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Antioxidant Ice Cream from *Opuntia streptacantha* Fruit Peel: Development and Characterization

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Abstract. *Opuntia streptacantha*, or nopal cardon, is a plant species belonging to the Cactaceae family. Its fruit (prickly pear) ranges in color from red to violet. It contains carbohydrates, proteins, dietary fiber, minerals, and peel rich in antioxidant compounds such as polyphenols, flavonoids, and betalains. The use of peels, an underutilized residue, represents a cost-effective alternative to obtain bioactive compounds of food interest, while promoting the health of the regional population through the development of functional foods. This research aimed to develop an ice cream enriched with antioxidant extracts from the *Opuntia streptacantha* fruit peels, sweetened with *Stevia rebaudiana*, and to determine, through sensory analysis, the extract concentration most accepted by consumers. Additionally, proximate chemical analysis, antioxidant capacity, and shelf-life studies were conducted. Three ice cream formulations were prepared with peel extracts (0.5, 1, and 1.5%). Based on sensory analysis and phytochemical concentration, the stevia-sweetened ice cream with 1.5% extract was selected for antioxidant capacity evaluation. The stevia ice cream's proximate composition and sensory evaluation (global hedonic rating of 81.2) was determined, and a predicted shelf life of 6.8 and 4.4 months at -18 and -6 °C, respectively. Consequently, it was considered the most promising formulation.

Keywords: *Antioxidant capacity, Betalains, Functional ice cream, Prickly pear peel*

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Introduction

Food development such as ice cream enriched with plant extracts is of great interest and utility for the food industry (Moolwong *et al*., 2023). These types of functional food offer an alternative for consumers by providing products which, in addition to their nutritional content, may help support physiological functions and improve overall health (Villagrán *et al*., 2022). Ice cream provides nutritional value like proteins with essential amino acids. In addition, it contains lactose from milk, and fats, which together help calcium assimilation and contribute to stability of the product (Deosarkar *et al*., 2016; Verruck *et al*., 2019).

Ice cream is a solid food due to freezing, in fact it is classified as a frozen dairy product, made from an emulsion of milk fats and derivatives, mixed with fruits, vegetables, flavoring, sweeteners, eggs and other additives such as stabilizers and emulsifiers, and that undergoes a stirring and freezing process that gives it the appropriate viscosity due to the internal uniformity of its components. It has its origins in Europe as iced drinks and from the evolution of condensed or dehydrated milks and along with technological development such as pasteurization, homogenization, and freezing, which have been essential in its formulation and conservation (Deosarkar *et al.,* 2016).

In the ice cream making process, its components are mixed with the liquid and solid ingredients at different temperatures, followed by pasteurization, cooling, and the addition or removal of air (overrun), resulting in a moist, semi solid, and creamy paste that is stored frozen (Fiol *et al*., 2017). This makes the ice cream more stable and tastier to consumers (Kusio *et al*., 2020). Prickly pear is the fruit of *Opuntia streptacantha,* a cactus usually called by the Mexican population "tuna". It contains different antioxidant compounds such as betalains, which are classified into betacyanins and betaxanthins. Also, it contains phenolic acids and flavonoids, as well as vitamin C (Patil and Dagadkhair, 2019). These compounds may prevent oxidative stress and inflammation, attributing to it the ability to reduce the risk of suffering cancer (Zourgui *et al*., 2020). The peel is rich in antioxidant compounds, such as phenolic compounds and betalains (Akbar *et al*., 2018). Additionally, it contains vitamins, minerals, and fiber with a low caloric intake. These extracts can be added to ice cream, adding nutritional and functional properties, and increasing the quality attributes and the content of bioactive compounds such as antioxidants (Liem *et al*., 2006, Gremski *et al*., 2019;).

The incorporation of prickly pear peel extract into ice cream can enhance color and flavor, while providing phenolic compounds with antioxidant activity, without compromising the product´s texture and stability (Chougui *et al*., 2015). Recent studies have highlighted a growing interest in developing frozen foods capable of delivering bioactive plant compounds to combat oxidative stress and inflammation-related diseases (Campo and Ramírez, 2021).

Sucrose is the common sugar used in the manufacture of ice cream; however natural sweeteners such as stevia are also used to replace commercial sugar (Jaimes-Tarazona *et al*., 2018). Stevia, derived from *Stevia rebaudiana,* a plant native to South America, is widely used as a natural sweetener because of its low caloric intake and in fact it is not metabolized in the human body (Mathur *et al*., 2017). The steviosides and reabaudiosides (steviol glycosides) in the plant confer its sweetness potential, being 300 times sweeter than sucrose (Reyes *et al*., 2014).

