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Sodium alginate edible films incorporating cactus pear extract: antimicrobial, chemical, and mechanical properties

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ORIGINAL ARTICLE

Abstract

The potential benefits of biodegradable and functional food packaging materials have garnered increasing attention in recent years. Sodium alginate (SA), a commonly utilized polysaccharide, is particularly noteworthy for producing biodegradable films for food packaging. This study aimed to investigate SA-based edible films enriched with various proportions of cactus pear peel extract (CPPE). We assessed the films and extracts for total phenolic content, antimicrobial and antioxidant activities, as well as mechanical properties. Cactus pear peels powder (CPPP) exhibited higher contents of total polyphenols (1243.82 mg GAE/100 g), total flavonoids (18.92 mg QE/100 g), and betalains (2.28 mg/100 g). The main constituents detected were catechol, pyrogallol, catechin, and alpha-coumaric acid, with concentrations of 1013.82, 223.45, 148.21, and 101.02 ppm, respectively, contributing about 45.71%, 9.85%, 6.54%, and 4.46% of the total phenolic compounds. The thickness of the SA films increased from 0.220 mm to 0.265 mm. The tensile strength values ranged from 1.98 to 3.12, while the elongation at break values for SA-CPPE films decreased relative to the plain SA film. Moreover, the inclusion of CPPE improved the barrier characteristics (with water vapor permeability values for SA films with 1%, 2%, and 3% CPPE ranging from 0.72×10^{-5} $g{\cdot}h^{-1}{\cdot}m^{-1}{\cdot}Pa^{-1}$ to 1.68×10^{-5} $g{\cdot}h^{-1}{\cdot}m^{-1}{\cdot}Pa^{-1}$) and induced variations in flexibility and resistance. The plain SA film did not exhibit any inhibitory activity against bacteria and fungi. However, the inclusion of CPPE in alginate films showed favorable antibacterial properties, which improved progressively with increasing CPPE concentration. These findings highlight the potential of incorporating active alginate-based films in food preservation.

Keywords: antimicrobial, antioxidant, cactus, film, mechanical characteristics, sodium alginate

Introduction

Approximately half of the cactus pear fruit consists of peel, which is commonly discarded raising environmental concerns. However, due to its rich content of bioactive compounds, prickly pear peel is increasingly used as a nutraceutical and functional ingredient in various food formulations. With growing concerns regarding environmental contamination from synthetic plastics and rising consumer demand for food safety, researchers and industry professionals are increasingly favoring recyclable and biodegradable food packaging films derived from natural biopolymers such as proteins, polylactides, and polysaccharides (Asgher *et al.*, 2020; Chen and Chi, 2021).

The preservation of food heavily relies on the critical role of food packaging. Traditionally, petroleum-based packaging materials have been extensively used in this domain.

However, these materials are known for their significant contribution to severe environmental issues (Flórez *et al.*, 2022). Natural polymers, such as lipids, polysaccharides, proteins, and their combinations, are increasingly being utilized for food packaging due to their ability to be consumed, break down naturally, interact well with biological systems, lack toxicity, and offer potential antioxidant and antimicrobial effects (Barbosa *et al.*, 2021; Kumar *et al.*, 2022). Extensive research has demonstrated that the preservation and longevity of food can be enhanced through the synergistic combination of alginates and plant-derived substances. These substances include pure bioactive substances, extracts from peels, leaves, roots, fruits, and seeds, as well as essential oils and peptides, owing to their antioxidant, antimicrobial, and anti-browning characteristics (Parreidt *et al.*, 2018; Manzoor *et al.*, 2023). The incorporation of phenolic compounds can modify the mechanical, chemical, physical, and barrier attributes of films, offering potential improvements (Capar, 2023). Research has focused on exploring the effectiveness of combining alginate with bioactive compounds derived from plants for food preservation.

Edible films or coatings, with a thickness of less than 0.3 mm, are used to preserve fresh and lightly processed foods. These films or coatings are made by dispersing biopolymers and various additives in an aqueous medium. To achieve a uniform and continuous film matrix, it is essential to fully dissolve and disperse the components responsible for film formation. To ensure a consistent and uninterrupted polymer matrix, it is common practice to filter the film-forming solutions during preparation to remove any insoluble particles and to subject them to sonication to eliminate bubbles (Liu *et al.*, 2019; Díaz-Montes *et al.*, 2021). The resulting films should exhibit key attributes similar to conventional packaging, including biodegradability, resistance to gases and moisture, antimicrobial and antioxidant efficacy, UV light protection, and prevention of mechanical damage.

Hydrogels are polymeric networks that swell in water and are formed through the reaction of one or more monomers (Ahmed, 2015). They absorb water due to hydrophilic groups on the polymer, while cross-links prevent dissolution. Among the various hydrogels, sodium alginate (SA) is a notable member. SA is a biodegradable polyuronic acid composed of β-D-mannuronic and α-L-guluronate units (Chen *et al.*, 2021). It is widely used in the medicinal and food industries due to its excellent film-forming ability, low toxicity, biodegradability, compatibility, and superior oxygen barrier properties. However, SA has limitations, including poor water barrier capacity, low UV light barrier effectiveness, and a lack of antimicrobial and antioxidant activities. To address these limitations, there is growing interest in enhancing SA properties by incorporating bioactive natural substances into food packaging films to improve their functionality (Feng *et al.*, 2018). Currently, various natural extracts, such as plant essential oils, citric acid, carvacrol, cinnamaldehyde, polyphenols, and flavonoids, are being combined with SA to impart additional functionalities to the films (Aloui *et al.*, 2021; Chen *et al.*, 2021). Therefore, our study aimed to investigate the impact of incorporating cactus pear peel (CPP) extract into SA films on their physicochemical and mechanical characteristics, as well as their antimicrobial and antioxidant properties.

Materials and Methods

Plant materials

Cactus pear fruit

Ripe cactus pear fruits (*Opuntia ficus-indica* (L.) Mill.), of the orange cultivar, were obtained from local vendors in Tanta City, Egypt, in June 2022 and used for preparing cactus pear peel (CPP).

Strawberry fruits

Strawberries (*Fragaria ananassa*) were procured from a local market in Tanta City, El-Gharbia Governorate, Egypt, and transported to the laboratory. Before treatment, the strawberries were refrigerated overnight. The following day, any strawberries showing lesions or decay were discarded, and only those that were well-shaped and uniformly sized were selected for further treatment.

Chemicals

Sodium alginate, glycerol, nutrient broth medium, bacteriological agar, and other chemicals were purchased from Sigma-Aldrich, Germany. Distilled water was used exclusively for all the experiments.

Cactus pear peel (CPP) powder preparation

To remove prickles and dirt particles, cactus pear fruits were cleaned with a nail brush under distilled water. Subsequently, the fruits were submerged in cold chlorinated water (50 mg/kg) for 1 min. The peels were then carefully separated from the pulp using a knife. The peels were blanched at 80°C for 5 min, then cut into 1–2 cm thick sections and subjected to air drying. Following this, the slices were placed on trays and dried in an oven at 60°C for 48 h. After drying, the specimens were cooled, milled with a milling machine, and sieved through a 100-mesh screen. The powdered specimens were then stored in polyethylene bags at 4°C until further examination (Castillo *et al.*, 2015).

Cactus pear peel extracts (CPPE) preparation

To deactivate pectinolytic enzymes, 10 grams (10 g) of the peel were subjected to a 5-min steam treatment.

Following this, the peel was extracted using 30 mL of 70% ethanol, and the resultant extract was stored in the dark for 24 h. The extract was then centrifuged, and the supernatant was separated. The extraction process was performed in triplicate, followed by filtration and concentration using a rotary evaporator until dry. The residue (3.98%) was powdered and stored at $^{-}20°C$ for further use.

