

Article

Effects of Calcium and Gibberellic Acid on the Quality and Shelf Life of ‘Gefner’ Atemoya Grown in a Semiarid Region

Lucilândia de Sousa Bezerra ¹, Alison Rocha de Aragão ¹, Maria Aparecida dos Santos Moraes ¹,
Letycia de Lima Costa ^{1,*}, Naama Jessica de Assis Melo ¹, Vladimir Rubiano Gonzalez ¹,
Carla Sonale Azevêdo Soares Silva ¹, Railene Hérica Carlos Rocha Araújo ²,
and Patrícia Lígia Dantas de Moraes ¹

¹ Laboratory of Post-Harvest Physiology and Technology, Postgraduate Program in Phytotechnics, Department of Agricultural and Forestry Sciences, Center for Agricultural Sciences, Universidade Federal Rural do Semi-Árido–UFERSA, Mossoró 59625-900, RN, Brazil

² Unit of Food Engineering, Center for Technology and Natural Resources, Academic, Universidade Federal de Campina Grande–UFCCG, Campina Grande 58429-900, PB, Brazil

* Correspondence: letycialima230@gmail.com

Highlights

What are the main findings?

- Calcium and Ca+GA₃ applications reduced cracking, delayed senescence, preserved bioactive compounds, and reduced electrolyte leakage in cold-stored atemoyas.
- Atemoyas remained edible for up to 12 days under refrigeration.

What are the implications of the main findings?

- Applying calcium and GA₃ provides an effective strategy to reduce cracking and extend the postharvest shelf life of semi-arid atemoyas.

Abstract

Atemoya is a climacteric and highly perishable fruit prone to cracking during ripening—a factor that limits its shelf life and marketability. Thus, this study aimed to evaluate the effect of gibberellic acid and calcium on reducing cracking and preserving atemoyas grown under semi-arid conditions and stored under refrigeration. Calcium and gibberellic acid applications were performed at 7, 27, 47, 67, and 87 days, with fruit harvest occurring 121 days after pollination. A completely randomized design (CRD) was used in a 4 × 6 factorial scheme (Control, Calcium, Gibberellic Acid, and Calcium + Gibberellic Acid [Ca + GA₃]) with six cold storage periods (0, 3, 6, 9, 12, and 15 days) and five replicates. Fruits were subjected to the following evaluations: appearance, mass, fresh mass loss, cracking index, pulp firmness, pH, titratable acidity, soluble solids, vitamin C, chlorophyll, electrolyte leakage, total sugars, starch, DPPH, polyphenols, peroxidase and polyphenoloxidase enzyme activity, and mineral quantification. The results demonstrated that Ca and Ca+GA₃ treatments favored a reduction in cracking and increased bioactive compounds—such as phenols, vitamin C, and chlorophyll—contributing to delayed senescence through reduced electrolyte leakage. Furthermore, the refrigerated fruits remained suitable for consumption for up to twelve days, regardless of the treatment.

Keywords: *Annona squamosa* × *A. cherimola*; storage; fruit cracking; phytohormones; antioxidants



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1. Introduction

Atemoya is an annonaceous fruit obtained by crossing the sugar apple or sweetsop (*Annona squamosa* L.) and the cherimoya (*Annona cherimola* Mill.), two distinct species. This hybridization resulted in a fruit that exhibits desirable characteristics from both parent plants [1]. Due to these traits, the fruit is highly appreciated by consumers, owing to its delicious, aromatic pulp, excellent organoleptic properties, and high nutritional value [2].

This annonaceous fruit is climacteric and has a short shelf life; it exhibits a high respiration rate and rapid metabolism, leading to early senescence [3]. Harvesting typically occurs before full ripening—at the stage of physiological maturity—to allow for a longer marketing window. Fruit ripening involves a series of physicochemical and structural changes, including softening, the conversion of starch into sugar, the synthesis of aromatic compounds, and color changes [4].

However, a major issue arises during the atemoya ripening process: the occurrence of splitting or cracking near the peduncle at the fruit's base, appearing as fractures in the cuticle. Such cracking poses a significant obstacle, leading to losses in productivity and commercial value during the post-harvest period [5].

Recent research has highlighted a significant link between phytohormones and fruit cracking, specifically regarding the ability to increase cell wall flexibility and facilitate skin expansion [6,7]. Gibberellin is widely used in various crops to increase fruit set and control fruit splitting; it also shows potential for reducing cracking in fruits such as pomegranates, sweet cherries, and apples [8].

Gibberellin is a growth regulator that plays a fundamental role in various plant growth and development processes. In commercial agriculture, gibberellin is widely used to maximize fruit size and quality by stimulating cell growth through cell division and elongation [9,10].

Plant nutritional status is another factor influencing growth, productivity, and fruit quality; calcium, for instance, plays a crucial role as a signaling agent in regulating cytosolic enzymes, while also significantly affecting the control of physiological disorders and the maintenance of fruit quality [11].

In this context, this study is justified by the need to evaluate sustainable management strategies—such as the use of growth regulators (GA_3) and calcium supplementation—capable of strengthening the exocarp structure and mitigating cracking incidence. Adopting these strategies during the pre-harvest phase can help improve fruit resistance to physiological stresses associated with development and ripening, thereby preserving quality and reducing postharvest losses. Furthermore, understanding how these treatments and parthenocarp influence fruit firmness, shelf life, and nutritional value is crucial for developing more efficient and sustainable production systems, contributing to high-quality fruit production and reduced losses throughout the supply chain.

Calcium (Ca^{+2}) plays a fundamental structural and physiological role in the formation and stabilization of the plant cell wall, acting predominantly within the middle lamella and the primary cell wall. It binds to the free carboxyl groups of pectins—specifically galacturonic acid—forming complexes known as “calcium pectates,” which function as a type of molecular “cement”. This pectin cross-linking, often described by the “egg-box” model, confers greater mechanical rigidity and cohesion between neighboring cells, thereby contributing to the maintenance of plant tissue firmness [12]. Furthermore, the interaction between pectins can hinder the activity of enzymes involved in cell wall degradation, such as polygalacturonase, thus contributing to the maintenance of structural integrity and the delay of fruit softening [13].

Therefore, the scientific hypothesis is that the application of calcium and gibberellic acid strengthens the atemoya cell wall, thereby reducing the incidence of physiological

cracking. It is believed that the treatment controls enzymatic degradation, preserving firmness and nutritional value (minerals and vitamin C) during the post-harvest period. Thus, the objective of this study is to evaluate the effect of gibberellic acid and calcium on the quality and cracking reduction in atemoya fruit grown under semi-arid conditions and stored under refrigeration.

2. Materials and Methods

The experiment was conducted in a commercial orchard at the Dani Frutas farm, located within the Jaguaribe-Apodi Project in the rural area of Limoeiro do Norte, Ceará, Brazil (5°08'38.0" S, 37°59'43.8" W), a semi-arid region. Soil and plant tissue analyses were performed initially, during the pre-flowering period (Tables 1 and 2). Following these analyses, treatments involving calcium (2 mL⁻¹; LIGOPLEX Ca: 10.1% calcium, 2.1% nitrogen), gibberellic acid (100 mg dm⁻³; ProGibb® 400: 40% gibberellic acid), and a combination of calcium and gibberellic acid were applied at 7, 27, 47, 67, and 87 days after pollination (DAP) (Figure 1). The applications were carried out between 07:00 and 09:00 using a manual high-pressure garden sprayer (7-L model; Palisad, Mossoró, Brazil). No adjuvant was used. Spraying was directed exclusively at the fruit, applying a spray volume of 1 L per plant to all marked fruits receiving the treatment on each application date.

Table 1. Chemical characterization of the soil in the ‘Gefner’ during the pre-flowering period at atemoya orchard area at Dani Frutas farm, Jaguaribe-Apodi Project, rural area of Limoeiro do Norte, Ceará, Brazil, 2022.

Soil Chemical Analysis								
pH	CTC	K	Ca	Mg	Al ³⁺	H+Al ³⁺	Na	
----- mmolc/dm ³ -----								
6.4		6.4	58	33	0	14	2.6	
V%	M.O.	P	S	Fe	Mn	Cu	Zn	B
%	g/dm ³	----- mg/dm ³ -----						
88	16	72	7	8	12.8	1.8	2.5	1.66

pH: Hydrogen ion concentration; CTC: Cation exchange capacity; K: Potassium; Ca: Calcium; Mg: Magnesium; Al³⁺: Aluminum; H⁺Al³⁺: Potential acidity; Na: Sodium; V%: Base saturation; OM: Organic matter; P: Phosphorus; S: Sulfur; Fe: Iron; Mn: Manganese; Cu: Copper; Zn: Zinc; B: Boron.

Table 2. Chemical characterization of atemoya plant tissue (cv. Gefner) during the pre-flowering period at Dani Frutas Farm, Jaguaribe-Apodi Project, rural area of Limoeiro do Norte, Ceará, Brazil, 2022.

Chemical Analysis of Plant Tissue												
N	P	K	Ca	Mg	S	Al ³⁺	Fe	Mn	Cu	Zn	Na	B
----- g/kg -----						----- mg/kg -----						
31.47	1.25	11	27.25	3.48	3.25	405	225	69.5	100	34	183.5	198.56

N: Nitrogen; P: Phosphorus; K: Potassium; Ca: Calcium; Mg: Magnesium; S: Sulfur; Al³⁺: Aluminum; Fe: Iron; Mn: Manganese; Cu: Copper; Zn: Zinc; Na: Sodium; B: Boron.

At 121 DAP, homogeneous fruit samples were collected from each treatment group. These fruits were transported to the Postharvest Physiology and Technology Laboratory at the Federal Rural University of the Semi-Arid (UFERSA) in Mossoró, Rio Grande do Norte. The fruits were sanitized in a sodium hypochlorite solution (0.1%) for 5 min.

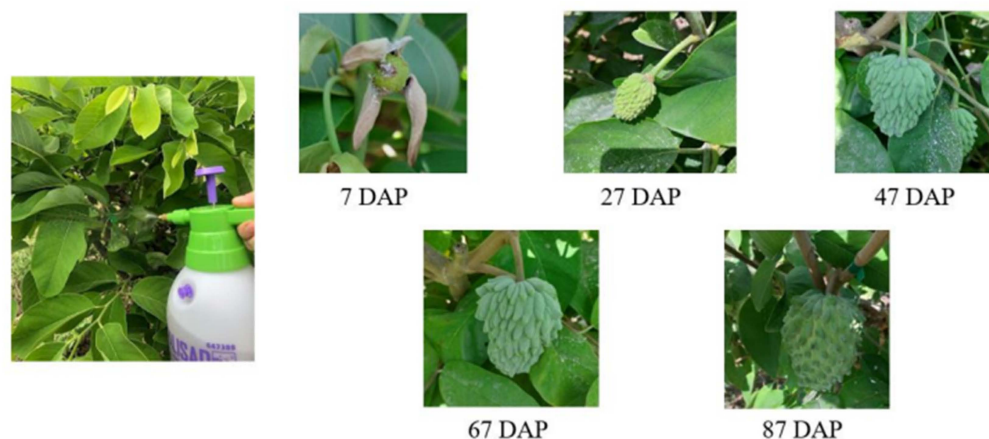


Figure 1. Applications of calcium (Ca) and gibberellic acid (GA3) at 7, 27, 47, 67, and 87 days after pollination (DAP).