The development of ice cream enriched with antioxidant extracts obtained from prickly pear (*Opuntia* spp.) peel represents an innovation and sustainable approach to adding value to cactus by-products. Prickly pear peel has been identified as a valuable by-product because it contains pigments, dietary fiber, and antioxidants; however, it is still commonly regarded as waste (Ortega Cardona *et al*., 2025). The incorporation of these extracts not only enhances its functional properties but also contributes to waste reduction in cactus agro-industries, this responds to the growing consumer demand for functional foods with potential health benefits; and although ice creams made with cactus pulp have been reported (El-Samahy *et al*., 2009), there are not enough studies focused on developing antioxidant functional ice cream using cactus by-products. In this context, it is essential to conduct sensory tests to evaluate the consumer's acceptance in terms of appearance, texture, and flavor, as well as to assess the stability of the ice cream during storage to ensure its quality and stability (Laqui *et al*., 2025).

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This study aims to develop two types of ice cream, one sugar-sweetened and the other stevia-sweetened, both enriched with extracts from the peels of *Opuntia streptacantha* fruit, and to identify the most suitable formulation based on sensory acceptance, antioxidant capacity, proximate composition, and shelf life.

Material and Methods

Ice cream was made using an extract from the peels of the prickly pear fruit, added at different concentrations. The prickly pear species used was *Opuntia streptacantha*, known in Mexico as nopal cardon, and collected in the municipality of Amacueca, Jalisco, Mexico. Botanical identification of the species was performed in the Herbarium of the Faculty of Biology at the Universidad Michoacana de San Nicolas de Hidalgo (Folio: 28947).

Extract obtention

Prickly pear peels without damage were selected based on their reddish color. They were washed with water and disinfected. The spines were manually removed, and the peels were retained for extraction. The peels were cut into 2×2 cm squares and oven-dried in an Ecoshel® 9053 A (EUA), at 50 °C for 24 h. The dehydrated peels were ground in a blender and sieved through a #40 mesh (400 μm). The powdered sample was stored in an amber glass bottle at -10 °C.

The extract was obtained according to the methodology proposed by Zourgui *et al*. (2020) with modifications. The extraction solvent was an ethanol-water mixture $[60:40]$ (v/v). Twenty grams of the dehydrated sample was mixed with 80 mL of the solvent and stirred for 24 h at 25 °C. The solution was filtered using a Whatman No. 42 filter, and then it was evaporated at 50 °C. The extract obtained was stored in an amber glass bottle at -10 °C.

Ice cream standardization

Two ice-cream formulations were developed: one using sugar as the sweetening agent (SS), and the other sugar-free, using powdered stevia as the sweetener (SF). The same ingredients and manufacturing procedures were maintained for both formulations. The extract of prickly pear peel was added to the SS and SF formulations at concentrations of 0.5, 1, and 1.5%. The formulation of both ice creams was as follows:

i) Sugar ice cream (SS) formulation: 70 g of Alpura® whole milk, butyric fat 7 g, and 2 g of Nido® powdered milk were mixed. The mixture was blended for 10 min at room temperature. Then, 7 g of the Aromitalia® additive was added, which provides the ice cream with a suitable texture, and blending continued for 5 min. Finally, 14 g of sucrose was added.

ii) Stevia ice cream (SF) formulation: as SS formulation except for 83 g of Alpura® whole milk, and sucrose was replaced by 1 g of powdered stevia.

The ice cream mixes were manually beaten with a mixing spoon until a smooth, homogeneous, and lump-free texture was achieved. An artificial strawberry flavoring (5 mL) was then added and blended for 1 min. Once the mixture was homogenized, it was transferred to a 2 L ice cream machine (BQ-40 T), and a constant churning time of 5 minutes was programmed at room temperature. A cold mixing process was then programmed at -8 °C for 30 min, ensuring that the ice cream had a creamy consistency after 25 minutes. The cold mixing process was poured into a container and kept frozen at -18 °C.

Composition of bioactive compounds and antioxidant capacity

Considering that a previous study determined the presence of phenols, flavonoids, β-cyanines, and β-xanthines, and the antioxidant capacity against H_2O_2•, ROO•, OH•, HClO•, NO•, and O_2• using the prickly pear peel extract (Valencia *et al*., 2024), the same methods were used to determine the total phenols, that was carried out according to Hernández (2019), total flavonoids (Zhishen *et al*., 1999), β-cyanines, and β-xanthines (Stintzing *et al*., 2005), and the capacity to scavenge H_2O_2• (Ruch *et al*., 1989), ROO• (López-Alarcón and Lissi, 2005), OH• (Smirnoff and Cumbes, 1989), HClO• (Aruoma and Halliwell, 1987), NO• (Sreejayan and Rao, 1997), and O_2• (Nishikimi *et al*., 1972) in SS and SF ice creams with the highest concentration of bioactive compounds.

Since there are differences in the handling of ice cream samples *vs.* the extract, for carrying out these tests the ice cream sample was prepared according to the methodology proposed by (Hernández-Carranza *et al*., 2019). One gram of the ice cream was taken and mixed with 19 mL of 50% ethanol, and stirred for 20 min, and the final mixture was filtered using Whatman® #42 filter paper.

