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Postharvest quality of atemoya at various stages of ripeness grown in semi-arid conditions

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ABSTRACT. Atemoya has a short post-harvest shelf life due to its high metabolic activity. Limited information is available on the optimal harvest time for atemoya grown in semi-arid conditions. This study aimed to evaluate the quality of atemoya fruits at various maturity stages under semi-arid conditions. Fruit was harvested from a commercial orchard and the experiment was conducted in a completely randomized design (CRD) with a 3x5 factorial scheme. This included three maturation stages (100, 105, and 110 days after pollination - DAP) and five refrigerated storage periods (0, 3, 6, 9, and 12 days), with four repetitions. The fruits were stored at 15 ± 2°C and 74 ± 2% RH and subjected to physical, chemical, and biochemical evaluations. Throughout storage, there was a significant fresh mass loss of 13.83, 11.99, and 11.92% for fruits harvested at 100, 105, and 110 DAP, respectively. Firmness and starch content also decreased as starch was converted into sugars. Across all maturation stages, the shelf life was limited to nine days due to compromised appearance, primarily cracks and peel darkening. Fruits harvested at 105 and 110 DAP exhibited better quality at the end of storage, including improved appearance, greater mass, lower weight loss, and higher soluble solids and vitamin C content. The results suggest that atemoya fruits can be harvested between 105 and 110 DAP under semi-arid conditions. Thus, atemoya shows commercial potential for production in the semi-arid region.

Keywords: *Annona squamosa* L. x *Annona cherimola* Mill., conservation, semi-arid conditions, appearance.

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Introduction

Atemoya is a fruit from the Annonaceae family, resulting from a cross between the custard apple (*Annona squamosa* L.) and the cherimoya (*Annona cherimola* Mill.). This interspecific hybrid combines desirable traits from both species, including the sweet flavor of cherimoya, which is highly appreciated by consumers, and the ability to adapt to regions with slightly colder climates than those required for custard apples. The Annonaceae family has a remarkable capacity for adaptation, allowing successful cultivation in tropical and subtropical regions (Chagas et al., 2022).

Atemoya is considered one of the most commercially valuable fruits in the *Annona* genus due to its excellent organoleptic characteristics and high nutritional value, making it increasingly popular (Gong et al., 2020; Zhang et al., 2023a). Classified as a climacteric fruit, atemoya has a relatively short shelf life due to its high respiration rate and soluble solids content, which accelerate the maturation process. These traits make atemoya susceptible to softening and cracking, leading to quality and commercial value loss (Pareek et al., 2011).

The ripening process involves significant physiological and biochemical changes (Wang & Seymour, 2022; Zhu et al., 2022). To improve fruit quality and extend shelf-life post-harvest, it is recommended to harvest climacteric fruits before ripening begins, as maturation continues during storage (Liu et al., 2015).

There are two opposing harvesting approaches: early and late. Early harvesting can prevent fruits from fully maturing, while late harvesting reduces shelf life. Consequently, fruits harvested too early or too late are more prone to developing physiological disorders compared to those harvested at the appropriate time (Moura et al., 2020). According to Pereira et al. (2019), superior quality fruits for commercialization in São Paulo, a reference for atemoya production in Brazil, are well-formed and weigh over 300 g.

However, information on the ripening and post-harvest aging processes of Annonaceae fruits remains limited. Given this context, determining the optimal harvest time for atemoya presents a significant challenge. Therefore, this study aimed to evaluate the quality and shelf life of atemoya fruits at different maturity stages grown in semi-arid conditions.

Material and methods

The harvest of atemoya (*Annona squamosa* x *Annona cherimola*) 'Gefner' fruits took place in April 2022 at the DaniFrutas farm's commercial orchard, located in the Jaguaribe-Apodi Project, rural area of Limoeiro do Norte, Ceará State, Brazil (5°08'38.0" S and 37°59'43.8" W), a semi-arid region. The area experiences an average annual temperature of 28.5°C, with minimum and maximum temperatures of 22 and 35°C, respectively. The average annual relative humidity is 62%, and the average annual rainfall is 772 mm. The climate is classified as BSw'h' (Oliveira et al., 2022).