Data was subjected to analysis of variance (ANOVA) at a 5% significance level. When a significant interaction between applied postharvest inputs and storage periods was observed, the qualitative factor (application treatments) was compared using [Tukey's] test ($p < 0.05$), while the quantitative factor (storage periods: 0, 3, 6, 9, 12 and 15 days) was subjected to regression analysis. Regression models (linear or quadratic) were selected based on the significance of the parameters ($p < 0.05$) and the highest coefficient of determination (R^2). Subsequently, the fruits were stored in a cold chamber at a temperature of 15 ± 3 °C and a relative humidity of $85 \pm 5\%$. At each storage interval, the following evaluations were performed: fruit and pulp appearance, weight, fresh mass loss (FML), cracking index, fruit firmness, pH, titratable acidity (TA), total soluble solids (TSS), vitamin C, chlorophyll, electrolyte leakage (EL), total sugars, starch, DPPH antioxidant activity, total extractable polyphenols (TEP), peroxidase (POD) and polyphenol oxidase (PPO) enzyme activity, and mineral quantification (calcium, magnesium, sodium, and potassium).

2.1. Fruit Appearance

Fruit appearance was evaluated on a subjective scale from 5 to 1, considering the presence of depression, shriveling, pathogen attack, and dark spots. Fruits were rated according to this scale: a score of 5 indicated the absence of these undesirable characteristics; 4 indicated slight traits; 3 indicated a mild presence; 2 indicated moderate intensity with slight microbial attack; and 1 indicated severe intensity with microbial attack. Fruits with a score of 3 or lower were considered unsuitable for commercialization [14].

2.2. Mass and Fresh Mass Loss (FML)

Fresh fruit mass was determined using a semi-analytical balance (0.01 g precision, Mark S line; BEL Engineering, Piracicaba, Brazil), and the result was expressed in grams (g); fresh mass loss was calculated as a percentage, where

$$FML (\%) = ((Mi - Md) / Mi) * 100$$

FML% = Mass loss; Mi = Initial mass (g); Md = Fruit mass on the day of analysis (g).

2.3. Cracking Index

All fruits from each treatment affected by the appearance of cracks were counted during the storage period [15].

2.4. Peel and Pulp Color

Peel and pulp color were determined using a benchtop digital colorimeter (CR-400, Konica Minolta, Tokyo, Japan). Two readings were taken at equidistant points on each fruit, and the results were expressed according to CIE $L^*a^*b^*$ coordinates, which include the variables L^* (lightness), a^* (variation between green and red), and b^* (variation between blue and yellow) [16]. The a^* and b^* values were converted into Hue angle (hue) (1) and chroma (saturation) (2)—variables that best represent the evolution of atemoya peel color during the ripening process—according to Equations (1) and (2).

$$H^\circ = 180^\circ + \arctg(b^*/a^*) \quad (1)$$

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

2.5. Firmness

Fruit firmness was determined using a texture analyzer (model TA.XTExpress/TA.XT2icon; model TA.XT Express, Stable Micro Systems, Vienna, UK) equipped with a cylindrical probe (5 mm in diameter). Two readings were taken per fruit at equidistant points along the equatorial region. To determine firmness with the skin intact, measurements were performed directly on the surface of the whole fruit. Subsequently, to measure flesh firmness, each fruit was cut in half, and measurements were taken at the center of each half. The probe operated at an insertion depth of 8 mm, a test speed of 2 mm s^{-1} , and a trigger force of 0.049 N. Results were expressed in Newtons (N).

2.6. pH

To perform the measurement, 5 g of pulp was weighed, and 50 mL of distilled water was added; the reading was determined using a direct-reading potentiometer (mPA-210, Tecnal, Piracicaba, Brazil), duly standardized with buffer solutions. Once the results displayed on the equipment panel stabilized, the measured data were expressed as actual pH values [17].

2.7. Titratable Acidity (TA)

Titrateable acidity (TA) was determined by volumetric titration with a NaOH solution [17]. 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 slowly titrated with a 0.01 M NaOH solution. Results were expressed as milliequivalents (meq) H^+ per 100 g of pulp.

2.8. Soluble Solids

Soluble solids (SS) content was determined using a digital refractometer (PR-101, Atago Palette Co., Tokyo, Japan), and the results were expressed as a percentage, °Brix [18].

2.9. Vitamin C

Vitamin C was determined by titration with Tillman's solution (DFI-2,6-dichlorophenol-indophenol at 0.02%) by taking 1 g of the samples and diluting them to a volume of 50 mL in a volumetric flask with 0.5% oxalic acid [17]; results were expressed as mg of ascorbic acid per 100 g of pulp.

2.10. Chlorophyll

To determine chlorophyll A and B, 0.8 g of fresh mass (FM) of the fruit peel was weighed and solubilized in 15 mL of 80% acetone. The tubes were stored in the dark for 48 h, and spectrophotometric readings were taken at wavelengths of 647 and 663 nm for

chlorophyll a and b [19]. Chlorophyll concentrations were estimated using the following equations, expressed in $\text{mg} \cdot \text{g}^{-1}$, where

$$FM, Chla = [(12.25 \times A663 - 2.79 \times A647)]$$

$$Chlb = [(21.5 \times A647 - 5.10 \times A663)]$$

FM = Fresh mass, Chla = Chlorophyll a, and Chlb = Chlorophyll b.

2.11. Electrolyte Leakage

The percentage of electrolyte leakage was determined according to the methodology proposed by [20]: eight 8 mm discs were removed and incubated in distilled water for 24 h. Initial electrical conductivity was measured using a conductivity meter ((model CD-820; Digimed, São Paulo, Brazil). Subsequently, the discs were subjected to a water bath for one hour, allowed to cool, and the final electrical conductivity was measured; the electrolyte leakage result was then calculated according to the equation, where

$$EL(\%) = (IEC/FEC) \times 100$$

EL (%) = Electrolyte leakage; IEC = Initial electrical conductivity; FEC = Final electrical conductivity.

2.12. Total Sugars

Total sugars were determined using the anthrone (9,10-dihydro-9-oxoanthracene) method. Starting with 1 g of sample diluted in a 100 mL volumetric flask with 80% alcohol, a 10 mL aliquot of the solution was transferred to another 100 mL flask, and the volume was made up with distilled water [21]. An aliquot was then taken for analysis; readings were performed on a spectrophotometer (model UV-1600; Pró-Tools, Porto Alegre, Brazil) at 620 nm, and results were expressed as a percentage (%).

2.13. Starch

The methodology used for starch quantification was described by the Association of Official Analytical Chemists [18] and by [22]. Quantification was determined using the DNS (3,5-dinitrosalicylic acid, Sigma) method. A spectrophotometer was used for measurements at 540 nm, and results were expressed as a percentage (%).

2.14. Antioxidant Activity (DPPH)

Total antioxidant activity was evaluated using the DPPH radical method as described by [23] and modified by [24,25]. Antioxidant extraction was performed by adding 2 g of the sample (pulp) to 10 mL of 50% methanol in a 50 mL tube, followed by homogenization and a 60-min resting period. Absorbance was measured at 515 nm using a spectrophotometer. All analyses were performed in triplicate, with a control used as a reference; results were expressed as % scavenging.

2.15. Total Extractable Polyphenols (TEP)

Extracts were prepared for the determination of total extractable polyphenols (TEP) using the Folin–Ciocalteu reagent and gallic acid as the standard. To obtain the extract, 2 g of pulp were subjected to extraction using two solvents—50% methanol and 70% acetone—with some modifications [25]. Absorbance was measured at 700 nm using a spectrophotometer, and results were expressed as $\text{mg} \cdot 100 \text{ g}^{-1}$ of pulp.

2.16. Peroxidase (POD) Enzyme Activity

The extraction and determination of the peroxidase (POD) enzyme were performed according to [26], with modifications. The extract was filtered, and the reaction mixture was prepared by pipetting 25 μ L of guaiacol (0.2 M), 250 μ L of hydrogen peroxide (0.38 M), 1 mL of sodium phosphate buffer (0.2 M, pH 6.0), and 25 μ L of the extract. Absorbance was measured using a spectrophotometer at a wavelength of 470 nm, with readings commencing 3 min after the initiation of enzyme activity; results were expressed as POD activity (U/min/mg of sample).

2.17. Polyphenol Oxidase (PPO) Enzyme Activity

The extraction and determination of the enzyme polyphenol oxidase (PPO) were performed according to the method of [27], with modifications. Spectrophotometric readings were taken at a wavelength of 395 nm, and results were expressed in EU·mg^{−1} of sample.

2.18. Minerals: Calcium (Ca), Magnesium (Mg), Sodium (Na), and Potassium (K)

For microwave-assisted sample digestion, 0.5 g of the oven-dried (at 65 °C) and ground sample was weighed. The samples were transferred to Teflon vessels, and 5 mL of nitric acid (HNO₃) was added. The vessels were placed in a microwave oven and heated to 170 °C; after cooling completely, the volume was made up to 25 mL with deionized water [28]. Ca and Mg concentrations were determined by atomic absorption spectrometry, while Na and K were measured using a flame photometer (model DM-62; Digimed, São Paulo, Brazil); results are expressed in g·kg^{−1}.

2.19. Use of Artificial Intelligence Tools

During the preparation of this manuscript, the authors used Gemini (Google)/ChatGPT (OpenAI) to assist with drafting, language editing, text organization, and preparation. All AI-generated content was critically reviewed and revised by the authors, who take full responsibility for the accuracy, integrity, and final content of the published manuscript.

2.20. Statistical Analysis

The evaluated variables were subjected to analysis of variance (ANOVA) using the F-test ($p < 0.05$); qualitative data were subjected to Tukey's test ($p < 0.05$), and the effects of quantitative treatments were subjected to polynomial regression. Analyses were performed using RStudio software version 4.1.1 [29]. Graphs were generated using SigmaPlot 14.0.3 software.