Proximal chemical analysis

The proximate composition analysis was conducted according to AOAC International methods (AOAC, 2000); moisture (method no. 934.01), protein (method no. 960.52), lipids (method no. 920.85), and ash (method no. 942.05). The content of carbohydrates was calculated by difference. The metabolizable energy was estimated using conversion factors of 4 kcal g^{-1} for proteins and carbohydrates, and 9 kcal/g for lipids, as indicated in the data provided by the FAO (Charrondiere *et al*., 2012). The analyses were conducted in triplicate.

Sensory analysis

Hedonic sensory tests to evaluate acceptance were conducted to assess ice cream with (1.5%) and without extracts. A 5-point scale was used: 0= strongly dislike; 25= dislike; 50= neither like nor dislike; 75= like; and 100= like a lot. Forty untrained judges, ranging from 15 to 60 years of age, participated evaluating color, odor, texture, and taste.

The sensory judges were selected based on predefined inclusion criteria, including regularly consuming of dairy foods as ice cream, absence of food allergies or intolerances related to the ingredients, no smoking, and availability to complete the evaluation session as documented in a signed consent form. Samples were coded with three-digit random numbers and presented in a randomized and balanced order to avoid deviations or interference effects. Evaluations were carried out in individual cabins, and water was provided as palate cleansing between samples.

Shelf life

The shelf life of Stevia ice cream added with the prickly pear extract at the highest concentration (1.5%) was determined using a Q10 shelf-life test. This was done by placing the ice cream at two different temperatures (-6 and -18 °C). Five samples were evaluated for each temperature at 0, 15, 30, 40 and 50 days, according with Park *et al*. (2018).

Shelf life was calculated using the average of the sensory tests (color, odor, texture, and taste) as a calculation parameter, as reported by Anzaldúa (1994). For each temperature, the corresponding equation, a linear model, and its corresponding slope and intercept with the Y axis were obtained. Using this equation, the time in days for 50% product acceptance was determined for each study

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temperature. A linear equation was obtained using the 50% acceptance value for each temperature, and the shelf life was determined at different temperatures using the Equation 1.

$$\theta_{Real} = 10^{(mT+b)} \quad \text{[1]}$$

Where: θ, shelf life in days; m = slope of the line; b = intersection with the Y axis; T = temperature.

Statistical analysis

Data are expressed as mean ± standard deviation. For analyses of nutritional composition, bioactive compound content and antioxidant capacity, results were subjected to a one-way analysis of variance (ANOVA) using JMP software version 8.0 (JMP Statistical Discovery LLC, USA). Means were compared using Tukey's test. For the sensory evaluation of acceptance degree of the two formulations, a student t test was carried out. The level of significance was fixed at 5%.

Results and Discussion

Proximal chemical analysis

Table 1 shows the results of the proximal chemical analysis of the two ice cream formulations, the sucrose-sweetened ice cream (SS) and the stevia-sweetened ice cream (SF) formulation. The sucrose content of commercial ice cream ranges from 9 to 28%, while the fat content ranges from 3 to 15% of the total ingredients (Atallah *et al*., 2022); in the product developed in this research is 14% sucrose for SS and sugar free for SF. A marked difference is observed between SF ice cream and that reported by commercial brands such as Neapolitan Holland® ice cream with 26 g of total carbohydrates and the ice cream from Nestlé® of strawberry and cream with 29 g. It is worth remembering that stevia has a sweetness level up to 300 times greater than sucrose (Aswin and Ramesh, 2025). On the other hand, the fat content in SS and SF is between the ranges previously reported by (Atallah *et al*., 2022), but higher compared with commercial brands, such as Neapolitan Holanda® ice cream (7.5 g) and Nestlé® strawberry ice cream (4.6 g) which could be a positive factor because fat concentration is crucial to obtaining the best sensory characteristics of ice cream, providing a better texture, preventing premature melting and promoting the incorporation of air (Hernandez, 2014).

Table 1. Proximal chemical analysis of ice cream formulations.

	SS	**SF**
Humidity	68.42 ± 0.29 [b*]	78.60 ± 0.37 [a]
Carbohydrates	18.31 ± 0.68 [a]	5.64 ± 0.94 [b]
Proteins	3.34 ± 0.13 [b]	3.80 ± 0.16 [a]
Lipids	9.31 ± 0.21 [b]	11.14 ± 0.35 [a]
Ashes	0.62 ± 0.05 [b]	0.82 ± 0.06 [a]
Kcal 100 g^{-1}	170 ± 13.2 [a]	152.7 ± 5.1 [b]

[*] Different letters in the same row show significant differences, $p<0.05$. Results expressed as g 100 g^{-1} of ice cream. SS = Sugar ice cream, SF = Stevia ice cream.

The energy content is higher in the SS formulation and lower in the SF formulation, since replacing sucrose with stevia reduces the amount of carbohydrates in the ice cream. Commercial brands add sugars to their formulations, such as Holanda® Neapolitan ice cream, which contains 174 kcal, and Nestlé® strawberry cream ice cream contains 163 kcal. These values are similar to SS and higher than

SF, making the last an attractive low-calorie product, considering a standard serving of ice cream contains almost 200 kcal 100 g^{-1}.

