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Opuntia ficus-indica L. Fruits Cold Storage Using Different Packaging Materials

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Abstract: The prickly pear is a non-climacteric fruit and highly perishable. Therefore, it is crucial to find methods to extend its shelf life. The objective of this study was to evaluate the storage behavior of prickly pears under modified atmosphere conditions (2 °C, 90% RH) using different packaging materials (a cardboard box commercially used by the company, a rigid PET (polyethylene terephthalate) box, and a biodegradable plastic flexible bag). The fruits were produced in the Alentejo region and belong to a regional variety usually referred to as the "orange" variety. According to this study, the "orange" variety fruits could be stored at the specified temperature for 30 days. Among the storage methods tested, the biodegradable plastic bag was the most effective in maintaining the fruit's quality throughout the entire period. The biodegradable package exhibited a weight loss lower than 5% for 30 days of storage, while the cardboard box showed great weight loss (>6%) and more fruit contamination by fungi. Fruit firmness also decreased during storage, going from 10.1 N to 4.35 N, with bigger losses happening in the PET box. Throughout the study, the fruit acidity remained stable with values of 0.03% and 0.02%.

Keywords: prickly pear; biodegradable material; modified atmosphere; packaging

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1. Introduction

The *Opuntia ficus-indica* (L.) Mill. cactus, known as prickly pear cactus, is a xerophyte plant widespread worldwide, established in arid and semiarid zones. The prickly pear cactus is a CAM (Crassulacean Acid Metabolism) plant, therefore showing high ecological adaptability and can thrive in very diverse regions with high temperatures, as extreme as 65 °C, with low water availability, which are very adverse conditions for many cultivated plants [1]. Due to its high water use efficiency (WUE) and increased biomass production caused by the increasing atmospheric CO_2 concentrations, the prickly pear cactus may play an increasingly important role in agricultural systems in the future. A study by Drennan and Nobel [2] based on longer-term research done for several CAM species showed that in situations of increasing temperature, drought duration, and increasing atmospheric CO_2 concentration, the percentage of daily net CO_2 uptake rises in these plants. Thus, net CO_2 uptake, productivity, and potential area for CAM species cultivation will be expanded due to higher atmospheric CO_2 concentrations and elevated temperatures associated with global climate change [3].

In Portugal, the area occupied, in 2016, by prickly pear plantations was approximately 820 ha, with new commercial plantations still appearing to this date, and it will likely keep expanding in the future. Some plantations are organized like orchards with drip irrigation, specific plant layouts, and spacing designs; however, in some plantations the prickly pear is cultivated traditionally, without irrigation [4]. Italy, a Mediterranean country, is Europe's primary cultivator of cactus pear fruit, mainly in the region of Sicily, with an area of 3000 ha of land exclusively allocated for commercial purposes [5]. In South America, this culture has a significant impact, with an area of 600,000 ha in Brazil, 70,000 ha in Mexico, and Chile and Argentina have more than 1000 ha each. In Africa, the position of Morocco is highlighted, where a very particular growth in the planted area reached 150,000 ha followed by 25,000 ha in Tunisia and 1000 ha in South Africa [6].

The fruits of *Opuntia* spp. have nutritive value and health benefits, including antioxidant properties, which are related to ascorbic acid, high antioxidant content of polyphenols, betalains, betacyanins, and vitamin C [7–9]. They also contain high concentrations of amino acids, as well as minerals including magnesium, calcium, iron, potassium, sodium, and phosphorus. Moreover, this fruit holds potential for various forms of utilization beyond the fresh consumption of whole or cut fruits [10]. It can be transformed into jams, liquors, juice, and marmalade. Furthermore, it can be consumed in its dehydrated form [11,12]. Additionally, the prickly pear also possesses medicinal properties, including anticancer effects and its ability to help control cholesterol levels [13].

Nonetheless, the prickly pear fruit poses a challenge due to its non-climacteric nature and high perishability. Typically, within a mere 20 days after harvesting, a staggering 70% of the prickly pear yield is lost [14]. Therefore, it becomes crucial to enhance the fruit's shelf life to ensure its longevity and minimize losses. According to Hertog et al. [15], shelf life is the maintenance of quality under defined storage conditions. The expected decline can be minimized by storage conditions and packaging. The control of temperature, humidity, and levels of O_2 and CO_2 play a decisive role in the shelf life. Modified atmospheres (MA) consist of the use of low optimum temperature simultaneously with adequate packages providing a high level of relative humidity, controlling the gas composition of the storage environment, and contributing to maintain the quality of fresh fruits after harvest [16]. The desired storage atmosphere is achieved by the fruit's physiological activity, by reducing the O_2 concentration and increasing the CO_2 concentration compared to the ambient air values. MA is a technology widely applied for more than 90 years, with many benefits that include, among others, reduced respiration and ethylene production; retarded softening; control of some physiological disorders; ensuring safety and the maintenance of the sensory characteristics; and reduced decay. The results of MA within the package with a passive modified atmosphere depend mainly on the film permeability, the temperature, relative humidity conditions, and the level of commodity respiration [17,18].

The response of the fruit to storage is significantly influenced by various factors, including storage conditions such as temperature and relative humidity, the specific cultivar, the maturity stage at harvest, as well as the soil, climate, and crop management, with a highlight on the effect of nutrition and irrigation on final fruit quality and behavior during storage. It has been repeatedly emphasized that all of these elements collectively contribute to the overall storage outcomes [19].