3. Results

3.1. Fruit Appearance and Cracking Index

It was observed that fruits treated with gibberellic acid (GA₃) exhibited carpel deformations. A decline in external and internal appearance scores was observed throughout the storage period (Figure 2). Significant quality loss occurred during this time; initial post-harvest scores of 4.60, 4.80, 4.20, and 4.80 dropped to 2.80, 2.80, 2.90, and 2.90 by the end of storage (15 days) for the Control, Ca, GA₃, and Ca+GA₃ applied postharvest inputs, respectively, with the calcium and gibberellic acid applied postharvest inputs achieving the best scores. The fruit's shelf life was 12 days; fruit treated with Ca+GA₃ exhibited the best visual appearance, maintaining a rating above the commercial acceptability threshold of 4.60 throughout the entire 12-day period. This decline in scores was primarily driven by skin browning and the development of cracks. Consequently, fruit quality gradually deteriorated, rendering the fruit unsuitable for marketing after 15 days of storage.

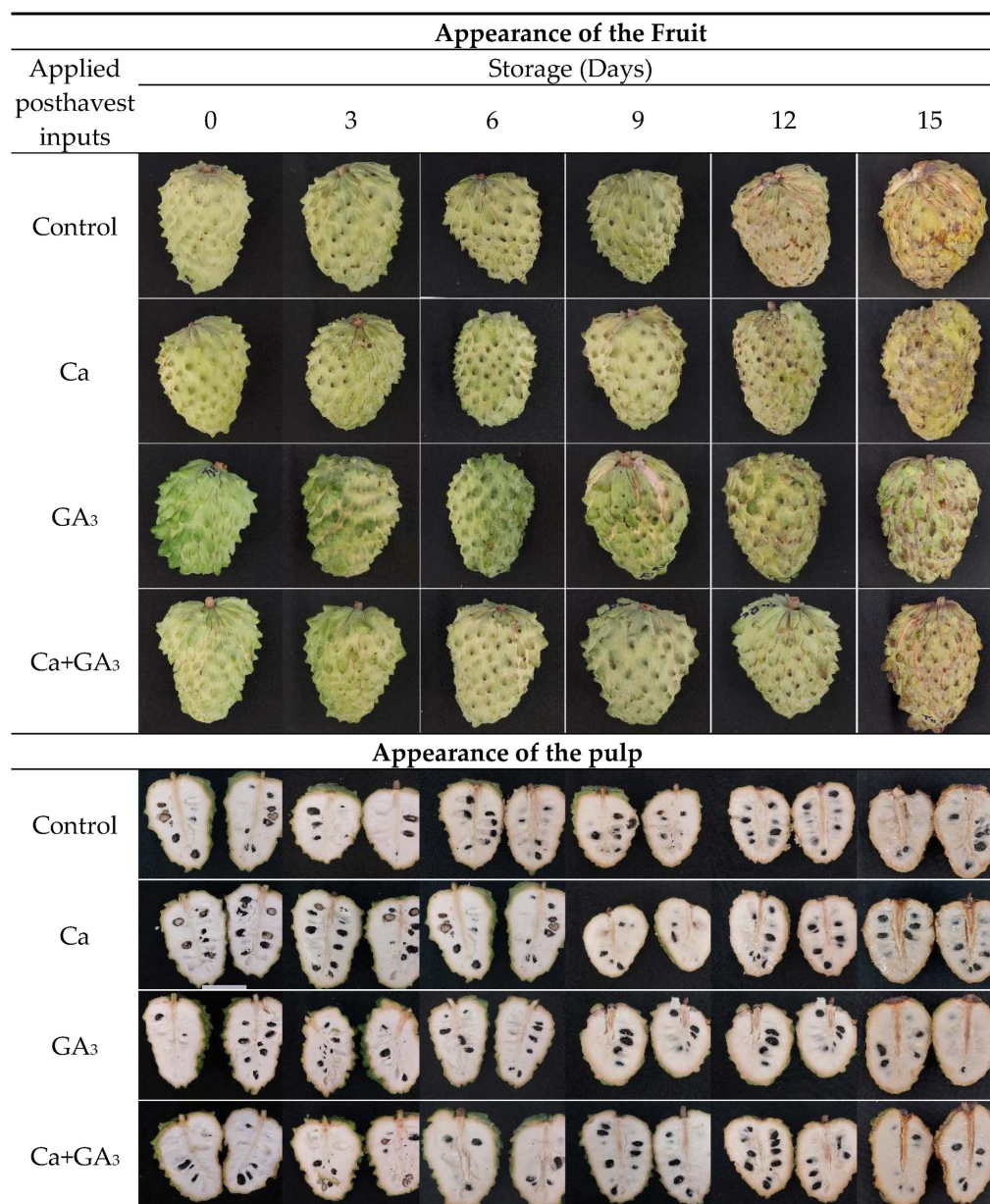


Figure 2. Appearance of ‘Gefner’ atemoya fruit and pulp treated with Ca, GA₃, Ca+GA₃, and untreated (control), stored for 15 days under refrigeration (15 ± 3 °C and $85 \pm 5\%$ RH).

During fruit storage period, cracking occurred near the peduncle and along the circumference (Figure 3); this physiological disorder appeared as early as the 6th day in the gibberellic acid (GA₃) applied postharvest inputs, affecting 20% of the fruit, whereas the other applied postharvest inputs showed the disorder starting on the 12th day, with incidence rates of 60%, 40%, and 40% for the control, calcium (Ca), and calcium + gibberellic acid (Ca+GA₃) applied postharvest inputs, respectively. By the end of the storage period (15 days), all fruits were cracked. As shown in Figure 2, after 15 days of storage, average crack diameters of 21.12 mm and 20.71 mm were observed in fruits treated postharvest with Ca and Ca+GA₃, respectively, while the control and GA₃ treatments presented average values exceeding 22 mm.

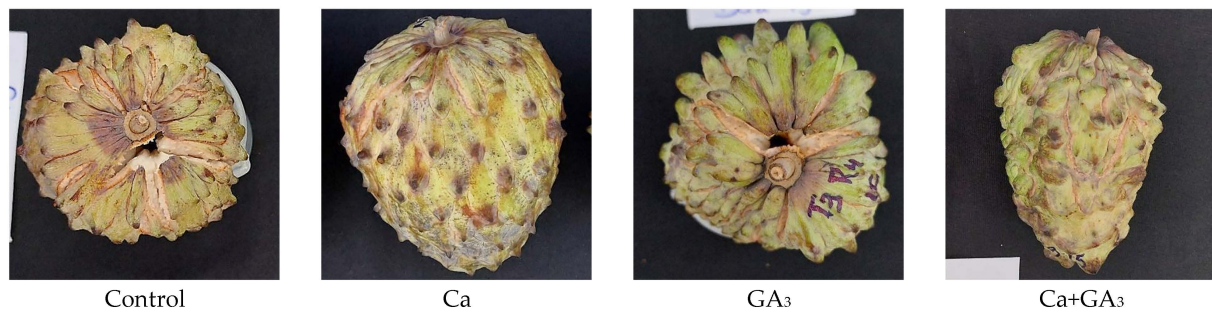


Figure 3. Cracking in ‘Gefner’ atemoya fruit treated with Ca, GA₃, Ca+GA₃, and untreated (control), stored for 15 days under refrigeration (15 ± 3 °C and $85 \pm 5\%$ RH).

3.2. Mass, Fresh Mass Loss, Fruit and Pulp Firmness

A significant interaction was observed between mass loss and pulp firmness ($p < 0.05$), whereas for fruit firmness, only storage time was a significant factor ($p < 0.05$). Across all applied postharvest inputs, fruits weighed more than 300 g at 21 days after pollination (DAP), the stage at which they were ready for harvest (Control: 333.33 g; Ca: 323.67 g; GA₃: 357.17 g; Ca+GA₃: 362.50 g). Analysis of mass loss in ‘Gefner’ atemoyas—subjected to Ca, GA₃, and Ca+GA₃ applied postharvest inputs as well as a control and evaluated over 15 days of storage—revealed a progressive increase in this parameter throughout the storage period (Figure 4A). By the end of storage, fruits exhibited significant mass loss, reaching 7.99%, 8.38%, 8.62%, and 8.31% for the control, Ca, GA₃, and Ca+GA₃ applied postharvest inputs, respectively.

Initially, atemoya fruits exhibited high firmness across all applied postharvest inputs; however, a reduction was observed over the storage period (Figure 5A), with an average of 90 N at harvest and a drop to values below 5 N by the 15th day. Pulp firmness showed a cubic polynomial interaction regarding the factors evaluated (applied postharvest inputs vs. storage), as illustrated in Figure 5B. Among the treatments, Ca+GA₃ applied postharvest inputs exhibited lower pulp firmness after harvest, with a difference of 9.13 N.

3.3. Peel and Pulp Color

In this case, significant differences were observed among the postharvest treatments for the peel color variables—chromaticity ($p < 0.001$), hue angle ($p < 0.05$), and lightness ($p < 0.001$)—with values remaining stable throughout the 15 days of cold storage. After 15 days of storage, pulp hue angle values for all postharvest treatments remained above 178° (Figure 5B), reflecting the characteristic color stability of the pulp during the storage period.

After harvest, fruits bore natural wax; this protective layer reduced initial lightness and chromaticity values across all applied postharvest inputs. This characteristic was observed to disappear during storage period, with values increasing up to the 12th day across applied postharvest inputs (Figure 5C). Therefore, high values for chromaticity, hue angle (°Hue), and lightness indicate glossy fruit with vivid colors and uniform color angles close to dark green. These coloration characteristics were exhibited by the atemoya fruits up to the 12th day.

An increase in pulp chromaticity values was observed up to the 12th day; however, color intensity decreased by the end of storage (Figure 5D), indicating that the fruit pulp was initially white and shifted to cream as ripening progressed (Figure 2). Regarding the pulp Hue angle, a significant interaction ($p < 0.001$) was observed between applied postharvest inputs and storage duration; mean values were 178.53 ± 0.05 , 178.55 ± 0.07 , 178.54 ± 0.08 , and 178.56 ± 0.06 for the Control, Ca, GA₃, and Ca + GA₃ applied postharvest inputs, respectively (Figure 5E). Pulp lightness values (L*) also showed an interaction between

factors (Figure 6F), with a decrease in brightness over the storage period. Changes in atemoya pulp lightness showed a difference of more than 13.00 L* units from the day of harvest to the end of the 15-day storage period. This reduction in brightness is attributed to the change in pulp color.