The fruits were transported to the Post-harvest Physiology and Technology Laboratory at the Universidade Federal Rural do Semi-Árido in Mossoró, Rio Grande do Norte State, Brazil. They were sanitized with a 0.1% sodium hypochlorite solution for 5 minutes, following the method described by Souza et al. (2015), with some adaptations. The experiment was conducted in a completely randomized design (CRD) with a 3x5 factorial scheme, including three stages of fruit maturation (100, 105, and 110 days after pollination - DAP) and five storage periods (0, 3, 6, 9, and 12 days), with four replications. Each experimental unit consisted of one fruit. The fruits were stored in a BOD at a temperature of 15 ± 2°C and a relative humidity (RH) of 74 ± 2%, where the following evaluations were conducted.

Physicochemical analysis

The fruits were evaluated for appearance using a rating scale from 1 to 5, considering characteristics such as depressions, wilting, pathogen attack, and dark spots. Scores ranged from 5 (no undesirable characteristics) to 1 (severe undesirable characteristics). Fruits scoring 3 or lower were deemed unsuitable for sale (Lima et al., 2004).

The cracking index was assessed in all fruits showing cracks during storage, as described by Barbosa et al. (2011). Fresh fruit mass loss was determined using a semi-analytical balance, with results expressed in grams (g). Fresh mass loss (FML) was calculated as a percentage using the formula:

$$\text{FML}\ (\%) = \left(\frac{\text{Im}-\text{Dm}}{\text{Im}}\right) * 100 \quad (1)$$

FML (%) = Fresh mass loss; Im= Initial mass (g); Dm= Fruit mass on the analysis day (g).

Peel and pulp colors were measured with a benchtop digital colorimeter. Two readings were taken at equidistant points on each fruit, and results were expressed using CIE Lab coordinates: L* (brightness), a* (green to red), and b* (blue to yellow) (Minolta, 2007). The a* and b* values were converted to Hue angle - H° (Equation 2) and Chroma - C (Equation 3), representing the color evolution of atemoya peel during ripening, using the formulas:

$$\text{H°} = 180° + arctg\left(\frac{b^2}{a^2}\right) \quad (2)$$

$$\text{C}= \sqrt{(\text{a*})^{\,2} + (\text{b*})^{\,2}} \quad (3)$$

Fruit firmness was determined using a digital texturometer with a 5 mm diameter cylindrical probe. Two readings were taken at equidistant points in the equatorial region of each fruit, with results expressed in Newtons (N).

Vitamin C content was determined by titration with Tillman solution (DFI - 2.6 dichlorophenol-indophenol at 0.02%), using 1 g of samples diluted in a 50 mL volumetric flask with 0.5% oxalic acid (Instituto Adolfo Lutz, 2008). Results were expressed in mg of ascorbic acid per 100 g of pulp.

To measure pH, 5 g of pulp was weighed and mixed with 50 mL of distilled water. The pH was determined using a potentiometer standardized with buffer solutions. The stabilized results were expressed as real pH values (Instituto Adolfo Lutz, 2008).

Titratable acidity (TA) was determined by volumetric titration with NaOH solution (Instituto Adolfo Lutz, 2008). Approximately 1 g of pulp was diluted in 49 mL of distilled water, and three drops of 1% phenolphthalein indicator were added. This mixture was titrated slowly with 0.01 M NaOH solution, and results were expressed in milliequivalents (meq) per 100 g of pulp.

Soluble solids (SS) content was measured with a digital refractometer with automatic temperature correction, following the Association of Official Analytical Chemistry (AOAC, 2002) methodology. Results were expressed as a percentage (°Brix).

Total sugars were determined using the Anthrone method (9,10-dihydro-9-oxoanthracene), as described by Yemn and Willis (1954). From 1 g of samples diluted in a 100 volumetric flask with 80% alcohol, 10 mL of the solution was transferred to another 100 mL flask and diluted with distilled water. An aliquot was analyzed using a spectrophotometer at 620 ηm, with results expressed as a percentage.

