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Development of Pericarp-Based Coatings from Corn Nixtamalization Residue for Stone Fruits: Applications for Peach and Tejocote

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Abstract: This study investigated corn pericarp, a by-product of the nixtamalization process, in developing sustainable films for fruit coatings. These films were evaluated for their optical, structural, barrier, and mechanical properties. The results showed that the pericarp films were transparent, had heterogeneous surfaces, and exhibited favorable mechanical and barrier properties, suggesting their potential as fruit coatings. The pericarp films significantly extended shelf life when applied to peaches and tejocotes postharvest. The films slowed the maturation process, as evidenced by minimal changes in peel and mesocarp color for up to five days for tejocotes and even longer for peaches. Additionally, coated fruits showed slower rates of weight loss, firmness reduction, and decreases in titratable acidity, total soluble solids, and total sugar content compared to control samples. These findings demonstrate the potential of corn pericarp films as effective coatings for extending the shelf life of stone fruits.

Keywords: stone fruit; food packaging; shelf life; biodegradable coatings

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1. Introduction

Approximately 715 million tons of fruits and vegetables are wasted yearly due to inadequate postharvest handling and quality deterioration. Stone fruits, including peaches and tejocotes, are prone to postharvest losses such as high weight loss, decay, over-ripeness, and physiological disorders like internal breakdown and chilling injury [1]. These issues significantly affect their storability and shelf life, leading to substantial economic losses. Addressing these challenges is crucial for extending the shelf life of stone fruits and reducing waste. Recent research highlights the potential of edible coatings to improve the postharvest quality of stone fruits by mitigating weight loss, decay, and other quality problems [2]. By focusing on coating formulation, properties, and mode of action, it is possible to develop more effective solutions for preserving the quality of stone fruits throughout their storage and distribution.

To address these challenges, biodegradable coatings have emerged as a promising solution to preserve the quality and extend the shelf life of postharvest fruits. These coatings maintain the sensory properties of the fruit without causing adverse effects, allowing for storage without refrigeration and providing a simpler method for extending shelf life [3,4]. For instance, coatings have been developed using various biopolymers, including cellulose [5] and starch [6], as well as other components like beeswax [3,4] and nanocomposites [7]. These innovations represent significant progress toward reducing postharvest losses and meeting the growing demand for sustainable packaging solutions.

The increasing environmental awareness among consumers has also driven the search for alternative packaging materials, emphasizing the importance of the circular economy and closing production cycles. By repurposing by-products from the food industry, such as agro-industrial waste, we can create new materials that reduce waste at multiple stages of production [8]. This approach addresses postharvest fruit losses and contributes to a more sustainable and circular food system.

A prime example of such waste is the by-products generated from nixtamalization, a traditional process used in corn-based food production. Nixtamalization involves the alkaline cooking of corn kernels by soaking and washing them in a calcium hydroxide solution. This process generates significant by-products, including the corn pericarp and wastewater known as nejayote. Nejayote is characterized by high solids, dissolved organic matter, calcium salts, and a pH greater than 11, which poses environmental contamination risks [9]. However, recent studies have shown that pericarp, traditionally considered a waste product, possesses valuable physicochemical properties, such as nanomechanical resistance and antioxidant activity [10], because it has a chemical composition rich in total carbohydrates including cellulose, hemicellulose or pectin (45%–50%), structural proteins and enzymes (5%–10%), and lipids (2%–5%) [11]. The sugar content in the pericarp popcorn ranges from 10.96% to 11.06%, with an ash content of approximately 67.77% and insoluble crude protein of 7% [10], as well as phenolic compounds (1%–2%), such as ferulic acid and caffeic acid, and other components such as tannins (0.5%–1%) [12]. These characteristics make it a promising candidate for use in developing biodegradable coatings. This research aims to repurpose corn pericarp to create coating films that can be applied to fruits, preserving and extending their shelf-life postharvest. A thorough analysis of the films was conducted, including structural analysis, color evaluation, and the mechanical and barrier properties assessment.

2. Materials and Methods

2.1. Sample

Popcorn kernels were obtained from a local store (Great Value, Walmart, Bentonville, AR, USA). All chemicals and reagents were of analytical grade ($\geq$99%).

2.2. Nixtamalization

The nixtamalization process was conducted by cooking 200 g of popcorn kernels with 1 g of calcium hydroxide in 400 mL of water for 40 min at 91 °C. After cooling, the nejayote was removed [10]. The nixtamalized popcorn was then added to 300 mL of a 2 N NaOH solution and cooled in a water bath for 15 min at 50 °C. The pericarp was subsequently removed and stored at 25 °C. The selection of the above parameters is based on the methodology of Rojas-Candelas et al. [10].

2.3. Preparation of Film

Biodegradable films were prepared using corn pericarp obtained from the nixtamalization process. The preparation method followed the protocols of Velickova et al. [3] and Ruzaina et al. [4] with some modifications. The film formulation included 1.5% beeswax, 2% glycerin, 4% potato starch, and 0.5% corn pericarp. The ingredients were placed into a water bath with constant stirring for around 15 min at 70 °C; then, the liquid was emptied into the petri dish (10 g) and dried at environmental temperature for the film to form.

2.4. Films Characterization

2.4.1. Scanning Electron Microscopy (SEM) and Image Analysis

The surface of the films was examined using a scanning electron microscope (SEM, Hitachi SU3500 I, Santa Clara, CA, USA) with an accelerating voltage of 10 kV. For image analysis, fractal dimension (FD) and entropy (ET) were evaluated using MapFractal and the Gray Level Co-occurrence Matrix (GLCM) in ImageJ (v. 1.46, National Institute of Health, Bethesda, MD, USA), as described by Arredondo-Tamayo et al. [13] and Hernández-Varela et al. [5].

2.4.2. Color

The films' color, both in liquid and solid states, was measured using a colorimeter (CHROMA METER CR-400, Konica Minolta, Tokyo, Japan). The parameters "L*", "a*", and "b*" were obtained from the CIELab color space [1].

2.4.3. Determination of Moisture Content

The moisture of films was measured using a methodology reported in the AOAC 942.05 [14], and a thermobalance was used (MB45, Ohaus, Parsippany, NJ, USA).

2.4.4. Water Solubility

The water solubility of the pericarp film was evaluated according to the method described by Arredondo-Tamayo et al. [13]. Measurements were conducted in triplicate and reported as mean values with standard deviations.

2.4.5. Water Adsorption Capacity (WA)

Water adsorption capacity was calculated following the method outlined by Hernández-Varela et al. [5]. Measurements were carried out in triplicate and reported as mean values with standard deviations.

2.4.6. Mechanical Properties

The mechanical properties of the pericarp film were determined using a texture analyzer (Brookfield CT3, Ametek, Inc., Berwyn, PA, USA) with a stress–strain test and double clamps (T-96). The test conditions were those reported by Valdespino et al. [5]. Measurements were performed in triplicate according to ASTM [15,16]. Strips of 80 × 20 mm were used, and the equipment parameters were as follows: a load of 0.045 N, a rate of 0.3 mm/s, 50 % of deformation, and a load cell of 4500 g [1,5,13].