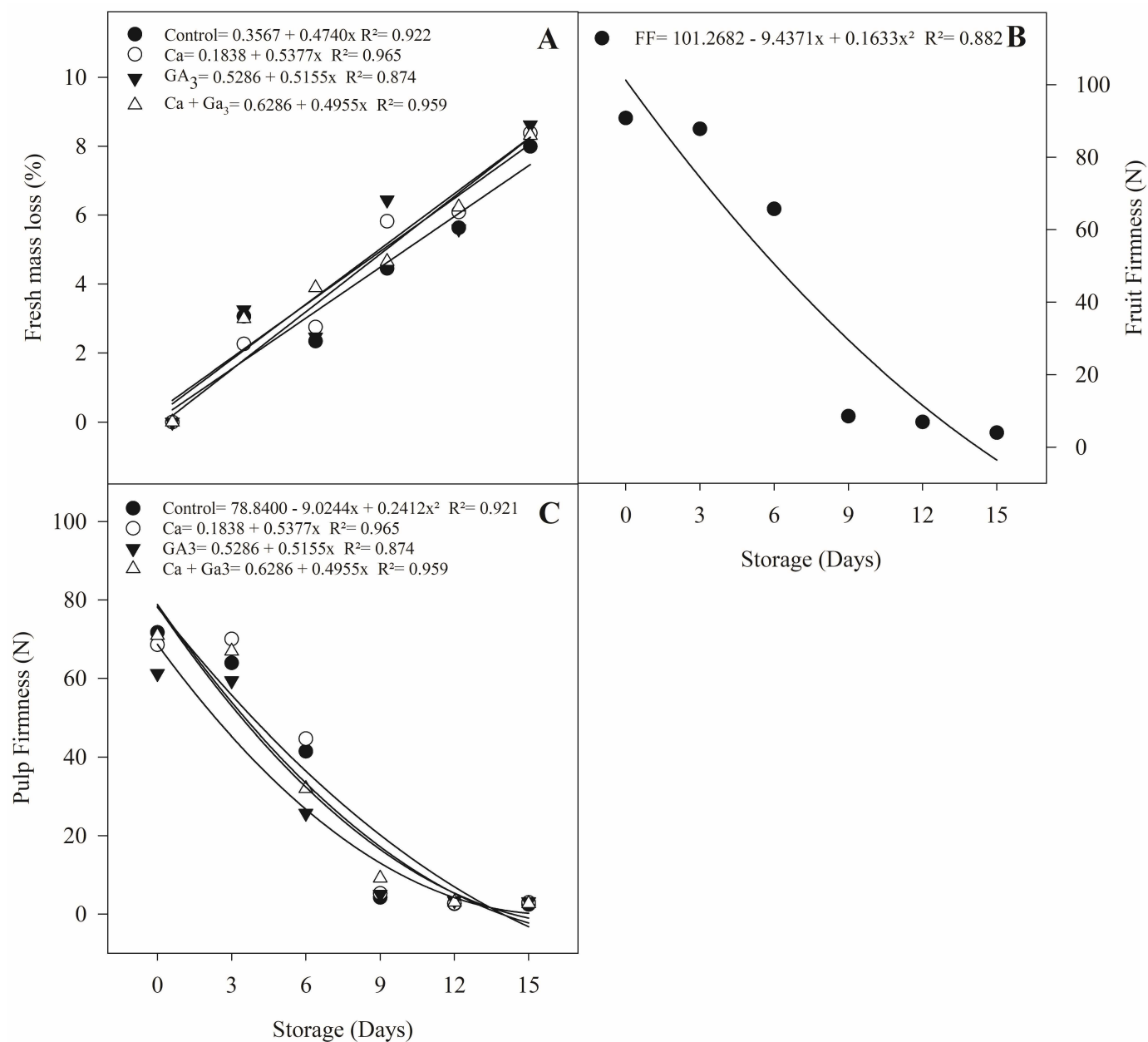


Figure 4. (A) Fresh mass loss (interaction effect: applied postharvest inputs $\times$ storage time), (B) fruit firmness (isolated main effect of storage time), and (C) pulp firmness (interaction effect: applied postharvest inputs $\times$ storage time) of 'Gefner' atemoya fruits treated with Ca, GA₃, Ca+GA₃, and untreated (control) stored for 15 days under refrigeration (15 ± 3 °C and $85 \pm 5\%$ RH).

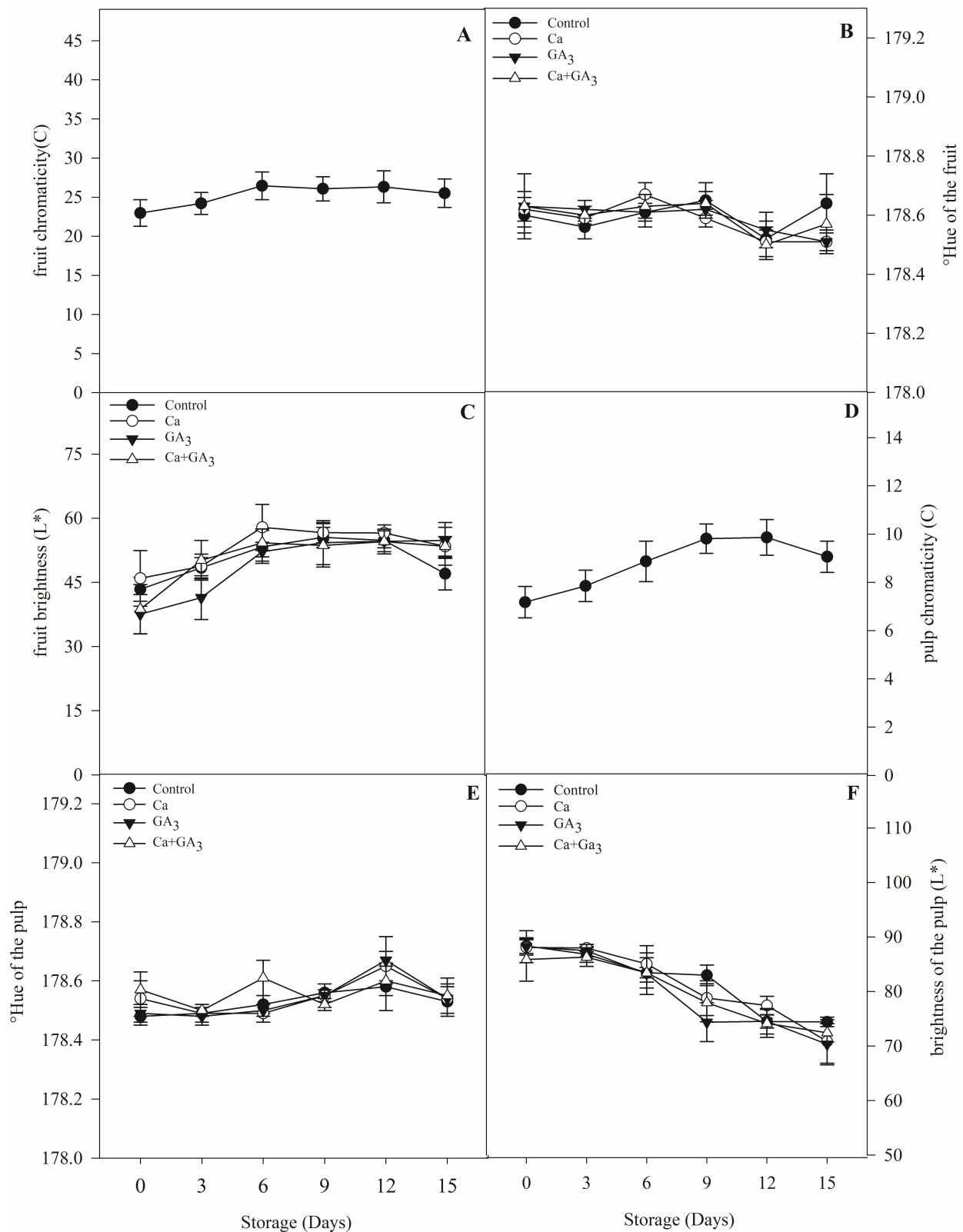


Figure 5. (A) Fruit chromaticity (C*; isolated main effect of storage time), (B) fruit hue angle (°Hue; interaction effect: applied postharvest inputs × storage time), and (C) fruit lightness (L*; interaction effect: applied postharvest inputs × storage time), and (D) pulp chromaticity (C*; isolated main effect of storage time), (E) pulp hue angle (°Hue; interaction effect: applied postharvest inputs × storage time), and (F) pulp lightness (L*; interaction effect: applied postharvest inputs × storage time) in 'Gefner' atemoya treated with Ca, GA₃, Ca+GA₃, and untreated (control) and stored for 15 days under refrigeration (15 ± 3 °C and 85 ± 5% UR).

