Edible Coating Based on Roselle (Hibiscus sabdariffa L.) Mucilage Applied to Soursop Fruits in Postharvest Storage

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The soursop fruit (Annona muricata L.) is a crop of significant economic value for Nayarit, which is characterized by having a bittersweet taste, making it attractive to the consumer. However, the soursop has rapid maturation which causes a short shelf life. Several postharvest management techniques have been applied to reduce its metabolic processes, such as refrigeration, use of 1-methylcyclopropene (1-MCP), and controlled and modified atmospheres. In recent years, polysaccharide-based coatings have been applied to fruits. Therefore, the objective of this investigation was to evaluate the physicochemical and biochemical changes, as well as the antioxidant activity of soursop fruits with a mucilage-based coating (2%), stored at 22°C and 15°C with a 90% RH. Weight loss, firmness, color, soluble solids, acidity, pH, phenols, flavonoids, vitamin C, and antioxidant activity were evaluated. The results obtained in the coated fruits stored at 15°C showed lower weight loss (6.4%), lower firmness (29.7 N), higher TSS concentration (10.4°Bx), and lower acidity (0.38%) compared with the uncoated fruits. The total phenolic content decreased in coated fruits stored at 22°C (54.3 mg EGA/100 g FW). The highest antioxidant activity (DPPH method) was recorded in fruits coated and stored at 15°C with an average value of 257.9 mg EAA/100 g FW. Moreover, a high concentration of vitamin C was observed in fruits coated and stored at 15°C and 22°C (20.5 and 17.5 mg EAA/100 g FW), concluding that the coating based on roselle mucilage (2%) in combination with a temperature of 15°C prevents weight loss, decreases titratable acidity, and increases the content of phenols and vitamin C. Furthermore, an increase in the shelf life up to eight days and in the antioxidant activity at the maturity of consumption was observed in the fruits coated with 2% roselle mucilage stored at 15°C.

1. Introduction

Soursop plants are natives of Central America and are grown in some countries in the Southeast of China to Australia as well as in low and warm areas of East and West Africa [1]. Mexico is the main worldwide producer of soursop. In 2018, a production of 29,228.46 T was recorded at national level. In this regard, the state of Nayarit was the largest producer of soursop fruits with 21,810 T [2]. Soursop production contributes to the economic growth of Nayarit; however, a problem in the crop management exits due to the high respiration rate and ethylene production leading to fruit softening, which causes a short postharvest shelf life [3–5]. In this context, the storage and commercialization of the
fruit are limited; therefore, it is necessary to implement safety storage methods for consumers [6]. Since the initial quality of the fruit cannot be improved, applying technologies during the postharvest period, it is possible to maintain its organoleptic characteristics using storage methods such as the use of packaging, refrigeration systems, and controlled or modified atmospheres [7]. The use of edible coatings stands out among the alternatives for the postharvest storage. Edible coatings from polysaccharides act as a modified atmosphere, creating a semipermeable layer in the fruit that allows gas exchange, reducing metabolic processes, which leads to the increase in the postharvest life of the fruit [8]. Among the polysaccharides used as a coating are chitosan [9], starch [10], alginate [11], and mucilage [12]. Mucilages are classified within hydrocolloids and are complex polymeric macromolecules of hydrocarbon nature that can modify the rheology of a solution due to their highly branched structure [13]. In this regard, they can be considered as a source of raw material for the preparation of edible coatings [14].

The Cactaceae family is one of the main sources of high mucilage content. Bello-Lara et al. [15] applied mucilage (1.5%) extracted from nopal (Opuntia spp.) on Has avocado fruits. The fruits showed a mass loss of 5.9% at 15 days of storage at 6°C and 6.01% at 20 days of storage at the same temperature.

Among the main plant sources that can be extracted from polysaccharides, roselle (Hibiscus sabdariffa L.) calyx is an excellent source of mucilage. Castañeda and Cáceres [16] reported that Hibiscus sabdariffa L. also has high pectin content and, therefore, can be used to make edible coatings applied to fruits and vegetables. However, its effect as a coating on fruit and vegetable products has not been studied.