Regarding the values obtained for the percentage of humidity, it was slightly higher in SF, due to the increase in whole milk. Indeed, value being closer to that reported by the (USDA, 2019a) with 55 g for a common chocolate ice cream, and 60 g for a vanilla ice cream. Blanco *et al.* (2023) created a yoghurt ice cream from *Passiflora edulis* fruits with 81% humidity, close to SF, due to the greater incorporation of milk in both cases. Regarding the carbohydrate content for Blanco´s ice cream is 17.33 g, closer than SS than SF, due to the sugar occurrence, unlike SF, which contains smaller amount of carbohydrates. The protein content was higher in SS and SF than in *Passiflora edulis* frozen yoghurt (0.96 g) and commercial ice creams (Neapolitan ice cream from the Holanda®, protein content of 0.7 g; and strawberries with cream ice cream from the Nestlé®,1.3 g of protein). It may be attributed to the high protein content in the powdered milk used as raw material and the increased percentage of whole milk added in SF compared to the SS formulation.

The ash percentage, has a value like USDA (2019b), with 0.7 and 1 g. A significant difference is observed in SF and SS, since milk minerals such as calcium contribute inorganic compounds to the ice cream.

Composition of bioactive compounds and antioxidant capacity

As can be seen in Table 2, the concentration of total phenols analyzed, total flavonoids, betacyanins and betaxanthins increased according to the amount of extract added from 0.5 to 1.5%.

Table 2. Bioactive compounds of the different ice cream formulations.

		Phenols (mg GAE g^{-1})	**Flavonoids (mg CAT g^{-1})**	**β-Cyanines (mg BET g^{-1})**	**β-Xanthines (mg IN g^{-1})**
	Extract (%)	19.98 ± 0.42 [a*]	14.72 ± 0.48 [a]	0.770 ± 0.03 [a]	0.580 ± 0.040 [a]
SS	0.5	7.04 ± 0.04 [d]	4.30 ± 0.14 [d]	0.080 ± 0.005 [d]	ND
	1.0	12.1 ± 0.09 [c]	9.50 ± 0.03 [c]	0.150 ± 0.002 [c]	0.040 ± 0.010 [c]
	1.5	15.4 ± 0.07 [b]	12.00 ± 0.05 [b]	0.250 ± 0.010 [b]	0.120 ± 0.020 [b]
SF	0.5	7.09 ± 0.04 [d]	4.20 ± 0.14 [d]	0.080 ± 0.005 [d]	ND
	1.0	12.00 ± 0.09 [c]	9.37 ± 0.03 [c]	0.140 ± 0.015 [c]	0.040 ± 0.010 [c]
	1.5	15.60 ± 0.07 [b]	12.44 ± 0.05 [b]	0.280 ± 0.010 [b]	0.120 ± 0.020 [b]

* Different letters in the same column indicate significant differences, $p<0.05$. GAE, gallic acid equivalents; CAT, catechins; BET, betanin; IN, indicaxanthin. ND = No presence detected. SS = Sugar ice cream, SF = Stevia ice cream.

This study found that prickly pear (*Opuntia streptacantha*) peel extract had a higher concentration of total phenols when compared with other studies on other fractions from the same genus. Total phenol concentrations in the peel of *O. ficus-indica* have been reported to reach 400-500 mg GAE 100 g^{-1} (Aguirre-Joya *et al*., 2013), which is higher than the levels found in the pulp (218-350 mg GAE 100 g^{-1}) and seeds have been reported with values ranging from 120-180 mg GAE 100 g^{-1} (El-Mostafa *et al*., 2014). That is agree with recent studies that have been reported differences in the distribution of bioactive compounds depending on cultivar and structure of the plant analyzed (Kolniak-Ostek *et al*., 2020). Lower concentrations (95-150 mg GAE 100 g^{-1}) have also been reported for cladodes, but these have an interesting functional profile (Razzak *et al*., 2024). Phenolic compounds have also been identified in oils and extracts derived from cactus seeds, which highlights the importance of this species

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as a potential source of antioxidants (Chbani *et al*., 2020), however the results presented in this paper demonstrate that peel is one of the main sources of phenolic compounds within Opuntia genus.

Upon adding the prickly pear peel extract to the ice cream, the content of TP, flavonoids, and betalains decreased, compared to the extract, a finding that is consistent with Soukoulis *et al*. (2014) who mentioned that antioxidant compounds from plant tissue extracts may undergo alterations and instability during ice cream processing, either in heat treatment, aeration, and/or storage, a possible reason why these compounds could decrease in each of the formulations mentioned. The stability of phenol-rich plant extracts is compromised by ice recrystallization during frozen storage, which causes structural damage and the loss of bioactive compounds (Mrázková *et al*., 2023). Neri *et al*. (2020) also mention that the freezing and thawing process accelerates the degradation of antioxidants in polyphenol-rich matrices due to cell rupture caused by ice crystals.

