



Research article

Effect of ripening stage on postharvest quality of abiu (*Pouteria caimito*) fruit during storage

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Abstract

Importance of the work: Abiu has many beneficial nutrients for the human body. However, the information is still limited on abiu fruit-related to physiological changes and fruit quality. The maturity stage at harvest is a critical factor that determines postharvest fruit quality throughout storage.

Objectives: To evaluate postharvest quality changes and determine better harvest maturity for good quality with a more extended storage period in abiu fruit.

Materials & Methods: Abiu fruit samples were harvested at both half-ripe and fully-ripe maturity stages and stored at ambient temperature ($28 \pm 1^\circ\text{C}$) for 12 d. The respiration pattern and physiological parameters were observed during the study.

Results: There was a significant effect between the maturity stages at harvest on fruit quality parameters in abiu fruit during storage. The respiration patterns of the abiu fruit followed the respiration patterns of climacteric fruit. The climacteric peak occurred on day 6 and day 8 for fully-ripe and half-ripe fruit, respectively. The pulp browning index of the harvested fully-ripe abiu fruit was 2-fold higher than for the half-ripe fruit. Fully-ripe harvested abiu fruit had a sweet taste, bright yellow color, shelf life of 6 d and turned brown quickly. However, the abiu fruit harvested when half ripe had a moderately sweet taste, yellow color, shelf life of 9–10 d and turned brown slowly.

Main finding: Considering the results of major postharvest quality parameters mentioned above, the abiu fruit harvested when half-ripe presented a better harvest maturity stage with good quality and longer shelf life.

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Introduction

Abiu (*Pouteria caimito*) is an exotic native plant of the Amazon, which is found in several regions of Latin America, especially Brazil and Peru (Love and Paull, 2011). Abiu has been introduced and developed in Indonesia. The abiu fruit usually is oval or round, has a bright yellow rind, varies in length size from 6.35 to 17.78 cm and it contains many beneficial nutrients and antioxidants for the human body, such as an inhibitor of acetylcholinesterase activity and being an antimicrobial (Abreu et al., 2019; Fernandez et al., 2020). Furthermore, abiu fruit has a soluble solid content of 10–12 °Brix, and titratable acidity of 0.04–0.08% (Meinhart et al., 2019); fruit with these characteristics is suitable for the tastes of consumers in Indonesia. However, studies on abiu fruit are still limited, especially regarding physiological changes and fruit quality.

Fruit quality can be maintained or any deterioration delayed during storage; however, the quality cannot be increased after the fruit is harvested. Therefore, the harvest factors affect the success of postharvest fruit management. The maturity stage at harvest is a critical factor that determines physiological changes and fruit quality throughout the storage period. Abiu fruit can be harvested as either half-ripe (Love and Paull, 2011) or fully-ripe (Love et al., 2014). In addition, the study of Sanches et al. (2017) stated that abiu fruit harvested at the maturity stage of 50% green and 50% yellow was preferred for consumption by consumers compared to abiu fruit harvested when green or yellow. Hence, it was hypothesized for the current study that abiu fruit harvested half-ripe would have better fruit quality with a longer shelf life. However, information is still limited on physiological changes and postharvest quality of abiu fruit at different maturity stages. However, it is essential to check the ripening quality at each maturity stage as it is the main feature that influences consumer preferences.

Thus, determining the fruit maturity stage is crucial to getting the best fruit quality and increasing the shelf life. More information regarding the respiration patterns and physiological changes of the abiu fruit will contribute to further research and development in extending storage life and maintaining the quality. Based on these reasons, the current study aimed to evaluate postharvest quality changes and determine the better harvest maturity for good quality with an extended storage period for abiu fruit. The results should help to determine the optimal maturity stage for the harvest of abiu fruit with better quality and a longer shelf life.

Materials and Methods

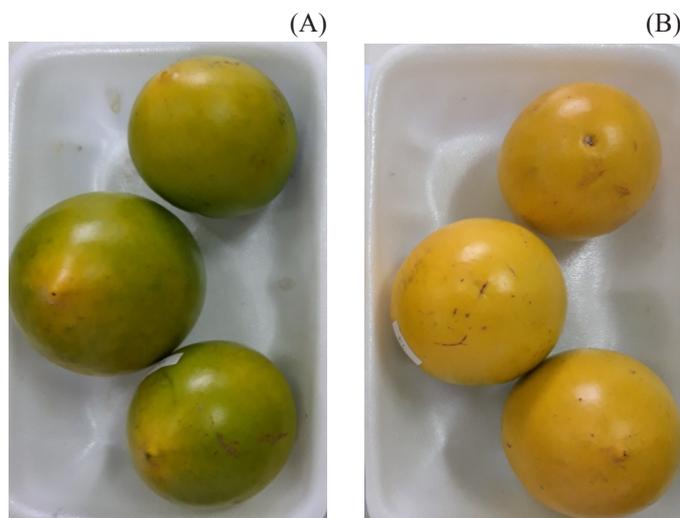
Fruit materials and storage treatment

The abiu fruits were obtained from farmers' gardens at an altitude of 200 m above sea level (60.21°E, 106.44°S) in Babakan Lebak, Balumbang Jaya Village, Bogor district, West Java province, Republic of Indonesia. Eighty abiu plants were used, all of which aged 3 yr and planted with a spacing of 3 m × 3 m. Each abiu plant was fertilized using 0.5 kg of NPK fertilizer (16:16:16) applied every 6 mth and 10 kg of manure spread once a year. Pruning was done on tree branches that received the least sunlight. The flowering stage of abiu in this research took place from January to February. The number of fruits growing on each tree was maintained at 10–15 and controlled using the fruit thinning method. Fruit bagging was carried out to protect the fruit from any potential damage caused by flies and birds. The harvesting period of abiu fruit in this research was during March and April. During this period, abiu fruits were selected by weight (250 ± 25 g) to obtain more uniform pieces of fruit; only fruit without any physical defects were picked.