Several studies evaluated the storage of prickly pear using different storage temperatures and concluded that the cold temperature enhances the storage period. Cruz-Bravo et al. [20] studied two cultivars, "Amarilla Olorosa" and "Roja Lisa", at room temperature and in cold conditions (10 °C 95% RH). The results showed that the nutraceutical properties were enhanced. Andreu-Coll et al. [21] evaluated and observed a suppressed-climacteric ripening pattern on the 'Orito' cultivar fruits and they maintained optimal quality for a period of 28 days under cold conditions (2 °C, 85–90% RH).

Further investigation is thus needed to assess how long it is possible to commercialize the fresh prickly pears with good organoleptic and nutritional quality, using simple and applicable storage methodologies, such as modified atmosphere packaging. In recent years, studies have been conducted concerning the storage of prickly pear fruits; however, most of these studies either use minimally proceeded fruits or edible coatings [22–24]. Furthermore, there are not many studies involving the usage of biodegradable plastics.

Currently, consumers are becoming more exigent. Besides looking for more environmentally friendly food products, they also seek environmentally friendly packaging options. Recent data based on a survey of 15,000 consumers in Europe, North America, and South America stated that more than 67% of consumers consider themselves environmentally conscious and prefer recyclable packaging and 54% consider sustainable packaging when selecting a product. In addition, 70% of all consumers are willing to pay more for recyclable packaging [25]. According to the European Green Deal, there is an urgent necessity in preventing packaging waste, one of the tools being the usage of recyclable materials until 2030 [26].

The aim of this research study is to investigate the changes occurring in prickly pear fruits when subjected to cold storage conditions (2 °C and 90% relative humidity) and simultaneously the effect of various packaging materials, including a biodegradable flexible plastic packing, an open cardboard packaging commonly utilized by the company, and a conventional PET box typically used for fruit packaging. The focus is on monitoring the evolution of the fruits under these different modified atmosphere (MA) modalities.

With the results obtained, it is intended to indicate to the producers which is the best packaging solution to maintain the quality of the fruit during storage.

2. Materials and Methods

2.1. Material

2.1.1. Fruits

The fruits employed in this study were sourced from a company located in the south of Portugal, in the Alentejo region (Latitude: 38.74000562683715, Longitude: 7.815030812780606), that produces fruits of a regional "orange" variety (Figure 1).

Figure 1. Prickly pear fruits of the "orange" variety.

2.1.2. Packaging Material and Chemicals

In this trial, three different packages were evaluated: cardboard boxes, rigid PET boxes, and biodegradable plastic flexible bags.

The company that produces the prickly pears normally uses cardboard boxes, with the dimensions of 16.5 × 11.0 × 6.0 cm and a perforation in the lid. This material can be in direct contact with the food product and is easy to recycle.

The rigid polyethylene terephthalate or simply polyester (PET) boxes used in this trial are common in the storage and sale of small fruits, with dimensions of 16.5 cm × 9.0 cm × 7.0 cm and perforations in the lid (12 holes of 2.0 cm × 0.5 cm each). This material has excellent transparency and good mechanical properties, is light, is shatter resistant, and simultaneously provides an adequate gas barrier property to O_2, CO_2, and moisture, being able to provide a MA behavior.

Biodegradable plastic bags are transparent and flexible, recently available for sale in Portugal; however, their exact composition remains undisclosed by the manufacturer. These are bags whose degradation results in organic compounds through the action of microorganisms. In the presence of oxygen, these bags decompose into carbon dioxide, water, minerals, and biomass; in the absence of oxygen, they decompose into carbon dioxide, methane, minerals, and biomass. These bags were tested considering their contact with food (Regulation 2017/752 of 28 April, amending and correcting Regulation 10/2011), and for permeability to CO_2 and O_2 as well as to water vapor transmission.

All chemicals were high-purity grade and were purchased from Sigma-Aldrich (St.Louis, MO, USA) or Merck KGaA (Darmstadt, Germany).

2.2. Methods

2.2.1. Experimental Design

The experimental design used to set up this trial was a factorial design, considering the package modality and storage time as factors. Three replicates were made for each experimental condition and each package contained three fruits. The fruits were stored at 2 °C, 90% RH. These temperatures and relative humidity conditions were decided upon following previous testing by this team. Although chilling injury symptoms are reported for temperatures below 8 °C, it is also known that varieties have very different sensitivities to cold. Three different types of packaging materials were used: the commercially used cardboard box, a rigid PET box, and a biodegradable plastic flexible bag. This trial had a duration of forty days, and every ten days, three packages of each type were taken out of the cold chamber, and the fruit quality was evaluated.

The prickly pear juice was frozen at −20 °C for later analyses of phenolic content and antioxidant activity.

2.2.2. Weight Loss

The weight loss evaluation, in %, was obtained by weighing each box on the first day and each day of the trial, using a digital scale Mettler Toledo PB1502.

The weight losses were calculated as usual using the equation:

$$WL = ((Wi - Wf)/Wi) * 100 \quad (1)$$

where WL is the weight loss (%), Wi is the initial weight (g), and Wf is the weight at each storage time (g).

2.2.3. Color

The exterior color of the fruits was analyzed using a Cr−400 da Konica Minolta colorimeter, using the CIE 1976 L*a*b* color space (also referred to as CIELAB), and the value of C* and h° was calculated. Two measurements in the surface of the fruits in the equatorial zone were taken, carefully avoiding brown spots or any other anomaly that could influence the results. The data were processed with the software Spectra MagicTM NC version 10.0.

2.2.4. Texture

To assess the mechanical properties of the fruits, they were subjected to a penetration test using a texture analyzer TA.HD.Plus (Stable Micro Systems Ltd., Surrey, UK) with a 2 mm cylindrical stainless probe. In each fruit, two tests were performed on each side of the equatorial zone of each prickly pear. These tests reached a deformation of 5 mm and the test speed was 1 mm/s.