2.5. Fruit Treatment

Peaches (*Prunus persica*) and tejocotes (*Crataegus mexican*) were selected for uniformity in external appearance, shape, maturity stage, and size, ensuring that these were free from noticeable defects. The selected fruits were cleaned before film application. The same film preparation was used, as explained in Section 2.3. Still, instead of emptying the liquid into the petri dish, the coating was applied at low temperatures using an immersion technique to avoid potential damage to the fruits. The coated fruits were then allowed to dry naturally at room temperature for 30 min and stored in a dark environment at room temperature for one week [1].

2.5.1. Color Analysis of Peel and Mesocarp

The color of the fruit peel and mesocarp was measured using a colorimeter (CHROMA METER CR-400, Konica Minolta, Japan). Eight fruits from each sample were analyzed following the method described by Rojas-Candelas et al. [1]. The parameters "L*", "a*", and "b*" were measured using the CIELab color space.

2.5.2. Weight Loss

Weight loss was assessed according to the method described by Velickova et al. [3]. On day zero, the initial weights of the control and coated fruits were recorded. The weight of ten fruits from each sample was measured daily throughout the one-week storage period. Weight loss was calculated by comparing the final weight with the initial weight using the following formula:

$$WL = (w_a \times 100)/w_b \quad (1)$$

where w_a = initial weight measured and w_b = final weight.

2.5.3. Fruits Firmness

Mesocarp firmness was measured following the method described by Rojas-Candelas et al. [1]. Measurements were performed using a Texturometer (Brookfield CT3, Ametek, Inc., Berwyn, PA, USA) with a load of 450 g and a maximum penetration depth of 9 mm. The penetration speed was set at 30 mm/min using a cylindrical probe with a diameter of 6 mm. Three fruits were selected for each sample, and 2 cm thick slices were cut from the mesocarp's peripheral zone. Within this zone, three points were evaluated, spaced 2 cm apart. Peel firmness was assessed similarly using a cylindrical probe with a diameter of 4 mm. All measurements were performed in triplicate on five fruits from each sample, and the results were averaged.

2.5.4. Total Soluble Solids and Titratable Acidity

Total soluble solids (TSS) and titratable acidity (TA) were measured following the method of Rojas-Candelas et al. [1] with modifications. TSS was expressed in degrees Brix (°Brix) using a refractometer (Atago, Tokyo, Japan). Titratable acidity was determined by titrating with 0.1 N NaOH until a pH of 8.2 was reached. The titratable acidity was calculated using the following formula:

$$TA = \left(\frac{V \times N \times meq \times Vf}{W \times V1}\right) \times 100$$

where V: volume of sodium hydroxide spent in the titration, N: sodium hydroxide normality = 0.1 N, meq: milliequivalents of 0.0067 malic acid for peach and tejocotes, Vf: final volume, W: sample weight, and $V1$: aliquot volume.

2.5.5. Total and Reducing Sugars

Total and reducing sugars were determined using a spectrometer (Shimadzu, Kyoto, Japan), following the methodology of Velickova et al. [3] and Rojas-Candelas et al. [10] with modifications. Results are presented as percentages.

3. Results

3.1. Film Characterization

3.1.1. Structural Characterization

Popcorn, widely recognized for its high fiber content and popularity as a healthy snack [17], undergoes significant mechanical changes when exposed to heat. These changes alter the kernel's size, shape, and diameter, including the expansion and bursting of its thicker endosperm [18,19]. These characteristics of popcorn make it a suitable candidate for generating by-products like nejayote during nixtamalization, which can be utilized in film production. In this study, texture image analysis (Figure 1) was performed on the films using SEM images, focusing on fractal dimension (FD) and entropy (ET) as critical parameters.

Low ET values correspond to homogeneous surfaces, indicating consistent texture across the image. Conversely, FD values close to 2 suggest smoother surfaces [13]. The analysis revealed distinct structural characteristics at different magnifications. The photos displayed noticeable heterogeneity at lower magnifications, indicating rougher surface areas. However, as magnification increased, the surface appeared more homogeneous, with a smoother texture and only minor cracks or irregularities visible. This suggests a transition in surface characteristics, evolving from roughness to smoothness with increased magnification.

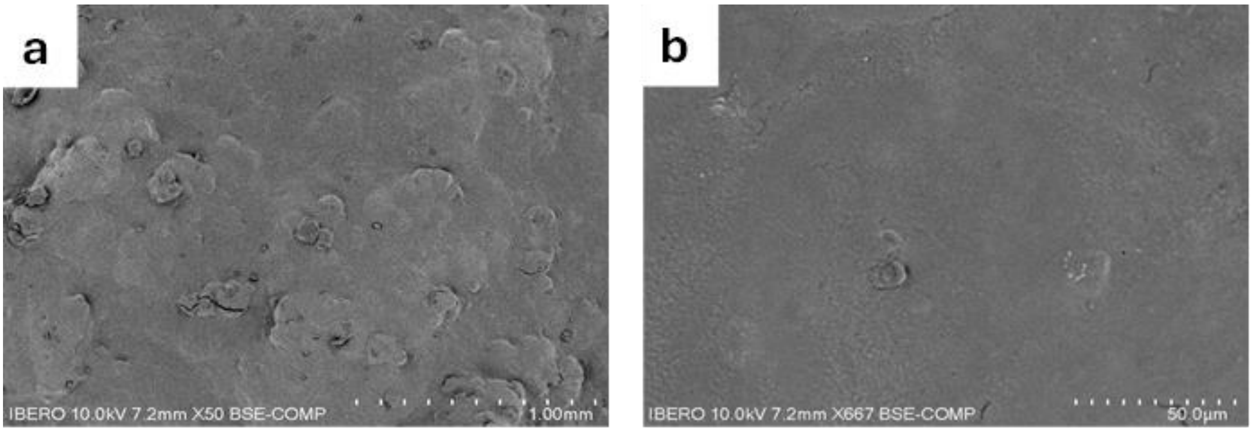


Figure 1. Images of pericarp films observed with SEM scale bar of 1 mm (**a**) and scale bar of 50 µm (**b**).

Further supporting these observations, the texture analysis revealed an ET value of 8.59 at lower magnification, indicating higher heterogeneity. The corresponding FD value was 2.77, consistent with a rough surface arrangement. At higher magnifications, both ET and FD values decreased. The ET value dropped to 7.65, reflecting a more homogeneous surface, while the FD value slightly reduced to 2.71, indicating a smoother texture.

3.1.2. Color

Color analysis of the films in both liquid and solid states was performed using CIELab parameters, which are crucial for assessing consumer perception. As shown in Figure 2, the liquid-state film's luminosity (L*) was lower than the solid-state film, indicating that the liquid-state film appeared darker.