Reducing sugars were quantified according to Yemn and Willis (1954) and Miller (1959). From 3 g of samples diluted in a 100 volumetric flask with 80% alcohol, 10 mL of the solution was transferred to another 100 mL flask and diluted with distilled water. Quantification was performed using the DNS method (3,5-Dinitrosalicylic acid, Sigma) and a spectrophotometer at 540ηm, with results expressed as a percentage (%).

Starch content was quantified using the methodology described by AOAC (2002) and Miller (1959). Quantification was performed using the DNS method (3,5-Dinitrosalicylic acid, Sigma) and a spectrophotometer at 540 ηm, with results expressed as a percentage (%).

Biochemical analyses

Total antioxidant activity was evaluated using the DPPH radical method, as described by Brand-Williams et al. (1995) and modified by Sánchez-Moreno et al. (1998). Different dilutions of the extract were prepared in test tubes. Absorbance was measured at 515 ηm after 2 minutes. All analyses were performed in triplicate, with a control used as a reference. Results were expressed as percentage sequestration (%).

Total extractable polyphenols (PET) were determined using the Folin-Ciocalteu reagent, with gallic acid as the standard, as described by Larrauri et al. (1997) with some modifications. Absorbance was measured at 700 ηm using a spectrophotometer. Results were expressed as mg per 100 g of pulp.

Statistical analysis

The evaluated variables were subjected to analysis of variance (ANOVA) using the F test ($p < 0.05$). The effects of quantitative treatments were analyzed using polynomial regression. All statistical analyses were performed using the ExpDes.pt package in R (Rstudio Team, 2021). Graphical figures were produced using SigmaPlot 14.0 software.

Results

Atemoya fruits exhibit a uniform green color at harvest. However, by the sixth day of storage, the fruits began to develop brownish spots (darkening) at the ends of the carpels, significantly decreasing their visual appeal (Figure 1). Cracks appeared during ripening, and after 12 days of storage, the fruits had average appearance scores of 2.05, 2.25, and 2.50 for 100, 105, and 110 DAP, respectively, rendering them unsuitable for commercialization.

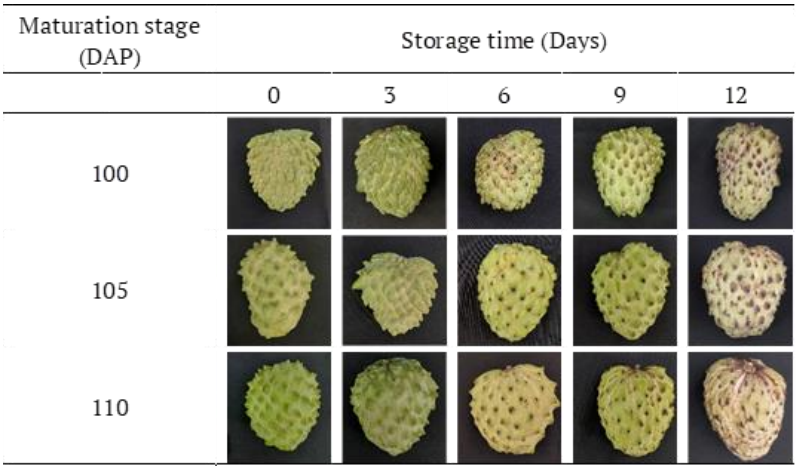

Figure 1. Appearance of atemoya fruit 'Gefner' harvested at different ripeness stages 100, 105, and 110 days after pollination (DAP) and stored at 15 ± 2°C and 74 ± 2% RH for 12 days.

Fruit mass showed significant differences between stages ($p < 0.001$), with masses of 293, 433, and 435 g at 100, 105, and 110 DAP, respectively. Fresh mass losses (FML) increased gradually during storage for all maturation stages (Figure 2A). The highest FML percentage was observed in fruits harvested at 100 DAP after 12 days of storage, with a loss of 13.83%. Fruits harvested at 105 and 110 DAP showed average FML percentages of 11.99 and 11.92%, respectively ($p < 0.001$).