2.2.5. Total Soluble Solids

To determine the total soluble solids (TSS), the fruits were cut in half, and each half was gathered and analyzed with a digital refractometer ATAGO PR-32α (ATAGO Co., Ltd., Tokyo, Japan). The results are expressed in °Brix.

2.2.6. Titratable Acidity

The juice of the prickly pear was gathered by squeezing the pulp and filtrated. Each cup used for analyses contained a composite sample obtained from the juice of three fruits.

Three grams of juice were then diluted with 50 mL of distilled water and then analyzed with a Crison compact titrator, version S (Crison Instruments, S.A., Barcelona, Spain), and the titration volume of NaCl was measured to calculate the quantity of citric acid.

2.2.7. Phenolic Content

To quantify the phenolic contents of the prickly pear fruits, an adaptation of the Folin–Ciocâlteu method [27] was used adapted to the microplate. Briefly, in a 96-well microplate, we added 10 µL of juice sample, 15 µL of Folin–Ciocâlteu reagent, 240 µL of bi-distilled water, and 30 µL of saturated sodium carbonate. After 2 h, the readings were performed at 730 mm on a Promega spectrophotometer.

2.2.8. Antioxidant Activity

The evolution of the antioxidant activity throughout the course of this study was monitored with the free radical DPPH method, adapted from Kim et al. [28]. Briefly, in a plastic cuvette, 200 µL of juice sample was added to 800 µL of DPPH 0.3 M prepared in ethanol. The readings were performed at 517 nm after incubating for 10 min.

The percentage antioxidant activity (%) at 517 nm was determined with the equation:

$$\text{Antioxidant activity (\%)} = ((\text{Abs 517 (blank)} - \text{Abs 517 (sample)})/\text{Abs 517 (blank)}) * 100 \quad (2)$$

2.2.9. Mineral Analysis

The analysis of mineral compounds was only performed on the first day to characterize the fruits. The analysis of mineral elements and moisture content was performed in the physical-chemical laboratory of the Centro de Apoio Tecnológico Agro Alimentar (CATAA) in Castelo Branco, using internal protocols such as the ones described by Antunes et al. [29].

2.2.10. Statistical Analysis

Statistical treatment was performed using Statistica software version 13.0 (StatSoft, Inc., Dell, Tulsa, OK, USA). Analysis of variance (ANOVA) was performed for a significance level of 0.05. The means were compared and the differences between groups were identified based on Tukey's honestly significant difference (HSD) test ($p < 0.05$). Tables were prepared for each parameter evaluated, with the results obtained in the ANOVA and Tukey's multiple comparisons test, using letters of the alphabet to indicate the significant differences found.

3. Results

3.1. Mineral Analysis

The prickly pears of the "orange" variety analyzed showcased a high amount of calcium, potassium, and magnesium (Table 1). These values were higher than the ones presented by Silva et al. [8], which had values of magnesium of 25.10 mg/100 g, 26.30 mg/100 g of calcium, and 158.30 mg/100 g of potassium. The value of calcium is also higher than the one found in the USDA database [30]; however, the potassium and magnesium values are inferior to the ones exhibited in the database. The humidity value is slightly lower than the one presented by Barba et al. [31], which was 87.5%.

Table 1. Mineral analysis results of the prickly pear fruit produced in Alentejo. Minerals with the result < LQ are residual. The results are presented in mg/100 g of fresh matter.

Parameter	Result
Calcium (mg/100 g)	65.0
Potassium (mg/100 g)	18.8
Sodium (mg/100 g)	<LQ
Copper (mg/100 g)	0.044
Iron (mg/100 g)	0.143

Table 1. *Cont.*

Parameter	Result
Phosphorus (mg/100 g)	16.77
Manganese (mg/100 g)	<LQ
Magnesium (mg/100 g)	37.7
Zinc (mg/100 g)	0.127
Humidity (%)	84.54

3.2. Weight Loss

Weight loss during storage is a critical factor in the characterization of the shelf life of the fruit. Many factors lead to weight loss during storage, including loss of water from the surface of the fruit, deterioration of the plant cell wall, and increased respiration [32,33].

The storage time, the package modality, and the interaction between those two factors all presented significant differences in the percentage of weight loss ($p < 0.05$), and the factor that best explains the differences recorded was the storage time, as F storage time = 305.03 > F modality = 68.13 > F interaction = 11.23 (Table 2). The fruits packed in cardboard boxes presented higher values of weight loss, reaching values higher than 8% by the end of the time of this trial (Figure 2), while the fruits in biodegradable bags presented the lowest values, inferior to 5% even after 40 days of storage. It is important to mention that the weight loss, in general, was below 5% until 20 days of storage, which according to Kader [34], is the limit value to prevent visible loss of quality in fruits. The biodegradable bags act as a barrier, preventing the transference of humidity to the exterior, and slowly increasing the humidity in the interior of the package, acting as a modified atmosphere [35].