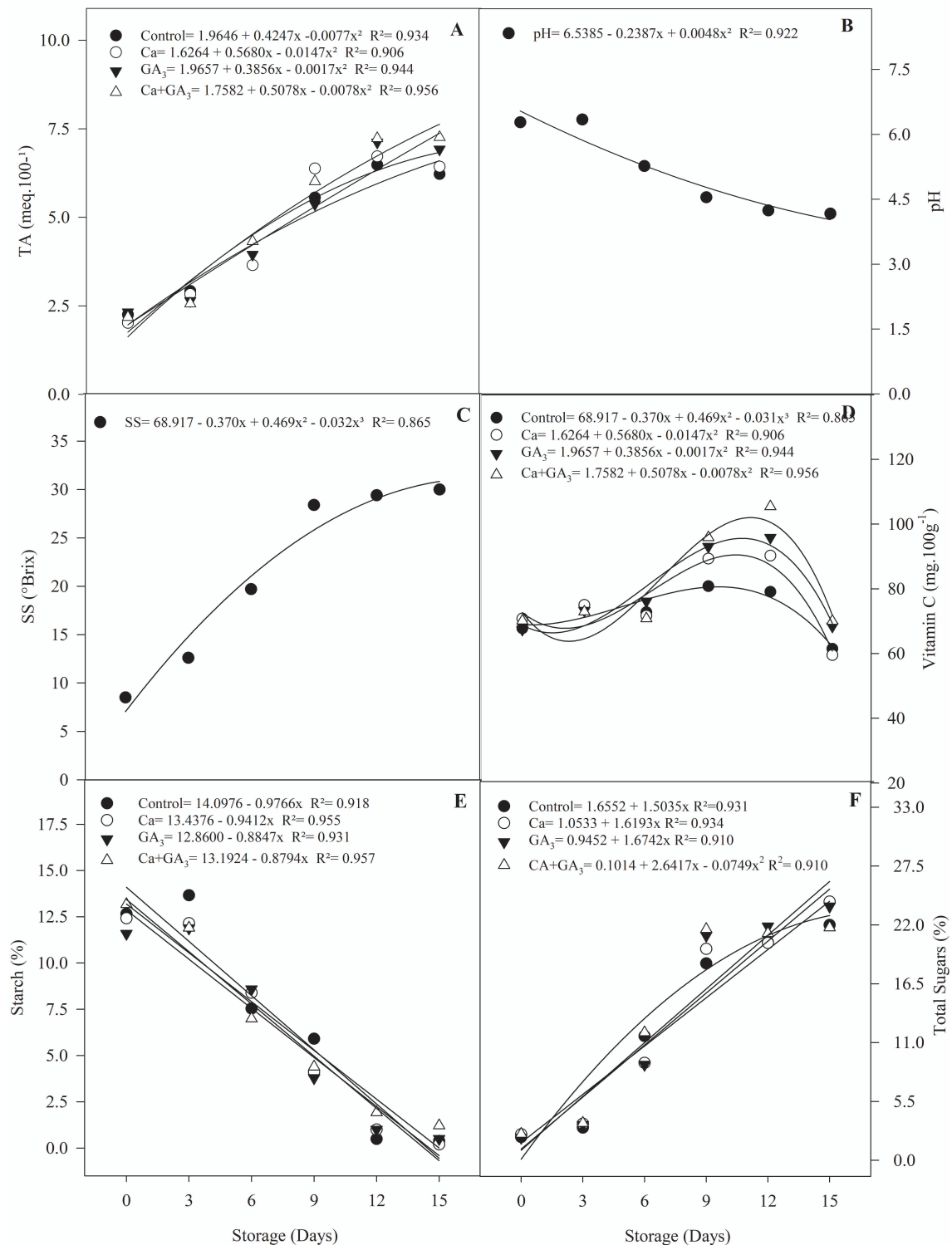


Figure 6. (A) Titratable Acidity (TA; interaction effect: applied postharvest inputs $\times$ storage time), (B) pH (isolated main effect of storage time), (C) Total Soluble Solids (SS; isolated main effect of storage time), (D) Vitamin C (interaction effect: applied postharvest inputs $\times$ storage time), (E) Starch (interaction effect: treatment $\times$ storage time), and (F) Total Sugars (interaction effect: applied postharvest inputs $\times$ storage time) in ‘Gefner’ atemoya treated with Ca, GA₃, Ca+GA₃, and untreated (control) and stored for 15 days under refrigeration (15 ± 3 °C and $85 \pm 5\%$ UR).

3.4. Titratable Acidity, pH, Vitamin C, Soluble Solids, Starch

Significant interactions were observed for titratable acidity ($p < 0.05$), vitamin C ($p < 0.05$), starch ($p < 0.05$), and total sugars ($p < 0.05$), whereas pH ($p < 0.05$) and soluble

solids ($p < 0.05$) were affected solely by storage time. Ti Based on the fitted quadratic regression models, titratable acidity showed a continuous increasing trend up to the 15th day of storage across all treatments (Figure 6A), with Ca+GA₃ applied postharvest inputs exhibiting the highest acidity accumulation curve toward the end of the storage period.

pH was significant only for the storage factor ($p < 0.001$), showing a decrease over the storage period; overall mean was 6.48 on the day of harvest and 4.17 after 15 days (Figure 6B). Figure 6 shows the vitamin C content, which exhibited an interaction between applied postharvest inputs and storage time ($p < 0.01$); a peak in vitamin C content was observed on the 9th and 12th days across all applied postharvest inputs, with values exceeding 70 mg·100g⁻¹ of pulp, notably in the Ca+GA₃ applied postharvest inputs, which showed the highest vitamin C content.

Regarding soluble solids, there was a significant difference among applied postharvest inputs, with fruits treated with GA₃ and Ca+GA₃ standing out (30.15 and 30.72 °Brix, respectively) for having the highest soluble solids content (Figure 6C). Meanwhile, a significant increase of 21.55% in soluble solids was observed by the end of the storage period.

Atemoya fruit showed high starch reserves at harvest, which were converted into sugars during storage (Figure 6E,F). For starch, there was a significant interaction between the evaluated factors, with Ca+GA₃ applied postharvest inputs showing the highest starch percentage at both the beginning and the end of storage (Figure 6E). Total sugars also showed a significant interaction, with an increase of over 20% in content from the day of harvest to the end of the 15-day storage period.

3.5. Total Chlorophyll, Electrolyte Leakage, DPPH, TEP, POD and PPO

Total chlorophyll content differed significantly among applied postharvest inputs ($p < 0.001$) (Figure 7A), while significant interactions were observed for EE ($p < 0.05$), DPPH ($p < 0.05$), PET ($p < 0.05$), POD ($p < 0.05$), and PPO ($p < 0.05$). The GA₃ (6.58 µg·g⁻¹) and Ca+GA₃ (5.92 µg·g⁻¹) applied postharvest inputs stood out, whereas the control and Ca applied postharvest inputs showed values below 5 µg·g⁻¹. Pigment degradation occurred throughout storage: mean values were 5.73, 6.82, 9.19, and 7.48 µg·g⁻¹ on day 0, declining to 3.72, 4.13, 5.46, and 5.06 µg·g⁻¹ by day 15 (Control, Ca, GA₃, and Ca+GA₃, respectively). This chlorophyll degradation is associated with the fruit ripening process and the onset of senescence.

Regarding electrolyte leakage, percentage increased gradually during storage based on the interaction between the evaluated factors (Figure 7B). On the 12th day of storage, a lower percentage of membrane damage was observed in the Ca+GA₃ applied postharvest inputs (77.04%), whereas higher percentages were observed in the control, Ca, and GA₃ applied postharvest inputs during the same period (84.15%, 82.62%, and 81.58%, respectively)—a difference of more than 5%. By the end of storage, all treatments showed membrane damage values exceeding 80%.

Regarding DPPH, values were higher at the beginning of storage, with means of 73.25% and 78.08% on days 0 and 3, respectively (Figure 7C); a decrease occurred across all treatments after 9 days, and by the end of storage, mean values were 28.79%, 35.13%, 35.35%, and 37.78% for the control, Ca, GA₃, and Ca+GA₃ applied postharvest inputs, respectively.

TEP showed an increase of approximately 2 mg·100g⁻¹ across all applied postharvest inputs during storage (Figure 7D); control treatment showed the lowest mean value (4.96 mg·100g⁻¹), while the Ca, GA₃, and Ca+GA₃ applied postharvest inputs had means of 5.63, 6.60, and 6.07 mg·100g⁻¹, respectively.

Figure 7E,F show a significant interaction ($p < 0.001$) between the factors for POD and PPO. POD enzyme activity fluctuated throughout the storage period (Figure 7E) across all

treatments. Regarding PPO, the control, Ca, and GA₃ applied postharvest inputs showed an increase in activity up to the 9th day of storage, followed by a gradual decrease until the end of the storage period; in contrast, Ca+GA₃ applied postharvest inputs exhibited a smaller increase compared to the other treatments, and this increase persisted until the 12th day of storage (Figure 7F).

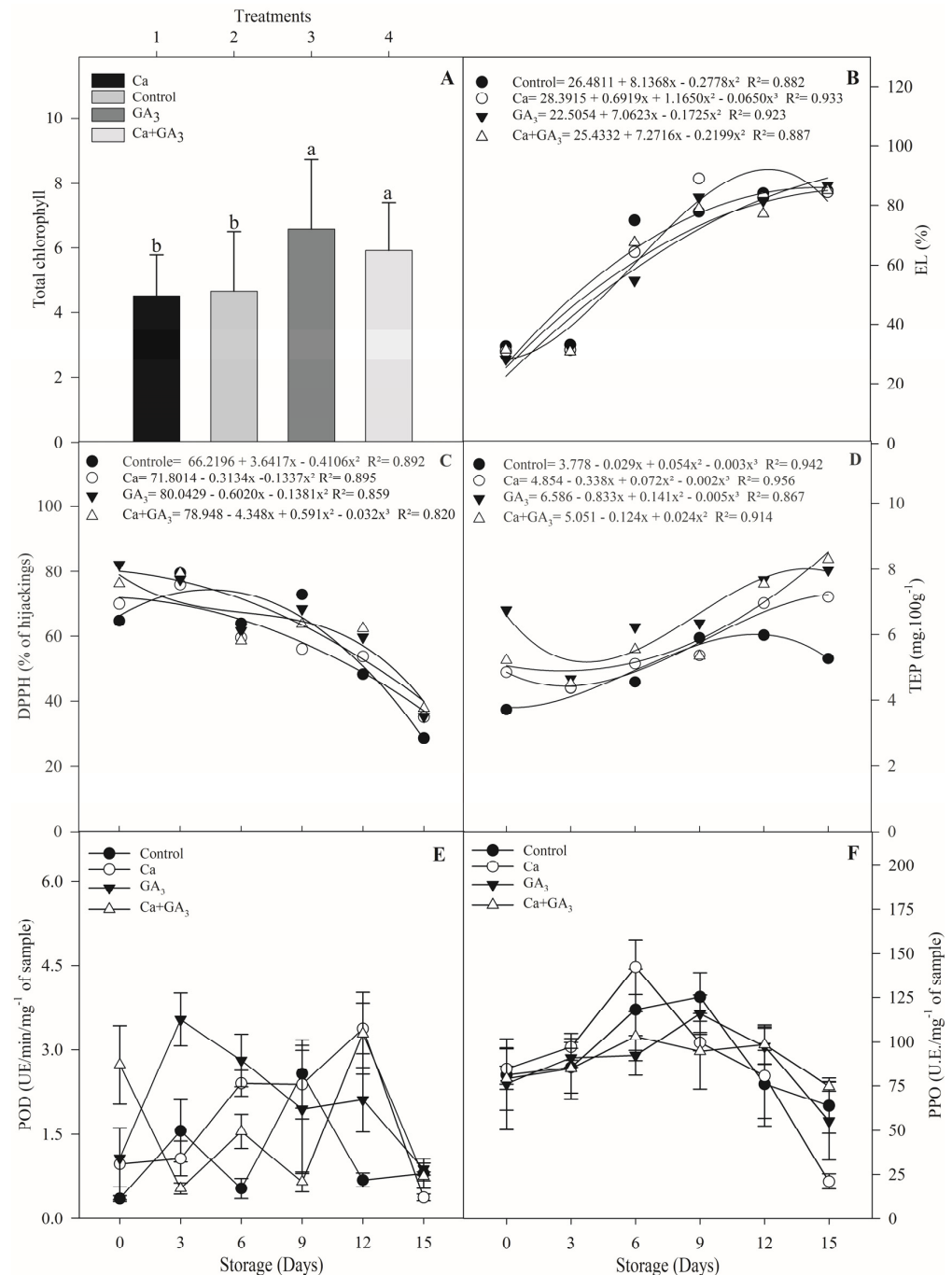


Figure 7. (A) Total chlorophyll (isolated main effect of applied postharvest inputs), (B) electrolyte leakage (EE; interaction effect: applied postharvest inputs $\times$ storage time), (C) antioxidant activity (DPPH; interaction effect: applied postharvest inputs $\times$ storage time), (D) total extractable polyphenols (TEP; interaction effect: applied postharvest inputs $\times$ storage time), (E) enzymatic activity of peroxidase (POD; interaction effect: applied postharvest inputs $\times$ storage time) and (F) polyphenol oxidase (PPO; interaction effect: applied postharvest inputs $\times$ storage time) in Atemoya 'Gefner' treated with Ca, GA₃, Ca+GA₃, and untreated (control) and stored for 15 days under refrigeration (15 ± 3 °C and 85 ± 5 % UR). Different letters indicate a significant difference (Tukey's test, $p < 0.05$).