In other functional foods which prickly pear extracts have been added, such as the frozen yogurt developed by Hernández *et al*. (2019), they recorded 0.20 mg ± 0.01 mg g^{-1} of TP, flavonoids 0.21 mg ± 0.01 mg g^{-1} yoghurt, and total betalains 0.006 mg g^{-1}, results below those obtained in this study (14.72 ± 0.48 mg g^{-1}, 1.35± 0.07 mg g^{-1} respectively). Ullah *et al*. (2016) developed different ice cream formulations where they added various concentrations of sugarcane juice (20, 40 and 60%) obtaining results for TP and flavonoids compounds increase too, according to the percentage of sugarcane extract added to the ice cream.

To carry out the antioxidant capacity analyses, as mentioned above, it was decided to consider the ice cream formulations that presented the highest concentration of bioactive compounds and for subsequent analyses, considered could be the most appropriate level to ensure both technological feasibility and functional relevance of the developed product.

Regarding the antioxidant capacity of the extract against the biological radicals H_2O_2•, ROO•, OH•, and HClO•, it was effective. In the SS and SF ice cream formulations, no capacity to scavenge ROO• and HClO• radicals were recorded (Table 3). An important factor to consider is the molecular interaction between carbohydrates, milk proteins and polyphenols, which reduces the capacity of reactive species to be scavenged, as demonstrated by Kabir et al. (2021). As expected, the EC_{50} value increased due to the decreased concentration of prickly pear peel extract in the ice cream formulation. Therefore, to neutralize at least 50% of the reactive H_2O_2• species, 1.14 ± 0.03 mg mL^{-1} of extract is required. By comparison, for both SF and SS presented EC_{50} values a higher concentration of extract is needed to detect antioxidant activity at 50% of the reactive H_2O_2• species.

The EC_{50} value of SS to capture the OH• radical was higher than SS but without a significant statistical difference. On the other hand, the *O. streptacantha* extract was efficient in capturing the NO• and O_2• radicals as observed, were obtained with a statistically significant difference ($p<0.05$) between SF and SS, most likely influenced by the increase in milk and the substitution of sugar in the formulation with stevia. However, there was no effect or decrease in the uptake of the O_2 radical•, as argued by Kabir *et al.* (2021), the antioxidant capacity is low due to protein-polyphenol bonds.

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Table 3. Antioxidant activity of ice creams with 1.5% prickly pear peel extracts.

Radical (EC_{50} ($\mu g\ mL^{-1}$))	**Extract**	**SS**	**SF**
$H_2O_2^{\bullet}$	1.14 ± 0.03 [b]	46.25 ± 1.04 [a]	45.34 ± 1.6 [a]
$ROO^{\bullet}$	0.040 ± 0.001[a]	ND	ND
$OH^{\bullet}$	1.02 ± 0.14 [b]	4.65 ± 0.16 [a]	4.52 ± 0.14 [a]
$HClO^{\bullet}$	1.73 ± 0.05 [a]	ND	ND
$NO^{\bullet}$	0.087 ± 0.01 [b]	0.437 ± 0.03 [a]	0.432 ± 0.04 [a]
$O_2^{\bullet}$	0.027 ± 0.002 [b]	0.592 ± 0.01 [a]	0.580 ± 0.03 [a]

Values are expressed as mean ± standard deviation. Different letters in the same row indicate significant differences, $p<0.05$. ND = No activity detected. SS = Sugar ice cream, 1.5% extract, SF = Stevia ice cream 1.5% extract.

For the SS and SF ice creams, the EC_{50} (NO•) values indicate a moderate antioxidant activity. According to Garcia *et al*. (2010), an EC_{50} > 1 mg mL^{-1} indicates a low antioxidant capacity; in their study, values above this threshold were reported for bark extracts from Canadian wood species. In contrast, Royer *et al*., (2011) reported EC_{50} values comparable to those of SS and SF, obtaining 0.660 mg mL^{-1} for branch bark extracts and 0.665 mg mL^{-1} for woody shoot extracts in aqueous maple preparations.

In the study of Ullah *et al*. (2015), the nitric oxide radical scavenging activity was 7.12 ± 0.32, 18.67 ± 0.55, and 42.35 ± 2.36% for the ice cream samples. They mention that nitric oxide free radicals were significantly inhibited ($p<0.05$) by phenolic compounds in ice cream samples containing sugarcane juice, compared to controls. Similar results were obtained in the present study, considering the ice cream formulation with 1.5% prickly pear peel extract.

Jayaprakasha *et al*. (2008) reported an acceptable O_2• radical scavenging for grapefruit extracts (*Citrus paradise*), EC_{50} 0.400 mg mL^{-1} (acetone) with 90% O_2• radical scavenging and with sour orange (*Citrus aurantium*), EC_{50} 0.400 mg mL^{-1} (hexane) with 65% O_2• radical scavenging; while the extract of the medicinal plant *Blumea balsamifera* using chloroform as a solvent, a relevant antioxidant capacity of 0.500 mg mL^{-1} was reported with 85% capture of the O_2• radical (Nessa *et al*., 2004), both researches recording values close to those of SS and SF.