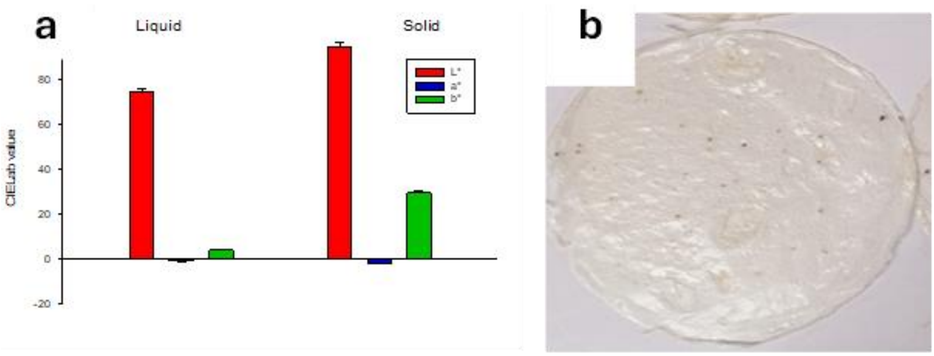


Figure 2. (**a**) Color of pericarp film and (**b**) appearance of films.

This difference in luminosity could be due to variations in composition, thickness, or other physical properties affecting light reflection and absorption.

Figure 2b reveals brown-colored particles in the film, attributed to pericarp residues, contributing to the brown hue. The a* parameter decreased from the liquid to the solid state, approaching 0, while the b* parameter increased in the solid-state film, enhancing the yellowness.

3.1.3. Mechanical and Barrier Properties

The film exhibited a tensile strength (TS) of approximately 0.27 MPa with 5% elongation, suggesting it has both hard and soft material characteristics observed in the stress–strain curve (Figure 3). This high elongation at break coupled with low tensile strength is consistent with the findings of Billmeyer and Wiley [20].

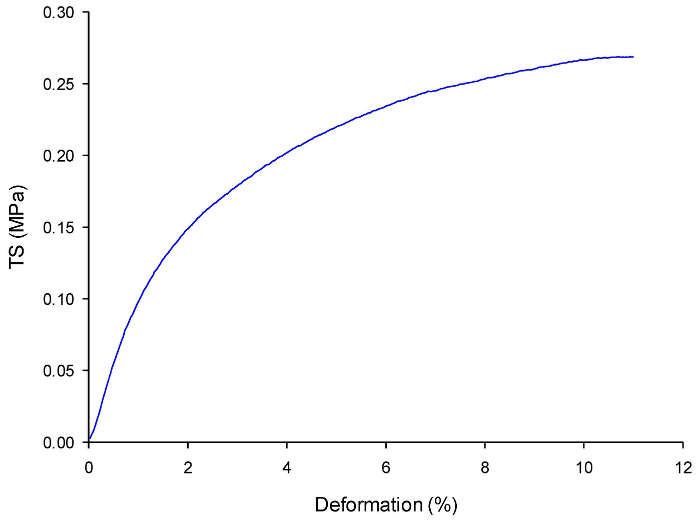


Figure 3. The stress–strain curve of pericarp film.

Moisture content is critical for assessing the film's barrier properties. Table 1 shows that the pericarp film had moisture values below 20%.

Table 1. Barrier properties of pericarp film.

Sample	M (g/100 g)	WS (g/100 g)	WA (g/100 g)
Film	10.60 ± 0.78	22.00 ± 1.20	162.00 ± 1.28

M: moisture; WS: water solubility; WA: water adsorption capacity.

The lower moisture content in the pericarp film is due to the hydrophobic nature of beeswax and the pericarp, which helps maintain fruit weight. The pericarp film's water solubility (WS) (Table 1) was 22%, attributed to the higher insoluble protein content in the pericarp, which acts as a semipermeable barrier [10]. The pericarp film's water adsorption capacity (WA) was 162% due to the hydrophilicity of the pericarp fibers and the presence of potato starch.

3.2. Fruits Characterization

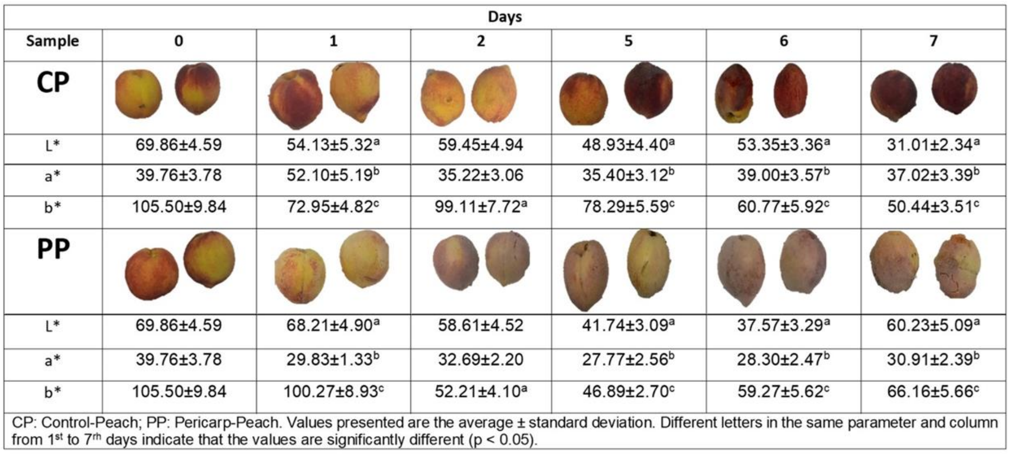
3.2.1. Color of Mesocarp Films and Peel of Coated Fruits

Fruit color in films and peels is crucial for consumer acceptance and changes during ripening. We monitored these changes throughout the storage period. Figure 4 shows a tendency towards a wine color in all samples, with notable differences on days 1, 5, and 7 for the peel of both control and coated peaches.

By day 7, the coated peaches had a higher L* value, indicating a lighter or whiter color than the control. The a* values varied across samples, with coated peaches generally showing lower values, reflecting a less intense red color. The b* values for coated peaches showed a trend towards yellow and were attributed to the coating, with coated peaches exhibiting more yellow areas than the control.

For the peach mesocarp (Figure 5), the L* value of coated peaches remained stable until day 5; then, it matched the control by day 7. The* values increased in coated samples, indicating a more intense red color. In contrast, the b* values for coated peaches tended towards yellow, contrasting with the control, which showed more wine color.