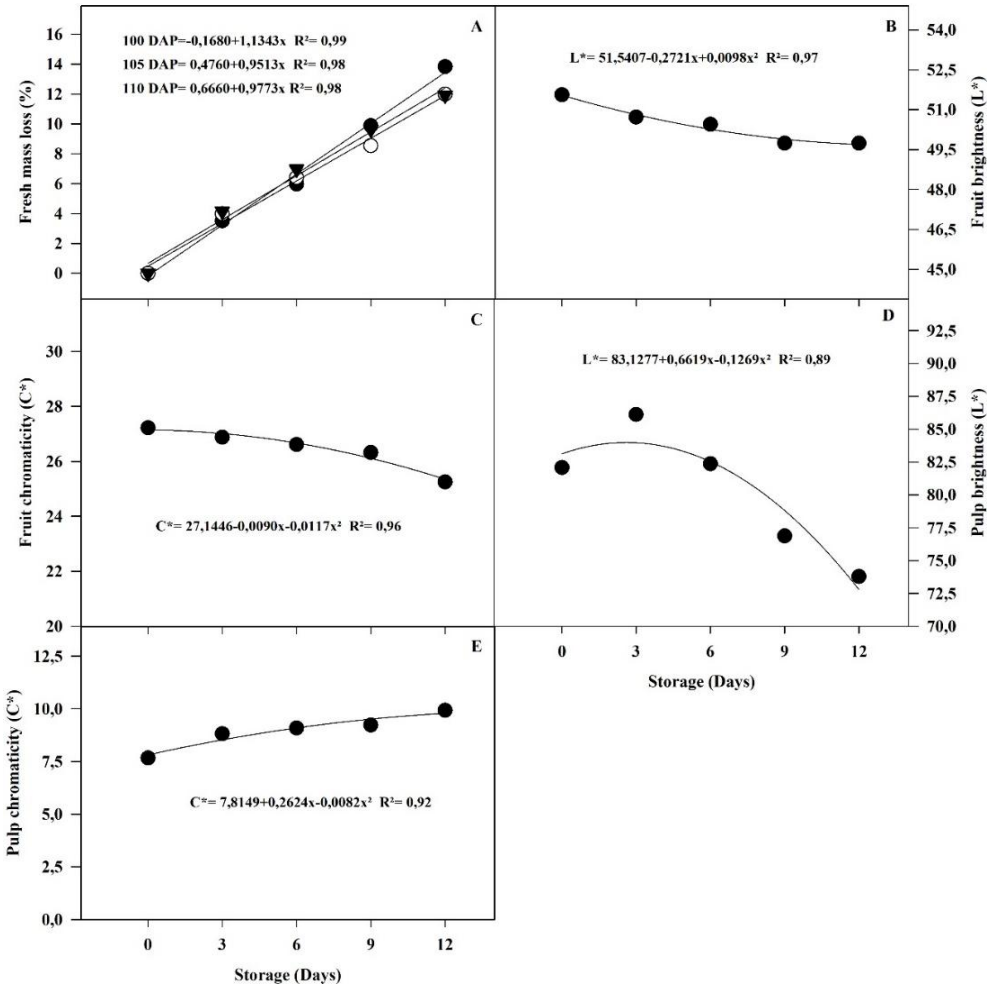

Figure 2. (A) Fresh mass loss (%), (B) fruit luminosity (L), (C) fruit chromaticity (C), (D) pulp luminosity (L*), and (E) pulp chromaticity (C*) in 'Gefner' atemoya fruits harvested at different ripening stages: 100 (●), 105 (○), and 110 (▲) days after pollination (DAP) and stored at 15 ± 2°C and 74 ± 2% relative humidity for 12 days.

Luminosity ($p < 0.001$) and chromaticity ($p < 0.001$) values of the fruit decreased throughout storage, as shown in Figure 2(B and C). This color reduction is likely associated with darkening due to the advancing ripening and senescence process. Regarding the maturation stages (100, 105, and 110 days), fruit luminosity and chromaticity showed no significant differences, indicating similar brightness and color at all stages (Figure 2B and 2C). The °Hue values of the peel did not show significant differences, with averages of 178.60, 178.59, and 178.58 for 100, 105, and 110 DAP, respectively. Thus, fruit color is not a reliable parameter for determining the harvest point.

