

Phytochemical and functional evaluation of the peels of six varieties of *Opuntia* spp. from Hidalgo, Mexico

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Abstract. The peels of *Opuntia* fruits are usually discarded as agri-food waste, yet they are a rich source of dietary fiber and bioactive compounds with potential functional applications. This study compared the phytochemical composition and antioxidant properties of the peels from six *Opuntia* species native to Hidalgo, Mexico; *O. albicarpa*, *O. megacantha*, *O. ficus-indica*, *O. xocnostle*, *O. robusta*, and *O. undulata* as a function of species identity and extraction solvent (aqueous vs. ethanolic). We hypothesized that interspecific variability in peel chemistry, combined with solvent polarity effects, would produce significant differences in all measured variables. Total, insoluble, and soluble dietary fiber in freeze-dried peel powder were determined. Aqueous and ethanolic extracts were evaluated for radical scavenging DPPH (2,2-diphenyl-1-picrylhydrazyl), antioxidant capacity ABTS (2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid)), β -carotene oxidative discoloration inhibition, total polyphenols (Folin-Ciocalteu), and total flavonoids. *O. robusta* showed the highest total dietary fiber (60.22% d.b.), followed by *O. ficus-indica* (55.73% d.b.). Aqueous extracts of *O. megacantha* and *O. undulata* showed the highest DPPH radical scavenging activity (21.38 and 23.99% FRS, respectively), statistically comparable to the BHT control. ABTS antioxidant capacity was highest in aqueous extracts of *O. ficus-indica* and *O. robusta* (91.07 and 90.98 $\mu\text{mol TE}/100\text{ g d.b.}$, respectively). Aqueous extracts consistently outperformed ethanolic extracts in polyphenol recovery, while ethanolic extracts showed higher flavonoid content in most species. The species \times solvent interaction was significant for all bioactivity variables ($p < 0.05$). These results indicate that *Opuntia* peels from these six Mexican species are a viable source of dietary fiber and bioactive compounds, supporting their use as functional food ingredients and nutraceutical raw materials.

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Introduction

In Mexico and other parts of the world, there is a large amount of postharvest and post-production waste generated from various plant sources. In most cases, this waste ends up in landfills, leading to a significant increase in pollution levels (Bhardwaj *et al.*, 2025). Recently, research has focused on the use of agro-industrial waste, supporting the fulfillment of the Sustainable Development Goals (SDGs) (Sikiru *et al.*, 2024).

One of the main by-products generated after pulp extraction is the peel of prickly pears belonging to the *Opuntia* genus. This genus is a dicotyledonous angiosperm belonging to the *Cactaceae* family, which can grow to a height of 3-5 m. Approximately 165 species of *Opuntia* have been identified, with Mexico hosting the largest number of these, some of which are native to this country. These species are found in desert and semi-desert areas of the southeastern United States, Central and South America, as well as in Africa and certain regions of Asia (Corral-Martínez *et al.*, 2025).

The flowers, seeds, whole fruit, fruit pulp, pads or stems, and roots of *Opuntia* have been researched (Moussaoui *et al.*, 2020), yielding various biologically active primary and secondary metabolites, as well as components that contribute to nutrition, such as fiber, polyunsaturated fatty acids, vitamins, antioxidants (Zenteno-Ramírez *et al.*, 2018), phenols, and other phytochemical compounds of importance such as sterols, terpenoids, and coumarins (Aruwa *et al.*, 2018). *Opuntia* fruits are ellipsoidal, approximately 7 cm long, with a pericarp that accounts for 37–59% of the fresh weight and is mostly considered a waste product, and an endocarp mainly used for consumption, which accounts for 28–58% of the total fruit's wet weight (Alshaikhi *et al.*, 2023). The most common colors for these fruits are green, white, purple, yellow, or red, depending on the species. They are considered the edible part of the plant and a functional food due to their beneficial nutritional effects, such as their vitamin C content (Heuzé and Tran, 2017). Furthermore, a study conducted with *Opuntia ficus-indica* demonstrated the presence of bioactive compounds such as flavonoids, polyphenols, alkaloids, and betalains, the latter having shown anti-inflammatory and antioxidant effects (Moussaoui *et al.*, 2020).