The experiment was conducted based on a randomized block design. The current study used two maturity stages, half-ripe (HR) and fully-ripe (FR) that were determined based on color (Fig. 1). The characteristics of different maturity stages are given in Table 1. Each maturity stage treatment was carried out in five replications, each of which consisted of 25 fruits. Therefore, the study used 250 fruit for both maturity stages. Replication was based on harvest time, where the harvest time between replications differed by 7 d for the five replications. All fruit per experimental unit were placed in container boxes (80 cm × 60 cm × 45 cm) without a lid and stored in a room under ambient conditions (28 ± 1 °C and $80 \pm 5\%$ relative humidity, RH). In total, 125 fruit from each maturity stage were used to measure the destructive and non-destructive parameters on 105 and 20 fruit, respectively. Destructive parameters (1-aminocyclopropane-1-carboxylic (ACC) concentration, soluble solid content (SSC), titratable acidity (TA), firmness and pulp browning index) were measured every 2 d after the harvest time. However, the peel surface structure was only observed at the beginning and the end of the storage period by observing one fruit per replication; thus, 20 whole abiu fruit were used for this observation. Non-destructive parameters (weight loss, color changes, peel browning index, ethylene production and respiration rate) were measured daily.

Table 1 Characteristics of abiu fruit for two maturity stages

Maturity stage	Surface color	Hue color value	Time after fruit set (days)
Half-ripe	≤ 20% of the fruit surface showing yellow color	108±2	61±1
Fully-ripe	> 80% of the fruit surface showing yellow color	95±2	66±1

**Fig. 1** Abiu fruit at two maturity stages: (A) half-ripe; (B) fully-ripe

The entire storage and analysis processes were carried out at the general laboratory of the Indonesian Center for Agricultural Postharvest Research and Development, Indonesian Agency for Agricultural Research and Development, Ministry of Agriculture, Indonesia.

Respiration rate, 1-aminocyclopropane-1-carboxylic concentration, and ethylene production

The respiration rate and ethylene production were measured following the method suggested by Song et al. (2019). The respiration rate and ethylene production during storage were measured using a gas analyzer (Merck Felix, type F-950; Washington, USA) by flowing air in a sealed glass bottle into the gas analyzer with an airflow rate of 70 mL/min (Felix instrument). Each fruit was stored in a 2 L sealed glass bottle for 1 hr in ambient conditions (28 ± 1 °C and $80 \pm 5\%$ RH). Then, the glass bottles were transferred to a room at 23 °C and 85% RH to measure the respiration rate and ethylene production. These conditions were based on the Felix instrument, so that the gas analyzer functioned optimally. Measurements were done by opening the two valves of the sealed glass bottle and linking each with one of the two interfaces of the gas analyzer to form a closed loop. After the digital display of the instrument had stabilized,

the total volumes of CO₂, O₂ and ethylene in the closed glass bottle were recorded and the respiratory rate and ethylene production were calculated according to the measurement results. In total, 20 fruit from each maturity stage were used in the measurement (20 measurements per treatment per day). The respiration rate was expressed in milliliters per kilogram per hour and the ethylene production was expressed in microliters per kilogram per hour.

The method of Concepcion et al. (1979) was used to determine the ACC concentration. Each sample (1 g) of the abiu fruit pulp was collected and macerated in 30 mL of 80% acetone at a temperature of 60 °C for 1 hr. The mixture was passed through Whatman No. 45 filter paper and evaporated until dry at 45 °C. The dried substrate was dissolved in 3 mL of water and 2 mL of chloroform. Next, 0.7 mL of extracted water/chloroform was added with 4 μmol of CuCl₂ in a 10 mL bottle. The bottle was sealed with a rubber lid and stored on ice. Then, 0.6 mL of NaOCl and 10 N of NaOH (2:1 volume per volume) were injected into the bottle through the rubber lid. The bottles were shaken before and after incubation for 4 min on ice. The solution in the bottle was incubated at 20 °C for 18 hr; 1 mL gas samples were taken using a syringe and measured for the ACC a gas chromatography (GC) system, consisting of a GC Merck Varian 450 (CA, USA) with an injector temperature of 80°C, a detector temperature of 100 °C, and a column temperature of 80°C, with a gas flow rate of N₂ at 0.6 mL/min. Finally, the ACC concentration was expressed as milliliters per kilogram fresh weight.

Weight loss and firmness

The weight loss that occurred in the abiu fruit during the storage period was calculated using the method proposed by Tilahun et al. (2017). First, each fruit was weighed before storage and reweighed after set periods of storage. Finally, the weight loss per day was calculated by subtracting the sample weight on the day of measurement from the sample weight one day before. On the other hand, the total weight loss was calculated by subtracting the sample weight on the day of sampling from the sample weight before the storage period. The weight loss per day and total weight loss were expressed as percentages.

The method developed by Tilahun et al. (2019) was used to determine fruit firmness. The fruit firmness measurement was carried out using a Brookfield digital texture analyzer. The texture analyzer was set at mode 20, with a maximum load of 10 kg, a pressing depth of 15 mm, a speed of 60 mm/min and a needle probe diameter of 2 mm. The firmness measurement of each abiu fruit was done three times in the equatorial section of the fruit. The firmness was expressed in newtons.

Soluble solid content and titratable acidity

The SSC was measured using the method suggested by Milosevic et al. (2016). The SSC was measured from some extracted abiu juice in triplicate using an Atago DR-A1 digital refractometer (Atago Co. Ltd.; Tokyo, Japan) at 28 ± 1 °C. The SSC was expressed in °Brix.