In the previous context, the roselle mucilage can be used as the preparation material of an edible coating to prolong the shelf life of fruits. Taking this into account, in this study we evaluated the effect of the coating based on roselle mucilage (2%) on the physicochemical changes and biochemical and antioxidant activity during postharvest storage.

2. Materials and Methods

2.1. Plant Material. Soursop fruits were harvested at physiological maturity (160 days after the anthesis) according to the recommendations of Balois-Morales et al. [3]. Moreover, we selected four fruits between 700 and 800 g of bright green color, with the absence of mechanical and phytosanitary damage. The fruits were washed with water, subsequently immersed in 1% (v/v) sodium hypochlorite, and allowed to dry until the water evaporated. Then, we collected 6 g of pulp from each of the soursop fruits. Next, 1 g of pulp was mixed with 10 mL of distilled water using ULTRA-TURRAX T-25 IKA®. This mixture was used for the quantification of pH, total soluble solids concentration (TSS), phenols, and antioxidant activity. On the other hand, for the quantification of flavonoids and vitamin C, we used methanol (reactive grade) and trichloroacetic acid (10%) instead of distilled water, respectively. Each independent mixture (24 in total) was centrifuged at 9000 rpm for 25 min at 4°C (Hermle Z 326 K). The supernatant was recovered and used for further analysis.

2.1.1. Development and Application of the Coating. A 2% solution of mucilage from roselle calyces and water (w/v) was prepared. Then, the solution was heated at 50 ± 2°C on a heating plate for 30 min under constant stirring. The temperature helps the solution take a viscous consistency, which will allow better adhesion of the mucilage to the fruits, resulting in the coating. The coating was applied to the soursop fruits by immersion for one min. Once the fruits were coated and left outdoors for the roselle mucilage (2%) to solidify, they were stored in controlled air conditioning chambers (ClimaCell®, CLC-B2V-M 404).

2.1.2. Experimental Design. The fruits were grouped into four batches (30 fruits per each). The treatments (T) were as follows: uncoated fruits (T1 and T3), coated fruits (T2 and T4). The fruits of T1 and T2 were stored for 6 days at 22°C and 90% RH. The fruits of T3 and T4 were stored for 8 days (4 days at 15°C, then 4 days at 22°C and 90% RH).

2.2. Variables Evaluated

2.2.1. Physicochemical Analysis. The weight loss was determined by gravimetry using a digital scale (Scout Pro, OHAUS®). Color was measured on the soursop peel, brightness or reflected light (L) (0: pure black, 100: pure white), hue angle (h) (0°: purple-red, 180°: green), and chromaticity (C, intensity from gray to pure color) with a colorimeter (Konica Minolta®). Loss of firmness was measured in the equatorial zones of the fruit (with peel) using a penetrometer (Force Gauge model GY-4) with an 8 mm diameter strut. The pH of the pulp was measured with a potentiometer (Hanna Instruments HI22). The total soluble solids concentration (TSS) was determined by placing an aliquot on a digital refractometer (Hanna HI 96801). Titratable acidity was determined according to the official method (AOAC) [17] by volumetric titration with 0.01 N NaOH and phenolphthalein as an indicator.

2.2.2. Biochemical Analysis. For the determination of total phenols and antioxidant capacity (AOX), we used 2,2'-diphenyl-1-picrylhydrazyl (DPPH), 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), and Ferric Reducing Antioxidant Power (FRAP) methods as recommended by Pérez-Jiménez et al. [18] to determine the antioxidant capacity (AOX), since the antioxidant capacity of vegetable products is determined by different mechanisms of action.

2.2.3. Total Phenolic Compounds. We determined total phenolic compounds according to the methodology described by Stintzing et al. [19]. We added 250 μL of Folin-Ciocalteu solution (v/v 1:10 in deionized water) to 50 μL of sample, and then 200 μL of sodium carbonate solution
(7.5%) was added. Absorbance was measured in a microplate reader (Power Wave XS, Biotek) at a wavelength of 765 nm. The results were expressed in mg equivalent of gallic acid (mg EGA/100 g FW).