Film-forming solutions preparing

To prepare the coating solutions, food-grade sodium alginate (5% w/v) was dissolved in sterile water. The alginate solution was then heated at 70°C for 15 min using a stirring hot plate, resulting in a clear solution. Next, 3 mL of glycerol was added as a plasticizer, and the mixture was stirred continuously. Four distinct coating solutions were formulated: one with cactus pear peel extract (CPPE) at 1 g/100 mL, another at 2 g/100 mL, a third at 3 g/100 mL, and a control without any extract.

Coating of strawberries

Prior to treatment, the selected strawberries were rinsed for 1 min with distilled water, and any residual water on the fruit surface was allowed to evaporate at room temperature. The untreated fruit was designated as the control. Subsequently, strawberries were immersed for 1 min in either a peel-enriched solution or the control solution. To facilitate the formation of an alginate gel, all coated fruits were then immersed in a 5% w/w calcium chloride solution for 2 min. The coated fruits were placed on a food tray with a pad and enclosed in commercially available air-tight polyethylene food bags. Control fruits without peel treatment were also prepared. All specimens were stored at 4°C and 80% relative humidity (RH), and their physicochemical characteristics were assessed.

Physical properties of cactus pear (CP) fruits

Measurements of the fruit dimensions and peel thickness were taken using a digital Vernier caliper (Zarei *et al.*, 2011). Additionally, a BOECO weighing balance (Germany BPS 51 Plus) was used to assess the weight.

Physicochemical analysis

Moisture content, crude fiber, ash, protein, total acidity (as citric acid), crude ether extract, and minerals were quantified using the methods described in AOAC (2010). To determine the carbohydrate content, the sum of moisture, ash, crude fiber, crude protein, and crude fat was subtracted from 100.

Following the standard procedure (AOAC, 2002), pH was measured using a digital pH meter (Crison Basic 20). The caloric value was estimated using the modified Atwater factor with the following equation: Total energy (kcal/100 g) = [(protein (g) × 4) + (lipid (g) × 9) + (carbohydrates (g) × 4)], as described by Falch *et al.* (2010).

Total phenols

To determine the total phenolic content in strawberries, the Folin-Ciocalteu method was employed. A 4 g homogenized sample was placed in a flask, and 5 mL of distilled water was added. The mixture was stirred for 5 min. Next, 50 mL of 96% ethanol was added, and the mixture was agitated for 2 h. The mixture was then filtered, and the resulting filtrate was diluted with distilled water in a volumetric flask to a final volume of 100 mL. To the filtrate, 2 mL of Folin-Ciocalteu reagent was added and allowed to react for 3 min at ambient temperature. Following this, 1.5 mL of 7% sodium carbonate was added, thoroughly mixed, and left undisturbed for 60 min. The absorbance was measured at 765 nm after 30 min. Total phenolic content was calculated using the formula:

$$C = a \times \gamma \times \left(\frac{V}{m}\right) \times 100$$

where C is the amount of total phenolic compounds, g/100g as pyrogallol; γ is the calibration curve-based concentration (mg/ml); a is the dilution number; V is the methanol volume utilized for extraction (100 ml); m is the sample weight (g). The findings were reported as mg gallic acid equivalents/100 g (mg GAE/100g) (Gao *et al.*, 2000).

Total flavonoid content

The total flavonoid content was assessed using spectrophotometric analysis (Yoo *et al.*, 2008). Absorbance at 510 nm was recorded, and the flavonoid content was quantified in triplicate and expressed as mg quercetin equivalents per 100 g (mg QE/100 g).

Carotenoids

In a dark bottle, 10 g of cactus pear samples were mixed with 30 mL of 85% acetone and left undisturbed at room temperature for 15 h. The mixture was then filtered through glass wool into a 100 mL volumetric flask, which was subsequently filled to the mark with 85% acetone solution. The absorbance was measured using a Pharmacia LKB NOVA SPEC II spectrophotometer (CT2200-s/n: RE1310004, Germany) at wavelengths of 440 nm, 644 nm, and 662 nm. Carotenoid pigments were analyzed using the following spectrophotometric formulas based on measurements at these wavelengths: 440, 644 and 662 nm: Chlorophyll a = (9.784 × E 662) – (0.99 × E644) = mg/liter Chlorophyll b = (21.426 × E644)-(4.65 × E662) = mg/liter Carotenoids = (4.695 × E440) – 0.268 (chl. a + chl. b) = mg/liter (Askar and Treptow, 1993). The findings were reported as mg/100g.

Betalains content

The prickly pear peels were diluted with distilled water, and the betalain content was measured calorimetrically at a wavelength of 535 nm. The readings were recorded as mg betalains per 100 g (Castellar *et al.*, 2003).

Fractionation of phenolic compounds by HPLC

An Agilent 1260 series system was used for HPLC analysis. Separation was achieved with a 5 μm Eclipse C18 column (4.6 mm × 250 mm). The mobile phase consisted of water (A) and 0.05% trifluoroacetic acid in acetonitrile (B), flowing at 0.9 mL/min. The mobile phase was adjusted using a linear gradient as follows: 0 min (82% A); 0–5 min (80% A); 5–8 min (60% A); 8–12 min (60% A); 12–15 min (82% A); 15–16 min (82% A); and 16–20 min (82% A). The detector, operating at multiple wavelengths, was set to 280 nm. A volume of 5 μL was injected for each sample solution, and the column was maintained at a constant temperature of 40°C. To identify phenolic compounds, their relative retention times were compared with those in the chromatogram of a standard mixture (Elbadrawy and Sello, 2016). The concentration of individual compounds was determined by measuring the peak area and converting it to ppm.

Characterization of SA and SA-CPPE films

The film-forming solution was poured into Petri dishes, with 40 mL of the mixture spread evenly in each plate (90 mm diameter). After eliminating bubbles, the plates were dried for 24 h at 50°C. The resulting films were then separated and conditioned at 25°C and 50% relative humidity in preparation for testing.

Color attributes

Color measurements were conducted using a Minolta colorimeter (CR-300, Konica Minolta, Tokyo, Japan) with 10 repetitions, following the CIE L*a*b* system. In this system, L* represents brightness, while a* and b* denote the trichromatic coordinates. The standard white plate used as the reference material exhibited the following color characteristics: L* = 95.99, a* = −0.14, and b* = 2.04.

Water Content (WC), swelling rate (SR), and water solubility (WS)

The film specimens were cut into 20 × 20 mm^2 fragments, weighed initially (m0), and then oven-dried at 105°C until a stable weight was achieved (m1). Afterward, the films (m_1) were submerged in 100 mL of water at 25°C for 24 h. Following this, they were blotted with filter paper and reweighing to obtain the measurement (m_2). The films were then dried for another 24 h at 105°C until a constant weight was reached (m3) (Liu *et al.*, 2023). The water content (WC) and water solubility (WS) of the films were calculated using the following equations

$$\text{Water content } (\%) = \frac{m_0 - m_1}{m_0} \times 100$$

$$\text{Water solubility } (\%) = \frac{m_1 - m_2}{m_1} \times 100$$

$$\text{Swelling ratio } (\%) = \frac{m_3 - m_1}{m_1} \times 100$$

Water Vapor Permeability (WVP)

We used the gravimetric technique described by Liu *et al.* (2023) to determine the water vapor permeability (WVP). A 10 mL aliquot of distilled water was sealed in a glass bottle with the films, and the assembly was placed in a desiccator for 48 h at ambient temperature. The WVP was then calculated using the following equation:

$$\text{WVP} = \frac{\Delta m \times L}{t \times A \times \Delta p}$$

where, Δm represents the glass bottle's weight change (g), L represents the film thickness (m), t is the time (h), A represents the exposed area (m^2) of the films to moisture, and Δp designates the water vapor pressure disparity between both film sides.

Thickness

A spiral micrometer was used to measure the thickness of the SA-CPPP films at 10 randomly selected positions across different areas of each sample, with a precision of 0.001 mm (Shivangi *et al.*, 2021).