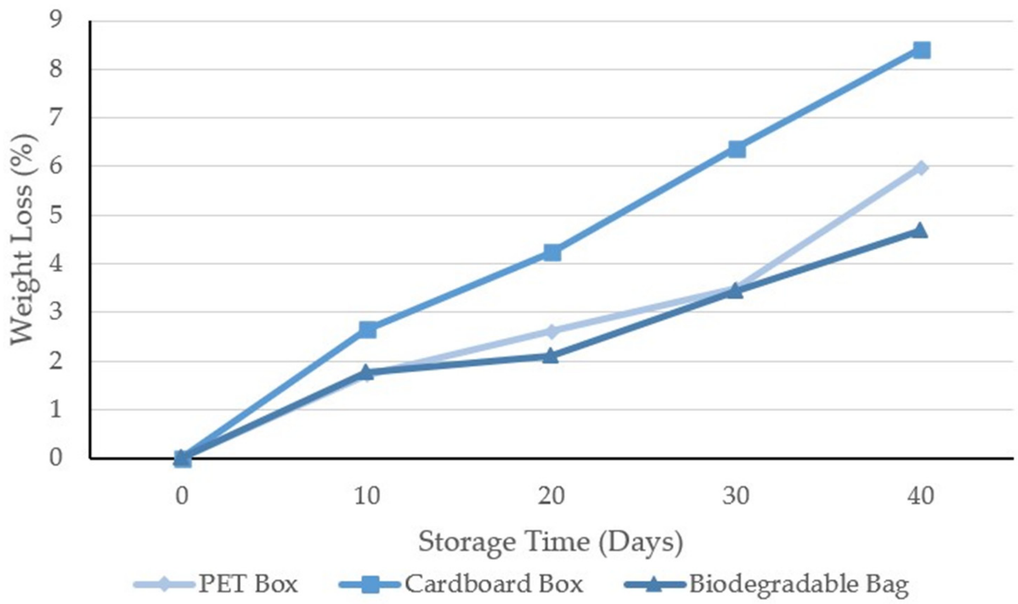

Figure 2. Weight loss (%) throughout the storage period in all modalities of packaging (cardboard box, rigid PET box, and biodegradable bag).

Kahramanoğlu [36] presented in his study weight loss values of 3%, after 18 days of storage, with fruits wrapped with cling film and kept at a temperature of 5 °C. The values obtained in this trial using the biodegradable bag and the PET box, both acting as MA, were in accordance with those of Kahramanoğlu [36]. At 20 days of storage, the weight loss of both MA modalities was about 3%, only surpassed after 30 days of storage. The cardboard box reached the same value after 10 days of storage. Thus, the use of biodegradable film seems to be a good strategy to reduce weight loss to acceptable levels until the 40th day of conservation.

Table 2. Statistical results for the weight loss, presenting means, standard deviation and ANOVA results, F and *p* values for each factor (storage time, packaging modality, and interaction between them) using a significance level of 0.05 and results of Tukey's multiple comparisons test (HDS) with distinct letters indicating significant differences for $p < 0.05$.

			Weight Loss (%)	
Factors and levels			Mean ± SD	*F* (*p*)
Storage time (day)	0		0 ± 0 a	305.03 (0.000)
	10		2.04 ± 0.51 b	
	20		2.98 ± 1.09 c	
	30		4.43 ± 1.6 d	
	40		6.30 ± 1.85 e	
Packaging modality	Cardboard Box		2.83 ± 3.09 a	68.13 (0.000)
	PET Box		1.97 ± 2.22 b	
	Biodegradable Bag		1.56 ± 1.68 c	
Interaction	0	Cardboard Box	0 ± 0 a	11.23 (0.000)
	0	PET Box	0 ± 0 a	
	0	Biodegradable Bag	0 ± 0 a	
	10	Cardboard Box	2.65 ± 0.37 bc	
	10	PET Box	1.72 ± 0.14 b	
	10	Biodegradable Bag	1.76 ± 0.18 b	
	20	Cardboard Box	4.23 ± 0,90 d	
	20	PET Box	2.60 ± 0.45 bc	
	20	Biodegradable Bag	2.10 ± 0.12 b	
	30	Cardboard Box	6.37 ± 0.27 e	
	30	PET Box	3.48 ± 1.10 cd	
	30	Biodegradable Bag	3.44 ± 0.15 cd	
	40	Cardboard Box	8.41 ± 1.16 f	
	40	PET Box	5.98 ± 1.53 e	
	40	Biodegradable Bag	4.69 ± 0.37 dg	

Cruz-Bravo et al. [20] studied the weight loss in two different prickly pear varieties at room temperature and using cold storage. Only the variety "Roja Lisa" showed a 3% weight loss when conserved in a cold room for 40 days.

The fruits continue metabolic processes after being harvested. When the fruit is separated from the mother plant, it cannot replace carbohydrates and water. According to Kader [37], transpiration is one important factor determining the shelf life of fruits and vegetables after harvest. Transpiration is a major cause of loss in cell turgor, softening, wrinkling of the skin (shrivel), loss of shine, and quality decay. Loss of weight appears due to water loss from the fruit. Excessive loss of weight may occur if the relative humidity is lower than the water vapor equilibrium of the fruit. Furthermore, according to Rezaiyan Attar et al. [38], respiration can lead to heat generation within the cell tissue, which consequently creates a water vapor pressure deficit, therefore increasing the evaporation.

Transpiration involves the evaporation of water from cell surfaces into intercellular spaces and the diffusion of water molecules out of the plant tissue or organ into the surrounding air [39]. The vapor pressure deficit (VPD) obtained by the difference between the vapor pressure of the air and the vapor pressure of the evaporating surface is decisive for the loss of water by the fruits and so the loss of weight [37,39].

3.3. Color

Color is an important quality indicator, and color changes happen as the fruits mature but also during the post-harvest period as the chlorophyll molecules degrade [40].