2.2.4. DPPH. The antioxidant activity was determined by the methodology of Morales and Jiménez-Pérez [20]. A DPPH solution (7.4 mg/100 mL of 80% ethanol) was prepared and then stirred for 60 min. Subsequently, it was diluted with methanol (80%) until reaching an absorbance of 0.70 ± 0.02 at 520 nm. An aliquot of 50 μL was added to 250 μL of the DPPH solution and then incubated in dark for 30 min. The absorbance was measured at a wavelength of 520 nm (Power Wave XS, Biotek). The AOX was expressed in mg equivalent of ascorbic acid (mg EAA/100 g FW).

2.2.5. ABTS. The determination of the inhibitory capacity of the 2,2′-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid) radical cation (ABTS⁺) was quantified according to the methodology of Re et al. [21]. An ABTS (7 mM) and potassium persulfate (2.45 mM) solutions were prepared with distilled water. The solutions were mixed in a 1 : 1 (v/v) ratio, then incubated for 16 h in the dark at 23 ± 1°C, and kept under constant stirring to form the ABTS⁺ radical. The solution was diluted with ethanol (20%) until reaching an absorbance value of 0.70 ± 0.02 at 754 nm (maximum absorption wavelength). 10 μL of the sample was taken and reacted with 490 μL of ABTS⁺ for seven min. The absorbance was read at 734 nm. The results were expressed in mg equivalent of ascorbic acid (mg EAA/100 g FW).

2.2.6. FRAP. This analysis was carried out by the methodology of Benzien and Strain [22] to evaluate the ability of sour sop pulp compounds to reduce iron (III) to iron (II). 25 μL of the aqueous solution, 63 μL of phosphate buffer (PBS) (0.2 M, pH 6.6), and 63 μL of potassium hexacyanoferrate (K₃Fe(CN)₆) at 1% were added and then stirred in a vortex. Thereafter, the reaction mixture was incubated in the dark for 30 min at 50°C, and 63 μL of trichloroacetic acid (10%) was added and then vortexed. Next, 126 μL aliquot of the supernatant was taken and mixed with 126 μL of distilled water and 25 μL of 0.1% ferric chloride (FeCl₃). Finally, the absorbance was measured at 700 nm. The results were expressed in mg equivalent of ascorbic acid (mg EAA/100 g FW).

2.2.7. Flavonoids. It was performed using the protocol established by Zhishen et al. [23]. 50 μL of the sample, 100 μL of deionized water, and 10 μL of NaOH (15%) were mixed, then stirred in a vortex, and kept in dark at 23°C for 6 min. After that time, 15 μL of AlCl₃ (10%) was added and then briefly vortexed. The solution was kept in dark for 6 min at 23°C. Finally, 200 μL of NaOH (4%) was added. The absorbance was measured at 510 nm. The results obtained were expressed in equivalent mg of quercetin (mg EQ/100 g FW).

2.2.8. Vitamin C. It was evaluated using the method reported by Dürüst et al. [24]. The following solutions were prepared: DCPI (2,6-dichlorophenolindophenol disodium salt) at 24 mg/L in deionized water; acetate buffer composed of 3 g of anhydrous sodium acetate, 7 mL of deionized water, and 10 mL of glacial acetic acid. 50 μL of the samples were mixed with 50 μL of acetate buffer and 400 μL of DCPI. The absorbance was determined at 520 nm in a microplate reader (Power Wave XS, Biotek). The results were expressed in mg equivalent of ascorbic acid (mg EAA/100 g FW).

2.3. Statistical Analysis. The treatments were analyzed under a completely randomized design with a 2 × 2 factorial arrangement. The factors were the temperature (15°C and 22°C) and the coating (coated and uncoated fruits). The results were analyzed using an ANOVA and the Tukey test with a level of significance P ≤ 0.05 using Statistical Analysis System software (SAS® V. 9.2) [25].

3. Results and Discussion

3.1. Weight Loss. Soursop fruits stored at 15°C showed a daily mass loss of 2.4% (T3) and 2.85% (T4). On the other hand, at four days of storage, an average of 4% was found, while at the end of the storage (8 days) the accumulated mass loss was 9.89 (T3) and 11.43% (T4) (Figure 1(a)). The fruits stored at 22°C showed a daily mass loss of 3.9% (T1) and 4.2% (T2). Further, at the end of the consumption maturity, the accumulated mass loss was 11.8% (T1) and 12.8% (T2). No significant statistical difference between treatments (P ≤ 0.05) was found (Figure 1(a)). Valero and Serrano [26] reported that the weight loss of fruits during postharvest handling is mainly due to their perspiration and respiration. The application of coatings helps to reduce weight loss [27].