Pulp luminosity (L*) showed no interaction between stages and storage time, but there was a significant difference in storage ($p < 0.001$). Luminosity decreased over storage time, with values of 82.08 on day zero and 73.79 on day 12, showing a difference of 8.29 L* (Figure 2D). Pulp chromaticity values varied, with 7.67 on day zero and 9.93 on day 12 (Figure 2C). Pulp hue angle showed no significant difference, with averages of 178.55, 178.52, and 178.52 for 100, 105, and 110 DAP, respectively.

Fruit and pulp firmness decreased throughout storage ($p < 0.001$) (Figure 3A and B). There was an interaction between storage and maturation stages for pulp firmness. On the day of harvest, fruits harvested at 110 DAP had lower firmness, but by the end of storage, no significant difference between stages was observed.

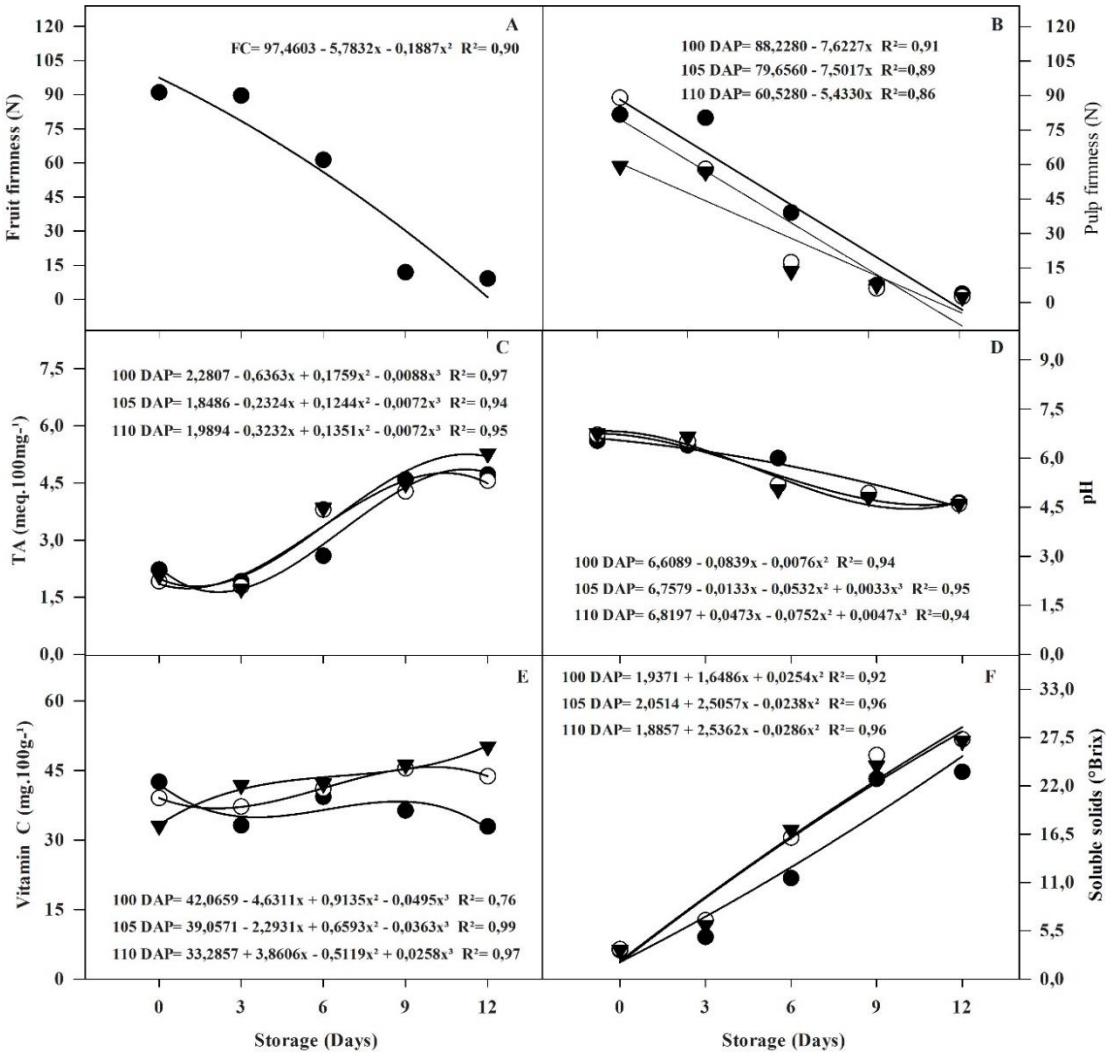

Figure 3. (A) Fruit firmness (FC, N), (B) Flesh firmness (N), (C) Titratable acidity (TA, meq 100 g^{-1}), (D) pH, (E) Vitamin C (mg 100 g^{-1}), and (F) Soluble solids (°Brix) in 'Gefner' atemoya fruits harvested at different ripening stages: 100 (●), 105 (○) and 110 (▲) days after pollination (DAP) and stored at 15 ± 2°C and 74 ± 2% RH for 12 days.

Total titratable acidity (TA) increased throughout storage. By nine days, fruits at all stages showed an approximately 50% increase in TA compared to the day of harvest. At 12 days, fruits at the 110 DAP stage had the highest TA value, averaging 5.27 meq 100 mg^{-1} (Figure 3C).