The NaOH titration method developed by Islam et al. (2013) was used to determine the titratable acidity content. A sample of 10 g of abiu pulp was added with distilled water up to 250 mL in an Erlenmeyer flask. The solution was blended until it was well mixed. Then, 10 mL of abiu pulp solution was added to the conical flask. Two-to-three drops of phenolphthalein indicator were added, and then the conical flask was shaken vigorously. Next, it was filtered immediately with 0.1 N of NaOH solution from a burette until a permanent pink color appeared. The volume of NaOH solution required for the titration process was recorded and the TA was expressed as a percentage.

Color changes

The color changes were measured by modifying the process proposed by Tilahun et al. (2018). A CR-400 chroma meter (Minolta, Japan) was used to measure the L (lightness) and hue values of the abiu peel. The color measurement was carried out in three different parts of the abiu fruit (basal, equatorial and tip sections) and the average value was recorded.

Browning index

The browning index was evaluated by modifying the method introduced by Tang et al. (2020). A data scoring technique was used to measure the browning index. First, each fruit was inspected at the maturity stage to assay any browning symptoms based on the browning proportion of the abiu fruit pulp and peel. Browning symptoms on the abiu peel were assessed by visually estimating a percentage of the

area showing browning symptoms on the abiu peel surface. The browning symptoms in abiu pulp were assessed by cutting the fruit in half (longitudinally through the middle) and visually estimating the percentage of the cut area showing browning symptoms. Then, the symptoms of browning were assessed on a scale of 0–4, where 0 = excellent visual quality without browning; 1 = $0\% < \text{browning} \leq 25\%$; 2 = $25\% < \text{browning} \leq 50\%$; 3 = $50\% < \text{browning} \leq 75\%$, and 4 = $> 75\%$ browning of the peel area or the sectional pulp area, respectively (Seo et al., 2015). The browning index was calculated using the formula: $\text{browning index} = [\sum (\text{browning scale}) \times (\text{number of fruit at browning level}) / (\text{total number of fruit at maturity stages}) \times 5] \times 100$. The browning index was expressed as a percentage.

Fruit peel surface structure

The surface structure of the abiu fruit peel was observed by modifying the technique developed by Konarska (2013). First, the fruit peel was dried using a freeze dryer at -55 °C for 24 hr. Then, the peels were sliced into $5 \text{ mm} \times 5 \text{ mm}$ pieces. Next, the samples were coated with gold material using a sputter coater (Merck Quorum Type Q150R ES; East Sussex, United Kingdom) using a sputter time of 60 s and a sputter current of 20 mA. Finally, the samples were observed using scanning electron microscopy (SEM) with a Merck Zeiss Type Evo Ma10 (Oberkochen, Germany).

Statistical analysis

Data were reported as mean \pm SD of five replications. The data were subjected to analysis of variance, then means were compared using the Student t test. All tests were considered significant at $p < 0.05$.

Results

Respiration rate, 1-aminocyclopropane-1-carboxylic and ethylene production

The respiration rate pattern changes (CO_2 production and O_2 consumption), ACC and ethylene production are presented in Fig. 2. The maturity stages of the abiu fruit influenced the respiration rate (Fig. 2). The peak production of CO_2 , ACC and ethylene of the abiu fruit harvested at the FR stage occurred on day 6, while it was on day 8 for those harvested at the HR stage (Fig. 2). The CO_2 production levels of the abiu fruit at

the beginning of the storage period for both maturity stages were not significantly different. The CO₂ production of abiu fruit was 80.63 mL/kg hr and 84.15 mL/kg hr at the FR and the HR stages, respectively (Fig. 2A). However, there was a significant difference on day 4, when the CO₂ production of abiu fruit harvested at the FR stage was higher than for the HR stage, which continued until day 6 of the storage period. The CO₂ production of abiu fruit harvested at the FR stage decreased after day 6 in storage. On the other hand, the CO₂ production of abiu fruit harvested at the HR stage increased on day 6 and continued to increase until day 8 of the storage period.

The oxygen consumption of the abiu fruit during the storage period was in the range 60–80 mL/kg hr (Fig. 2B). The oxygen consumption of abiu fruit at the FR stage increased during the storage period and the peak of oxygen consumption ((80.32 mL/kg hr) for the FR stage occurred on day 7. On the other hand, the peak O₂ consumption of the HR stage was 78.01 mL/kg hr, which occurred on day 9.

The ACC concentration of abiu fruit at the beginning of the storage period was significantly different depending on

the maturity stage. The ACC concentration of abiu fruit was 33.64 mL/kg and 28.31 mL/kg for the FR and the HR stages, respectively (Fig. 2C). The ACC concentration of abiu fruit harvested at the FR stage was higher than for the HR stage from day 0 until day 6 of the storage period. However, after 8 d of storage, the ACC concentration of the HR stage became higher than for the FR stage. The ACC concentration decreased substantially after the peak until day 12 of the storage period. The ACC concentration of the abiu fruit was not significantly different between the two maturity stages at the end of the storage period.

Furthermore, the ethylene production on day 0 was 21.32 μL/kg hr and 20.85 μL/kg hr for the FR and the HR stages, respectively (Fig. 2D). The abiu fruit harvested at the FR stage substantially increased ethylene production to day 6 of the storage period. Similarly, the abiu fruit harvested at the HR stage increased ethylene production until day 8 of the storage period. At this point, the ethylene production had increased to five times higher than at the beginning of the storage period.