3.2. Firmness. We observed a gradual decrease in the firmness of the fruits stored at 22°C during storage. Furthermore, we recorded values of 27.1 N (T1) and 22 N (T2) at the six days of storage (consumption maturity) in comparison to the initial firmness values (physiological
maturity) of 69.4 N and 45.6 N, respectively. In the fruits of the T3 (49.1 N) and T4 (36.1 N), the firmness decreased to 24.8 N (T3) and 22.7 N (T4) (consumption maturity). According to the statistical analysis, significant differences ($P \leq 0.05$) were observed in the treatments, where T1 and T3 showed greater firmness during storage (51.7 and 35.1 N, respectively) (Figure 1(b)). The loss of firmness in climacteric fruits such as soursop is ascribed to the degradation of the cell wall and the loss of interconnection of pectins and hemicelluloses due to the effects of solubilization and enzymatic depolymerization [32, 33]. However, the storage of soursop fruits using refrigeration decreases physiological activities such as softening [34]. The results obtained in this investigation are superior (<22 N) as reported by Montalvo-González et al. [35], who obtained final firmness values of 9.41 N in soursop fruits coated with candelilla wax and beeswax stored at 25°C. Nevertheless, values similar to those obtained by Coelho de Lima et al. were observed [36]; their firmness values were 19 N in soursop “Morada” fruits without coating stored at 23°C. The results obtained in this investigation were also greater (<22.7 N) than those reported by Márquez et al. [33] indicating firmness values of 4.74 N (five days after harvest) and 7.5 N (seven days after harvest) as the optimum ripeness for the soursop fruit consumption. On the other hand, Ramos-Guerrero et al. [37] applied chitosan (1%) to soursop fruits and reported values of 10.9 N after 8 days of storage.

Figure 1: Weight loss (a), firmness (b), pH (c), and total soluble solids (d) in soursop fruits stored at 22°C and 15°C. Each point represents the average of six observations and its standard error. The dotted line indicates the end of refrigeration storage.
3.3. **pH.** The pH of the soursop pulp in fruits stored at 22°C decreased during ripening, whose initial values were 5.7 (T1) and 5.4 (T2) up to values of 4.3 and 4.2, respectively. Similar results were obtained in fruits stored at 15°C and 22°C (T3 and T4), with initial values of 5.7 (T3) and 5.8 (T4). Subsequently, these values decreased to 4.7 and 4.5 in consumption maturity, respectively. According to the statistical analysis, significant statistical differences were observed ($p \leq 0.05$) (Figure 1(c)). The results obtained in this investigation are in the range established by the Colombian technical standard for commercialization (NTCC) at physiological or commercial maturity, “soursop fruits must have the minimum pH value of 3.38” [38], and agree with those reported by Ramírez et al. [39]. Jiménez-Zurita et al. [40] performed a characterization of soursop fruits in Tepic, Nayarit, at 26°C, obtaining a pH of 3.6 in consumption maturity. Villalba et al. [41] carried out an investigation with soursop fruits from Colombia at consumption maturity, reporting pH values of 3.04. These results indicate that the fruits of that region of Colombia are more acidic than those analyzed in this investigation. This characteristic can be explained to different geographical regions, temperature, light intensity, and soil-climatic conditions [42]. González [35] reported similar results of $pH = 4.47$ in soursop fruits coated with candelilla wax and beeswax stored at 16°C. Furthermore, Jiménez-Zurita et al. [30] coated soursop fruits using wax and 1-MCP emulsions stored at 13 ± 2°C, reaching pH values of 4 ± 0.2. Similar results were obtained in this investigation.

3.4. **Total Soluble Solids (TSS).** The concentration of TSS in soursop fruits stored for four days at 22°C was 15.7°Bx (T1) and 15.6°Bx (T2), while at the end of storage (six days), values of 13.79 and 14.45°Bx were recorded, respectively. On the other hand, TSS concentration of fruits (T3 and T4) stored at 15°C for four days was 11.8°Bx and when exposed to 22°C was 10.75 and 11.95°Bx, respectively, showing significant differences in the treatments ($p \leq 0.05$). Yashoda et al. [43] suggest that changes in the TSS concentration for climacteric fruits are attributed to the reduction of total sugars, starch, and cellulose during ripening, which are converted to oligosaccharides and monosaccharides that confer the texture and flavor characteristics of the fruit. The NTCC states that “soursop fruits must be above 13°Bx,” which is the ripeness indicator used for soursop fruits [37].