The peel of the *Opuntia* fruit, which is considered a by-product and is often discarded, accounts for up to 60% of the total weight of the whole fruit. Some studies have attributed various applications to it, such as a source of natural fiber and antioxidant properties due to the presence of compounds such as epicatechin and gallic acid (Aruwa *et al.*, 2018). Similarly, El-Beltagi *et al.* (2023) have established that, when wheat bread is supplemented with *Opuntia* peel flour, its nutritional properties and shelf life are increased. Another study conducted with hamsters supplemented with methanolic extracts of *Opuntia* peels revealed an increase in LDL cholesterol release and a decrease in liver cholesterol levels, demonstrating a beneficial effect (Milán-Noris, 2016).

Several studies (Kolniak-Ostek *et al.*, 2020; Ramadan *et al.*, 2021; Tunç *et al.*, 2025) have based their research on the use of various morphological parts of cacti, mostly their cladodes or their fruits, but knowledge is limited when it comes to waste from other parts of the plant such as the flowers or peels. These by-products are rich in bioactive compounds that remain largely uncharacterized at the species level. Published reviews on cactus pear peel (Manzur-Valdespino *et al.*, 2022) specifically, confirm that the peel contains relevant amounts of phenols, flavonoids, dietary fiber, and pigments with antioxidant, hypoglycemic, and hypolipidemic properties; however, systematic species-amount comparisons for peels from Mexican-native varieties are scarce. A detailed phytochemical characterization of the peels of three pigmented cultivars of *O. ficus-indica* showed that the peel fraction contains up to 145 identifiable bioactive compounds including extractable and hydrolysable polyphenols, betalains, carotenoids, and phytosterols, with polyphenol content ranging from 8.62 to 12.28 mg GAE g⁻¹ d.b. (Amaya-Cruz *et al.*, 2019). Further evidence supporting interspecific comparisons comes from studies conducted with *Opuntia* peels collected from the same region (Santiago Tulantepec, Hidalgo, Mexico). Alaiz *et al.* (2025) reported significant interspecific differences in total and free amino acid composition between the peel and pulp of seven Mexican *Opuntia* species, while Garzón *et al.* (2025) demonstrated that gastrointestinal pH significantly affects the betalain

content and bioactivity of peel extracts from six *Opuntia* species, which confirms that species identity is a key determinant of the functional properties of the peel fraction. The choice of extraction solvent is equally critical since aqueous and ethanolic extractions recover different fractions of bioactive compounds due to differences in polarity, and this effect has been specifically documented for *Opuntia* peel extracts (Santana-Farré *et al.*, 2025). The objective of this study was to evaluate the phytochemical composition and functional properties of the peels from six Mexican *O. albicarpa*, *O. megacantha*, *O. ficus-indica*, *O. xocconostle*, *O. robusta*, and *O. undulata* as functional food ingredients and nutraceutical raw materials through functional and phytochemical characterization, specifically evaluating how species identity and solvent polarity interact to determine bioactive compound recovery. We hypothesized that peel chemistry would vary significantly among species and between extraction solvents and that aqueous extracts would yield higher recovery of polar bioactive compounds.

Material and Methods

Obtaining the *Opuntia* samples

Opuntia cactus fruits were harvested in Santiago Tulantepec, Hidalgo, Mexico, at a latitude of 20° 2'10''N, a longitude of 98° 21'24''W, and an altitude of 2,174 m above sea level. For this study, the following species were sampled: *O. albicarpa*, *O. megacantha*, *O. ficus-indica*, *O. xocconostle*, *O. robusta*, and *O. undulata*. Between 15 and 20 ripe fruits per species were harvested at full maturity, which was confirmed by the characteristic coloration of each species, pooled into a single composite sample per species, and processed uniformly. The fruit was washed with distilled water and cut into approximately 2 cm pieces. After cleaning, the seeds and peels were separated from the pulp, which was used for another purpose unrelated to this project. The peels were freeze-dried using a LABCONCO® FreeZone 4.5 USA freeze dryer at -45 °C/0.02 mBar. The samples were ground using a Moulinex food processor, model AR9868, and then sieved through a 60-mesh screen to obtain a fine powder (90 µm). All analytical determinations were carried out in triplicate on each of three independently prepared extracts per species (n = 3 biological replicates × 3 technical replicates per treatment).