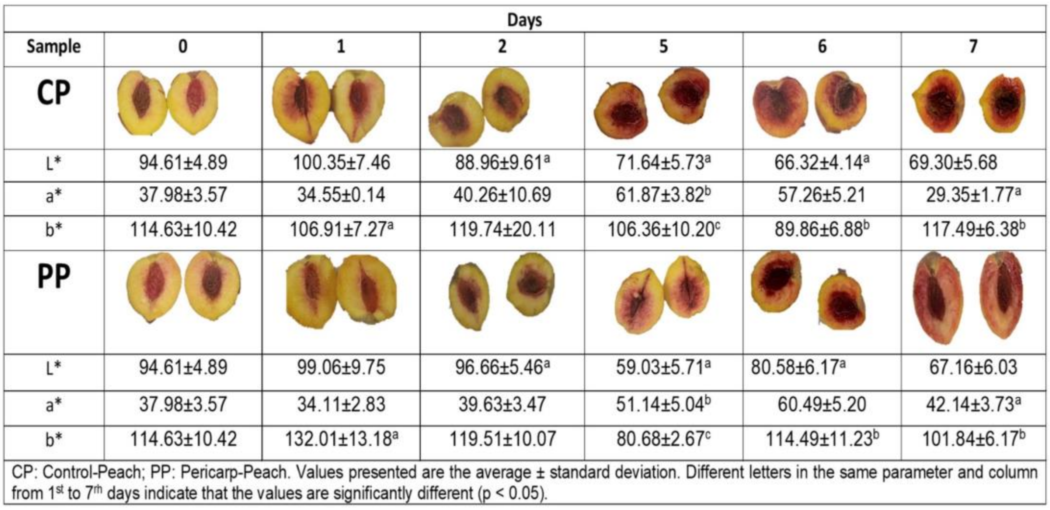
The tejocote peel (Figure 6) had a light brown and orange hue in all samples. Coated samples maintained yellow for the first five days but had lower L* values than the control. The* values for coated tejocote decreased on days 5, 6, and 7, indicating reduced green tonality. Yellow tonality (b* values) varied among samples, with the control showing brown areas from day 5, whereas coated samples showed these areas from day 6.



Sample	Days 0	1	2	5	6	7
CP						
L*	69.86±4.59	54.13±5.32^a	59.45±4.94	48.93±4.40^a	53.35±3.36^a	31.01±2.34^a
a*	39.76±3.78	52.10±5.19^b	35.22±3.06	35.40±3.12^b	39.00±3.57^b	37.02±3.39^b
b*	105.50±9.84	72.95±4.82^c	99.11±7.72^a	78.29±5.59^c	60.77±5.92^c	50.44±3.51^c
PP						
L*	69.86±4.59	68.21±4.90^a	58.61±4.52	41.74±3.09^a	37.57±3.29^a	60.23±5.09^a
a*	39.76±3.78	29.83±1.33^b	32.69±2.20	27.77±2.56^b	28.30±2.47^b	30.91±2.39^b
b*	105.50±9.84	100.27±8.93^c	52.21±4.10^a	46.89±2.70^c	59.27±5.62^c	66.16±5.66^c

CP: Control-Peach; PP: Pericarp-Peach. Values presented are the average ± standard deviation. Different letters in the same parameter and column from 1st to 7th days indicate that the values are significantly different ($p < 0.05$).

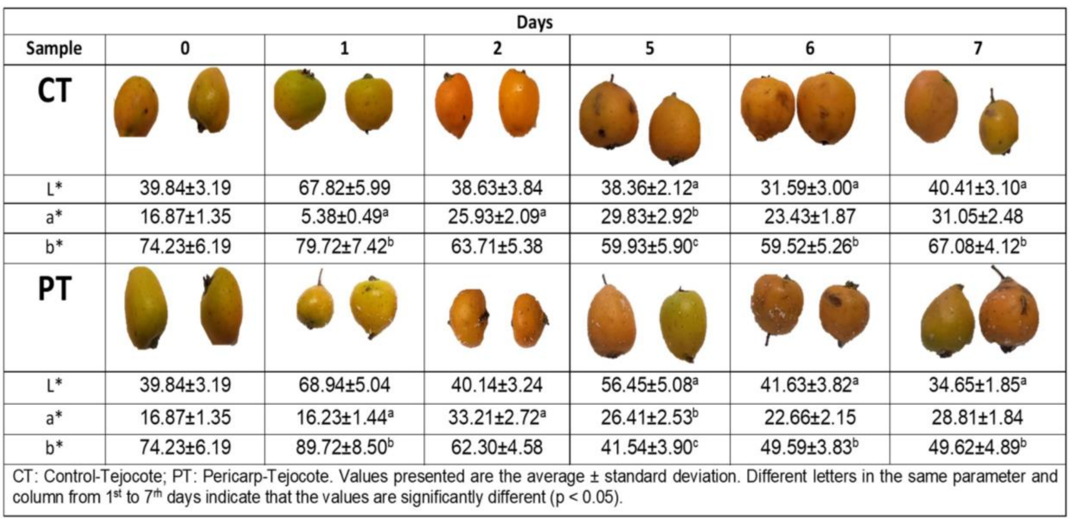
Figure 4. Images and values of the color space CIELab of the peels from coated peaches and control stored at room temperature. At different sampling times (0, 1, 2, 5, 6, and 7 days).



Sample	Days 0	1	2	5	6	7
CP						
L*	94.61±4.89	100.35±7.46	88.96±9.61^a	71.64±5.73^a	66.32±4.14^a	69.30±5.68
a*	37.98±3.57	34.55±0.14	40.26±10.69	61.87±3.82^b	57.26±5.21	29.35±1.77^a
b*	114.63±10.42	106.91±7.27^a	119.74±20.11	106.36±10.20^c	89.86±6.88^b	117.49±6.38^b
PP						
L*	94.61±4.89	99.06±9.75	96.66±5.46^a	59.03±5.71^a	80.58±6.17^a	67.16±6.03
a*	37.98±3.57	34.11±2.83	39.63±3.47	51.14±5.04^b	60.49±5.20	42.14±3.73^a
b*	114.63±10.42	132.01±13.18^a	119.51±10.07	80.68±2.67^c	114.49±11.23^b	101.84±6.17^b

CP: Control-Peach; PP: Pericarp-Peach. Values presented are the average ± standard deviation. Different letters in the same parameter and column from 1st to 7th days indicate that the values are significantly different ($p < 0.05$).

Figure 5. Images and values of the color space CIELab of the mesocarp from coated peaches and control stored at room temperature. At different sampling times (0, 1, 2, 5, 6, and 7 days).



Sample	Days 0	1	2	5	6	7
CT						
L*	39.84±3.19	67.82±5.99	38.63±3.84	38.36±2.12^a	31.59±3.00^a	40.41±3.10^a
a*	16.87±1.35	5.38±0.49^a	25.93±2.09^a	29.83±2.92^b	23.43±1.87	31.05±2.48
b*	74.23±6.19	79.72±7.42^b	63.71±5.38	59.93±5.90^c	59.52±5.26^b	67.08±4.12^b
PT						
L*	39.84±3.19	68.94±5.04	40.14±3.24	56.45±5.08^a	41.63±3.82^a	34.65±1.85^a
a*	16.87±1.35	16.23±1.44^a	33.21±2.72^a	26.41±2.53^b	22.66±2.15	28.81±1.84
b*	74.23±6.19	89.72±8.50^b	62.30±4.58	41.54±3.90^c	49.59±3.83^b	49.62±4.89^b

CT: Control-Tejocote; PT: Pericarp-Tejocote. Values presented are the average ± standard deviation. Different letters in the same parameter and column from 1st to 7th days indicate that the values are significantly different ($p < 0.05$).