González et al. [35] reported 18.65°Bx at 10 days after harvest using combinations of 1-MCP and wax emulsions in the conservation of soursop stored at 25°C. Lima et al. [36] reported the final TSS results of 14.4°Bx in soursop fruits stored at 23.4 ± 1°C. Tovar-Gómez et al. [29] recorded similar results to those obtained in this investigation at 12 days of storage in soursop fruits treated with 1-MCP stored at 13 ± 2°C. Espinosa et al. [44] indicate that the increase in TSS can be attributed to the hydrolysis of starch, sucrose, pectins, and other soluble compounds such as organic acids or amino acids. The variation in the TSS can be attributed to the type of fruit; the soursop is classified as a multiple fruit derived from several separate individual flowers, whose fertilized ovaries merge to form a single structure, in which each individual fruit corresponds to a berry [45, 46]. The pollination of the fruit is not carried out homogeneously, which means that the ripening of the fruit is not uniform.

3.5. **Titratable Acidity.** Soursop fruits of T1 and T2 had initial values of 0.12 and 0.09% after four days of storage (consumption maturity), respectively. Acidity (%) increased to 0.8 (T1) and 1.0 (T2) (Figure 2(a)). Regarding the fruits of T3 and T4 (stored for four days at 15°C and then four days at 22°C), T3 presented a decreasing behavior from 0.5 to 0.42%, while those of T4 showed an increase from 0.45 to 0.53%, with a significant statistical difference between treatments ($p \leq 0.05$) (Figure 2(a)). Tovar-Gómez et al. [29] observed that titratable acidity in soursop fruits increases during the ripening process. However, titratable acidity decreases at the end of storage, indicating that organic acids are used as substrates in the respiration process [47–49].

Paull [46] observed that, at room temperature, the decrease in titratable acidity of soursop coincided with the appearance of a slightly unpleasant odor. Jiménez-Zurita et al. [30] have reported values of 0.88 and 0.96% in soursop fruits stored at 22°C after eight days of storage, while Do Sacramento et al. [50], in selections of soursop fruits (“Lisa,” “Morada,” and “Comum”), obtained values between 0.92 and 1.0% titratable acidity when the fruits ripened. The values obtained in fruits stored at 15°C were lower than the values (0.92–1.00) found in soursop fruits from Brazil [50] but similar to those reported by Márquez et al. [33] for soursop from Colombia. Lima et al. [36] found values of 0.71% titratable acidity after 15 days of storage in soursop fruits coated with 1-MCP and stored at 15°C. Mosca et al. [51] indicate that, during ripening, the titratable acidity of the soursop fruit increases from 0.067 to 0.67% of malic acid while it remains at 0.67% after 10 days at 16°C.

3.6. **Color (L * C * h).** The fruits stored at 22°C (T1 and T2) initially presented average brightness values ($L$) of 44.2 and 44, respectively. On the other hand, a decrease in luminosity was observed once the fruits reached the maturity of consumption, 40.5 (T1) and 41.2 (T2) (Figure 2(b)). Regarding the chromaticity ($C$) of the fruits of these treatments, the initial value was 16.3 and the final value was 9.2 (Figure 2(c)). Likewise, the hue angle (‘h’) presented by these fruits in physiological maturity (T1 and T2) was 109.5 on average and then decreased to 80.49 (Figure 2(d)). The fruits stored for 8 days (4 days at 15°C and then 4 days at 22°C) recorded average initial values of $L = 105$ (T3) and 113.7 (T4) (Figure 2(b)).