Total dietary (TDF), soluble (SDF), and insoluble (IDF) fiber

TDF, SDF, and IDF were quantified according to the methodology reported by Prosky *et al.* (1988). 14. 1 g (d.b.) of the sample (W_1) was placed in four Erlenmeyer flasks with 50 mL phosphate buffer (0.05 N) at pH 6. The flasks were placed in a boiling water bath at ~100 °C (10 min), 0.1 mL of α -amylase (Sigma A-3306, USA) was added, and they were incubated for 15 min by stirring (60 rpm). Once that time had elapsed, the samples were cooled, and the pH was adjusted to 7.5. The flasks were placed in a water bath at 60 °C (10 min). 0.1 mL of protease (Sigma P-3910, USA, 50 mg in 1 mL of phosphate buffer) was added to each flask and incubated for 30 min by stirring (60 rpm). The samples were cooled, the pH was adjusted to 4, and then they were returned to the water bath; 0.3 mL of amyloglucosidase (Sigma A-9913, USA) was added to each one and incubated for 30 min with stirring (60 rpm). Later, 95% ethanol was added at 60 °C in a 1:4 (v:v) ratio, and they were left to stand for 1 h. The samples from each flask were filtered in crucibles for dietary fiber (Bx) (previously prepared at constant weight and with 1 g of celite Sigma C-8656, USA). Each flask was washed three times with 20 mL of 78% ethanol, two times with 10 mL of 95% ethanol, and two times with 10 mL of acetone. These washes were filtered in their corresponding crucibles. The crucibles were placed in an oven at 130 °C for 1.5 h and subsequently weighed (W_2). Two of the crucibles were calcined in a muffle at 550

°C for 4 h (W_3), and the protein content was determined for the remaining two (W_4). The TDF was calculated as follows, as shown in equation 1.

$$TDF = \left(\frac{W_2 - W_3 - W_4 - B_x}{W_1} \right) \times 100 \quad [1]$$

The IDF was determined following the methodology described above but without the addition of 95% ethanol in a 1:4 ratio (v:v). SDF was obtained by calculating the difference between TDF and IDF (Prosky *et al.*, 1998).

Preparation of aqueous and ethanolic extracts from *Opuntia* spp. peels

To prepare the aqueous and ethanolic extracts of each of the *Opuntia* samples, the methodology reported by Madane *et al.* (2019) was used. For the process, 50 mg of each sample was weighed in a 2 mL Eppendorf tube; 1 mL of distilled water or 96% ethanol, depending on the extract to be made, was added to the peels of *O. albicarpa*, *O. megacantha*, *O. ficus indica*, *O. xocconostle*, *O. robusta*, and *O. undulata* for dissolution. The solutions were vortexed for 1 min and then centrifuged using a Fresco 17 microcentrifuge (Thermo Fisher Scientific, USA) at 4 °C at 1200 rpm for 15 min. The supernatant was recovered in a second 2 mL Eppendorf tube; subsequently, 1 mL of the solvent used was added again to the first tube, repeating the centrifugation process. The supernatant was recovered again and added to the first portion present in tube 2. Finally, 2 mL of each sample for both extracts were stored frozen until experimental determination.

Antioxidant capacity using DPPH (2,2-diphenyl-1-picrylhydrazyl)

A modification of the methodology reported by Shimada *et al.* (1992) was used to perform the *in vitro* antioxidant activity assay using the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical method. Two milligrams of DPPH (Sigma, 189866-4) were weighed, 10 mL of absolute ethanol were added, and the solution was stirred for 2 h at room temperature until the reagent was completely dissolved. In a 96-well microplate, 100 μ L of 0.5 mM DPPH reagent, 5 μ L of *Opuntia* extract, and 5 μ L of the solvent used in the sample (water or ethanol) were added. The mixture obtained was left to react for 30 min in the dark at room temperature. All determinations were performed in triplicate and measured on a Multiskan Spectrum microplate reader (Thermo Scientific LabSystems, USA, serial no.: 357-708179T) at 517 nm. As a control, 10 μ L of distilled water in 100 μ L of 0.5 mM DPPH and 5 μ g of butylated hydroxytoluene (BHT) (Sigma, 128-37-0) were used for both extracts. Free radical scavenging (FRS) was expressed as a percentage, calculated using equation 2:

$$\% FRS = \frac{(\text{Control Abs} - \text{Sample Abs})}{\text{Control Abs}} \times 100 \quad [2]$$