3.6. Minerals: Ca, Mg, Na and K

Figure 8A shows a significant interaction between postharvest treatments and storage time for calcium ($p < 0.001$), while magnesium also exhibited a significant interaction effect ($p < 0.05$; Figure 8B). On the 15th day of storage, fruits treated with Ca+GA₃ showed a calcium content of 0.045 g kg⁻¹ of pulp, compared to 0.038, 0.036, and 0.044 g kg⁻¹ for the control, Ca, and GA₃ treatments, respectively. Magnesium content varied according to the interaction between treatment and storage time (Figure 8B), with the Ca treatment reaching 0.29 g kg⁻¹. For sodium, a significant main effect of postharvest treatment was observed ($p < 0.05$; Figure 8C); the Ca treatment showed the highest mean content (0.82 g kg⁻¹), not differing statistically from the other treatments but exceeding the Ca+GA₃ treatment. Potassium also showed a significant treatment effect ($p < 0.05$; Figure 8D); fruits treated with GA₃ showed a mean value of 32.35 g kg⁻¹, while those receiving Ca+GA₃ showed a mean value of 30.33 g kg⁻¹. Different letters indicate significant differences between treatment means according to Tukey's test ($p < 0.05$).

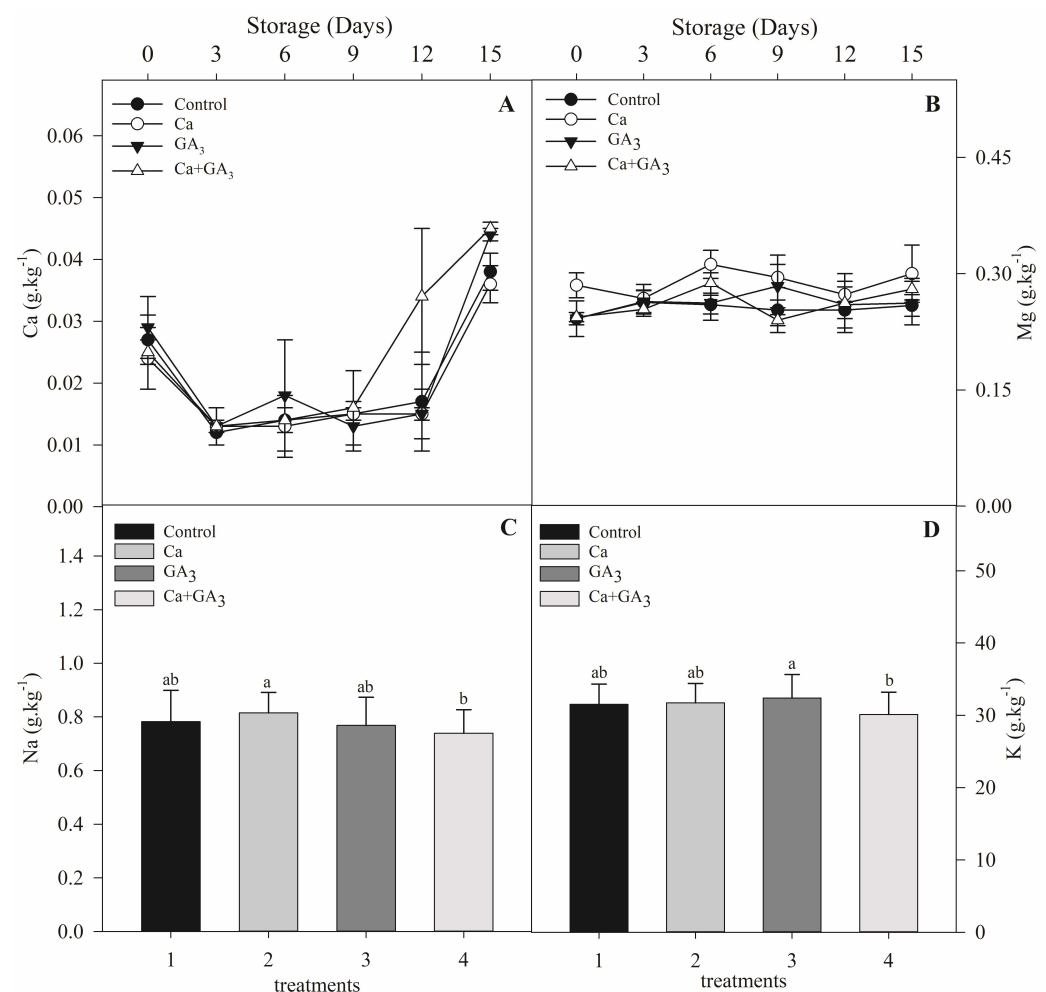


Figure 8. Calcium (Ca; (A)) and magnesium (Mg; (B)) contents as affected by the interaction between postharvest treatments and storage time, and sodium (Na; (C)) and potassium (K; (D)) contents as affected by the main effect of postharvest treatments in ‘Gefner’ atemoya fruits treated with Ca, GA₃, Ca+GA₃, or left untreated (control) and stored for 15 days under refrigeration (15 ± 3 °C and 85 ± 5% relative humidity). For Ca and Mg (A,B), data are presented according to storage time. For Na and K (C,D), bars represent treatment means. Different letters indicate significant differences among means according to Tukey's test ($p < 0.05$).

4. Discussion

Physical characteristics are the first parameters evaluated by consumers regarding the quality of a product. Fruit appearance and color play an important role in assessing ripeness and quality [30]. During storage, there was a visible change in the atemoya pericarp, resulting in the darkening of the fruits. This resulted in a significant decrease in appearance, loss of mass, firmness, and color of the fruit and pulp in all treatments. Fruits treated with GA₃ exhibited deformations in the carpels. Given these results, the observed deformation of the fruits possibly occurred as a result of the incomplete fertilization of multiple ovaries, a process influenced by both the inefficient deposition of pollen and the dynamics of the stigmatic exudate, which resulted in an irregular distribution of seeds and consequent carpel asymmetry [31,32]. Linked to this, the authors mention that the application of chemical products via spraying can act as a factor of mechanical interference, since the jet of solution removes part of the pollen grains previously deposited on the stigma, compromising the uniformity of the fruit. Corroborating the results of this study, the incidence of irregularities in treatments with growth regulators was less than 23% [31], a value that is more favorable than the 27% reported in ‘Gefner’ atemoya under application of gibberellic acid (GA₃) [33].

The ripening process of atemoya fruits is due to physiological changes that directly influence appearance, firmness, flavor and aroma, as evidenced in the present work. Confirming these characteristics, ref. [34] describes that fruit softening is another factor that contributes to shelf life, transport and storage capacity. Extensive studies have been carried out on the softness of various fruits, and the reduction in firmness represents one of the most evident characteristics as observed in the present work.

Figure 3 illustrates the physiological disorder characteristic of atemoyas—namely, cracking during storage—for which lower mean cracking values were numerically observed in fruits treated with Ca and Ca+GA₃; this response may be associated with the higher Ca levels observed in the Ca+GA₃ treatment. This reduction may be linked to the higher Ca levels observed in the Ca+GA₃ treatment. Conversely, the use of GA₃ alone did not yield positive results regarding this disorder. Similar findings were reported by [8], who observed that the use of Ca and GA₃ was effective in reducing fruit cracking in pomegranates. Furthermore, calcium strengthens cell walls by stabilizing pectin in the middle lamella, thereby reducing the incidence of fruit cracking. This effect occurs because calcium plays an essential role in cell wall structure, enhancing the mechanical properties of plant tissues. Additionally, it interacts with pectic acid, promoting greater cell wall cohesion and minimizing structural failures during development. Foliar applications of calcium chloride or calcium nitrate have proven effective in reducing cracking in fruits such as cherries and tomatoes [35,36].

Cracking results from alterations in cell wall structure caused by pectin degradation and starch hydrolysis, which lead to a loss of fruit firmness [37]. This disorder is also influenced by water uptake and intrinsic fruit properties, such as size, hardness, tissue structure, and the resistance and osmotic pressure of the skin and pulp [38].

Starch hydrolysis is closely linked to the fruit ripening and aging process and can supply carbon for sugar production and flavor development [39]. The increase in total fruit sugar is directly related to its breakdown into soluble sugars. These sugars influence the soluble solids content of the pulp, which consists primarily of sugars, alongside organic acids and vitamins [40]. The present study confirms that the starch degradation process during ripening led to progressive changes in titratable acidity, soluble solids, and total sugars, as well as a reduction in firmness, as shown in Figures 4–6, respectively.

Firmness has been highlighted in numerous studies as a key parameter for the postharvest evaluation of fruit, as it affects both flavor and shelf life [41]. The significant decline

in firmness observed over time in this study indicates that fruit is ripening and entering senescence. This pattern suggests that the rate of softening varies depending on the treatment applied. In the case of the Ca+GA₃ group, initial firmness was lower, suggesting postharvest alterations in cellular architecture. Biochemically, this phenomenon is driven by enzymes (such as pectinases and cellulases) that degrade the cell wall and solubilize pectin, thereby reducing the pulp's resistance [42].

Ascorbic acid (C₆H₈O₆), commonly known as vitamin C, is a compound found ubiquitously in natural sources, though it is notable for its high chemical instability. Due to its water-soluble nature, this vitamin is particularly prone to drastic losses during handling or industrial processing [43]. Nevertheless, it is of vital importance to health owing to its antioxidant potential. In the present study, higher values were found in the pulp across all treatments (Control, Ca, GA₃, and Ca+GA₃). Consistent with our study [44] evaluating the physical and chemical characteristics of 'Gefner' atemoya fruit, vitamin C levels were determined in different fruit fractions; peel showed values of 105.41 mg·100g⁻¹, while the pulp showed 60.97 mg·100g⁻¹. Similarly, a previous study evaluating foliar applications of GA₃ and calcium nitrate during the flowering stages of pomegranate trees yielded positive results regarding fruit quality, such as reduced cracking and increased vitamin C concentration [45].

The data from this study confirm that atemoya fruits remain important dietary sources of Ca, Mg, K, and Na. This reiterates their high nutritional value, which remains significant regardless of the variations observed among treatments. These findings corroborate previous results evaluating the mineral composition and nutritional properties of two atemoya cultivars ('Gefner' and 'African Pride'), both of which showed excellent levels of K, Mg, vitamin C, and phenolic compounds, representing a fruit with significant antioxidant potential [1].

During storage, fruits exhibited chlorophyll degradation and increased electrolyte leakage; natural process of fruit ripening and senescence is one of the factors driving these characteristics. Electrolyte leakage also indicates changes in cell membrane permeability in fruit tissues subjected to stress, depending on the exposure environment [46]. In this regard, primary stress responses—such as increased cell membrane permeability—are notable, as are secondary responses, including electrolyte release, reduced metabolic energy (respiration), and oxidative damage caused by the formation of reactive oxygen species [47,48].