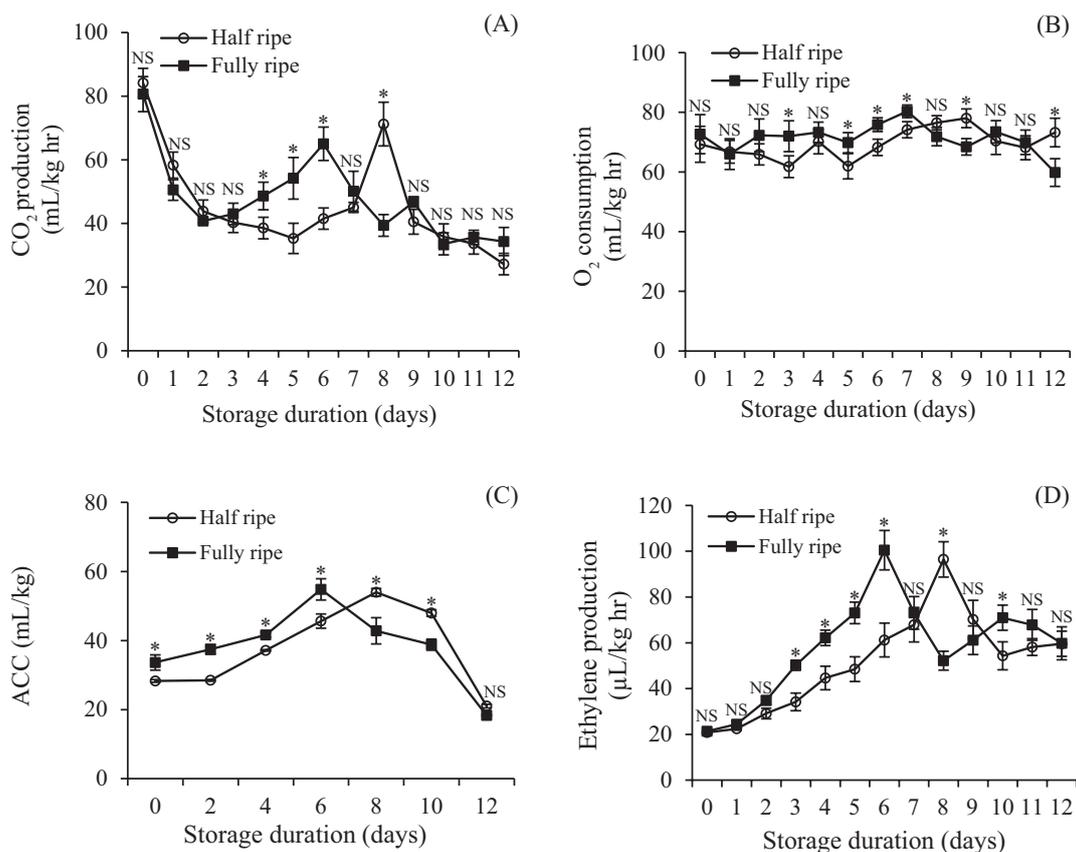


Fig. 2 Changes in: (A) respiration rate; (B) O₂ consumption; (C) 1-aminocyclopropane-1-carboxylic (ACC); (D) ethylene production for abiu fruit during storage; where data are means (\pm SD) of five replicates; NS = non-significant ($p > 0.05$) different and * = significant ($p < 0.05$) different between half- and fully ripe

Weight loss and firmness

The abiu fruit harvested at the FR stage increased in weight loss on day 5 until day 8 of the storage period and substantially decreased on day 9 (Fig. 3A). Similarly, the abiu fruit harvested at the HR stage substantially increased in weight loss on day 7 until day 10 of the storage period. The weight loss of the abiu fruit harvested at the FR stage was higher than for the HR stage from day 6 until day 8. The total weight loss at the end of the storage period (day 12) was not affected by the fruit maturity stage (Table 2). The total weight loss of abiu fruit continuously increased from day 1 until day 12 of the storage period.

For each maturity stage, the firmness of abiu fruit at the beginning of the storage period was significantly different being 10.659 N and 13.447 N for the FR and the HR stages, respectively (Fig. 3B). The abiu fruit firmness gradually decreased throughout the storage period. More specifically, the firmness of abiu fruits harvested at the FR stage was lower than for the HR stage.

Soluble solid content and titratable acidity

The maturity stage of the abiu fruit influenced the SSC from the beginning to the end of the storage period (Fig. 4A).

The SSC of abiu fruit harvested at the FR stage was higher than for the HR stage. At the beginning of the storage period, the SSC values of the abiu fruit were 10.04°Brix and 8.26°Brix for the FR and the HR stages, respectively, while at the end of the storage period, they had increased to 12.33°Brix and 10.67°Brix, respectively.

The TA of the abiu fruit decreased throughout the storage period (Fig. 4B) and the TA of the fruit harvested at the FR stage was lower than for the HR stage from day 0 to day 6 of the storage period. However, on day 6 of the storage period, the TA was not significantly different between the two maturity stages.

Color change

The color of the abiu fruit picked at the FR stage slightly changed throughout the storage period (Fig. 5A). The hue value of the abiu fruit harvested at the FR stage decreased during the storage period from 94.09 on day 0 to 86.60 on day 12, whereas the peel color of the abiu fruit harvested at the HR stage turned yellow on day 8 with a hue value of 94.55. Furthermore, the peel lightness color change at the FR stage increased by 1.66 units throughout the storage period from 69.79 to 71.45 (Fig. 5B), while the peel lightness color at the HR stage increased by 8.95 units throughout the storage period from 60.12 to 69.07.