In this trial, the color showed significant differences ($p < 0.05$) for storage time in all coordinates (L*, a*, b*), but only presented significant differences for L* for the factor packaging modality, $p = 0.020$). However, considering the color coordinate L*, the F value for storage time = 24.97 and the F value for packaging modality = 4.10, so we can refer to the importance of the storage time (Table 3). The more noticeable changes in the exterior peel happened in the first 10 days of storage. The biodegradable packaging was also the package that better maintained the fruit color, preventing big alterations to the pigmentation.

Table 3. Statistical results for the color coordinates L* a* b*, presenting means, standard deviation and ANOVA results, F and p values for each factor (storage time, packaging modality, and interaction between them) using a significance level of 0.05 and results of Tukey's multiple comparisons test (HDS) with distinct letters indicating significant differences for $p < 0.05$.

			L*		a*		b*	
Factors and levels			Mean ± SD	F (p)	Mean ± SD	F (p)	Mean ± SD	F (p)
Storage time (day)	0		58.97 ± 2.83 a	24.97 (0.000)	2.94 ± 2.28 a	42.998 (0.000)	38.55 ± 3.10 a	15.28 (0.000)
	10		56.31 ± 5.01 b		10.10 ± 3.26 b		36.70 ± 4.85 ab	
	20		56.77 ± 2.57 b		10.51 ± 4.29 b		35.46 ± 3.61 b	
	30		51.99 ± 3.58 c		8.80 ± 4.18 b		36.26 ± 3.96 ab	
	40		55.02 ± 3.28 b		5.75 ± 4.67 c		31.99 ± 4.50 c	
Packaging modality	Cardboard Box		55.91 ± 4.54 a	4.10 (0.020)	5.78 ± 4.30	3.00 (0.052)	36.29 ± 4.14	0.39 (0.679)
	PET Box		57.18 ± 3.99 a		6.27 ± 4.80		36.77 ± 4.77	
	Biodegradable Bag		56.95 ± 3.75 a		6.95 ± 5.05		36.59 ± 4.23	
Interaction	0	Cardboard Box	58.97 ± 2.88	1.72 (0.097)	2.94 ± 2.41 a	2.81 (0.006)	38.55 ± 3.14	0.72 (0.671)
	0	PET Box	58.97 ± 2.88		2.94 ± 2.41 a		38.55 ± 3.14	
	0	Biodegradable Bag	58.97 ± 2.88		2.94 ± 2.41 a		38.55 ± 3.14	
	10	Cardboard Box	52.88 ± 4.83		10.92 ± 3.81 bc		35.05 ± 3.74	
	10	PET Box	58.43 ± 5.26		10.32 ± 2.38 bcd		38.22 ± 6.73	
	10	Biodegradable Bag	57.63 ± 3.23		9.06 ± 3.50 bcde		36.85 ± 3.41	
	20	Cardboard Box	57.18 ± 2.55		9.62 ± 4.47 bcd		36.44 ± 3.21	
	20	PET Box	56.75 ± 3.03		11.72 ± 4.34 c		35.38 ± 3.83	
	20	Biodegradable Bag	56.37 ± 2.34		10.19 ± 4.30 bcd		34.58 ± 3.92	
	30	Cardboard Box	50.77 ± 3.88		5.76 ± 2.12 abde		35.34 ± 3.38	
	30	PET Box	53.07 ± 3.43		8.60 ± 3.84 bcde		37.19 ± 3.74	
	30	Biodegradable Bag	52.11 ± 3.44		12.03 ± 3.89 c		36.24 ± 4.85	
	40	Cardboard Box	53.97 ± 3.16		5.07 ± 3.31 ade		31.81 ± 4.67	
	40	PET Box	55.26 ± 3.35		4.09 ± 4.38 ae		31.16 ± 4.30	
	40	Biodegradable Bag	55.83 ± 3.43		8.10 ± 5.55 bcde		33.03 ± 4.84	

Some changes were observed in terms of the exterior peel color, they were the darkening of the color, the appearance of a reddish tone, and the disappearance of the yellow tone that the fruits initially exhibited. These changes are represented in the alteration of the values of the L*a*b* space color coordinates. L* represents lightness, so a decrease in its value means that the fruits are becoming darker. a* is the red/green coordinate so an increase in value means an appearance of reddish tones. Finally, the b* is the yellow/blue coordinate; a drop in its values means that the fruits lose yellow pigmentation. The natural occurrence of chlorophyll degradation can justify the observed changes, as was mentioned by González et al. [41].

3.4. Texture

Fruit texture can serve as an indicator to judge a fruit's shelf-life, it is also known that loss of firmness can be caused by the loss of water, degradation of the pectin, and a reduction in the cells' turgor [42].

Considering the peel's firmness, the storage time was the most contributing factor to the alterations observed in fruits and the only one that presented significant differences, $p = 0.00$ (Table 4). The fruits lose firmness during storage time, from 10.1 N, on the first day, to 4.35 N after 40 days of storage, more noticeable in the PET box. These results were within the range of values presented by Corrales-García and Andrade-Rodríguez [43] with Mexican varieties of prickly pears, whose fruits presented values ranging from 22.56 N and 9.81 N at the start of the storage and also exhibited a strong decrease, presenting values of 9.81 N and 2.45 N, respectively, after 30 days at 9 °C. Thus, while there was a decrease in firmness, this decrease was lower than the observed in the literature. The possible reason could be the storage conditions applied in this trial, which involved a low temperature and high RH. These conditions allowed the fruits to achieve a state of water/vapor equilibrium, as visually confirmed by the absence of any shriveling appearance.

Table 4. Statistical results for the texture parameters, firmness of epidermis, gradient, and firmness of the pulp, presenting means, standard deviation and ANOVA results, F and *p* values for each factor (storage time, packaging modality, and interaction between them) using a significance level of 0.05 and results of Tukey's multiple comparisons test (HDS) with distinct letters indicating significant differences for $p < 0.05$.

