper blade. Fruits with an edible aril include durian (Paull and Duarte, 2012), mangosteen (Nito, 2008), Sapindaceae fruits (Kothagoda and Rao, 2012), and pomegranate (Cui et al., 2004), but their arils are not as complex as passion fruit. For fruits with edible arils, characteristics such as TSS, TA, and aril weight vary among varieties (Aziz and Jalil, 2019; Paull and Duarte, 2011), and there are no reports about the characteristics of the different aril parts. Differences in pulp qualities of different parts have been reported in many fruits that do not have edible arils (Kim and Park, 2010; Nomura et al., 2005; Taira et al., 2016), and no common tendency has been observed regardless of the species or varieties.

In conclusion, the OP was heavier in purple passion fruit and that of DIP was heavier in yellow passion fruit, while the hybrid cultivar was between the two, showing intermediate characteristics. Citric acid content and TA at DIP was higher than those at OP and BIP and TSS at BIP was higher than those at DIP and OP, although there were some differences among the cultivars. Thus, the juice extracted at a low extraction intensity had low acidity and a high sugar content and juice extracted at a high extraction intensity had high acidity and a low sugar content. The demanded juice characteristics vary with the handling after juice extraction. For example, if no sugar is added after juice extraction, low acidity juice is demanded and if sugar is added high acidity juice is demanded. Therefore, adjusting the juice extraction intensity may be needed depending on the juice quantity and quality required.

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