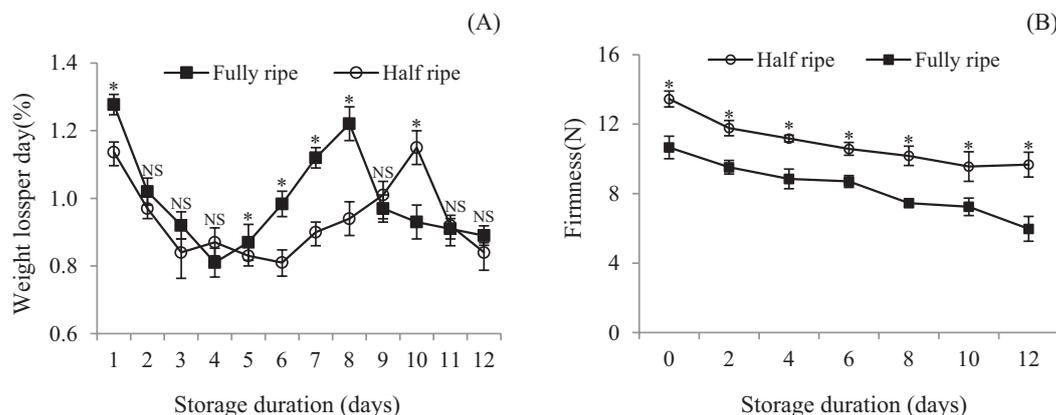


Fig. 3 Changes in: (A) weight loss per day; (B) firmness of abiu fruit during storage, where data (\pm SD) are means of five replicates; NS = non-significant ($p > 0.05$) different and * = significant ($p < 0.05$) different between half- and fully ripe

Table 2 Total weight loss of abiu fruit for two maturity stages

Maturity stage	Total weight loss (%)		
	Day 4	Day 8	Day 12
Half-ripe	4.03 \pm 0.69	8.22 \pm 0.85	11.22 \pm 1.59
Fully-ripe	3.82 \pm 0.73	7.30 \pm 0.89	11.92 \pm 1.76
Significance	NS	*	NS

Mean values (\pm SD) of five replications; NS = non-significant ($p > 0.05$) different and * = significant ($p < 0.05$) different between half- and fully ripe

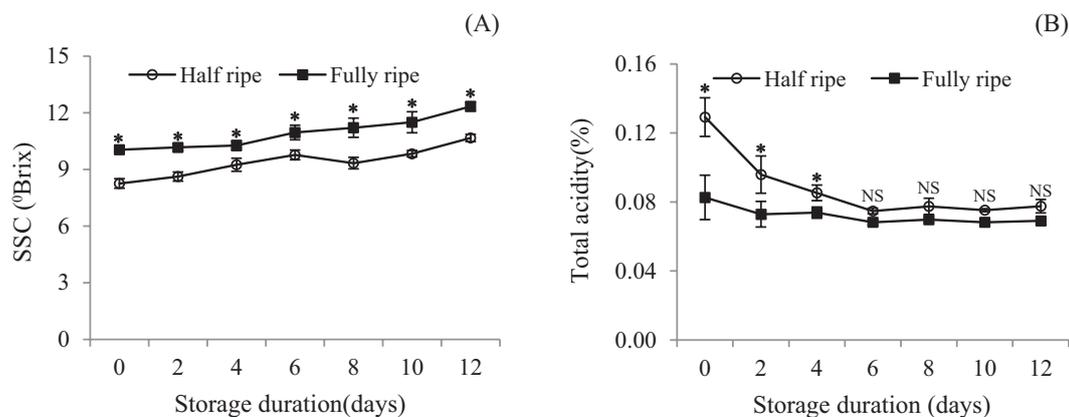


Fig. 4 Changes in: (A) soluble solids content (SSC); (B) total acidity of abiu fruit during storage, where data (\pm SD) are means of five replicates; NS = non-significant ($p > 0.05$) different and * = significant ($p < 0.05$) different between half- and fully ripe

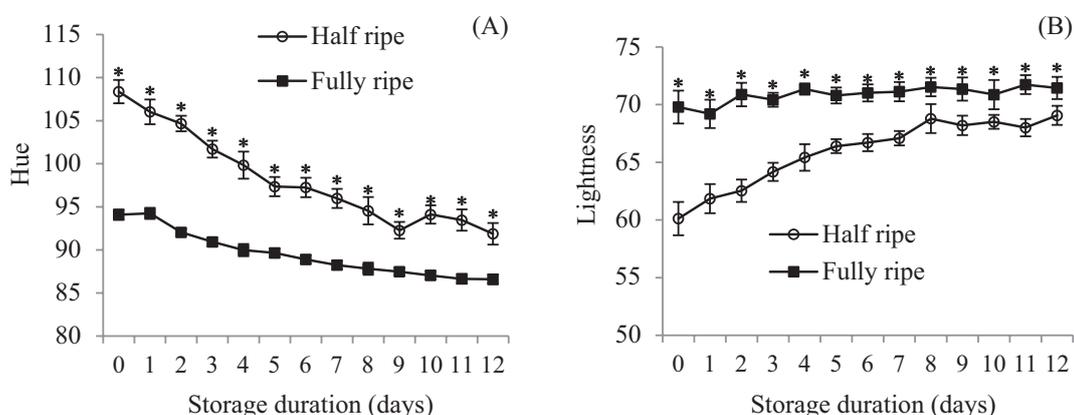


Fig. 5 Changes in: (A) hue; (B) lightness of abiu fruit peel during storage, where data (\pm SD) are means of five replicates; NS = non-significant ($p > 0.05$) different and * = significant ($p < 0.05$) different between half- and fully ripe

Browning index

Browning symptoms on the abiu fruit peel harvested at the FR stage began to appear on day 3, but only began to appear on day 5 for the HR stage (Fig. 6A). After 6 d of storage, the browning index of the abiu fruit harvested at the FR stage was higher than for the HR stage. The browning index of the abiu fruit peel at the end of the storage period was 10% and 2% for the FR and the HR stages, respectively.

The browning symptoms of the abiu pulp harvested at the FR stage appeared sooner than for the HR stage. For the FR stage, the browning symptoms began to occur on day 4, while the symptoms appeared on day 6 for the HR stage (Fig. 6B). The browning index of the abiu fruit pulp harvested at the FR stage increased significantly after 2 d of storage, and the fruit pulp browning was 40% on day 12. On the other hand, the fruit pulp browning index was 21.33% on day 12 for the HR stage.