			Firmness of Epidermis (N)		**Gradient (N/mm)**		**Firmness of Pulp (N)**	
Factors and levels			Mean ± SD	F(*p*)	Mean ± SD	F(*p*)	Mean ± SD	F(*p*)
Storage time (day)	0		10.11 ± 1.35 a	69.79 (0.000)	5.05 ± 1.09 a	80.94 (0.000)	2.03 ± 0.73 a	26.59 (0.000)
	10		8.15 ± 1.32 bc		4.19 ± 0.52 b		1.28 ± 0.37 b	
	20		8.87 ± 1.33 b		4.19 ± 0.60 b		1.48 ± 0.56 b	
	30		7.15 ± 2.09 c		3.45 ± 0.77 c		1.35 ± 0.52 b	
	40		4.35 ± 2.19 d		1.52 ± 0.83 d		0.74 ± 0.41 c	
Packaging modality	Cardboard Box		8.56 ± 2.44	1.09 (0.339)	4.07 ± 1.47	0.37 (0.693)	1.57 ± 0.78	0.08 (0.921)
	PET Box		8.22 ± 2.90		3.99 ± 1.57		1.56 ± 0.76	
	Biodegradable Bag		8.36 ± 2.25		4.10 ± 1.40		1.54 ± 0.70	
Interaction	0	Cardboard Box	10.11 ± 1.37	1.25 (0.271)	5.05 ± 1.10	0.29 (0.969)	2.03 ± 0.74	0.48 (0.873)
	0	PET Box	10.11 ± 1.37		5.05 ± 1.10		2.03 ± 0.74	
	0	Biodegradable Bag	10.11 ± 1.37		5.05 ± 1.10		2.03 ± 0.74	
	10	Cardboard Box	8.39 ± 1.78		4.13 ± 0.63		1.21 ± 0.33	
	10	PET Box	8.04 ± 1.17		4.24 ± 0.37		1.49 ± 0.48	
	10	Biodegradable Bag	8.03 ± 1.00		4.20 ± 0.57		1.15 ± 0.15	
	20	Cardboard Box	9.23 ± 1.18		4.25 ± 0.79		1.69 ± 0.81	
	20	PET Box	9.22 ± 1.54		4.22 ± 0.40		1.27 ± 0.37	
	20	Biodegradable Bag	8.13 ± 1.03		4.09 ± 0.60		1.47 ± 0.35	
	30	Cardboard Box	7.17 ± 2.59		3.57 ± 0.66		1.32 ± 0.53	
	30	PET Box	7.09 ± 2.41		3.14 ± 0.92		1.39 ± 0.66	
	30	Biodegradable Bag	7.2 ± 1.31		3.63 ± 0.69		1.33 ± 0.40	
	40	Cardboard Box	4.93 ± 1.71		1.51 ± 0.64		0.75 ± 0.51	
	40	PET Box	3.1 ± 2.28		1.32 ± 1.11		0.70 ± 0.41	
	40	Biodegradable Bag	5.01 ± 2.19		1.73 ± 0.72		0.78 ± 0.34	

The gradient is a parameter calculated through the ratio maximum force/deformation at which that value is reached, representing the slope of the linear part of the curve force deformation. It characterizes the elasticity of the fruit's epidermis. A higher value implies a lower elasticity of the peel, suggesting a fruit with greater turgidity. In this case, storage time was statistically the only factor that influenced the gradient values. Throughout the storage time, the fruits became more elastic as they lost firmness; nevertheless, it was possible to observe that the fruits stored in the biodegradable packages presented the highest gradient values after 30 days of storage, which was consistent with the observed lower values of weight loss (Figure 3).

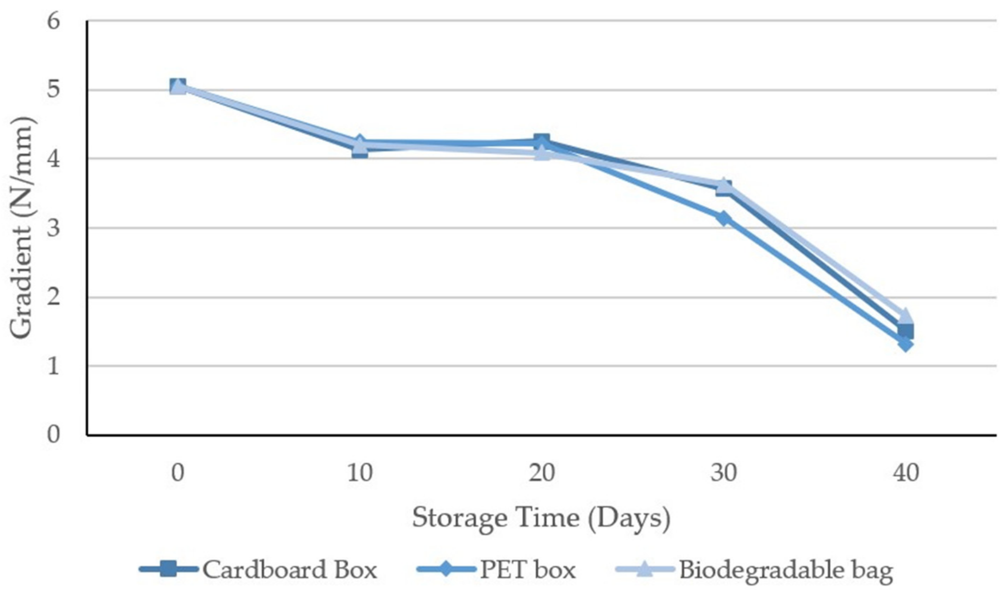

Figure 3. Gradient evolution during storage time for all packaging modalities (cardboard box, rigid PET box, and biodegradable bag).