These findings highlight the potential of organic waste such as shells of the prickly pear *Opuntia streptacantha* in the content of antioxidant compounds such as phenols, flavonoids and betalains, which could be considered as a good source of bioactive compounds for the development of functional foods like an ice cream.

Sensory analysis

The results of the hedonic sensory evaluation tests of SF with and without prickly pear peel extract are shown in Table 4. The scores for the sensory attributes of smell, color, taste, and texture were above 75 (liked) in the ice cream with and without extract. The highest-scoring value was texture in both formulations. That could be attributed to the concentration of fat in ice cream (Hernandez, 2014). No significant differences were found between ice cream with and without extracts, implying that the extracts added to the stevia-sweetened ice cream did not influence the smell, color, taste, and/or texture of the ice cream.

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Table 4. Degree of acceptance of the two ice cream formulations.

Sensory attribute	SF	Control
Smell	76.0 ± 23.3[a *]	76.6 ± 17.5 [a]
Color	82.0 ± 17.4[a]	82.3 ± 14.3 [a]
Taste	83.5 ± 16.5 [a]	82.4 ± 18.3 [a]
Texture	92.0 ± 13.1 [a]	93.8 ± 12.5 [a]
Overall	81.2 ± 5.7 [a]	83.8 ± 7.2 [a]

* Different superscript letters within the same row indicate significant differences between treatments according to Student-t test ($p<0.05$). SF = Stevia ice cream 1.5% extract, Control = Stevia ice cream without extracts.

Different studies indicate the addition of plant tissue-based extracts results in high sensory acceptance and a strong association between this, the antioxidant activity and the potential purchase of the product and (Gremski *et al*., 2019). However, according with the sensory evaluation of the ice cream with and without prickly pear extract, the adding of it, is not affected the degree of acceptance for smell, color, taste, texture and the overall perception like Campo and Ramírez (2021), it has been shown that dairy-derived food products, such as ice cream, with the incorporation of phenolic compounds from plant extracts, suppress the flavor characteristics, because these compounds are related to the flavor profile of the fruit, which is why this parameter has not been altered in the present study. Also Kavaz *et al*. (2016) developed ice cream formulations with dried Besni grapes (*Vitis vinifera* L.), clearly observing the increase in phenolic compounds and flavonoids, but not in the flavor and texture or in the general sensory acceptance, as well as (Borrin *et al*., 2018) who fabricated ice cream with curcumin nano emulsion without causing significant effects on the sensory properties of the ice cream, those findings are consistent with the sensory evaluation of the ice cream with and without prickly pear extract.

Shelf-life study

The data obtained for the sensory analysis of Q10 shows a decrease in shelf life as temperature increases, the cut-off point set is 50 points on the hedonic scale. Changes in the sensory characteristics of most products when determining shelf life are one of the most critical parameters, along with safety and nutritional determinations (Hough *et al*., 2006, Giménez *et al*., 2012;). The sensory analysis (Table 5) of the ice cream stored at -6 °C yielded the least favorable score overall after 50 days. The color attribute was the one that resulted in a better score, and the lowest was the texture at the end of 50 days, this is understandable due to the release of air trapped between the fat molecules and the ice cream additives, a decrease in its volume was observed in the container (Goff, 2002; Santos *et al*., 2025).

Table 5. Shelf-life study. Sensory analysis. Stevia ice cream.

	Color		**Odor**		**Texture**		**Taste**		**Average**	
Days	-18 °C	-6 °C	-18 °C	-6 °C	-18 °C	-6 °C	-18 °C	-6 °C	-18 °C	-6 °C
0	86.0±2.5	86.0±2.5	86.0±3.0	86.0±3.0	94.0 ±2.0	94.0±2.0	88.0±2.0	88.0±2.0	88.5±3.0	88.5±3.0
15	85.0±3.0	85± 3.5	79±4.0	79±4.5	92.0±3.0	91±3.5	86.0±2.8	85.0±3.0	85.5±3.3	85.0±3.6
30	84.0±4.0	82±4.5	78±4.5	73±5.0	88.0±3.8	85.0±4.0	84.0±3.2	80.0±4.0	83.5±3.9	80.0±4.4
40	84.0±5.0	80.0±5.5	77±4.0	73±4.8	86.0±4.0	83.0±4.5	83.0±3.5	79.0±3.8	82.5±4.1	78.8±4.7
50	77.5±12.6	78.3±12.1	75.5±9.0	56.6±11.8	70.8±13.6	69.0±9.0	72.2±2.9	69.0±9.0	72.2±2.9	69.0±9.0

The data represents the acceptance percentage, a maximum of 100 points. Data are shown at two temperatures, -6 and -18 °C.

For the sensory analysis of the ice cream stored at -18 °C, a more favorable score was recorded from the overall total compared to the ice cream stored at -6 °C at the end of the 50 days. The color attribute resulted in the highest score, while the flavor attribute had the lowest score, remaining close to the threshold of 75, indicating "I like it." The texture attribute obtained a higher score for ice cream at -6 °C. This effect was attributed to improved preservation and retention of air among the fat molecules, resulting in a creamier texture and more pleasant mouthfeel.