Figure 6. Images and values of the color space CIELab of the peels from coated tejocotes and control stored at room temperature. At different sampling times (0, 1, 2, 5, 6, and 7 days).

For the tejocote mesocarp (Figure 7), the color tended to be yellow with brown areas in all samples, resulting in variable L* values. The a* values showed variability, reflecting heterogeneous coloration. Coated samples tended towards yellow, while the control displayed brown areas starting from day 5, with coated samples showing these areas from day 6.

	Days					
Sample	0	1	2	5	6	7
CT						
L*	68.66±3.80	45.93±2.35	66.33±6.49^{a}	64.13±5.13^{a}	59.89±4.49	66.87±6.39^{a}
a*	2.66±0.26	29.71±2.04	9.70±0.92^{b}	13.65±0.61^{b}	13.21±0.71	7.75±0.70^{b}
b*	76.36±4.13	76.95±4.39^{a}	74.84±7.31	62.18±4.22	72.13±6.26	78.23±4.83^{c}
PT						
L*	68.66±3.80	41.62±4.05	57.99±4.76^{a}	53.29±5.01^{a}	57.01±4.49	53.29±3.20^{a}
a*	2.66±0.26	30.47±2.51	13.15±1.02^{b}	8.57±0.49^{b}	13.37±1.18	22.58±0.37^{b}
b*	76.36±4.13	57.59±5.58^{a}	74.28±6.24	67.10±5.67	68.32±3.39	71.40±5.37^{c}

CT: Control-Tejocote; PT: Pericarp-Tejocoteh. Values presented are the average ± standard deviation. Different letters in the same parameter and column from 1st to 7th days indicate that the values are significantly different ($p < 0.05$).

Figure 7. Images and values of the color space CIELab of the mesocarp from coated tejocotes and control stored at room temperature. At different sampling times (0, 1, 2, 5, 6, and 7 days).

3.2.2. Fruit Weight Loss

Weight loss in fruits is primarily due to respiration, where oxygen is taken in, and carbon dioxide is released during ripening, reducing weight and shrinkage [4]. Figure 8a shows that control peaches had the lowest weight loss on day 1 compared to coated peaches. However, from day 2 onward, coated peaches consistently exhibited lower weight-loss values.

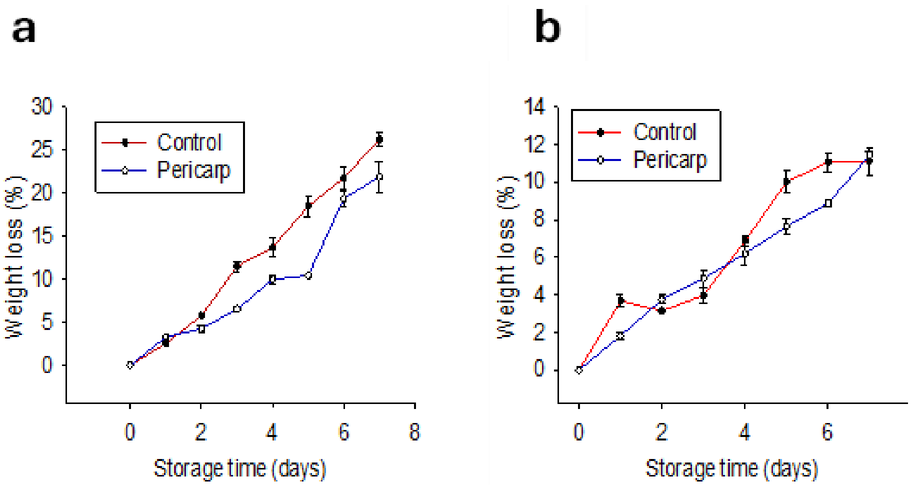


Figure 8. Loss of weight of fruits stored at room temperature. Control (red, circles), pericarp (blue, points), (**a**) peach, and (**b**) tejocote. The vertical bars indicate the standard deviation.

For coated tejocote (Figure 8b), weight-loss behavior differed. On day 1, coated tejocote had the lowest weight loss (3.67%), but by days 2 and 3, control tejocotes showed lower values. From days 4 to 6, coated tejocote had lower weight-loss values again. At the end of the seven days, weight loss was similar for both control and coated tejocotes (11%).

3.2.3. Mechanical Properties of Fruits

Fruit firmness, a key factor for consumer selection, changes during ripening. Figure 9 shows the firmness of peach and tejocote mesocarp during storage.

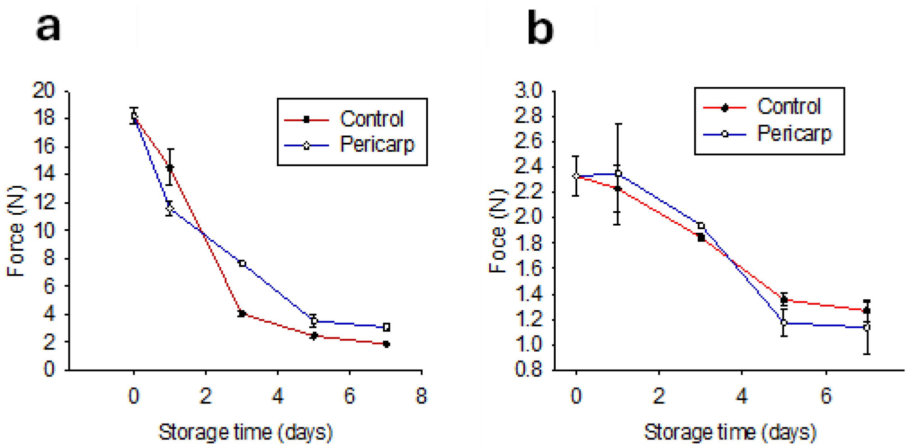


Figure 9. Effect of the coating on the mesocarp firmness of fruit stored at room temperature. Control (red, circles), and pericarp (blue, points). (**a**): peach, and (**b**): tejocote. The vertical bars indicate the standard deviation.

For peaches (Figure 9a), the control had the lowest firmness (14.51 N) on day 1, while coated peaches measured 11.58 N. From day 3, coated peaches showed slower firmness loss, with values of 7.64 N on day 3 and 3.09 N on the last day, indicating the coating helps preserve peach texture. For tejocote (Figure 9b), coated samples had lower firmness than the control until day 3. However, on days 5 and 7, controls tejocote exhibited lower firmness than coated tejocote, suggesting that the coating might allow texture damage in tejocote fruit. The control peaches showed superior behavior at 3 days, but its behavior decreased fast the next days compared to the coated peach, which kept the firmness of the mesocarp constant on days 5 and 7. The tejocote coat showed superior behavior at 3 days but decreased more than the control in the following days.