The chromaticity (T3 and T4) decreased during storage, registering initial values of 17 (T3) and 13.2 (T4); subsequently, these values reached 11.3 and 5.9 in consumption maturity, respectively (Figure 2(c)). The hue angle of the fruits of T3 and T4 (4 days at 22°C) was 105.2 on average, decreasing to 81.4 (T3) and 78.51 (T4) in the consumption maturity (Figure 2(d)). The fruits stored at 15°C and 22°C presented similar values in color, indicating that the fruits presented an opaque green color with low luminosity.
Significant differences were observed in the treatments evaluated ($P \leq 0.05$). The fruits of T3 presented greater luminosity ($L = 44.4$) and chromaticity ($C = 15.8$); however, the hue angle was higher in the coated fruits (hue = 102.7).

The color changes in the peel of soursop fruits are due to enzymatic oxidation (polyphenol oxidase and peroxidase) and the action of polyphenol oxidases on phenolic compounds that are present in the fruit [52, 53]. Baloi-Morales et al. [3] observed an increase in the activity of the POD enzyme and reported 83.26U·mg$^{-1}$ of protein in soursop fruits after 6 days of storage at 22°C. Lima et al. [36] reported values of $L = 50$, hue = 118, and $C = 24$ in uncoated soursop fruits stored at 23°C. Tovar-Gómez et al. [29] reported brightness values of 43 and 45 in soursop fruits coated with wax and 1-MCP emulsions stored at $13 \pm 2^\circ C$, observing from day 10 a dark peel that caused a decrease in the values of luminosity (43.5).

Lima et al. [47] used 1-MCP as a coating on soursop fruits stored at 15°C and reported final values of 40 for luminosity, 21 for chromaticity, and 130 for hue angle after 15 days of storage. The bright green color of the soursop fruits evaluated in this investigation decreased during ripening to an opaque green with a low luminosity index due to the darkening of the epidermis. This indicates the onset of senescence as a result of the degradation of chlorophyll and the synthesis of pigments, such as carotenoids and anthocyanins [54]. However, the application of edible coatings based on polysaccharides decreases metabolic activities such as...
as enzymatic browning, which helps to maintain the color of the fruits [55].

3.7. Total Phenolic Content (TPC). The coated and uncoated fruits stored at 22°C (T1 and T2) had initial phenolic values of 66.9 and 35.3 mg EAG/100 gFW, respectively. When the fruits reached the maturity of consumption, the concentration of phenols increased to 107.5 and 67.4 mg EAG/100 gFW, respectively (Figure 3(a)). Regarding the fruits stored at 15°C for four days and at 22°C (T3 and T4), a decrease in total phenols was observed during storage. T3 fruits had a phenolic content of 139.6 mg EAG/100 gFW, while the fruits of T4 showed values of 42.94 mg EAG/100 gFW. Moreover, when the fruits reached the maturity of consumption, the total phenolic content was 99.75 mg EAG/100 gFW (T3) and 74 (T4). Statistically significant differences (P ≤ 0.05) were observed in the treatments evaluated.

The increase in the concentration of phenolic compounds can be attributed to the physiological and biochemical process of fruit ripening; therefore, in the maturity of consumption, an increase in phenols is recorded. A decrease in these compounds could be related to oxidative stress due to the low temperature. Soursop fruits show chilling injury in temperatures below 15°C of storage for more than 4 or 6 days. Furthermore, it may be due to the senescence of the fruit which produces the oxidation of phenolic compounds. Phenolic compounds are associated with AOX because of their ability to eliminate free radicals due to the redox properties of their hydroxyl groups attached to the chemical structure of phenolic compounds [56, 57]. The decrease in the concentration of the phenols could be influenced by the oxidation of these compounds and by the activity of the enzyme polyphenol oxidase and peroxidase [53, 58]. An investigation conducted by Jiménez-Zurita et al. [30], in soursop fruits stored at 22°C, reported 74.20 mg EAG/100 gFW, whose values are similar to those found in the present investigation. Silva and Sirasa [59] reported 86.5 mg EAG/100 gFW in fruits of Annona muricata L. and 199.1 mg EAG/100 gFW in the pulp of Annona reticulata fruits from Sri Lanka. Furthermore, Almeida et al. [60] reported a total phenolic content of 54.8 mg EAG/100 gFW in soursop fruits from Brazil. Hassimoto et al. [61] reported values similar to those of our investigation (120.0 mg of GAE/100 gFW.). In addition, Balois-Morales et al. [3] observed that POD activity in soursop fruits increases after storage at 15°C and indicated that the increase of POD could be related to oxidative stress caused by low temperatures.