Table 6 shows the predicted shelf life of Stevia ice cream, using the Equation (2) designed based on the parameters, ranging from 3.5 to 8.5 months. When storage temperature decreases, the predicted shelf-life increases. For example, the predicted shelf life for ice cream stored at -24 °C have a shelf life around of 255 days (8.5 months), compared to 106 days (3.5 months) at 0 °C. These results can be expressed as an inverse correlation between the storage temperature and the predicted shelf life, indicating that a low storage temperature slows down oxidation, microbial activity, and moisture migration, preserving the product stability. With these results, it has been demonstrated that storing ice cream at temperatures below -18 °C preserves its sensory and physicochemical properties best. This finding is consistent with that reported by Ayyash et al., (2018), they found that reducing the storage temperature from -10 °C to -20 °C significantly improved sensory stability and reduce fat destabilization in camel milk ice cream. Similarly, Kavaz *et al*. (2016) reported that adding natural fruit extracts to ice cream during freezing improved antioxidant protection and prolonged its shelf life without affecting its sensory qualities.

Table 6. Predicted shelf life for stevia ice cream.

Temperature (°C)	Days	Months
0	106.1	3.5
-6	132.1	4.4
-12	164.5	5.5
-18	204.8	6.8
-24	255.1	8.5

Furthermore, the result of this study aligns with predictive kinetic models describing the reduction in degradation rates with decreasing temperature (Pandey *et al*., 2021b). These outcomes suggest that enzymatic and oxidative reactions slow down at temperatures below zero degrees Celsius, which delays the structural and flavor degradation of ice cream.

$$Days = 10^{(-0.0159*Temperature+2.0257)} \qquad [3]$$

Microstructural composition of ice cream

In scanning electron micrographs of SF with 1.5% ethanolic extracts, morphological features reminiscent of protein, aggregates and carbohydrate matrices can be observed (Figure 1). At 100 X (A), the image shows globular particles that likely correspond to agglomerations of milk proteins and fat droplets. In the micrography at 250 X, the globules become more defined (B), the image shows spherical structures attributable mainly to lipid droplets. When the magnification is increased (C), more complex assemblages become apparent, suggesting networks of lipids and carbohydrates, while at the highest magnification (D), the structures appear amorphous, which may reflect the interactions between denatured proteins and coalesced fats within the frozen matrix.

These findings are consistent with the structure known about microstructure of ice cream, like the scanning electron microscopy that reveals that ice cream is a multiphase system composed of ice

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cream crystals (around 30% volume), air cells (around 50%) and dispersed fat droplets (approximately 5%) embedded in an unfrozen viscous sugar solution (Kamal *et al*., 2021). This microstructure is critical for sensory quality: small ice crystals and air bubbles give a smooth texture, whereas large crystals lead to a sandy mouthfeel. In industrial processing homogenization is employed to break up thick milk fat globules. Milk proteins and added emulsifiers adsorb to the surface of these droplets and stabilize them, forming the fat component of the microstructure. When the milk is aerated and frozen, partially crystallized fat droplets and casein micelles adsorb at the air water interface, creating a rigid network that stabilizes air cells. The final structure consists of fat globules and protein aggregates intertwined with ice crystals and air bubbles (Kamal *et al*., 2021).