Tensile strength (TS) and maximum elongation at break (EB)

The composite film specimens were cut into 10 mm × 60 mm rectangles and divided into 5 parallel groups. Measurements were taken using the TMS-PRO texture instrument (FTC, Virginia, USA) with the following parameters: initial clamp distance of 20 mm, a weighing sensor with a capacity of 25 N, a drawing rate of 0.5 mm/s, and probe A/MTG. Each sample was analyzed 5 times, and the average values were calculated. Tensile strength (TS) and elongation at break (EB) were computed using the following formulas:

$$\text{TS} = \frac{F}{TW}$$

$$\text{EB } (\%) = \frac{L - L_0}{L_0} \times 100$$

where, F denotes the utmost tension encountered by the sample upon fracture (N), T and W signify the film thickness and width. L denotes the film elongation distance upon breaking, and L0 denotes the film's initial length.

Antioxidant activity of SA and SA-CPPP films

Following the technique outlined by Wu *et al.* (2023), the DPPH radical scavenging rate was determined. To prepare the solution, 0.5 g of the film sample was combined with 10 mL of deionized water and subjected to oscillation in the dark for 24 h. Afterward, the supernatant was collected for the free radical scavenging assessment following 10 min of centrifugation at 6000 rpm. The mixture was prepared by combining 20 μL of the supernatant with 5 mL of DPPH solution (0.2 mmol/L, prepared in 95% ethanol), and the resulting reaction was allowed to proceed in the dark for 30 min at 25°C. Subsequently, the absorbance was measured at 517 nm. To calculate the DPPH radical scavenging rate, the following formula was used

$$\text{DPPH radical scavenging rate (\%)} = A_0 - A_t A_0 \times 100\%.$$

where, A_0 and A_t designate the absorbance of the control and the film sample, respectively.

Antimicrobial activity of SA and SA-CPPP films

The antibacterial effectiveness of pure alginate films and those incorporated with CPPE was evaluated against *B. cereus* (EMCC 1080), *Staph. aureus* (ATCC13565), *S. typhi (*ATCC 15566), *E. coli* (ATCC 51659) and *A. niger (*ATCC 56091). Overnight, the bacteria were cultured in nutrient broth and then diluted to 10^6 CFU/mL with saline. Nutrient agar plates were inoculated by uniformly spreading 100 μL of the diluted bacteria, after which circular film discs with a diameter of 9 mm were placed on the plates. Prior to the experiments, the films were sterilized under UV light for 10 min. The nutrient agar plates were then incubated for 24 h at 37°C. The resulting inhibition zones surrounding the film discs were measured in millimeters, and all test strains were subjected to triplicate experiments.

Physical properties of strawberries

Weight loss

During the storage period, the weight of the strawberries was recorded to determine the percentage weight loss using the formula:

$$\text{WL (\%)} = \left[\frac{\text{Wi} - \text{Wf}}{\text{Wi}}\right] \times 100.$$

where WL (%) represents the percentage weight loss at time t, Wi denotes the initial weight and Wf denotes the weight at time t. Coated samples were weighted with their coating. A digital technical balance (± 0.1 g) (Gibertini Europe, Milan, Italy) was employed. All measurements were accomplished in triplicate (AOAC, 2010).

Sensory analysis

A sensory evaluation was conducted on the strawberries to assess their organoleptic attributes, including appearance, taste, texture, aroma, color, and overall acceptability. This evaluation involved a panel of 10 members from the Department of Food Science and Technology. The panelists used a 9-point hedonic scale for rating, ranging from 1 (Extremely Dislike) to 9 (Extremely Like), following the methodology outlined by Peter-Kechukwu *et al.* (2017).

Statistical analyses

Each experiment was conducted three times, and the data were statistically analyzed using ANOVA with Duncan's multiple range test to compare the various treatments.

Results and Discussions

Technological parameters of cactus pear (CP) fruit

The measured parameters of cactus pear (CP) fruit are presented in Table 1. The number of fruits per kilogram, along with fruit weight, length, and width, were recorded as 8.0, 143.0 g, 8.40 cm, and 5.62 cm, respectively. According to Dehbi *et al.* (2014), seed content and weight significantly affect fruit size. The identification of various CP varieties is based on their shape, size, and color. Ferreira *et al.* (2016) reported that the final weight of cactus pear fruit can fluctuate between 80 and 200 g. CPs typically exhibit a cylindrical or ovoid shape, measuring 4–8 cm in width and 5–10 cm in length. The weights of the peel, pulp, and seeds were 60.03 g, 77.24 g, and 5.37 g, respectively. These findings are consistent with those of El-Samahy *et al.* (2006a; b) and Cassano *et al.* (2010). Of the total weight of CP fruit, 41.98% corresponds to the peel, 54.03% to the pulp, and 4.01% to the seeds. The cactus pear fruit had a yellow-orange peel with a thickness of 0.38 cm. These outcomes align with those reported by Inglese *et al.* (2017).

Proximate composition of CPPP

Table 2 displays the chemical analysis of cactus pear peel powder (CPPP). The moisture content was found to be 6.20%. This moisture content serves as an indicator

Table 1. Cactus pear fruit technological parameters.

Parameters	Range	% of fruit
Number of fruits per kg (unit)	8.00	–
Fruit weight (g)	143.00	–
Fruit length (cm)	8.40	–
Fruit width (cm)	5.62	–
Peel thickness (cm)	0.38	–
Pulp weight (g)	77.24	54.03
Seeds weigh (g)	5.73	4.01
Peels weight (g)	60.03	41.98
Peels color	(Yellow-orange)	–

Table 2. Physicochemical composition of CPPP on DW.

Constitute (%)	Cactus pear peel powder (CPPP)
Moisture	6.20
Crude Protein	4.01
Crude Lipid	5.64
Ash	8.94
Crude Fiber	23.92
Carbohydrates	57.49
Energy	296.76
pH	5.72
Total acidity (% of a citric acid)	0.11

Table 3. Mineral contents of CPPP.

Minerals (ppm)	Cactus pear peel powder (CPPP)
phosphorus (P)	40.68
Magnesium (Mg)	6984.42
potassium (K)	3118.43
sodium (Na)	5741.18
Calcium (Ca)	6812.72
Iron (Fe)	126.24
manganese (Mn)	521.91
Zink (Zn)	310.82
Copper (Cu)	382.64
Selenium (Se)	21.83

of the powder's storage suitability, with recommended levels below 14% for optimal preservation. Maintaining low moisture levels has several advantages, including an extended shelf life by minimizing moisture content, which inhibits the growth of mold and other microorganisms that can lead to product spoilage (Mahloko *et al.*, 2019). From the same table, the crude protein, crude fat, and ash contents of CPPP were recorded at 4.01%, 5.64%, and 8.94%, respectively. Comparable findings were reported by Parafati *et al.* (2020).

The crude dietary fiber content of 23.92 g/100 g dry weight (D.W.) represents one of the most significant substances found in prickly pear peel due to its key role in the human diet. The data obtained confirm the substantial potential of this tested by-product for nutritional and pharmaceutical applications, given its abundant concentration of bioactive compounds. According to Al-Weshahy and Rao (2012), dietary fiber is recognized as a bulking agent that enhances fecal hydration and intestinal motility. Various authors have emphasized the importance of consuming moderate amounts of dietary fiber for overall well-being (Ballesteros *et al.*, 2001). From a scientific perspective, dietary fiber encompasses a wide range of carbohydrates, including hemicelluloses, cellulose, gums, pectins, and lignins (Gallaher and Schneeman, 2001). The carbohydrate content and total energy of CPPP were found to be 57.49% and 296.76 kcal/100 g, respectively. Additionally, the pH value and total acidity of CPPP were measured at 5.72 and 0.11%, respectively, consistent with the results reported by Abou-Zaid *et al.* (2022).