Fruit peel surface structure

The abiu peel surface structure was characterized using SEM, as illustrated in Figs. 7 and 8. The SEM images showed that amount of microcracking on the abiu peel surface of the FR stage was higher than for the HR stage (Fig. 7). In addition, microcracks increased during the storage period, for both the FR and the HR stages. The cells of abiu peel in the FR stage had large compartments and less intercellular space (Fig. 8.) The quantification of the cell structure compositions to describe and compare the abiu peel anatomy of each maturity stage is summarized in Table 3. The thickness of the epidermis on the abiu fruit peel harvested at the FR stage was less than for the HR stage.

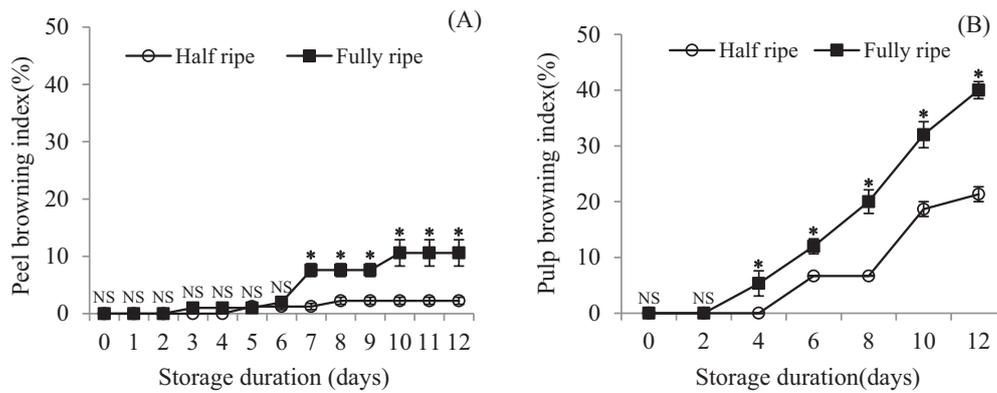


Fig. 6 Changes in: (A) browning index of abiu fruit peel; (B) abiu fruit pulp during storage, where data (\pm SD) are means of five replicates; NS = non-significant ($p > 0.05$) different and * = significant ($p < 0.05$) different between half- and fully ripe

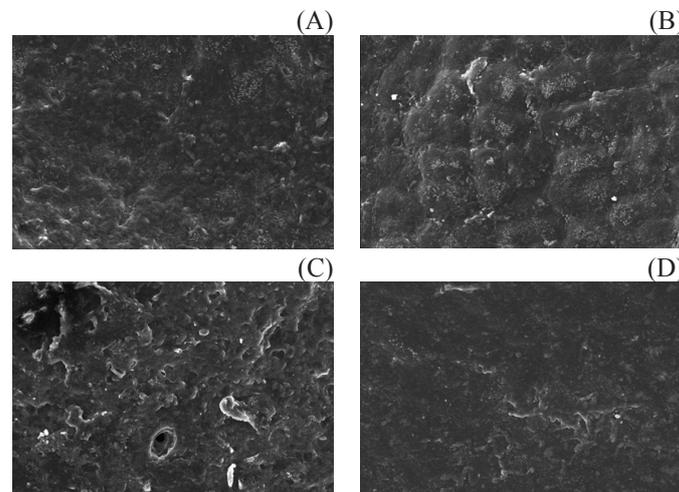


Fig. 7 Scanning electron microscopy images of abiu fruit peel in horizontal section at magnification $\times 500$ for: (A) half-ripe fruit at day 0; (B) half-ripe fruit at day 12; (C) fully-ripe fruit at day 0; (D) fully-ripe fruit at day 12; where scale bars = 20 μ m

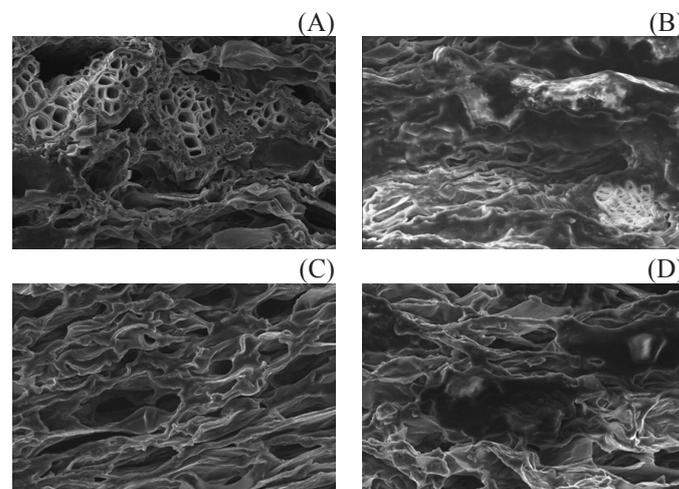


Fig. 8 Scanning electron microscopy images of abiu fruit peel in crosswise section at magnification $\times 500$ for: (A) half-ripe fruit at day 0; (B) half-ripe fruit at day 12; (C) fully-ripe fruit at day 0; (D) fully-ripe fruit at day 12; where scale bars = 20 μ m

Table 3 Anatomical components of abiu peel for two maturity stages based on scanning electron microscopy

Anatomical component	Day 0		Day 12	
	Half-ripe	Fully-ripe	Half-ripe	Fully-ripe
Epidermal thickness	++++	+++	+++	++
Number of intercellular spaces	++++	+++	+++	++
Size of intercellular space	++	+++	+++	+++
Cell compartment size (μm)	15.3–72.6	21.9–86.5	25.2–87.4	43.9–91.6

Number of + signs indicates level from highest (++++) to lowest (+) of each anatomical component

Discussion

The maturity stage affects the shelf life and fruit quality (Toivonen, 2007). One of the essential parameters to determine the shelf life of fruit is the respiration rate. The respiration rate of the abiu fruit at the HR stage was delayed 2 d longer than for the FR stage, indicating that the shelf life of abiu fruit harvested at the HR stage was longer for than the FR stage. The fruit maturity stage affected the rate and intensity of physiological changes, where the rate and intensity of CO_2 production in the FR stage were higher than for the HR stage (Bhutia et al., 2011).