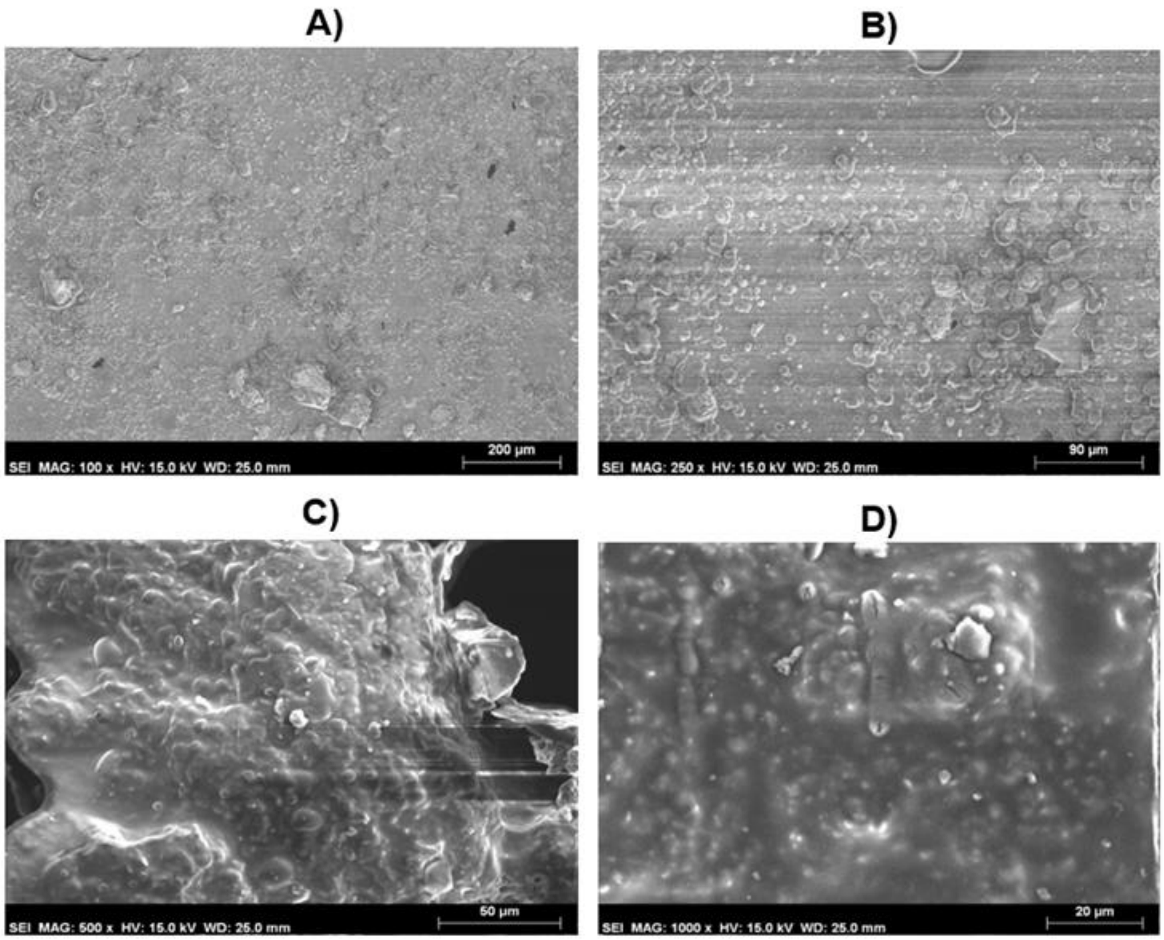

Figure 1. Micrography A) 100x B) 250x C) 500x D) 1000x.

The micrographs obtained in the present study suggest that adding the prickly pear extract at 1.5%, the organization of proteins and fats is modified (Li *et al*., 2021). The globules of protein that show a well –defined morphology at intermediate magnifications implies that the extracts may have influenced fat crystallization or emulsifier interactions, possibly by providing additional polyphenols that interact with proteins (Bogdanova *et al*., 2022). At 1000X, the amorphous structures observed could result from enhanced protein denaturation and fat coalescence during freezing (Sangsuriyawong *et al*., 2024). These findings support that the microstructural composition of ice cream is sensitive to both formulation and processing variables, and they reinforce the importance of controlling homogenization (Jia *et al*., 2025), stabilizer, and freezing conditions to achieve a desirable texture and stability.

Conclusions

This study demonstrates the technological feasibility of incorporating peel extracts form *Opuntia streptacantha* into a frozen dairy matrix as a strategy to valorize cactus by-products. The SF containing 1.5% peel extract achieved the best balance between functional enhancement and consumer acceptance, without negatively affecting sensory attributes.

Compared with the extract alone, the incorporation into ice cream resulted in a reduction of measurable phenolics and radical scavenging capacity, confirming that there could be interaction and partial instability during processing and frozen storage. Nevertheless, the ice cream exhibited moderate antioxidant capacity against selected reactive species, demonstrating that bioactive compounds from prickly pear peel can be delivered through a complex dairy system.

The addition of the extract did not compromise overall acceptability, supporting its compatibility with ice cream structure and flavor profile. Shelf-life modeling further indicates that sensory quality is strongly temperature dependent with predicted stability exceeding six months at -18 °C, consistent with typical frozen storage conditions.

This study provides evidence of the functional and technological performance of a peel-derived extract incorporated into ice cream. It contributes new data on the response of betalain- and phenolic-rich extracts within a frozen dairy matrix, their impact on radical scavenging capacity after processing, and the sensory and predicted shelf-life implications of such incorporation. However, it will be important to propose successive experiments in biological models to visualize the functional properties of ice cream with added nopal peel extract.

ETHICS STATEMENT

The sensory evaluation performed in this study followed internationally accepted ethical principles for research involving human participants, including the Declaration of Helsinki. The study consisted of hedonic testing of food products and was considered minimal risk. All participants were informed about the purpose and procedures of the study and provided informed consent prior to participation. Food samples were safe for consumption and prepared under hygienic conditions, and participants were screened for potential allergies. Participation was voluntary, and all data were collected anonymously and handled confidentially.

CONSENT FOR PUBLICATION

All authors revised the paper and agreed to the final version.

AVAILABILITY OF SUPPORTING DATA

The main contributions given in the study are included in this paper, further inquiries can be directed to the corresponding author.

COMPETING INTERESTS

The authors declare that they have no conflicts of interest.

AUTHOR CONTRIBUTIONS

R. Z.-V., H. E. M.- F., J. O. R.-L., and E. V.-A.: conception, design, writing, discuss and analyzed the data obtained. E. T.-R. and M.-E. G.-P.: discuss and analyzed the results. Material preparation, data collection and analysis were performed by I.U. C.-G. All authors revised the paper and are agree to the final version.

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