Mineral contents of CPPP

Table 3 provides the mineral content of cactus pear peel powder (CPPP) as part of its nutritional composition. The results indicate that cactus pear peels are a rich source of minerals. The mineral analysis revealed a higher concentration of magnesium (Mg), followed by calcium (Ca) and sodium (Na), with values of 6984.42, 6812.72, and 5741.18 ppm, respectively. For most individuals, the intake of just 20 grams of peel would suffice to fulfill 90% of the recommended daily intake for magnesium and 20% for calcium (WHO, 2004). However, it is important to note that calcium has limited bioavailability (Piga, 2004; Bensadón *et al.*, 2010). The peel also contains lower levels of copper (Cu), zinc (Zn), iron (Fe), and selenium (Se), with concentrations of 382.64, 310.82, 126.24, and 21.83 ppm, respectively. Therefore, cactus pear peel can significantly contribute to meeting the recommended dietary allowances (RDA) for these nutrients (Feugang *et al.*, 2006).

Phytochemical compounds of CPPP

Table 4 presents the phytochemical findings for cactus pear peel (CPPP), revealing high levels of total polyphenols (1243.82 mg GAE/100g) and total flavonoids (18.92 mg QE/100g). These flavonoid values are consistent with those reported by Chang *et al.* (2008) and Chavez-Santoscoy *et al.* (2009). Additionally, the carotenoid content was measured at 201.60 mg/100g, which aligns with dietary guidelines recommending the inclusion of fruits rich in carotenoids to help prevent chronic diseases (Rao and Rao, 2007). The betalain content was recorded at 2.28 mg/100g. Our findings on total betalain content are consistent with previous studies by Chávez-Santoscoy *et al.* (2009) and Coria-Cayupán *et al.* (2011), which reported ranges from 0.39 to 48.4 mg/100g. Cactus pear peels are particularly rich in betalains, which are naturally occurring water-soluble pigments that impart colors ranging from reddish-purple (betacyanins) to yellowish-orange (betaxanthins) (Rahimi *et al.*, 2019). In contrast, peels from green varieties show minimal concentrations of these pigments (Bousbia *et al.*, 2022). Overall, the analysis confirms the elevated levels of polyphenols, flavonoids, and betalains in CPPP.

Table 4. Phytochemical compounds of CPPP on DW.

Parameters	Cactus pear peel powder (CPPP)
Total phenolic (mg GAE/100g)	1243.82
Total flavonoid (mg QE/100g)	18.92
Total carotenoids (mg/100g)	201.60
Betalains (mg/100g)	2.28

Phenolic compounds profile of cactus pear peel extract

Phenolic compounds, characterized by their hydroxyl groups, are vital constituents of plants, primarily due to their ability to scavenge free radicals (Heim *et al*., 2002). In this study, the total phenolic compounds measured 2267.44 ppm, with the dominant constituents being pyrogallol, catechol, catechin, and α-coumaric acid, which accounted for 1013.82, 223.45, 148.21, and 101.02 ppm, respectively. These four compounds contribute approximately 45.71%, 9.85%, 6.54%, and 4.46% of the total phenolic content. Subdominant phenolic components included gallic acid, ferulic acid, e-vanillic acid, chlorogenic acid, rutin, syringic acid, ellagic acid, and isoferulic acid, with concentrations of 98.64, 81.90, 68.92, 62.10, 56.92, 48.20, 46.87, and 38.56 ppm, respectively. The least abundant phenolic constituents were vanillin, quercetin, protocatechuic acid, cinnamic acid, apigenin, and coumaric acid, which measured 12.58, 11.64, 11.54, 9.43, 9.12, and 1.74 ppm, contributing about 0.55%, 0.51%, 0.42%, 0.40%, and 0.08% of the total phenolic content, respectively. These findings are consistent with those reported by Anwar and Sallam (2016).

Films appearance

The appearance and color properties of the obtained edible alginate films were uniform and elastic, exhibiting no signs of brittleness, cracks, or pores (Figure 1).

Table 5. Fractionation of phenolic compounds CPPE of extract.

No.	Phenolic compounds	Cactus pear peel powder (CPPP)		Rt. min
		Concentration (mg/ kg)	Percentage (%)	
1	Gallic acid	98.64	4.35	1.433
2	Ferulic acid	81.90	3.61	1.652
3	Iso ferulic	38.56	1.70	1.873
4	Chlorogenic acid	62.10	2.74	2.289
5	Syringic acid	48.20	2.13	2.308
6	Quercetin	11.64	0.51	2.341
7	Caffeic acid	17.48	0.77	3.221
8	P-Coumaric acid	38.20	1.68	4.253
9	Protocatechuic acid	11.54	0.51	4.634
10	Coumaric	1.74	0.08	5.212
11	Caffien	34.12	1.50	5.432
12	Vanillin	12.58	0.55	5.510
13	Catechol	223.45	9.85	5.980
14	Alpha-coumaric	101.02	4.46	6.221
15	Catechin	148.21	6.54	7.452
16	Rutin	56.92	2.51	12.654
17	Elagic	46.87	2.06	18.654
18	E–Vanillic	68.92	3.04	22.128
19	Cinnamic acid	9.43	0.42	25.245
20	Pyrogalol	1013.82	45.71	25.563
21	Apigenin	9.12	0.40	25.881
22	Salycilic acid	16.65	0.73	26.123
23	P-hydroxy benzoic acid	68.21	3.01	27.187
24	Benzoic acid	48.12	2.12	28.341
	Total	2267.44		

CPPE: cactus pear peal extract

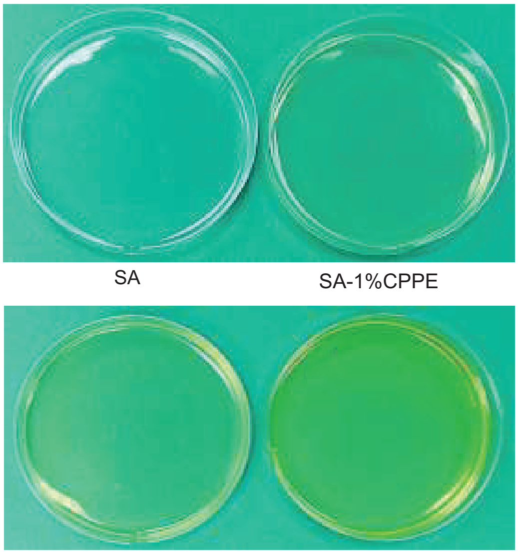

Figure 1. Films of SA, SA-CPPE-1%, SA-CPPE-2% and SA-CPPE-3% developed and tested in this study.

The transparent control film samples displayed a slight yellowish tint, while the films incorporated with cactus pear peel extract (CPPE) appeared translucent with a yellow-brownish hue (Figure 1).

Color measurement of tested film

Table 6 displays the color parameters of the synthesized films using sodium alginate (SA) with varying concentrations of cactus pear peel extract (CPPE). The control SA film had an L* value of 80.36, an a* value of 0.64 (indicating a slight red tint), and a b* value of −2.85 (leaning towards blue). Upon the addition of 1.0%, 2.0%, and 3.0% CPPE, the films exhibited lower L* values, indicating a darker appearance ($p < 0.05$). The film with the highest CPPE concentration (3%) recorded the lowest L value at 49.86. Additionally, the a* values increased from 0.64 for the plain SA film to 4.62 for the SA-3% CPPE film, suggesting a stronger reddish hue. The b* values also significantly increased ($p < 0.05$), indicating a transition towards a more yellowish color. This change aligns with findings by Dou *et al.* (2018), who noted that incorporating tea polyphenols into composite films led to decreased L values and increased a* and b* values compared to gelatin-SA films. These results indicate that the composite films possess enhanced opacity, making them suitable for packaging food products sensitive to light exposure.

Table 6. Color attributes of films depending on SA as the control and tested (SA-1%, 2%, 3% CPPE) films.