3.8. DPPH. Uncoated fruits stored at 22°C (T1) showed a decrease in AOX with initial values from 272.5 to 256.2 (mg EAA/100 gFW), while coated fruits (T2) stored under the same conditions showed increased AOX, registering initial values from 181.6 to 234.8 (mg EAA/100 gFW). Uncoated fruits stored at 15°C for four days and 22°C (T3) showed a decrease in antioxidant activity presenting initial values of 290.9 to 255.7 (mg EAA/100 gFW) at the end of storage, while the fruits of T4 stored under the same conditions showed an increase in AOX with initial values of 212.2 mg EAA/100 gFW which then increased to 276.9 mg EAA/100 gFW. Significant differences (P ≤ 0.05) were observed in the treatments (Figure 3(b)). The initial differences between treatments in the antioxidant activity could be related to the type of fruit. Soursop is a multiple climacteric fruit, which means that, in a single structure, a large number of fruits are fused and are developed as they are pollinated, which usually is not at the same time. Therefore, the soursop fruits might not have a homogeneous maturity. The radical elimination capacity of the soursop fruit pulp could be due to the synergistic effect of several phytochemicals present in total phenolic extracts, as well as the influence of the modified atmosphere in the fruit on the production of phenolic compounds [62, 63]. The strong inhibitory effect on the DPPH radical of soursop could be linked to polyphenolic compounds that are able to donate electrons to neutralize free radicals [64]. Fruits stored at 22°C had a higher AOX, which could be related to the high phenolic content found in this investigation. Lower AOX (16.94 mg GAE/100 gFW) has been reported in soursop fruits from Brazil [60]. Chavan et al. [65] suggest that the differences in antioxidant activities can be explained by the variation in the polarities of the solvents used, as well as the weather and soil conditions. The results obtained in this investigation are greater than those reported by Oboh et al. [66], whose values were 102.86 ± 0.215 (µg/mL) of DPPH radical inhibition in soursop fruits from Nigeria. A study performed in Sri Lanka reported antioxidant activity values of 2.47 ± 0.09 gFW for Annona muricata L. and 3.13 ± 0.07 gFW for A. reticulata fruits [58]. As can be seen, we obtained higher results than the previously mentioned ones. The soursop fruits produced in Nayarit (Mexico) have higher antioxidant activity, possibly due to the edaphoclimatic characteristics (soil and temperature, mainly) and the genetic characteristics that Nayarit has. These factors contribute to the production of bioactive compounds with antioxidant activity. Furthermore, Berumen-Varela et al. [5] reported a high genetic variability among soursop fruits from different countries, supporting our previous statement.

3.9. ABTS. The AOX of the fruits of T1 and T2 stored at 22°C increased during storage, presenting initial values of 72.5 and 36.6 mg EAA/100 gFW, respectively. Then, this activity increased with values of 120.1 (T1) and 72.6 (T2) mg EAA/100 gFW six days after storage. Uncoated fruits stored at 15°C (T3) recorded a decrease in AOX, reporting initial values from 113.1 to 111.8 (mg EAA/100 gFW) at the end of storage. Nonetheless, on day eight of storage, T4 fruits stored under the same conditions recorded an increase in AOX with initial values from 37.1 to 98.2 (EAA mg/100gFW), respectively. Significant differences (P ≤ 0.05) were observed in the treatments (Figure 3(c)). Correa-Gordillo et al. [67] mention that the antioxidant compounds of Annona muricata L. are mainly lipophilic, and the mechanism of action is through the donation of hydrogen. The results obtained are similar to those reported by Beserra et al. [60], who observed an AOX of 91.29 and 93.16 mg EAA/100 gFW in fruits of Annona muricata L. and Annona squamosa L. Kuskoski et al.
investigated the AOX in soursop fruit pulp and reported 76.8 mg AA/100 g DW. Singh et al. [69] reported that the difference in AOX is influenced by genotype, fruit maturity status, and edaphic factors.