For pH, there was a significant interaction ($p < 0.001$) between the studied factors (Figure 3D). The pH gradually decreased throughout storage for all stages, averaging 6.6 on day 0 and 4.6 on 12 days, corresponding with the increase in titratable acidity that lowers pH.

Vitamin C content exhibited an interaction between factors ($p < 0.01$). Values for fruits harvested at 100 DAP decreased throughout storage, while those harvested at 105 DAP increased up to nine days (Figure 3E). Fruits harvested at 110 DAP also showed an increasing trend in vitamin C until the end of storage and had the highest levels compared to fruits at other stages.

Soluble solids (SS) content increased during storage for all stages. At the beginning of storage, the average SS content was 3.3 °Brix. By the end of storage, average SS values were 23.55, 27.25, and 27.05 °Brix for 100, 105, and 110 DAP, respectively (Figure 3F).

Figure 4A shows the quantification of starch, which exhibited a significant interaction ($p < 0.001$). Starch content decreased throughout storage, with values of 8.0, 11.02, and 10.80% on the day of harvest and 0.7, 1.08, and 1.2% at the end of storage for 100, 105, and 110 DAP, respectively.

Total sugars showed a significant increase ($p < 0.001$) during storage, rising from 1.42% on day zero to 16.29% on day 12 (Figure 4B). Reducing sugars also increased from 0.25 to 2.27% between day zero and the end of storage (Figure 4C). These data indicate that starch breakdown is linked to increased sugar levels.