Film sample	Color parameters		
	L*	a*	b*
SA	80.36^{a} ± 1.15	0.64^{d} ± 0.02	−2.85^{d} ± 0.21
SA-1%CPPE	71.02^{b} ± 1.07	1.41^{c} ± 0.11	8.98^{c} ± 0.24
SA-2%CPPE	62.48^{c} ± 1.13	3.14^{b} ± 0.20	12.15^{b} ± 0.55
SA-3%CPPE	49.86^{d} ± 0.49	4.62^{a} ± 0.91	21.22^{a} ± 1.19

Mean values± standard deviation; Significantly different samples ($p < 0.05$) are identified by distinct letters within a single column. SA: sodium alginate, CPPE: cactus pear peal extract, SA-1%CPPE: sodium alginate with 1% CPPE, SA-2%CPPE: sodium alginate with 2% CPPE, SA-3%CPPE: sodium alginate with 3% CPPE.

Water content, water solubility, swelling rate, and water vapor permeability of tested films

Table 7 presents the water content, water solubility, swelling rate, and water vapor permeability of the alginate films with varying concentrations of cactus pear peel extract (CPPE). As the concentration of CPPE increased, the SA-3% CPPE film exhibited the lowest water content, highlighting a reduction in hydrophilicity of the composite membrane. This reduction may result from the formation of hydrogen bonds between the polysaccharides and the components of the cactus pear peel (Dinh *et al.*, 2023). The water content of the films ranged from 8.13% to 11.87%. Notably, with increasing CPPE concentration, there was a significant decline ($p < 0.05$) in water content.

Table 7. Water content, swelling rate, water solubility and WVP of films depending on SA as the control and test (SA-1%, 2%, 3% CPPE) film.

Film sample	Water content (%)	Swelling rate (%)	Water solubility (%)	WVP ($\times 10^{-5}$ g. h^{-1}. m^{-1}. Pa^{-1})
SA	11.87^{a} ± 0.87	48.32^{a} ± 0.40	34.56^{a} ± 2.18	1.68^{a} ± 0.03
SA-1%CPPE	10.22^{b} ± 0.62	46.12^{b} ± 0.14	31.18^{b} ± 1.70	1.24^{b} ± 0.22
SA-2%CPPE	9.12^{c} ± 0.31	38.46^{c} ± 0.73	28.34^{c} ± 1.47	0.91^{c} ± 0.16
SA-3%CPPE	8.13^{c} ± 0.28	36.82^{d} ± 0.87	26.15^{c} ± 1.46	0.72^{d} ± 0.03

Mean values± standard deviation; Significantly different samples ($p < 0.05$) are identified by distinct letters within a single column. SA: sodium alginate; CPPE: cactus pear peal extract; SA-1%CPPE: sodium alginate with 1% CPPE, SA-2%CPPE: sodium alginate with 2% CPPE, SA-3%CPPE: sodium alginate with 3% CPPE.

The higher water content observed in the CPPE-0 film is likely due to the abundant hydroxyl and carboxyl groups present in the alginate molecules. When the extract is incorporated, the hydroxyl groups in CPPE interact with the hydrophilic groups in alginate, potentially limiting the interaction between water and alginate. These findings align with previous studies indicating decreased water content in films that incorporate various plant extracts (Luo *et al.*, 2019). Overall, the incorporation of CPPE effectively enhances the properties of the alginate films, contributing to improved performance in food packaging applications.

The incorporation of cactus pear peel extract (CPPE) significantly reduced the swelling rate of alginate films compared to the control group. This effect can be attributed to factors such as sample concentration, structural properties, and glycerol content (Abdin *et al.*, 2021). The swelling behavior of the alginate–CPPE films showed a notable decline ($p < 0.05$) in comparison to the pure alginate films, with swelling values ranging from 36.82% to 48.32%. According to Roger *et al.* (2006), the carboxyl groups in alginate play a crucial role in swelling behavior due to their strong interaction with water molecules. The polyphenols present in CPPE interact with these carboxyl groups, limiting their accessibility to water. As a result, higher concentrations of CPPE lead to a further reduction ($p < 0.05$) in the swelling capacity of the composite films. This finding suggests that the addition of CPPE not only enhances the mechanical properties of the films but also modifies their water absorption characteristics, potentially improving their performance in food packaging applications.

Pure sodium alginate (SA) is highly soluble in water, which limits its application in film production (Fabra *et al.*, 2018). To enhance the physical, mechanical, and barrier properties of alginate films, cross-linking with polyvalent cations, such as calcium, is commonly employed (Benavides *et al.*, 2012; Bekin *et al.*, 2014). The introduction of calcium ions induces conformational changes in the alginate structure, allowing the G blocks to organize in a way that forms divalent salt bridges between sodium alginate chains, a phenomenon referred to as the "eggbox" model (Bekin *et al.*, 2014; Parreidt *et al.*, 2018). This cross-linking significantly decreases the water solubility of alginate films, making them more suitable for various applications (Santana and Kieckbusch, 2013). In this study, both pure alginate and alginate–CPPE composite films exhibited solubility values ranging from 26.15% to 34.56% (Table 7), indicating that the addition of CPPE may further influence the solubility properties of the films. These results highlight the effectiveness of cross-linking in improving the functional characteristics of alginate films for food packaging and other uses.

The incorporation of cactus pear peel extract (CPPE) into sodium alginate (SA) films resulted in significantly lower solubility compared to control films without the extract ($p < 0.05$). Specifically, the solubility values decreased to 31.18% for SA-CPPE1%, 28.34% for SA-CPPE2%, and 26.15% for SA-CPPE3%. This reduction in solubility can be attributed to the interactions between CPPE polyphenols and alginate, which likely strengthen the film matrix, leading to enhanced water resistance. As noted by Adilah *et al.* (2018), increasing concentrations of mango peel extract similarly decreased the solubility of fish gelatin films, attributing this effect to the robust interactions formed between proteins and polyphenols, which contribute to a more stable film network. The improved water resistance of the alginate–CPPE films indicates their potential applicability in food storage, where maintaining product integrity and safety is crucial. Edible coatings and films serve an important role in extending shelf life and ensuring food safety by minimizing water vapor transmission (Jaramillo *et al.*, 2015). Thus, these findings support the use of alginate films enhanced with CPPE as effective materials for food packaging applications.

Packaging films play a crucial role in preventing moisture transfer between food items and the surrounding environment (Wang *et al.*, 2019). A low water vapor permeability (WVP) is essential as it effectively minimizes moisture loss through evaporation in packaged foods. In this study, the incorporation of increasing concentrations of cactus pear peel extract (CPPE) resulted in a significant reduction in WVP, decreasing from 1.68×10^{-5} $g \cdot h^{-1} \cdot m^{-2} \cdot Pa^{-1}$ for control films to 0.72×10^{-5} $g \cdot h^{-1} \cdot m^{-2} \cdot Pa^{-1}$ in films with higher CPPE concentrations.

Studies often report an increase in water vapor permeability (WVP) when plant extracts are incorporated into polymer matrices (Norajit *et al.*, 2010; Yan *et al.*, 2013; Kim *et al.*, 2018, 2020). However, other research indicates a decrease in WVP with the addition of plant extracts (Jaramillo *et al.*, 2015; Fabra *et al.*, 2018; Luo *et al.*, 2019; Abdin *et al.*, 2021; Aloui *et al.*, 2021). The variability in WVP outcomes can be attributed to the intermolecular forces among the film's components. When plant extracts are added, they can disrupt these interactions, potentially altering the internal structure of the film. This modification may enhance solvent mobility and facilitate water diffusion through the polymer matrix, leading to an increased WVP. Conversely, in cases where the extract enhances the film's structural integrity or forms stronger bonds with the polymer, a reduction in WVP may be observed. The specific effects of plant extracts on WVP are thus influenced by factors such as the type of extract, concentration, and the overall composition of the film, highlighting the complexity of interactions in biopolymer systems (Norajit *et al.*, 2010; Kim *et al.*, 2018, 2020).