Figure 10 illustrates the effect of coating on peel firmness at room temperature. Control peaches showed significant decreases in peel firmness ($p < 0.05$) compared to coated peaches, with the most critical differences at day 3 (Figure 10a). In contrast, control tejocotes showed a significant decrease in peel firmness ($p < 0.05$) compared to coated tejocote, with the coated tejocote exhibiting superior behavior (Figure 10b).

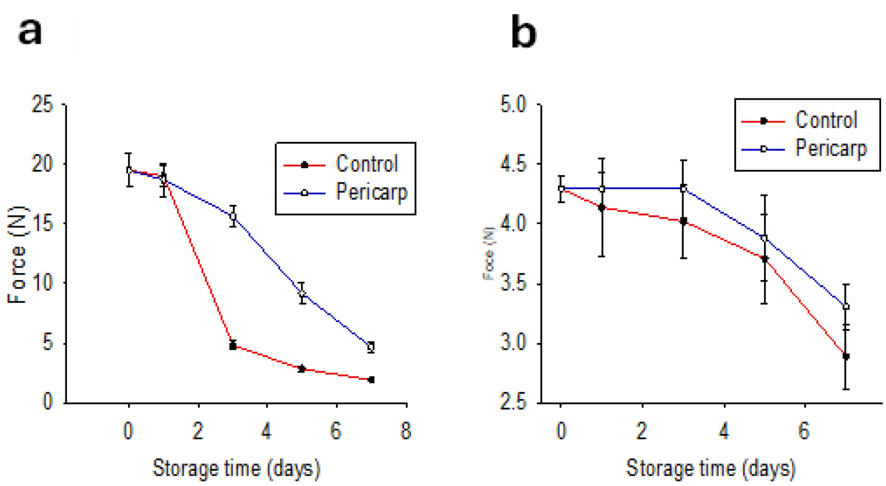


Figure 10. Effect of the coating on the peel firmness of fruit stored at room temperature. Control (red, circles), pericarp (blue, points), (**a**) peach, and (**b**) tejocote. The vertical bars indicate the standard deviation.

Similarly, the control tejocotes exhibited significant firmness reduction compared to coated tejocote (Figure 10b). The decrease in firmness is attributed to the loss of sugars like arabinose and galactose, which depolymerize and solubilize, along with reduced cell wall component size [21–23].

3.2.4. Total Soluble Solids (TSS) and Titratable Acidity (TA)

Table 2 shows changes in TA for peaches and tejocote during storage. Control peaches had stable TA values from 0 to 3 days but decreased by the last day.

Table 2. Total soluble solids (TSS) and titratable acidity (TA) of control and coated fruits.

Parameter		Avocados		Peach		Tejocote	
	Day	**Control**	**Pericarp**	**Control**	**Pericarp**	**Control**	**Pericarp**
TA (g acid/100 g)	0	0.11 ± 0.01	0.11 ± 0.01	0.83 ± 0.04	0.83 ± 0.04	3.98 ± 0.04	3.98 ± 0.04
	3	0.07 ± 0.01 a	0.09 ± 0.01 a	0.83 ± 0.04 a	0.75 ± 0.03 a	3.91 ± 0.04 a	3.88 ± 0.01 a
	7	0.07 ± 0.01	0.07 ± 0.01	0.69 ± 0.04	0.70 ± 0.04	3.55 ± 0.01	3.55 ± 0.01
TSS (°Brix)	0	0.65 ± 0.07	0.65 ± 0.01	0.66 ± 0.05	0.66 ± 0.05	1.33 ± 0.05	1.33 ± 0.05
	3	1.13 ± 0.05 a	0.3 ± 0.01 a	0.75 ± 0.07 a	0.97 ± 0.1 a	1.66 ± 0.05 a	1.83 ± 0.05 a
	7	1.2 ± 0.01 a	1.4 ± 0.05 a	1.40 ± 0.01 b	0.83 ± 0.05 b	1.60 ± 0.01	1.60 ± 0.02

Values presented are the average ± standard deviation. Different letters indicate that the values are significantly different ($p < 0.05$).

Coated peaches showed a decrease in TA throughout storage, reaching the lowest values on the final day. Similarly, TA for tejocote decreased for both control and coated samples during storage. TSS results indicate changes in sugar content. Peaches showed increased TSS during storage, with control samples exhibiting a faster increase (1.40 °Brix) than coated samples (0.83 °Brix) by the last day, suggesting that the coating influenced sugar accumulation. For tejocote, TSS values differed between control and coated samples after three days, with both showing decreased TSS by day seven, indicating that the coating initially affected sugar content, but its influence diminished over time.

3.2.5. Total and Reducing Sugars

Table 3 shows the effect of the edible coating on the total and reduced sugar content. Coated peaches exhibited higher total sugar over the seven days than control peaches. Reduced sugar remained stable in control samples throughout storage, indicating that the coating affected total sugar accumulation but did not reduce sugar.

Table 3. Total and reduced sugar content of control and coated fruits.

Parameter		Avocados		Peach		Tejocote	
	Day	**Control**	**Pericarp**	**Control**	**Pericarp**	**Control**	**Pericarp**
Total sugar (%)	0	29.80 ± 0.43	29.80 ± 0.43	16.90 ± 0.84	16.90 ± 0.84	45 ± 1.35	45.60 ± 1.35
	3	22.30 ± 1.50 a	28.50 ± 0.49 a	36.30 ± 1.50 a	62.20 ± 2.86 a	58.60 ± 0.28 a	48.10 ± 2.55 a
	7	23.50 ± 1.76	26.00 ± 1.03	60.80 ± 1.53 b	79.30 ± 2.66 b	67.10 ± 0.80	70.00 ± 2.44
Reductor sugar (%)	0	2.30 ± 0.30	2.30 ± 0.30	3.83 ± 0.12	3.83 ± 0.12	2.17 ± 0.04	2.17 ± 0.04
	3	2.46 ± 0.04	3.36 ± 0.21	2.01 ± 0.06	2.33 ± 0.08	1.04 ± 0.10 b	1.64 ± 0.05 b
	7	3.97 ± 0.13	4.30 ± 0.08	3.92 ± 0.084	2.54 ± 0.03	2.84 ± 0.07 c	4.24 ± 0.22 c

Values presented are the average ± standard deviation. Different letters indicate that the values are significantly different ($p < 0.05$).

In tejocote, the coating similarly influenced the total and reduced sugar during the initial three days, helping to maintain sugar content early in storage.