In order to assess the pulp firmness, an average of the values obtained from conducting penetration tests in the pulp of each fruit was calculated. It is important to highlight that the pulp of the prickly pear contains dispersed seeds, which can pose challenges in obtaining an accurate measurement of pulp firmness that was not influenced by the presence of seeds. Despite this fact, it was determined that the only factor that influenced the firmness of the pulp was storage time, as can be seen in Table 4. The modality of packaging did not influence in the pulp firmness ($p > 0.05$). Throughout the storage time, the firmness of the pulp showed a slight decrease, with a bigger reduction of firmness being observed on the 40th day of storage; this could be given that, by that point, some fruits were contaminated by fungi. The contamination caused tissue decay, and consequently the softening of the pulp [38].

3.5. Total Soluble Solids and Titratable Acidity

The total soluble solids content (TSS) stands as an important parameter for fruit quality, due to the fact that it plays a significant role in the determination of the flavor of the fruit [44].

Regarding the TSS, the storage time and the packing modality were both responsible for the changes in the results, as can be seen in Table 5 (F value of storage time = 30.03 and F value of packaging modality = 7.31). Based on the observed results regarding weight loss, it was expected that such changes would occur. When there is a decrease in fruit weight, it typically corresponds to an increase in TSS values. This relationship can be attributed to the method of TSS measurement, which utilizes refractometry. Additionally, it was observed that the fruits packed in the cardboard box exhibited the greatest increase in TSS. This observation aligns with the fact that these fruits also experienced the highest percentage of weight loss. The TSS results obtained were higher than the results presented by Corrales García and Andrade-Rodríguez [43] and Gurrieri et al. [45] for Mexican and Sicilian varieties, respectively. In their study, Alzaeem and Ebrahim [46] had an initial TSS value of 14.33 °Brix, and throughout the storage time, the authors reported a decrease in values. Although the initial value reported in the study is higher than the ones found in this trial, the behavior exhibited by the fruits was completely different.

Table 5. Statistical results for SST and AT, presenting means, standard deviation and ANOVA results, F and p values for each factor (storage time, packaging modality, and interaction between them) using a significance level of 0.05 and results of Tukey's multiple comparisons test (HDS) with distinct letters indicating significant differences for $p < 0.05$.

			SST (°Brix)		**AT (% Citric Acid)**	
Factors and levels			Mean ± SD	F (p)	Mean ± SD	F (p)
Storage time (day)	0		11.98 ± 1.10 a	30.03 (0.000)	0.03 ± 0.01 a	3.53 (0.013)
	10		14.31 ± 10.6 b		0.03 ± 0.01 a	
	20		13.67 ± 1.41 b		0.02 ± 0.01 a	
	30		13.75 ± 1.45 b		0.02 ± 0.01 a	
	40		13.93 ± 1.46 b		0.04 ± 0.01 a	
Packaging modality	Cardboard Box		13.45 ± 1.64 a	7.31 (0.001)	0.03 ± 0.01	1.73 (0.189)
	PET Box		12.8 ± 1.43 b		0.02 ± 0.01	
	Biodegradable Bag		13.06 ± 1.60 ab		0.03 ± 0.01	
Interaction	0	Cardboard Box	11.98 ± 1.12	1.92 (0.059)	0.02 ± 0.01	0.46 (0.877)
	0	PET Box	11.98 ± 1.12		0.02 ± 0.01	
	0	Biodegradable Bag	11.98 ± 1.12		0.02 ± 0.01	
	10	Cardboard Box	14.94 ± 0.82		0.03 ± 0.02	
	10	PET Box	13.48 ± 1.15		0.02 ± 0.01	
	10	Biodegradable Bag	14.49 ± 0.64		0.03 ± 0.02	
	20	Cardboard Box	14.19 ± 1.33		0.03 ± 0.02	
	20	PET Box	13.84 ± 0.96		0.02 ± 0.01	
	20	Biodegradable Bag	12.98 ± 1.70		0.03 ± 0.02	
	30	Cardboard Box	14.59 ± 1.07		0.03 ± 0.01	
	30	PET Box	12.76 ± 1.23		0.02 ± 0.02	
	30	Biodegradable Bag	13.9 ± 1.48		0.02 ± 0.01	
	40	Cardboard Box	14.34 ± 0.76		0.04 ± 0.01	
	40	PET Box	13.48 ± 1.88		0.04 ± 0.01	
	40	Biodegradable Bag	13.96 ± 1.55		0.04 ± 0.00	

The titratable acidity consists of the total acid content present in the fruit; therefore, it is the best indicator of the acid taste and like the TSS, it also influences the flavor [47]. Among the various factors considered, only the storage time had an impact on the acidity of the fruits. As depicted in Table 5, it was evident that there was remarkable stability in the acidity values throughout the storage period. Only a marginal increase in acidity values was observed, particularly in the fruits packed in the cardboard box and biodegradable bag. Regarding the fruits packed in the PET box, the results were 0.02% of acidity until the 40th day of storage, at which point an increase was observed. These results were similar to those found in Sicilian varieties, with values of acidity of 0.02% [45], but lower than the ones presented in a study involving varieties from different regions in Portugal [4]. This difference in values can be attributed to the fact that the prickly pear composition is influenced by the climate, location of exploration, irrigation use, and use of herbicides and pesticides [48]. By the end of storage, the presence of fungi could be responsible for the changes in these results, where an increase was observed in all packaging options.