As indicated in Table 8, the SA/CPPE composite films demonstrated enhanced moisture barrier properties compared to the pure SA film, largely due to their lower water vapor permeability (WVP). This improvement is attributed to the formation of hydrogen bonds, which create a tightly condensed internal network structure between sodium alginate (SA) and cactus pear peel extract (CPPE) within the films (Zhang and Jiang, 2020). Similar reductions in WVP have been observed in films made with other polysaccharides when tea polyphenols were added (Dou *et al.*, 2018). For instance, a significant decrease in WVP from 1.24 × 10–6 g/m/h/Pa to 0.54 × 10–6 g/m/h/Pa was noted with increasing concentrations of the polyphenol extract. This reduction is likely due to the formation of stronger hydrogen bonds between CPPE and SA, which effectively hinders water vapor exchange. Furthermore, Fourier Transform Infrared (FTIR) analysis confirmed that higher levels of the polyphenol extract resulted in an increased number of intermolecular hydrogen bonds between the extract and SA. This increase reduces the availability of hydrophilic groups in the film, thereby decreasing the interactions between water and SA. As a result, the water permeability of the films is diminished, making them more effective barriers against moisture transfer (Martins *et al.*, 2012; Yong *et al.*, 2020).

Impact of CPPE on thickness and mechanical characteristics of SA-based films

Table 8 presents the mechanical properties of plain sodium alginate (SA) films compared to composite films made with cactus pear peel extract (CPPE), including thickness (T), elongation at break (EB), and tensile strength (TS). The thickness of active films is a crucial parameter influencing various characteristics such as mechanical strength and barrier performance. The thickness of the SA film was measured at 0.109 mm. Upon the addition of CPPE, the thickness increased to 0.142 mm. This rise in thickness is attributed to the higher solid content introduced by the CPPE, which alters the arrangement of alginate chains and contributes to the overall film structure (Table 8). Film thickness is essential as it affects properties like tensile strength and barrier efficacy, and it is influenced by the formulation conditions and the duration of film preparation (Hosseini *et al.*, 2015). The data indicates that pure alginate films require a minimum thickness for optimal performance, while composite films exhibit significant thickening ($p < 0.05$) as CPPE concentration increases. This observation aligns with findings from Luo *et al.* (2019), which reported an increase in film thickness when guava leaf ethanolic extract was incorporated into alginate films. The increased thickness in films with higher extract concentrations is likely due to the enhanced solid content from the added extract, reinforcing the structural integrity of the films.

Table 8. Thickness (T), tensile strength (TS) and elongation at break (E) of films based on sodium alginate as the control (SA) and test (SA-1%, 2%, 3% CPPE) film.

Film sample	Thickness (mm)	Tensile strength (m Pa)	Elongation (%)
SA	0. 109^{c} ±0.011	1.98^{c}± 0.31	130.80^{a} ±0.51
SA-1%CPPE	0.121^{c} ±0.008	2.36^{b}± 0.24	110.48^{b} ±0.68
SA-2%CPPE	0.130^{b} ±0.018	2.80^{b}± 0.18	100.20^{c} ±0.30
SA-3%CPPE	0.142^{a} ±0.009	3.12^{a}± 0.05	88.56^{d} ±0.16

Mean values± standard deviation; Significantly different samples ($p < 0.05$) are identified by distinct letters within a single column SA: sodium alginate. CPPE: cactus pear peal extract; SA-1%CPPE: sodium alginate with 1% CPPE, SA-2%CPPE: sodium alginate with 2% CPPE, SA-3%CPPE: sodium alginate with 3% CPPE,

The mechanical properties of packaging films, particularly tensile strength (TS) and elongation at break (EB), play a crucial role in maintaining the integrity of the packaged products. These parameters reflect the flexibility and strength of the films, making them essential indicators of performance (Pranoto *et al.*, 2005). As shown in Table 8, the incorporation of cactus pear peel extract (CPPE) significantly influenced ($p < 0.05$) the mechanical characteristics of the films. Notably, the tensile strength of the composite films improved markedly, with values ranging from 1.98 to 3.12, indicating enhanced structural integrity compared to the plain sodium alginate (SA) films. Conversely, the elongation at break decreased significantly ($p < 0.05$) with the addition of CPPE, suggesting a trade-off between strength and flexibility. These findings indicate that while the inclusion of CPPE enhances the strength of the films, it may also lead to reduced flexibility, which is an important consideration for applications requiring both durability and pliability. The balance between these mechanical properties is crucial for optimizing the performance of packaging films in preserving the quality of food products.

Elongation at break represents the utmost capacity of the films to withstand alterations in their length. The elevated values for E in the extract-free SA film (130.80%) can be attributed to the plasticizer employed (glycerol). SA-1%CPPE, 2%, and 3% showed lower EB values than those of the control film (110.48%, 100.20%, and 88.56%, respectively); the differences were significant ($p < 0.05$).

Elongation at break represents the maximum capacity of the films to withstand changes in their length. The elevated values for elongation in the extract-free sodium alginate film (130.80%) can be attributed to the plasticizer employed (glycerol). The sodium alginate films containing 1%, 2%, and 3% cactus pear peel extract showed lower elongation at break values compared to the control film, measuring 110.48%, 100.20%, and 88.56% respectively. The differences observed were significant ($p < 0.05$).

Total phenolic contents and antioxidant activity of SA and SA-CPPE composite films in various ratios (1.0, 2.0 and 3.0%)

Table 9 illustrates the total phenolic contents and free radical scavenging rates (DPPH) of SA and SA-CPPE composite films. Data show that the addition of CPPE to the coating solutions induced a rise in total phenolic content (TPC) and antioxidant activity (AA) of the tested composite films. Furthermore, the AA significantly increased as the addition ratio (0.0, 1.0, 2.0, and 3%) increased ($p < 0.05$). TPCs were 0.0, 42.11, 73.02, and 101.82 mg GAE/g, respectively.

Meanwhile, as the proportion of the cactus pear peel (CPP) extract increased from 1% to 3%, there was an evident improvement in the films' DPPH radical scavenging capabilities, with a corresponding increase in antioxidant activity (AA) from 25.22% to 72.16%. Conversely, the plain SA film had no DPPH radical scavenging capability (Table 9).

Table 9. Total phenolic contents and antioxidant activity of SA edible films and containing CPPE in various ratios (1.0, 2.0 and 3.0%).

Film sample	Total Phenolic Content (TPC) (mg GAE/g)	Antioxidant Activity (AA) (%)
SA	0	0
SA-1%CPPE	42.11±1.03	25.22±1.86
SA-2%CPPE	73.02±1.07	53.22±1.01
SA-3%CPPE	101.82±1.93	72.16±1.78

Mean values± standard deviation; Significantly different samples ($p < 0.05$) are identified by distinct letters within a single column. SA: sodium alginate. CPPE: cactus pear peal extract; SA-1%CPPE: sodium alginate with 1% CPPE, SA-2%CPPE: sodium alginate with 2% CPPE, SA-3%CPPE: sodium alginate with 3% CPPE.

Antimicrobial action of cactus pear peel extracts CPPE against pathogens

Table 10 presents the antibacterial and antifungal activity of pure alginate and alginate–CPPE films against *B. cereus*, *Staph. aureus*, *S. typhi*, *E. coli*, and *A. niger* using the disc diffusion technique. No inhibitory impact on the test bacteria was observed in the pure alginate film, which aligns with Oliveira Filho *et al.* (2019). Conversely, incorporating CPPE into alginate films exhibited notable antibacterial activity that progressively intensified with higher CPPE levels. Alginate–CPPE composite films demonstrated a stronger growth-inhibiting effect on gram-positive bacteria compared to other types of bacteria. The antibacterial activity of CPPE-1%, CPPE-2%, and CPPE-3% films was greater against S. aureus and B. cereus, with values ranging from 8.43 mm to 18.65 mm and 9.26 mm to 21.81 mm, respectively, while the antibacterial activity of the composite films (CPPE-2% and CPPE-3%) against *E. coli* and *S. typhi* was significantly increased ($p < 0.05$) compared to CPPE-1% films. Conversely, the antibacterial activity of the composite films (CPPE-3%) against A. niger was significantly elevated ($p < 0.05$) compared to CPPE-1% and CPPE-2% films. The prevailing mechanism underlying the antibacterial properties of plant extracts involves the infiltration of active compounds into the lipid bilayer of the cell membrane. This augments membrane permeability, which, in turn, induces the release of vital cellular contents (Biswas *et al*., 2013; Gonelimali *et al*., 2018). Gram-negative and gram-positive bacteria have different cell wall structures, which influence their interaction with antimicrobial compounds. Gram-positive bacteria possess cell walls comprising a peptidoglycan layer.