Furthermore, the respiration rate was related to the ethylene production rate, whereas the ethylene production rate during the ripening process was controlled by the ability of the tissue to synthesize ACC (Paul et al., 2012; Maduwanthi and Marapana, 2019). The highest ACC concentration of the abiu fruit occurred on day 6 for the FR stage, while it took place on day 8 for the HR stage during the storage period. It was directly proportional to the pattern of CO_2 production and ethylene production throughout the storage period. The ACC concentration is correlated with ethylene production in the fruit ripening process (Tatsuki, 2010), where ethylene production is induced by the concentration of ACC in fruits through the ACC oxidase enzyme activities (Khan, 2016; Saquet and Streif, 2017). Next, the ACC is converted to ethylene, CO_2 , and cyanide by the ACC oxidase enzyme (Argueso et al., 2007).

In the current study, the ethylene production of abiu increased significantly up until day 6 and day 8 throughout the storage period for the FR and the HR stages, respectively. These results indicated that abiu fruit belongs to the category of climacteric fruits. In addition, the peak of ethylene production of the abiu fruit harvested at the FR stage took place 2 d earlier than for the HR stage. The fruit categorized into the climacteric type significantly increased its respiration rate and ethylene

production (Liu et al., 2015; Chen et al., 2018). During the ripening process, ethylene stimulates biosynthesis and induces the expression of many genes associated with the maturation process (Botton et al., 2019). Some of these genes are involved in flavor, aroma, pigment synthesis, changes of starch to sugar, and degradation of cell walls associated with the softening of fruit (Botton et al., 2019). It will cause some phenomena such as accelerated ripening, senescence and even spoilage (Saraiva et al., 2018; Cai et al., 2019). The ethylene production of abiu fruit is also associated with weight loss and fruit firmness.

Weight loss is one of the crucial factors related to fruit shelf life, as it interferes with the visual appearance of the fruit (Ribeiro and de Freitas, 2020). The current results showed that weight loss per day in the FR and HR fruits decreased from day 1 to day 5 perhaps because the abiu fruit was still under stress conditions after being harvested. This condition was shown by a decreased respiration rate (CO_2) at the beginning of the storage period. In addition, the highest weight loss per day occurred on day 8 and day 10 for FR and HR fruits, respectively. It was thought to be caused by the increased respiration rate and ethylene production, which was shown by the peaks of the respiration rate and ethylene production that occurred on day 6 and day 8 for FR and HR fruit, respectively. However, the total weight loss of abiu fruit increased during the storage period at two maturity stages. Due to respiration and evaporation, it caused water loss in the abiu fruit. In addition, abiu fruit carries out the process of respiration during the storage period, where it requires energy that is obtained from the breakdown of starch, amino acids, pectin and other compounds. The increase in weight loss is driven the higher respiration rates and ethylene production (Kowitcharoen et al., 2018). The total weight losses on day 12 were 11.92% and 11.22% for the FR and the HR stages, respectively. The abiu fruit harvested at the HR stage showed a lower weight loss, which indicated a better quality of abiu fruit.

As one of the fundamental parameters of postharvest quality, fruit firmness affects shelf life and consumer acceptance. The abiu fruit harvested at the HR stage was harder than the FR stage in terms of firmness. The major firmness loss of abiu fruit took place during the climacteric rise in respiration. Furthermore, it initiated the degradation of pectin in the cell wall, which decreased the firmness of the abiu peel. The decreasing firmness of fruit has been associated with an increasing rate of ethylene production (Pongprasert and Srilaong, 2014), hydrolytic enzyme activities and the degradation of pectin, cellulose and hemicellulose (Wang et al., 2018; Zhang et al., 2019). In addition, as the stage of fruit maturity increases, the fruit firmness will decrease throughout the storage period (Jiang et al., 2020). The current results showed that abiu fruit harvested at the HR stage maintained a higher firmness during the storage period.

SSC and TA are not only compounds that determine sweet and sour, but also the important indicators that determine fruit quality and consumer acceptance (Crisosto and Crisosto, 2005). In the current study, SSC in abiu fruit showed an upward trend from the HR stage to the FR stage. We suspect this is mainly due to the accumulation of sugars and a decline in moisture content. As increasing the fruit maturity stage, the SSC also increases, but the TA decreases. It might be due to the conversion of acid to sugar (gluconeogenesis) (Undurraga et al., 2011; Zhao et al., 2021). Additionally, the SSC of abiu fruit on each maturity stage increased, and the TA content decreased throughout the storage period. When the respiration occurred, organic acids were converted to sugar, their derivatives, or their utilization during the storage period, and it might become a factor that causes the increase of SSC and the decrease of acidity content (Choi et al., 2019; Tilahun et al., 2019, 2020). Abiu fruit harvested at the FR stage has a sweet taste and a moderately sweet taste for the HR stage. Besides the SSC and TA, the fruit color is also a parameter that contributes to fruit quality.