4. Discussion

In Mexico, the most essential form of corn consumption is as a tortilla, a food produced both for the home and industrially using the nixtamalization process. This process involves alkaline cooking, soaking, washing the cooked grain, and removing the pericarp. This ancestral method of preparing the dough and tortilla is as old as the domestication of corn and generates significant waste. However, many articles reported that the pericarp has many positive effects when consumed, mainly due to its antioxidant activity or fiber content [10]. That's why the pericarp recovered was used in a coating where their surfaces studied by SEM demonstrated findings are consistent with previous research by Hernández-Varela et al. [5] and Arredondo-Tamayo et al. [13], who reported similar FD values in biopolymeric films made from garlic skin and gellan gum films with eggshell nanoparticles, respectively. Hernández-Varela et al. [5] observed FD values ranging from 2.41 to 2.60 in garlic skin-based films, while Arredondo-Tamayo et al. [13], reported FD values between 2.51 ± 0.03 and 2.64 ± 0.05 in their study on gellan gum films. These values are optimal because our surfaces are smooth and homogeneous. Also, the films exhibited transparency (L*), which is essential so that it goes unnoticed by consumers. The values are similar to the reports by Gaona-Sánchez et al. [23], which obtained 96.65 for pectin citrus peel films, and Rhim et al. [24], which obtained 96.86 for soy protein isolate films. In contrast, studies on pectin and alginate films, such as Galus and Lenart [25], reported slightly lower L* values (91–89), and Ghanbarzadeh et al. [26] noted even lower values for modified starch and carboxymethyl cellulose films. Meanwhile, the a* and b* parameters vary depending on the film's composition. Pectin and alginate films typically have positive a* values (0.69 to 0.40) and b* values (5.81 to 3.61) [25], which are lower than those found in this study. Soy protein isolate films, on the other hand, show lower a* values (-2.84 to -3.51) but similar b* values to the pericarp films [21]. Negative a* values similar to those in this study were reported by Paschoalick et al. [27] in muscle protein-based films. Ghanbarzadeh et al. [26] reported a* values of -1.36 to -1.61 and b* from 18.38 to 10.48 for modified starch and carboxymethyl cellulose films. Values of a* and b* approaching zero indicate a less-colored film, which can benefit applications requiring color stability. Evaluating these parameters is crucial based on the film's specific requirements and intended use.

The films displayed favorable mechanical and barrier properties; the TS values were similar to those reported by Hernández-Varela et al. [5] for biopolymeric films made from garlic skin. Velickova et al. [3] reported tensile strength values of 10 MPa for chitosan-beeswax edible coatings, while Bátori et al. [28] found values ranging from 28 to 36 MPa for films made from pectin derived from orange waste. In addition to the mechanical properties that help resist and completely cover the fruit, an optimal balance in WS is crucial for practical fruit preservation while allowing acceptable degradation over time. The values found in this coating of pericarp were optimal and similar to those reported in rice starch films, with Colussi et al. [6] reporting WS values from 18.14% to 20.13%. Diyana et al. [29] found 24.15% to 32.96% WS values in thermoplastic cassava starch. Arredondo-Tamayo et al. [15] reported higher WS values (68.28% to 84.54%) in gellan gum films with eggshell nanoparticles. Variations in WS depend on film composition, including the presence of insoluble proteins and types of starch. Abdullah and Dong [7] reported a % water adsorption capacity of 170% in poly(vinyl) alcohol and starch films. Hernández-Varela et al. [5] obtained similar results, with WA values of around 168.69% in biopolymeric films made from potato starch. These findings highlight the water-absorbing properties of the pericarp film, which can be advantageous for specific applications but requires careful moisture control to ensure film stability. The change in the color of the fruits was delayed by the coating compared to the power, for peaches until 7 days and tejocotes until 6 days. The film of the pericarp protects by reducing oxygen permeability, minimizing oxidation, and preserving the structural integrity of the fruit. The barrier properties of coating mentioned before to reduce weight loss for fruit, the coated peaches, and tejocote in this study demonstrated slower weight loss, indicating the improved performance of the coatings. Considering the relevant literature, Velickova et al. [3] reported 15%–20% weight loss in coated strawberries after seven days, higher than observed in this study. Films based on palm stearin and palm kernel olein for guavas showed 45.89% weight loss after 14 days. Overall, the coating positively impacts fruit firmness, benefiting both tejocotes and peaches from its protective effects. The coating helps slow firmness loss during storage, although its impact on tejocote firmness is less consistent. The coating influences TA and TSS based on fruit type and storage conditions. Further research is needed to understand the precise mechanisms by which the coating affects these parameters and to optimize coating formulations for enhanced fruit preservation. Overall, the pericarp coating shows promise for extending the shelf life of tejocotes and peaches. However, further research is needed to fully understand the coating's mechanisms and optimize its formulation for improved preservation. These results suggest that the coating may delay maturation by limiting oxygen permeability, reducing ascorbic acid oxidation, and affecting citric acid usage in respiration. This contributes to increased total sugars, impacting fruit quality and consumer acceptance [30,31].

5. Conclusions

These findings suggest that the pericarp-based film positively affected the shelf life of fruits at room temperature. The coated fruits showed slower changes in various quality parameters, including peel and mesocarp color, weight loss, firmness, titratable acidity, total soluble solids, and total sugar losses compared to the control and other samples studied. By slowing down the maturation process and maintaining the quality attributes of fruits, the pericarp coating effectively extended their useful life up to 7 days. This protective effect is attributed to the coating's ability to reduce oxygen permeability, minimize oxidation, and preserve the fruit's structural integrity. These results indicate that pericarp-based coatings can reduce food waste and enhance fruit preservation across various storage and distribution scenarios. Future research should focus on expanding the coating's applicability to a broader range of fruit types and storage conditions, assessing its long-term stability beyond 7 days, and evaluating its impact on sensory attributes such as taste and texture.

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References

1. Rojas-Candelas, L.E.; Díaz-Ramírez, M.; Rayas-Amor, A.A.; Cruz-Monterrosa, R.G.; Méndez-Méndez, J.V.; Salgado-Cruz, M.D.l.P.; Calderón-Domínguez, G.; Cortés-Sánchez, A.D.J.; González-Vázquez, M. Development of Biodegradable Films Produced from Residues of Nixtamalization of Popcorn. *Appl. Sci.* **2023**, *13*, 8436. [CrossRef]
2. Riva, S.C.; Opara, U.O.; Fawole, O.A. Recent developments on postharvest application of edible coatings on stone fruit: A review. *Sci. Hortic.* **2020**, *262*, 109074. [CrossRef]
3. Velickova, E.; Winkelhausen, E.; Kuzmanova, S.; Alves, V.D.; Moldão-Martins, M. Impact of Chitosan-Beeswax Edible Coatings on the Quality of Fresh Strawberries (Fragaria ananassa Cv Camarosa) under Commercial Storage Conditions. *LWT* **2013**, *52*, 80–92. [CrossRef]
4. Ruzaina, I.; Norizzah, A.R.; Zahrah Halimahton, M.S.; Cheow, C.S.; Adi, M.S.; Noorakmar, A.W.; Mohd Zhaid, A. Utilisation of Palm-Based and Beeswax Coating on the Postharvest-Life of Guava (*Psidium guajava* L.) during Ambient and Chilled Storage. *Int. Food Res. J.* **2013**, *20*, 265.