Gram-negative bacteria, alternatively, have a protective outer layer called the lipopolysaccharide layer, which acts as a shield that hinders the penetration of small substances like antibiotics into the bacteria (Martínez de Tejada *et al*., 2012; Biswas *et al*., 2013). This layer contributes to increased resistance to plant-derived antimicrobials. In contrast, the peptidoglycan cell wall of Gram-positive bacteria, while mechanically strong,

Table 10. Antimicrobial action of cactus pear peel extracts CPPE (diameter in inhibition in mm) against pathogens.

Pathogens	Inhibitory zone (mm)			
	SA	SA-1%CPPE	SA-2%CPPE	SA-3%CPPE
B. cereus (EMCC 1080)	0	9.26	14.21	21.81
Staph. aureus (ATCC13565)	0	8.43	12.26	18.65
S. typhi (ATCC 15566)	0	2.10	6.89	7.89
E. coli (ATCC 51659)	0	3.50	11.20	13.80
A. niger (ATCC 56091)	0	3.22	5.45	11.10

SA: sodium alginate film, SA-1%CPPE: sodium alginate with 1% CPPE, SA-2%CPPE: sodium alginate with 2% CPPE, SA-3%CPPE: sodium alginate with 3% CPPE.

inadequately limits the diffusion of small molecules, raising the vulnerability of these organisms to plant extracts (Biswas *et al.*, 2013; Atef *et al.*, 2019). Del Nobile *et al.* (2009) confirmed that the application of an alginate-based coating on partially peeled prickly pears resulted in an extension of the microbiological shelf life from 9 to 13 days. The direct utilization of cactus pear peels on fruits is likely to enhance their effectiveness, as evidenced by the study conducted by Dilucia *et al.* (2021). In this particular case study, incorporating these by-products in the formulation of fish burgers exhibited remarkable efficacy in inhibiting microbial growth.

Weight loss, pH meter and total acidity of SA edible films and containing CPPE in various ratios (1.0, 2.0 and 3.0%)

Table 11 illustrates the percentage of weight loss, pH value, and total acidity of coated strawberry fruits with SA-1%, SA-2%, and SA-3% CPPE, as well as those without an edible coating. During refrigerated storage, the weight loss of strawberry samples was assessed. This parameter is significant, as it can impact the overall freshness and quality of minimally processed fruits (Kader, 2002). With respect to weight loss, a reduction was observed compared to the control (Table 11), and a significant decrease ($p < 0.05$) was noted in all samples stored at 4°C. As expected, weight loss was higher in the control sample kept at refrigeration temperature (5.27%) compared to the other samples; the reduction in weight was minimal in the coated samples. Fruits with SA-3% CPPE exhibited lower weight loss (2.89%), followed by fruits with SA-2% CPPE (3.44%). The weight loss of the fruits is attributed to water losses induced by respiration and transpiration. Our findings indicate that coatings, when combined with refrigeration, reduce water loss. Núñez-Castellano *et al.* (2012) stated that a plastic cover protects the fruit from water loss during storage, positively affecting the enrichment of the atmosphere with $CO_{2,}$ which decreases the fruit's respiratory processes and reduces oxygen, resulting in less loss of fresh mass. Liguori *et al.* (2021) confirmed that uncoated samples of Opuntia ficus-indica experienced weight loss that was 2 to 2.5 times greater compared to the coated samples during cold storage. Significant disparities between the coated and uncoated fruit were evident throughout the entire 9-day cold storage period, starting from day 1.

Table 11. Weight loss, pH meter and total acidity of SA edible films and containing CPPE in various ratios (1.0, 2.0 and 3.0%) after 7 days of storage period.

Tested films	Weight loss %	Total acidity%	pH
Ctrl	5.27	0.906	3.12
SA	4.68	0.884	3.47
SA-1%CPPE	3.82	0.862	3.51
SA-2%CPPE	3.44	0.803	3.62
SA-%CPPE	2.89	0.763	4.01

Ctrl = sample without coating; SA= sample with sodium alginate coating; SA-CPPE= sample with sodium alginate coating + peel extract 1,2 and 3%

In relation to pH, this parameter showed an increase during storage at 4°C (Table 11), which was statistically significant ($p < 0.05$) in all treatments, with values ranging from 3.12 to 4.01. The increase in pH presented an inversely proportional relationship with total acidity (TA); as acidity decreased, an increase in pH values was observed in SA-CPPE. On the other hand, the increased pH values can be attributed to the union of fragments of free pectin in the cell wall with phenolic compounds during the maturation process (Villegas and Albarracín, 2016). The trend of pH values, which varied according to the components forming the coating, was clear (Han, 2014). In this study, it was evident that refrigeration temperature retarded and/or decreased the rate of cellular respiration in the fruit tissues (González *et al.*, 2016). All treatments significantly decreased ($p < 0.05$) relative to the control at refrigeration temperature, indicating that these coated fruits delay the ripening process due to the barrier formed by the peel extract. The decreased acidity was linked to the low rate of respiration of the fruit, which, in turn, translated into a longer fruit shelf life (Domene-Ruíz, 2017).

Sensory evaluation of coated and uncoated strawberry fruits during storage

Sensory evaluation of coated strawberry fruits (Figure 2) with SA-1%, SA-2%, and SA-3% CPPE, as well as those without an edible coating, is presented in Table 12. The fruits were evaluated for appearance, color, odor, taste, texture, and overall acceptability, with the first evaluation session carried out on day 1 of fruit storage. Data showed no significant difference ($p < 0.05$) in the appearance scores of fruits coated with SA-0%, SA-1%, and SA-2% CPPE compared to those with SA-3% CPPE and the uncoated sample. Regarding color scores, there was a significant difference ($p < 0.05$) between fruits coated with SA-0%, SA-1%, and SA-2% CPPE, SA-3% CPPE, and the uncoated sample (Figure 2). For odor scores, data revealed that the uncoated fruit had the highest score, followed by the SA-0% and SA-1% CPPE samples, and then by the SA-2% and SA-3% CPPE samples. Table 12 indicates significant differences ($p < 0.05$) in taste and texture scores for the coated fruits with SA-0%, SA-1%, SA-2%, and SA-3% CPPE compared to the uncoated fruit.

Data in Table 12 pertains to the overall fruit quality, with the trend observed reflecting the evaluation of individual sensory attributes such as appearance, taste, color, odor, and texture. Notably, all sensory parameters received high ratings during the first day of storage.