Research on okra using GA showed that the produce retained a bright green color for longer and had an extended shelf life due to reduced chlorophyll degradation during storage. These results indicate that GA signaling plays a fundamental role in the process of chlorophyll degradation in okra after harvest [49]. Consistent with the present study, it was also observed in atemoya that fruits treated with GA₃ and Ca+GA₃ exhibited higher chlorophyll content and less degradation during storage—as evidenced by fruit appearance—whereas, by the end of storage, the fruits showed a color change from green to brown (browning process).

In postharvest fruit, browning is associated with a rise in reactive oxygen species (ROS), which compromises cell membrane permeability and causes the leakage of cellular contents, directly leading to skin browning [50]. Plant cells typically possess a highly effective antioxidant system responsible for neutralizing excessive ROS accumulation. This system comprises both enzymatic and non-enzymatic antioxidant mechanisms. The non-enzymatic antioxidant system relies on biologically active substances within the cells such as polyphenols, vitamins, and reduced glutathione, which can directly scavenge ROS [51].

This study observed increases in non-enzymatic parameters, including total extractable polyphenols (Figure 7B), vitamin C (Figure 6D), and chlorophyll content, as well as an

increase in DPPH antioxidant activity (Figure 7C); GA₃ and Ca+GA₃ treatments yielded the highest values for these variables. Enzymatic factors—specifically peroxidase (POD) and polyphenol oxidase (PPO), which are implicated in fruit browning—were also analyzed. POD activity fluctuated throughout the storage period across all treatments (Figure 7E). Similar behavior was observed in a study evaluating polyphenol oxidase and peroxidase activity in atemoya fruit, where POD activity fluctuated during the ripening process [52].

POD performs various biochemical functions in plants, but its primary role is catalyzing browning reactions due to its oxidative potential regarding organic substrates [53]. Furthermore, it was observed that increased POD activity is associated with the fruit's stress response, as one of its primary functions is to protect cells against oxidative reactions—specifically the generation of ROS such as hydrogen peroxide [54]. Enzymatic browning involves the oxidation of phenolic compounds; this reaction is catalyzed by enzymes like PPO and proceeds through the oxidative polymerization of quinones to form brown pigments, resulting in browning [2]. In most cases, this enzymatic process is driven by polyphenol oxidase (PPO), considered one of the most significant oxidative reactions in fruit—leading to a loss of sensory and nutritional quality [55]. This is evidenced by a study, which showed high PPO activity starting on the sixth day of storage, resulting in a significant increase in fruit browning (Figure 7F).

Fruit surface condition plays a crucial role as a direct indicator of freshness and is a key factor in consumer purchasing decisions [56,57]. Delaying browning and reducing cracking indicate a slowdown in atemoya ripening process and enhance post-harvest quality, thereby extending shelf life and the product's marketability. The present study demonstrates that the Ca+GA₃ treatment had a positive effect on reducing cracking and improving quality throughout the storage period.

5. Conclusions

Fruit treated with Ca and Ca+GA₃ tended to show lower average values regarding fruit cracking. Notably, Ca+GA₃ treatment not only reduced cracking but also increased the levels of non-enzymatic antioxidants—such as phenolic compounds, vitamin C, and chlorophyll—which helped delay senescence, as evidenced by reduced electrolyte leakage. The evaluated postharvest treatments (Ca, GA₃, and Ca+GA₃) along with the control maintained the fruit in a marketable condition for up to twelve days of storage. Given these positive results, further research is needed to enhance quality and extend the shelf life of atemoyas.

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Abbreviations

The following abbreviations are used in this manuscript:

Ca	Calcium
GA3	Gibberellic acid
Ca+GA ₃	Calcium+gibberellic acid
FML	Fresh mass loss
pH	Potential of hydrogen
TA	Titrateable acidity
TSS	Total soluble solids
EL	Electrolyte leakage
TEP	Total extractable polyphenols
POD	Peroxidase
PPO	Polyphenol oxidase
H°	Hue angle
C*	Chroma
Chla	Chlorophyll a
Chlb	Chlorophyll b

References

1. Santos, W.N.D.; Sauthier, M.C.S.; Cavalcante, D.D.; Benevides, C.M.; Dias, F.S.; Santos, D.C. Mineral composition, nutritional properties, total phenolics and flavonoids compounds of the atemoya fruit (*Annona squamosa* L. × *Annona cherimola* Mill.) and evaluation using multivariate analysis techniques. *An. Acad. Bras. Cienc.* **2016**, *88*, 1243–1252. [\[CrossRef\]](#)
2. Zhang, W.; Pan, Y.; Jiang, Y.; Zhang, Z. Advances in control technologies and mechanisms to treat peel browning in postharvest fruit. *Sci. Hortic.* **2023**, *311*, 111798. [\[CrossRef\]](#)
3. Cordeiro, N.; Sousa, L.; Freitas, N.; Gouveia, M. Changes in the mesocarp of *Annona cherimola* Mill. ‘Madeira’ during postharvest ripening. *Postharvest Biol. Technol.* **2013**, *85*, 179–184. [\[CrossRef\]](#)
4. Lekshmi, S.G.; Sethi, S.; Paul, V.; Sindhu, P.M.; Nayak, S.L. Physiology and Ripening of Fruits and Vegetables. In *Fruits and Vegetables Technologies: Postharvest Processing and Packaging*; Springer Nature: Berlin/Heidelberg, Germany, 2025; pp. 31–55.
5. Pareek, S.; Yahia, E.M.; Pareek, O.P.; Kaushik, R.A. Postharvest physiology and technology of Annona fruits. *Food Res. Int.* **2011**, *44*, 1741–1751. [\[CrossRef\]](#)
6. Santos, M.; Egea-Cortines, M.; Gonçalves, B.; Matos, M. Molecular mechanisms involved in fruit cracking: A review. *Front. Plant Sci.* **2023**, *14*, 1130857. [\[CrossRef\]](#)
7. Liu, Y.; Liu, W.; Xu, C.; Fan, X.; Zhou, G.; Yi, C.; Wang, J.; Zhou, J.; Zou, X. A multi-omics approach reveals the effects of wax, cell wall polysaccharides and hormones on pepper skin cracking. *Hortic. Plant J.* **2025**, *in press*. [\[CrossRef\]](#)
8. Hosein-Beigi, M.; Zarei, A.; Rostaminia, M.; Erfani-Moghadam, J. Positive effects of foliar application of Ca, B and GA3 on the qualitative and quantitative traits of pomegranate (*Punica granatum* L.) cv. ‘Malase-Torshe-Saveh’. *Sci. Hortic.* **2019**, *254*, 40–47. [\[CrossRef\]](#)
9. Castro-Camba, R.; Sánchez, C.; Vidal, N.; Vielba, J.M. Plant development and crop yield: The role of gibberellins. *Plants* **2022**, *11*, 2650. [\[CrossRef\]](#)
10. Zhang, M.; Liu, Y.; Chen, Z.; Zhi, Z.; Wang, A.; Yue, H.; Li, F.; Zhang, S.; Zhu, G. Progress in Fruit Cracking Control of Gibberellic Acid and Absciscic Acid. *Forests* **2024**, *15*, 547. [\[CrossRef\]](#)
11. Taiz, L.; Zeiger, E. *Fisiologia e Desenvolvimento Vegetal*, 6th ed.; Artmed: Porto Alegre, Brazil, 2017; p. 858.
12. Anderson, C.T.; Pelloux, J. The dynamics, degradation, and afterlives of pectins: Influences on cell wall assembly and structure, plant development and physiology, agronomy, and biotechnology. *Annu. Rev. Plant Biol.* **2025**, *76*, 85–113. [\[CrossRef\]](#)
13. Hocking, B.; Tyerman, S.D.; Burton, R.A.; Gilliam, M. Fruit calcium: Transport and physiology. *Front. Plant Sci.* **2016**, *7*, 569. [\[CrossRef\]](#)
14. Lima, M.A.C.D.; Alves, R.E.; Biscegli, C.I.; Filgueiras, H.A.; Coccozza, F.D.M. Conservação de melões Gália ‘Solar King’ tratados com 1-metilciclopropeno. *Hortic. Bras.* **2004**, *22*, 121–126. [\[CrossRef\]](#)
15. Barbosa, M.C.F.; Souza, P.A.; Coelho, E.L.; Silva, M.S.; Sousa, D.V.; Freitas, R.V.S.; Ferreira, E.O. Avaliação do índice de rachadura em atemoia Gefner armazenada a temperatura ambiente. *Bragantia* **2011**, *4*, 21–28.
16. Minolta, C. *Precise Color Communication: Color Control from Feeling to Instrumentation*; Minolta Co., Ltd.: Osaka, Japan, 2007.
17. IAL—Instituto Adolfo Lutz. *Métodos Físico-Químicos para Análise de Alimentos*, 1st ed.; Instituto Adolfo Lutz: São Paulo, Brazil, 2008; p. 1020.