5. Hernández-Varela, J.D.; Chanona-Pérez, J.J.; Resendis-Hernández, P.; Gonzalez Victoriano, L.; Méndez-Méndez, J.V.; Cárdenas-Pérez, S.; Calderón Benavides, H.A. Development and Characterization of Biopolymers Films Mechanically Reinforced with Garlic Skin Waste for Fabrication of Compostable Dishes. *Food Hydrocoll.* **2022**, *124*, 107252. [CrossRef]
6. Colussi, R.; Pinto, V.Z.; Lisie, S.; El Halal, M.; Da, E.; Zavareze, R.; Renato, A.; Dias, G. Physical, Mechanical, and Thermal Properties of Biodegradables Films of Rice Starch. *Curr. Agric. Sci. Technol.* **2014**, *20*.
7. Abdullah, Z.W.; Dong, Y. Biodegradable and Water Resistant Poly(Vinyl) Alcohol (PVA)/Starch (ST)/Glycerol (GL)/Halloysite Nanotube (HNT) Nanocomposite Films for Sustainable Food Packaging. *Front. Mater.* **2019**, *6*, 58. [CrossRef]
8. Guillard, V.; Gaucel, S.; Fornaciari, C.; Angellier-Coussy, H.; Buche, P.; Gontard, N. The next generation of sustainable food packaging to preserve our environment in a circular economy context. *Front. Nutr.* **2018**, *5*, 121. [CrossRef]
9. Niño-Medina, G.; Carvajal-Millán, E.; Lizardi, J.; Rascon-Chu, A.; Marquez-Escalante, J.A.; Gardea, A.; Martinez-Lopez, A.L.; Guerrero, V. Maize processing wastewater arabinoxylans: Gelling capability and cross-linking content. *Food Chem.* **2009**, *115*, 1286–1290. [CrossRef]
10. Rojas-Candelas, L.E.; Díaz-Ramírez, M.; Rayas-Amor, A.A.; Cruz-Monterrosa, R.G.; Méndez-Méndez, J.V.; Villanueva-Carvajal, A.; Cortés-Sánchez, A.D.J. Nanomechanical, Structural and Antioxidant Characterization of Nixtamalized Popcorn Pericarp. *Appl. Sci.* **2022**, *12*, 6789. [CrossRef]
11. Haug, W.; Lantzsch, H.J. Sensitive method for the rapid determination of phytate in cereals and cereal products. *J. Sci. Food Agric.* **1983**, *34*, 1423–1426. [CrossRef]
12. Coco, M.G., Jr.; Vinson, J.A. Analysis of popcorn (*Zea mays* L. var. everta) for antioxidant capacity and total phenolic content. *Antioxidants* **2019**, *8*, 22. [CrossRef] [PubMed]
13. Arredondo-Tamayo, B.; Méndez-Méndez, J.V.; Chanona-Pérez, J.J.; Hernández-Varela, J.D.; González-Victoriano, L.; Gallegos-Cerda, S.D.; Martínez-Mercado, E. Study of gellan gum films reinforced with eggshell nanoparticles for the elaboration of eco-friendly packaging. *Food Struct.* **2022**, *34*, 100297. [CrossRef]
14. *Official Methods of Analysis*; AOAC International: Gaithersburg, MD, USA, 2005.
15. *E8/E8M−13a*; Standard Test Method for Tensile Properties of Plastics. Standard Test Method International: Conshohocken, PA, USA, 2015.
16. *D638-14*; Standard Test Method for Tensile Properties of Plastics. Standard Test Method International: Conshohocken, PA, USA, 2015.
17. Thakur, S.; Kumar, R.; Vikal, Y.; Vyas, P.; Sheikh, I.; Dhaliwal, H.S. Molecular mapping of popping volume QTL in popcorn (*Zea maize* L.). *J. Plant Biochem. Biotechnol.* **2021**, *30*, 496–503. [CrossRef]
18. Karababa, E. Physical properties of popcorn kernels. *J. Food Eng.* **2006**, *72*, 100–107. [CrossRef]
19. Sweley, J.C.; Rose, D.J.; Jackson, D.S. Quality Traits and Popping Performance Considerations for Popcorn (*Zea mays* Everta). *Food Rev. Int.* **2013**, *29*, 157–177. [CrossRef]
20. Billmeyer, F.W.; Wiley, J. *Text Polymer Book, 3rd ed*; A Wiley-Interscience Publication: Hoboken, NJ, USA, 1984; pp. 246–253.
21. Goulao, L.F.; Oliveira, C.M. Cell wall modifications during fruit ripening: When a fruit is not the fruit. *Trends Food Sci. Technol.* **2008**, *19*, 4–25. [CrossRef]
22. Sakurai, N.; Nevins, D.J. Relationship between Fruit Softening and Wall Polysaccharides in Avocado (*Persea americana* Mill) Mesocarp Tissues. *Plant Cell Physiol.* **1997**, *38*, 603–610. [CrossRef]
23. Gaona-Sánchez, V.A.; Calderón-Domínguez, G.; Morales-Sánchez, E.; Chanona-Pérez, J.J.; Arzate-Vázquez, I.; Terrés-Rojas, E. Pectin-based films produced by electrospraying. *Appl. Polym. Sci.* **2016**, *133*, 43779. [CrossRef]
24. Rhim, J.W.; Park, H.M.; Ha, C.S. Bio-nanocomposites for food packaging applications. *Prog. Polym. Sci.* **2013**, *38*, 1629–1652. [CrossRef]
25. Galus, S.; Lenart, A. Development and characterization of composite edible films based on sodium alginate and pectin. *J. Food Eng.* **2013**, *115*, 459–465. [CrossRef]
26. Ghanbarzadeh, B.; Almasi, H.; Entezami, A.A. Physical properties of edible modified starch/carboxymethyl cellulose films. *Innov. Food Sci. Emerg. Technol.* **2010**, *11*, 697–702. [CrossRef]
27. Paschoalick, T.M.; Garcia, F.T.; Sobral, P.J.A.; Habitante, A.M.Q.B. Characterization of some functional properties of edible films based on muscle proteins of Nile Tilapia. *Food Hydrocoll.* **2003**, *17*, 419–427. [CrossRef]
28. Bátori, V.; Jabbari, M.; Åkesson, D.; Lennartsson, P.R.; Taherzadeh, M.J.; Zamani, A. Production of Pectin-Cellulose Biofilms: A New Approach for Citrus Waste Recycling. *Int. J. Polym. Sci.* **2017**, *2017*, 9732329. [CrossRef]
29. Diyana, Z.N.; Jumaidin, R.; Selamat, M.Z.; Suan, M.S.M. Thermoplastic starch / beeswax blend: Characterization on thermal mechanical and moisture absorption properties. *Int. J. Biol. Macromol.* **2021**, *190*, 224–232. [CrossRef]
30. Mederos-Torres, Y.; Bernabe-Galloway, P.; Ramirez-Arrebato, M.A. Polysaccharide-based films as biodegradable coatings in fruits postharvest. *Cultiv. Trop.* **2020**, *41*, e09.
31. Li, C.; Tao, J.; Zhang, H. Peach gum polysaccharides-based edible coatings extend shelf life of cherry tomatoes. *Biotech* **2017**, *7*, 168. [CrossRef]