3.6. Phenolic Content and Antioxidant Activity

Polyphenols are extremely sensitive compounds that are affected by many factors, from crop production to storage [49]. The factors of storage time, packaging modality, and the interaction between those two factors statistically influenced the phenolic contents of the fruits, with $p < 0.05$ with F values of 73.99, 6.27, and 8.14 (Table 6). During storage time, the phenolic contents increased, especially in the biodegradable packaging. By the 40th day, the results of that modality were not viable since the fruits were contaminated by fungi, identified as *Botrytis* spp. and *Penicillium* spp. Nevertheless, this behavior of increased phenolic content was expected and was observed in other studies of different varieties of prickly pear cactus [50,51]. Furthermore, this behavior was also expected because plant polyphenols play an important role in the resistance against pathogens and they possess a chemical reactivity known to cause substantial biological activities, ranging from antioxidants to antiproliferative compounds.

Table 6. Statistical results for phenolic compounds and antioxidant activity, presenting means, standard deviation and ANOVA results, F and *p* values for each factor (storage time, packaging modality, and interaction between them) using a significance level of 0.05 and results of Tukey's multiple comparisons test (HDS) with distinct letters indicating significant differences for $p < 0.05$.

			Phenolic Compounds (µg/mL)		**Antioxidant Activity (%)**	
Factors and levels			Mean ± SD	*F* (*p*)	Mean ± SD	*F* (*p*)
Storage time (day)	0		266.04 ± 52.37 a	73.99 (0.000)	21.76 ± 17.17 a	27.89 (0.000)
	10		418.25 ± 56.88 b		42.63 ± 4.99 b	
	20		508.10 ± 174.42 b		48.46 ± 2.70 b	
	30		711.72 ± 181.42 c		72.07 ± 4.14 c	
	40		702.71 ± 186.04 c		52.45 ± 14.13 c	
Packaging modality	Cardboard Box		426.44 ± 229.92 ab	6.27 (0.004)	35.28 ± 20.79	1.2 (0.309)
	PET Box		408.71 ± 189.32 a		41.46 ± 22.65	
	Biodegradable Bag		472.38 ± 229.66 b		40.49 ± 22.63	
Interaction	0	Cardboard Box	266.04 ± 54.51 a	8.14 (0.000)	21.76 ± 17.87	0.69 (0.698)
	0	PET Box	266.04 ± 54.51 a		21.76 ± 17.87	
	0	Biodegradable Bag	266.04 ± 54.51 a		21.76 ± 17.87	
	10	Cardboard Box	393.99 ± 46.32 ab		39.16 ± 7.56	
	10	PET Box	395.89 ± 42.53 ab		44.36 ± 1.74	
	10	Biodegradable Bag	464.85 ± 64.01 b		44.37 ± 3.54	
	20	Cardboard Box	393.21 ± 14.91 ab		48.33 ± 4.67	
	20	PET Box	406.39 ± 34.40 ab		47.76 ± 0.94	
	20	Biodegradable Bag	724.70 ± 120.81 cd		49.28 ± 2.18	
	30	Cardboard Box	791.63 ± 61.80 cd		73.03 ± 1.37	
	30	PET Box	549.77 ± 223.20 bc		70.68 ± 7.29	
	30	Biodegradable Bag	820.41 ± 4.88 d		72.82 ± 1.06	
	40	Cardboard Box	881.60 ± 10.31 d		33.02 ± 1.36	
	40	PET Box	710.81 ± 187.43 cd		62.15 ± 7.42	
	40	Biodegradable Bag	511.65 ± 9.84 bc		57.33 ± 0.78	

The antioxidant activity is an important parameter to evaluate since antioxidant compounds have health benefits [52].

The antioxidant activity results were influenced by the storage time (Table 6), and as results showed, there was an increase until the 30th day. All types of packaging showed similar behavior throughout the study. Although the results of day 40 should not be considered due to the presence of fungi. Other studies confirmed the increase of antioxidant activity during storage [35,51,53,54]. The increase in antioxidant activity could be caused by the water loss and softening of the fruits during storage, as pointed out by Ochoa-Velasco and Guerrero-Beltrán [51]. Phenolic compounds are the main compounds responsible for antioxidant activity in the prickly pear, thus an increase in phenolic content would cause an increase in antioxidant activity [21,35,54]. In stress conditions, the synthesis of phenolic compounds in fruits can increase as a defense mechanism [55].

4. Conclusions

Based on the findings of this trial, it can be concluded that this variety of prickly pears can be effectively stored in a modified atmosphere (MA) for a period of 30 days, at a temperature of 2 °C and 90% of RH. The biodegradable package was the most suitable packaging option for these fruits. The fruits stored in this packaging material presented the best appearance, and maintained the characteristics of color and texture, during storage time. The weight loss was lower than 5% when using the biodegradable material packaging, for 30 days, while the weight loss when using the cardboard box reached values superior to 6% during the 30 days of storage. Due to the weight loss observed, it was also possible to observe losses in fruit firmness; however, only the storage time affected the fruit texture.

The cardboard box commercial use is not recommended for this proposal. This package caused weight loss, cooling injuries, and fruit contamination by fungi, *Botrytis* spp. and *Penicillium* spp. Hence, it is advised that the company transitions to alternative packaging options, such as biodegradable packages, since they could increase the shelf life and be an environmentally friendly packaging option. More studies should be performed featuring the conservation of these fruits using rigid environmentally friendly packaging, since it can physically protect the fruits during transportation, which this flexible biodegradable plastic would not be able to provide.

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