18. AOAC—Association of Official Analytical Chemistry. *Official Methods of Analysis of the Association of Official Analytical Chemistry*, 17th ed.; AOAC: Washington, WA, USA, 2002; p. 1115.
19. Lichtenthaler, H.K.; Buschmann, C. Extraction of photosynthetic tissues: Chlorophylls and carotenoids. *Curr. Protoc. Food Anal. Chem.* **2001**, *1*, F4.2.1–F4.2.6. [[CrossRef](#)]
20. Azevedo, I.G.; Oliveira, J.G.; da Silva, M.G.; Pereira, T.; Corrêa, S.F.; Vargas, H.; Façanha, A.R. P-type H⁺-ATPases activity, membrane integrity, and apoplastic pH during papaya fruit ripening. *Postharvest Biol. Technol.* **2008**, *48*, 242–247. [[CrossRef](#)]
21. Yemn, E.W.; Willis, A.J. The estimation of carbohydrate in plant extracts by anthrone. *Biochem. J.* **1954**, *57*, 508–514. [[CrossRef](#)]
22. Miller, G.L. Use of dinitrosalicylic acid reagent for determination of reducing sugars. *Anal. Chem.* **1959**, *31*, 426–428. [[CrossRef](#)]
23. Brand-Williams, W.; Cuvelier, M.E.; Berset, C. The phenolic constituents of *Prunus* L.—The quantitative analysis of phenolic constituents. *Leb. Wiss. Technol.* **1995**, *28*, 25–30.
24. Sanchez-Moreno, C.; Larrauri, J.A.; Saura-Calixto, F. A procedure to measure the antiradical efficiency of polyphenols. *J. Sci. Food Agric.* **1998**, *76*, 270–276. [[CrossRef](#)]
25. Larrauri, J.A.; Rupérez, P.; Saura-Calixto, F. Effect of drying temperature on the stability of polyphenols and antioxidant activity of red grape pomace peels. *J. Agric. Food Chem.* **1997**, *45*, 1390–1393. [[CrossRef](#)]
26. Bezerra Neto, E.; Barreto, L.P. *Análises Químicas e Bioquímicas em Plantas*; Embrapa: Brasília, Brazil, 2011; p. 900.
27. Campos, Â.D.; Ferreira, A.G.; Hampe, M.M.V.; Antunes, I.F.; Brancão, N.; Silveira, E.P.D.; Osório, V.A.; Augustin, E. Atividade de peroxidase e polifenoloxidase na resistência do feijão a antracnose. *Pesqui. Agropecuária Bras.* **2004**, *39*, 637–643. [[CrossRef](#)]
28. Silva, F.C. *Manual de Análises Químicas de Solos, Plantas e Fertilizantes*; Embrapa Solos: Rio de Janeiro, Brazil, 2009; p. 632.
29. Rstudio Team. *RStudio: Integrated Development Environment for R*; RStudio PBC: Boston, MA, USA, 2021. Available online: <http://www.rstudio.com/> (accessed on 10 May 2023).
30. Faruh, M.; Copes, B.; Le-Navenec, G.; Marroquin, J.; Cantu, D.; Bradford, K.J.; Guinard, J.-X.; Van Deynze, A. Sensory, physicochemical and volatile compound analysis of short and long shelf-life melon (*Cucumis melo* L.) genotypes at harvest and after postharvest storage. *Food Chem. X* **2020**, *8*, 100107. [[CrossRef](#)]
31. Chagas, P.C.; Crane, J.; Chagas, E.A.; Vendrame, W.; Costa, B.N.S.; Rubio, A.; Moura, E.A.D. Effect of plant-growth regulators, adjuvants and artificial pollination on the fixation and quality of *Annona squamosa* L cultivars' fruit. *Acta Sci. Agron.* **2023**, *45*, e62036. [[CrossRef](#)]
32. Chagas, P.C.; Crane, J.; Chagas, E.A.; Vendrame, W.; Costa, B.N.S.; Rubio, A.; Moura, E.A.D. Artificial pollination and use of growth regulators in atemoya 'Gefner' fruits. *Biosci. J.* **2023**, *39*, e39040. [[CrossRef](#)]
33. Pereira, M.C.T.; Santos, R.K.A.; Nietzsche, S.; Mizobutsi, G.P.; Santos, E.F.D. Doses de ácido giberélico na frutificação efetiva e qualidade de frutos de atemoieira 'Gefner'. *Rev. Bras. Frutic.* **2014**, *36*, 184–191. [[CrossRef](#)]
34. Ren, Y.Y.; Sun, P.P.; Wang, X.X.; Zhu, Z.Y. Degradation of cell wall polysaccharides and change of related enzyme activities with fruit softening in *Annona squamosa* during storage. *Postharvest Biol. Technol.* **2020**, *166*, 111203. [[CrossRef](#)]
35. Bakeer, S.M. Effect of ammonium nitrate fertilizer and calcium chloride foliar spray on fruit cracking and sunburn of Manfalouty pomegranate trees. *Sci. Hortic.* **2016**, *209*, 300–308. [[CrossRef](#)]
36. Kumar, A.; Tandon, C.; Singh, R.; Kumar, V.; Choudhary, V.; Singh, G.; Singh, A.P.; Tiwari, V. Study of fruit cracking's physiological and biochemical mechanisms: A review. *Int. J. Res. Agron.* **2025**, *8*, 346–349. [[CrossRef](#)]
37. Dautt-Castro, M.; Ochoa-Leyva, A.; Contreras-Vergara, C.A.; Pacheco-Sanchez, M.A.; Casas-Flores, S.; Sanchez-Flores, A.; Kuhn, D.N.; Islas-Osuna, M.A. Mango (*Mangifera indica* L.) cv. Kent fruit mesocarp de novo transcriptome assembly identifies gene families important for ripening. *Front. Plant Sci.* **2015**, *6*, 62. [[CrossRef](#)]
38. Khadivi-Khub, A. Physiological and genetic factors influencing fruit cracking. *Acta Physiol. Plant.* **2015**, *37*, 1718. [[CrossRef](#)]
39. Li, J.; Luo, M.; Zhou, X.; Zhou, Q.; Wei, B.; Cheng, S.; Ji, S. Polyamine treatment ameliorates pericarp browning in cold-stored 'Nanguo' pears by protecting mitochondrial structure and function. *Postharvest Biol. Technol.* **2021**, *178*, 111553. [[CrossRef](#)]
40. Oliveira, Z.L.; de Souza, P.A.; Moura, C.F.H.; da Costa, F.B.; da Silva Freitas, R.V.; Batista, E.M.; Regis, A.d.A.; Reges, S.C.N. Armazenamento refrigerado de atemoia 'Gefner' em atmosfera modificada. *Res. Soc. Dev.* **2021**, *10*, e367101118095. [[CrossRef](#)]
41. Moura, E.A.D.; Chagas, P.C.; Oliveira, R.R.; Taveira, D.L.L.; Grigio, M.L.; Araújo, W.F. Determination of the harvest time of sugar apples (*Annona squamosa* L.) in function of carpel interspace. *Acta Sci. Agron.* **2020**, *43*, e48732. [[CrossRef](#)]
42. Santos, R.C.; Nietzsche, S.; Pereira, M.C.T.; Ribeiro, L.M.; Mercadante-Simões, M.O.; dos Santos, B.H.C. Atemoya fruit development and cytological aspects of GA3-induced growth and parthenocarp. *Protoplasma* **2019**, *256*, 1345–1360. [[CrossRef](#)]
43. Sanadi, R.M.; Deshmukh, R.S. The effect of Vitamin C on melanin pigmentation—A systematic review. *J. Oral Maxillofac. Pathol.* **2020**, *24*, 374. [[CrossRef](#)]
44. Cruz, L.S.; Lima, R.Z.; de Abreu, C.M.P.; Correa, A.D.; Pinto, L.D.M.A. Physical and Chemical Characterization of Fractions of Fruit Atemoya Gefner/Caracterização Física e Química das Frações do Fruto Atemoia Gefner. *Ciência Rural*, 2013. Available online: <https://link.gale.com/apps/doc/A441769764/IFME> (accessed on 7 April 2026).

45. Korkmaz, N.; Aşkin, M.A.; Ercişli, S.; Okatan, V. Foliar application of calcium nitrate, boric acid and gibberellic acid affects yield and quality of pomegranate (*Punica granatum* L.). *Acta Sci. Pol.-Hortorum Cultus* **2016**, *15*, 105–112. Available online: <https://agro.icm.edu.pl/agro/element/bwmeta1.element.agro-af4fc712-6250-4e52-966d-8cb121c7f513> (accessed on 2 July 2023).
46. Rey, F.; Zacarías, L.; Rodrigo, M.J. Carotenoids, vitamin C, and antioxidant capacity in the peel of mandarin fruit in relation to the susceptibility to chilling injury during postharvest cold Storage. *Antioxidants* **2020**, *9*, 1296. [[CrossRef](#)]
47. Balaguera-López, H.E.; Ortega, E.A.P.; Consuegra, S.A.L. Effects of thermal treatments on chilling injury and shelf life time of *Citrus reticulata* Blanco. *Pesqui. Agropecuária Trop.* **2019**, *49*, e56821. [[CrossRef](#)]
48. Wang, Y.; Ji, S.; Dai, H.; Kong, X.; Hao, J.; Wang, S.; Zhou, X.; Zhao, Y.; Wei, B.; Cheng, S.; et al. Changes in membrane lipid metabolism accompany pitting in blueberry during refrigeration and subsequent storage at room temperature. *Front. Plant Sci.* **2019**, *10*, 829. [[CrossRef](#)]
49. Xiao, X.; Yang, M.; Dong, W.; Zhou, C.; Shi, L.; Chen, W.; Cao, S.; Yang, Z.; Li, S. Gibberellic acid inhibited chlorophyll degradation in post-harvest okras. *Postharvest Biol. Technol.* **2022**, *190*, 111951. [[CrossRef](#)]
50. Zhang, W.; Jiang, H.; Zhang, Y.; Cao, J.; Jiang, W. Synergistic effects of 1-MCP and hot air treatments on delaying softening and promoting anthocyanin biosynthesis in nectarines. *Postharvest Biol. Technol.* **2021**, *180*, 111598. [[CrossRef](#)]
51. Zhang, W.; Jiang, H.; Cao, J.; Jiang, W. Advances in biochemical mechanisms and control technologies to treat chilling injury in postharvest fruits and vegetables. *Trends Food Sci. Technol.* **2021**, *113*, 355–365. [[CrossRef](#)]
52. Gong, X.; Wu, X.; Qi, N.; Li, J.; Zhang, H.; Huo, Y. Changes in the biochemical characteristics and volatile fingerprints of atemoya during postharvest ripening at room temperature. *Qual. Assur. Saf. Crops Foods* **2020**, *12*, 26–35. [[CrossRef](#)]
53. Lima, F.T.D.; Martins, L.P.; Toscano, B.L.M.D.; de Sousa Costa, E.; de Souza, W.F.C.; de Lucena, F.A.; Filho, J.F.d.S.; de Sousa, S. Cold damage 74 affects the quality of noni fruits (*Morinda citrifolia* L.). *Biocatal. Agric. Biotechnol.* **2023**, *47*, 102566. [[CrossRef](#)]
54. Bhattacharjee, S. *Reactive Oxygen Species in Plant Biology*; Springer: New Delhi, India, 2019; pp. 107–125.
55. Zainal, B.; Ding, P.; Ismail, I.S.; Saari, N. Physico-chemical and microstructural characteristics during postharvest storage of hydrocooled rockmelon (*Cucumis melo* L. reticulatus cv. Glamour). *Postharvest Biol. Technol.* **2019**, *152*, 89–99. [[CrossRef](#)]
56. He, M.; Wu, Y.; Hong, M.; Yun, Z.; Li, T.; Jiang, Y. α -Lipoic acid treatment alleviates postharvest pericarp browning of litchi fruit by regulating antioxidant ability and energy metabolism. *Postharvest Biol. Technol.* **2021**, *180*, 111629. [[CrossRef](#)]
57. Hou, C.Y.; Hazeena, S.H.; Li, P.X.; Hsieh, S.L.; Hsieh, C.W.; Chen, M.H.; Shih, M.K.; Yu, M.C.; Liang, Y.S. Postharvest quality and prolong storage time of atemoya (*Annona squamosa* $\times$ *A. cherimola* hybrids) fruit: Coating with D-limonene nanoemulsion edible film. *Int. J. Food Prop.* **2023**, *26*, 1098–1113. [[CrossRef](#)]

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