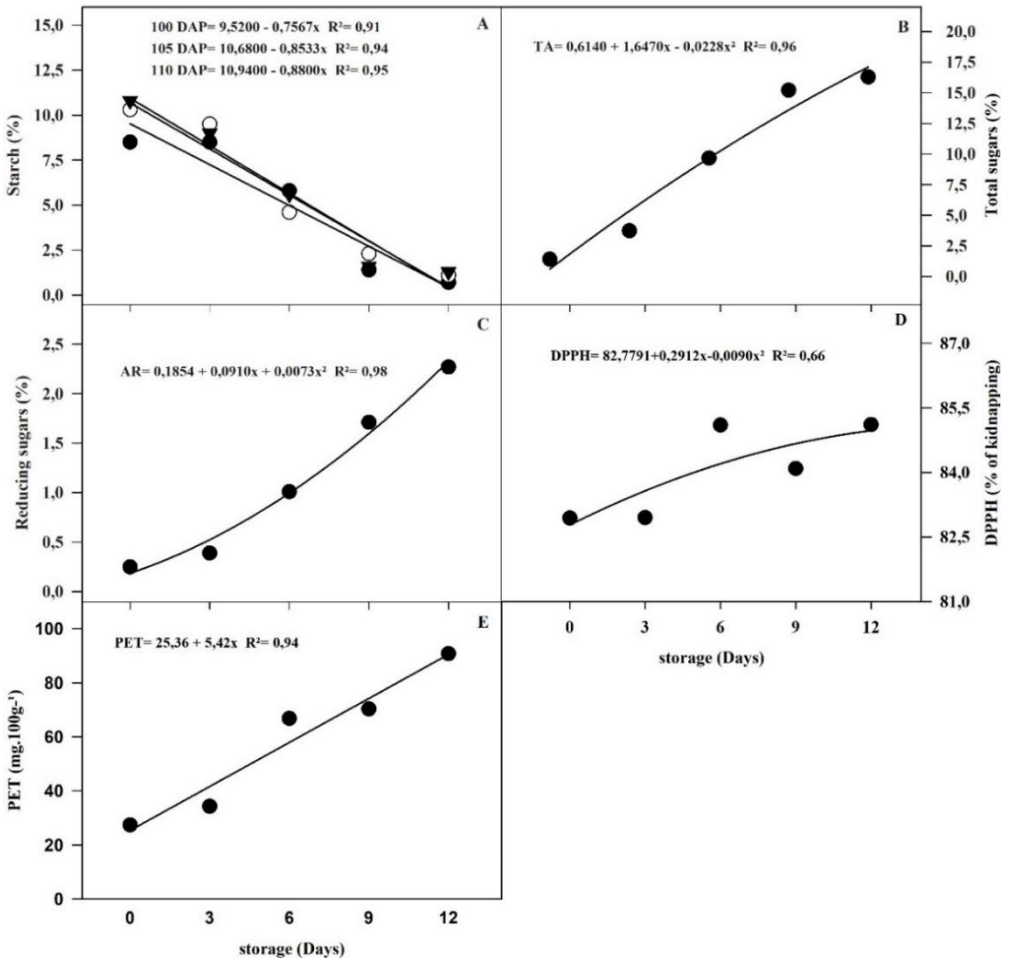

Figure 4. (A) Starch content (%), (B) Total sugars content (%), (C) Reducing sugars content (%), (D) DPPH antioxidant activity (%), and (E) Total extractable polyphenols (PET, mg 100 g^{-1}) in 'Gefner' atemoya fruits harvested at different maturation stages: 100 (●), 105 (○), and 110 (▲) days after pollination (DAP) and stored at 15 ± 2°C and 74 ± 2% RH for 12 days.

For antioxidant activity, there was a significant increase ($p < 0.001$) during storage (Figure 4D). Antioxidant activity rose from the sixth day onwards, averaging 85.24% and reaching 85.18% on the 12th day.

Total extractable polyphenols showed no interaction between the two factors (Figure 4E). However, there was a significant difference in storage time ($p < 0.001$), following the trend of antioxidant activity. An increase was observed from the sixth day, with an average of 67.14 mg 100 g^{-1}, and by the end of storage, the average was 91.04 mg 100 g^{-1}.

Discussion

Fresh fruits play a fundamental role in daily human diets due to their attractive flavor and high nutritional value (Li et al., 2021; Zhang et al., 2021a). However, post-harvest logistics face significant challenges due to rapid senescence and decomposition in these foods, leading to considerable losses and reduced commodity value (Zhang et al., 2021b).

During storage, atemoya fruits exhibited visible changes, turning from green to a brownish tinge at the ends of the carpels, significantly decreasing their visual appeal. This browning process, caused by enzymatic reactions, affects fruit quality and renders the product unsuitable for commercialization (Zheng et al., 2019; Zhang et al., 2023a).

Cracking is another physiological problem occurring during atemoya ripening, crucially affecting its quality. In this study, cracks appeared after the 6th day of storage, likely due to ripening, starch degradation into sugars, and cell wall metabolism, promoting physiological disorders and rapid senescence (Yang et al., 2011; Zhang et al., 2021a).