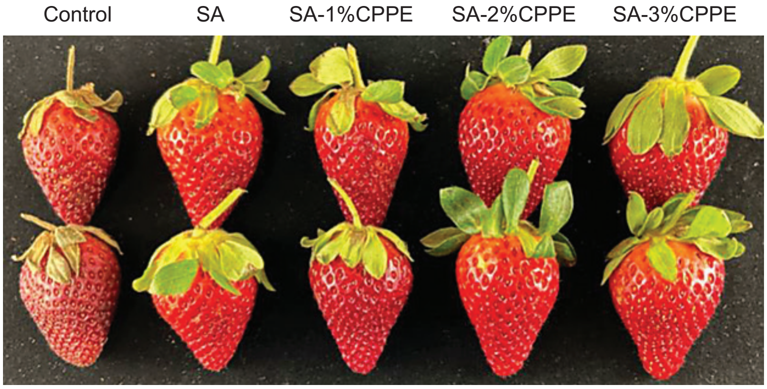

Figure 2. **Strawberry fruit stored for 7 days after being coated with SA, SA-CPPE-1%, SA-CPPE-2%, and SA-CPPE-3% films.**

Table 12. **Sensory evaluation of coated and uncoated strawberry fruits during storage at 4°C.**

Treatments	Storage period	Appearance	Color	Odor	Taste	Texture	Overall acceptability
Ctrl	Fresh	7.2^{c}	7.0^{c}	8.7^{a}	8.9^{a}	7.3^{b}	7.9^{a}
	7-day	3.2^{C}	4.5^{c}	5.8^{b}	5.1^{c}	3.1^{c}	4.34^{e}
SA	Fresh	8.0^{b}	7.8^{b}	8.0^{b}	8.7^{a}	8.7^{a}	8.24^{a}
	7-day	5.3^{B}	5.1^{c}	6.1^{a}	6.2^{b}	3.9^{b}	5.32^{d}
SA-1%CPPE	Fresh	8.4^{b}	8.2^{b}	7.8^{b}	8.7^{a}	8.7a	8.36^{a}
	7-day	$5{,}8^{a}$	5.6^{b}	6.3^{a}	6.3^{b}	4.7^{b}	5.74^{c}
SA-2%CPPE	Fresh	8.5^{b}	8.3^{b}	7.5^{c}	$8{,}6^{a}$	8.8^{a}	8.34^{a}
	7-day	6.1^{a}	6.1^{b}	6.4^{a}	7.0^{a}	7.3^{a}	6.58^{b}
SA-3%CPPE	Fresh	8.8^{a}	8.5^{a}	7.3^{c}	8.2^{b}	9.0^{a}	8.36^{a}
	7-day	6.4^{a}	6.8^{a}	6.4^{a}	7.2^{a}	7.6^{a}	6.88^{a}

Mean values ± standard deviation; Significantly different samples ($p < 0.05$) are identified by distinct letters within a single column. Ctrl = sample without coating; SA= sample with sodium alginate coating; SA-CPPE = sample with sodium alginate coating + peel extract 1,2 and 3%.

Minor declines in scores were observed for uncoated and simply coated (SA-0% CPPE) fruits, whereas strawberries coated with peel-enriched coatings consistently achieved the highest scores across all sensory attributes (Figure 2). This finding reaffirms the fruit peel's capability to effectively preserve the sensory quality of the product during storage. Dilucia *et al.* (2021) examined the impact of incorporating cactus pear by-products, specifically fruit peels, into fish burgers. They found that the fortified samples, both raw and cooked, exhibited improved retention of odor, color, and texture compared to the control fish products. The authors attributed this enhancement in sensory quality throughout the observation period to the addition of peel to the coating. The extensive literature on the various active properties of these peels supports the positive influence on the overall food quality observed in the peel-enriched coated samples (Melgar *et al.*, 2017; Amaya-Cruz *et al.*, 2019). After 7 days of cold storage, uncoated and SA-coated fruits had the lowest scores for all sensory parameters, while the coated strawberries with SA-3% CPPE received high scores, followed by those with SA-2%.

Heatmap clustering analysis

Heatmap clustering analysis was conducted to identify the associations between different proportions of CPPE compared to SA-based films based on the investigated parameters (Figure 3). The parameters were placed on the Y-axis, while the SA and SA-based edible films enriched with different proportions of CPPE were placed on the X-axis (Figure 3). The SA and SA-based edible films were grouped into two major clusters, A and B (Figure 3). The results of the heatmap clustering indicated distinct variations in measured parameters in response to various proportions of CPPE compared to the SA-based film (Figure 3). The parameters clustered into two major clusters, with the latter subdivided into two subclusters containing most of the parameters. It is clear from the heatmap analysis that incorporating SA with 3% CPPE had the greatest effect on appearance, color attributes,

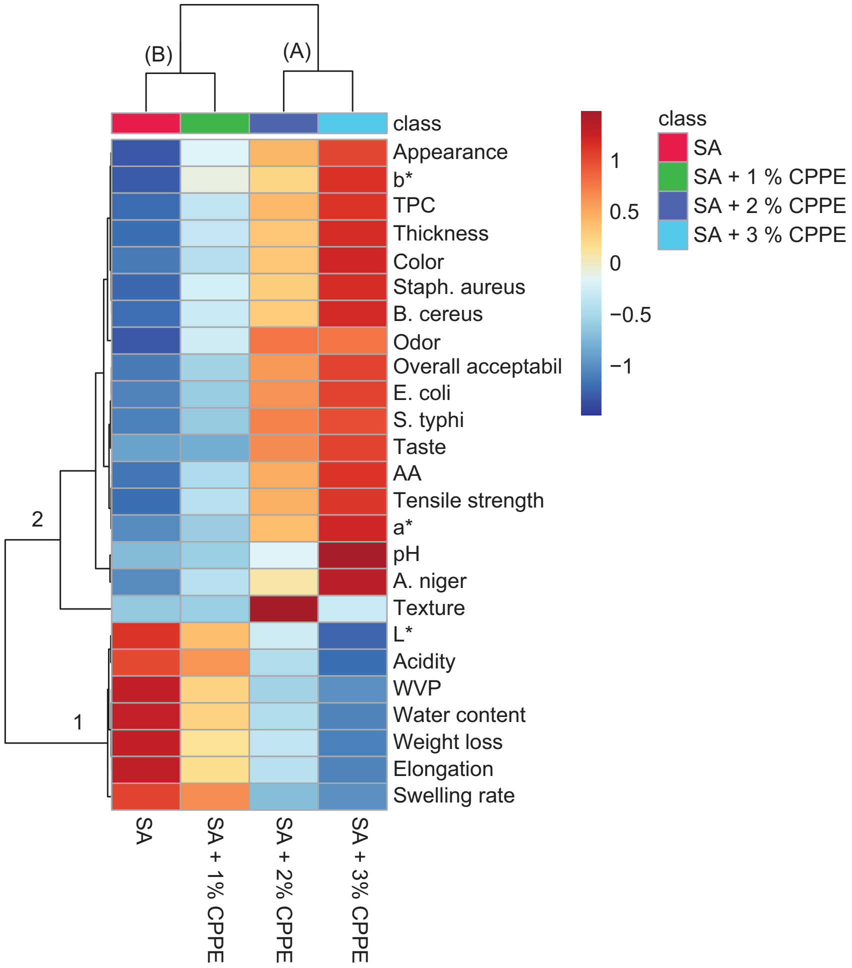

Figure 3. Heatmap hierarchical cluster analysis based on measured parameters of SA and SA-based edible films enriched with different proportions of CPPE. Parameters are placed on the Y-axis, while the SA and SA-based edible films enriched with different proportions of CPPE are on the X-axis. Colors indicate high (red) and low (blue) associations between the SA and SA-based edible films enriched with different proportions of CPPE and the investigated parameters.

total phenolic content, antimicrobial activity, and antioxidant activities. However, parameters such as swelling rate, acidity, WVP, water content, weight loss, L*, and elongation were higher in the SA-only samples without CPPE. These results indicate that the addition of CPPE had a considerable influence on the majority of investigated parameters in response to varying amounts of CPPE.

Conclusion

Fruit wastes, such as cactus pear peels, were effective in prolonging the shelf life of strawberry fruits stored at 4°C and 80% RH. The quality of both coated and uncoated strawberry fruits was observed over 7 days of refrigerated storage. Peeled fruits were coated with sodium alginate or with alginate containing cactus pear peel extract to assess the effects of these by-products on fruit quality throughout the storage period. The chemical and sensory properties of the fruits were thoroughly investigated. Cactus peel extract could serve as a protective coating that enhances the shelf life of coated fruit, demonstrating antioxidant and antimicrobial effects. Incorporating this extract into the edible coating may improve its overall efficiency. Comparisons among the results highlighted differences between coated and uncoated fruit, confirming the known effectiveness of the alginate-based coating while also demonstrating that peels can further promote product preservation.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability

The data presented in this study are available on request from the corresponding author.

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