Typically, fruit color is a critical parameter that determines consumer preferences. The fruit colors are determined by the pigmentation of flesh and fruit peel during ripening (Youryon and Supapvanich, 2017; Penchaiya et al., 2020). The peel color of abiu fruit harvested at the FR stage slightly changed throughout the storage period in the current study. The peel color of abiu fruit harvested at the FR stage was more than 80% yellow on day 0, turning to full yellow on day 12,

indicating that there was a slight degradation of chlorophyll, as was shown by a decrease in the hue value of 7.49. In contrast, the color of the abiu fruit harvested at the HR stage significantly changed throughout the storage period. The hue value of the HR stage was 108.38 on day 0 and 91.87 on day 12, indicating that there was a degradation of chlorophyll in the HR fruit during the storage period. The color changes were caused by chlorophyll degradation and ethylene production during the storage period (Charoenchongsuk et al., 2018). Ethylene regulates color changes involving chlorophyll degradation and increases in carotenoids or anthocyanins (Iqbal et al., 2017). Furthermore, the chlorophyll degradation was mediated through an increase in chlorophyllase. When the chlorophyllase activity increased, the chlorophyll content decreased, while the β -carotene increased. In this process, the β -carotene pigment induced the yellow color to the rind (Ketsa et al., 1999).

The browning symptom is a primary disorder that causes fruit quality loss during storage and affects consumer preferences (Win et al., 2019). With browning in apples, if the relative browning area reaches 8.2%, then 50% of consumers will discard some of each apple; if the browning is more severe ($> 30\%$ relative area), then 50% of consumers would throw away the whole apple (Jaeger et al., 2018). The browning symptom may be a problem that prevents the consumer from choosing and consuming abiu fruit. The browning index of abiu fruit harvested during the FR stage reached more than 10% on day 6 of the storage period. Subsequently, consumers may reject it based on the incidence of browning on apples in the Jaeger et al. (2018) study. Furthermore, consumer acceptance is significantly related to the shelf life of a product. The criticality of fruit shelf life can be indicated by the decreasing fruit quality and the increased percentage of consumer rejection. Thus, based on the browning index, the shelf life of abiu fruit harvested at the FR stage was only 6 d, while the browning index of the pulp of abiu fruit harvested at the HR stage reached 6.7% on day 8 and 18.7% on day 10, so the shelf life of abiu fruit harvested at the HR stage was 3–4 d longer than for the FR stage.

In addition, the browning symptom of the abiu fruit harvested at the FR stage appeared earlier than for the HR stage. It was assumed that the CO_2 production was correlated to the browning symptom of the abiu fruit harvested at the

FR stage, where the highest value occurred on day 6. On the other hand, the browning symptoms of the abiu fruit harvested at the HR stage increased on day 8 throughout the storage period, when the peak of the CO₂ production also occurred. Larrigaudiere et al. (2004) reported that the browning disorder might start with an induction of the fermentative pathway under high CO₂ concentrations. The browning index was influenced by the storage period, the concentration of H₂O₂, malondialdehyde (MDA) and the enzyme oxidative activities that are involved (Xu et al., 2020). The browning symptom was also influenced by the total phenolics and their interaction with oxidative enzymes (Tejacal et al., 2007; Luengwilai et al., 2016, 2018). Basically, the browning phenomenon is related to the oxidation of flavonoids, mostly ortho-diphenol (O-diphenol, 1,2-diphenol) to semiquinones and quinones. The enzymes involved in the browning process are polyphenol oxidase and peroxidase (Kaewjumpol et al., 2021). Semiquinones and quinones react with each other enzymatically to produce brown pigment (Pourcel et al., 2007).

In the current study, the thickness of the epidermis of the abiu fruit decreased with increasing maturity. The decreased thickness was associated with peel firmness, which declined with the maturity stage (Amnuaysin et al., 2012). During maturity and ripening in most fruits, parenchymal cell walls are extensively modified, changing their mechanical properties, with the walls of some cells collapsing, while some cells fuse with others (Harker et al., 1997). In addition, the thickness of the epidermis is associated with microcracks on the surface of the abiu fruit peel. The cuticular microcracks formed through the breakdown of cell wall components caused by large amounts of water penetrating this element of the apoplast (Glenn and Poovaiah, 1985). Furthermore, there is collapse of the wall support structure and the formation of microcracks. During the ripening and storage periods, epidermal and hypodermal cells contain only a few starch grains, which may be related to the previous degradation of starch and its transition to soluble sugars (fructose and sucrose), cell shrinkage, middle lamella dissolution processes and cuticle removal (Konarska 2013, 2015). On the other hand, the cell compartment size on the peel of the abiu fruit increased with increasing maturity. The formation of compartment spaces indicated that the modification of polysaccharides in the middle lamella and the cell wall was induced by the increased activity of degrading enzymes of the cell wall, which caused cell wall damage and

cell separation, thereby forming the large compartment spaces (Amnuaysin et al., 2012). The abiu fruit harvested at the HR stage maintained higher epidermal thickness, indicating better quality during the storage period.

Cell wall degradation and membrane damage in the abiu fruit increased with increasing maturity during the storage period, as shown by the decrease in fruit firmness. Cell wall degradation and the loss of membrane integrity disrupted the cell structure, increasing the direct contact between substrates (phenolic compounds) located in the vacuole and oxidative enzymes (polyphenol oxidase enzymes) located in the plastids. These trigger a reaction known as enzymatic browning (Vaughn and Duke, 1984).

The current study confirmed that the maturity stage significantly affected the respiration rate and physiological changes during storage. The abiu fruit harvested at the HR stage could delay browning disorder so that its shelf life was 3–4 d longer than for the FR stage. However, the symptom of browning in abiu fruit is one of the critical factors that can reduce fruit quality. Therefore, future research should be undertaken on the treatment of anti-browning agents to inhibit browning symptoms. These data are essential because they can show the complexity of determining the appropriate stage of fruit harvesting. This research should be considered by those involved in the abiu fruit industry to determine the ideal maturity stage at harvest that can meet the demand based on consumer preference and balance the interests of farmers.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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