Fresh mass reduction is critical for evaluating fruit durability during post-harvest conservation. The study observed a progressive increase in fresh mass loss (Figure 2A), with 13.55% at the end of 12 days of storage

and 11.84 and 11.89% for 100, 105, and 110 DAP, respectively. Zhang et al. (2023a) reported similar findings with atemoya fruits stored at 15 and 25°C, showing fresh mass losses of 7.62% (10 days) and 13.18% (5 days), respectively. Fresh mass losses result from evaporation, respiration, and other physiological changes (Chen et al., 2022). When fresh mass loss exceeds 8%, the fruit appears withered, negatively impacting consumer acceptance (Cruz-Bravo et al., 2019).

Color was not a determining factor for the harvest point, as no differences were observed between maturation stages on day 0. However, during storage, changes in luminosity and chromaticity were noted (Figure 2B and C). Color intensity is crucial for identifying the appropriate harvest time and estimating ripening duration (Pareek et al., 2011). Reduced luminosity likely results from darkening, water loss, and physical damage post-harvest (Zhang et al., 2023b). Minimizing browning delays ripening, improving fruit quality, and prolonging shelf life (Hou et al., 2023). Fruit surface appearance, particularly a shiny peel, is vital for consumer purchase decisions, as it indicates freshness (Santos et al., 2018; He et al., 2020).

Firmness, another quality parameter, progressively decreased in fruit and pulp during storage (Figure 3A and B). Reduced firmness indicates ripening and cell wall structure deterioration (Deng et al., 2019). However, details on the mechanical changes in atemoya fruit during ripening and post-harvest processing are limited (Gong et al., 2020). According to Lin et al. (2018), firmness reduction and color change during ripening and senescence are crucial factors affecting fruit durability and market value.

Total titratable acidity (TA) increased throughout storage, with a 50% rise by nine days compared to the day of harvest. At 12 days, the 110 DAP stage had the highest TA value, averaging 5.27 meq 100 mg^{-1} (Figure 3C). This increase in acidity is due to citric acid accumulation during early maturation and increased organic acid concentration from cell wall degradation by pectic enzymes (Moura et al., 2020; Pinto et al., 2011). These organic acids also influence pH and play a crucial role in fruit ripening (Anese & Fronza, 2015).

Soluble solids levels increased during ripening, with smaller increases in fruits harvested at 100 DAP, likely due to incomplete physiological maturation at 100 DAP (Figure 3F). Soluble solids include water-soluble elements like carbohydrates, vitamins, acids, and amino acids, and their concentration increases due to polysaccharide degradation (Chitarra & Chitarra, 2005). The increase in soluble solids in fruits harvested at 105 and 110 DAP can be associated with starch conversion into soluble sugars during storage.

Figure 4(A, B, and C) illustrate the relationship between the increase in sugars and starch hydrolysis. The contents of total sugars increase due to starch breakdown, producing soluble sugars like glucose. These sugars directly impact soluble solids content in pulp, enhancing flavor, and are closely related to the fruit ripening and aging processes (Oliveira et al., 2021; Li et al., 2021).

Besides being palatable, atemoya fruits contain significant amounts of vitamin C, potassium, and acids such as citric and malic (Chou et al., 2021). Sousa et al. (2013) reported similar values for vitamin C in atemoya 'Gefner' at two maturation stages, with averages of 41.18 and 61.26 mg 100 g^{-1} for ripe and semi-ripe fruits, respectively (Figure 3E).

Atemoya has potential as a source of bioactive compounds due to its high content of total phenolic compounds (Santos et al., 2016; Moraes et al., 2020). The data in Figure 4(D and E) demonstrate that atemoya fruits can be considered a source of bioactive compounds. The high antioxidant activity observed in this research can be attributed to the significant content of phenolic compounds and vitamin C.

Conclusion

For all maturation stages studied, the shelf life of atemoya fruit for fresh consumption was limited to nine days due to compromised appearance, mainly from cracks and skin darkening. Fruits harvested at 105 and 110 days after pollination (DAP) showed better post-harvest quality at the end of storage, with improved appearance, greater mass, less mass loss, and higher soluble solids and vitamin C content. This indicates that, under semi-arid conditions, atemoya fruits can be optimally harvested between 105 and 110 DAP. Therefore, atemoya has commercial potential for production in semi-arid regions.

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