**3.10. FRAP.** The uncoated and coated fruits stored at 22°C (T1 and T2) had initial values of 10.5 and 9.9 (mg EAA/100 g FW), respectively. Subsequently, this activity increased with values of 17.1 (T1) and 10.5 (T2) mg EAA/100 g FW. The behavior of the fruits stored at 15°C (T3 and T4) recorded an increase from 12.35 to 16.6 (T3) and from 10.26 to 13.29 (T4) mg EAA/100 g FW. Significant differences (P ≤ 0.05) were observed in the treatments (Figure 1(d)). Akomolafe and Ajayi [64] reported that the soursop pulp has electron donor molecules that can react with free radicals to convert them into stable products. They also reported a reduction capacity of 1.54 mmol EAA/g, indicating a lower AOX compared to this investigation. The results obtained in this study are lower than those reported by Chukwunonso-Agu et al. [70] who found 34.2 mg EAA/100 g DW in pulp stored at 4°C. Sanchez et al. [71] observed that AOX depends on the type of solvent and time and temperature of extraction.

**3.11. Flavonoids.** Uncoated and coated fruits stored at 22°C (T1 and T2) showed initial flavonoid concentrations of 35.6 and 34.7 (mg EQ/100 g FW). Subsequently, an increase on the sixth day of storage of 50.8 (T1) and 50.3 (T2) mg EQ/100 g FW was observed. On the fourth day of storage, in uncoated and coated fruits stored at 15°C (T3 and T4), we recorded values of 62.7 and 54.3 mg EQ/100 g FW.
respectively. Further, on day eight of storage, the concentration decreased to 58.7 mg EQ/100g FW (T3), while in T4 no changes were recorded. Significant differences ($P \leq 0.05$) were observed in the treatments (Figure 4(a)).

Flavonoids and other polar compounds (saponins, tannins) are phenolic compounds that provide antioxidant properties through an antiradical activity conferred by OH phenolic groups and the double bonds present in their fundamental chemical structure [72–74]. An investigation reported by Silva and Sirasa [59] obtained values of 34.4 and 66.5 (mg EQ/100g FW) in fruits of Annona muricata L. and Annona reticulata L. from Sri Lanka. The variability in flavonoids can be attributed to the cultivar, geographical space of the crop, agricultural practices, harvest and storage, conditions and methods of processing [75].

3.12. Vitamin C. In this investigation, the concentration of vitamin C in fruits stored at 22°C (T1) during storage showed no significant changes (14.7–14.5 mg EAA/100g FW) from the beginning until the end of storage, respectively. Coated fruits (T2) recorded initial vitamin C values of 18.6 mg EAA/100g FW decreasing on the sixth day of storage (16.36 mg EAA/100g FW). Uncoated fruits stored at 15°C (T3) showed values of 14.97 mg EAA/100g FW on the fourth day of storage. However, after eight days of storage, the concentration decreased to 13.92 (mg EAA/100g FW). T4 fruits recorded 13.25 mg EAA/100g FW of vitamin C on day four of storage. After that time, the concentration increased to 17.12 mg EAA/100g FW on day eight of storage. Significant differences ($P \leq 0.05$) were observed between treatments (Figure 4(b)).

Vitamin C is an enantiomer of L-ascorbic acid; it is recognized as an important antioxidant natural origin compound [76, 77]. Agatha et al. [78] report vitamin C values of 22.59 (mg EAA/100 g FW), which coincide with the results found in our research. Moreover, Singh et al. [79] conducted a study on sour sop fruits in the Andaman Islands and reported higher concentrations (48 mg EAA/100 g FW) than those obtained in this study. The results obtained in this investigation are superior (<17.12) to those reported by Silva and Sirasa [59] whose values are 12.6 mg EAA/100g FW in frozen sour sop pulp. The difference between vitamin C values may be associated with factors such as storage temperature, fruit ripening stage, agronomic management conditions, and weather [80].

4. Conclusion

The sour sop fruits coated with roselle mucilage (2%) and stored at 15°C for eight days showed the lowest weight loss and titratable acidity. Likewise, the total phenolic content and vitamin C were increased. In the same storage conditions, the antioxidant activity increased during the fruit ripening at the stage of maturity of consumption. No negative effect on the color of the peel was observed due to the application of the mucilage coatings.

Data Availability

The statistic analysis data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors of this manuscript declare that there are no conflicts of interest.
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