Antioxidant capacity using ABTS⁺ 2,2'-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid)

To determine *in vitro* antioxidant activity based on the ABTS⁺ cation (2,2'-azino-bis 3-ethylbenzothiazoline-6-sulfonic acid) (Sigma, 30931-67-0), an adaptation of the methodology reported by Floegel *et al.* (2011) was used. An eleven-point standard curve was performed in triplicate to obtain the equation of the line. A solution was prepared with 19.2 mg of ABTS⁺ and 5 mL of distilled water, to which 88 μ L of a potassium persulfate solution (Sigma, 7727-21-1) (0.378 mg in 10 mL of water) was added. The solution was incubated in a dark room at room temperature for 16 hours before use; subsequently, the ABTS⁺ cation was diluted to a pH of 7.4. The *Opuntia* samples were tested by

placing 5 μL of the aqueous or ethanolic extract in the wells of a microplate and adding 395 μL of a diluted ABTS⁺ solution prepared with 2.3 mL of a Trolox solution (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid) (Sigma, 53188-07-1), which was subsequently dissolved in 350 mL of 96% ethanol. The samples were incubated for 6 min at room temperature in a dark room; the measurement was performed in a Multiskan Spectrum microplate reader (Thermo Scientific Labsystems, USA, serial no.: 357-708179T) at a wavelength of 734 nm. Results were expressed as μmol trolox equivalent/g sample.

Oxidative discoloration of β -carotene

The β -carotene oxidative discoloration assay was included as a complementary lipid-phase antioxidant test since the activity of antioxidants in emulsion systems differs from that measured by radical-scavenging methods in homogeneous solutions; the use of multiple complementary assays is therefore recommended for multifunctional antioxidant samples (Frankel and Meyer, 2000). In the oxidative determination of β -carotene, a modification of the methodology reported by Marco (1968) was used. To prepare β -carotene (Sigma, 7235-40-7), 10 mg was weighed into a test tube and 1 mL of chloroform (Sigma, 67-66-3) was added; the mixture was shaken until completely dissolved. Subsequently, 20 mg of linoleic acid (Sigma-Aldrich, CAS 60-33-3) and 200 mg of Tween 20 (Sigma-Aldrich, CAS 9005-64-5) were added and mixed by vortexing. The chloroform was completely evaporated by applying a constant flow of N_2 gas. Immediately after solvent removal, 50 mL of aerated distilled water were added with vigorous agitation to form a stable emulsion. For the experimental study, 200 μL of the β -carotene solution and 5 μL of *Opuntia* extract (aqueous or ethanolic) were placed in the wells of a microplate. For the blank, β -carotene without sample and 5 μg of BHT (Sigma, 128-37-0) were used as the standard. β -carotene degradation was measured in a Multiskan Spectrum microplate reader (Thermo Scientific Labsystems, USA, serial no.: 357-708179T) at 450 nm every 15 min for 90 min. The percentage of antioxidant activity (%AA) was calculated using equations 3 and 4.

$$\% AA = \frac{(DR_b - DR_s)}{DR_b} \times 100 \quad [3]$$

Where DR_b = degradation rate of the blank, DR_s = degradation rate of the sample. The degradation rate was obtained using the following formula:

$$DR = \frac{\ln(a/b)}{t} \quad [4]$$

Where: a = absorbance at 0 min, b = absorbance at n min, and t = time (n min).

Phenols determination

To obtain the total polyphenol content, a modification of the technique established by Hui *et al.* (2021) was used. A stock solution was prepared for a standard eleven-point curve by weighing 1 mg/mL (w/v) of gallic acid (Sigma, 149-91-7) diluted in water or ethanol, depending on the extract to be evaluated. 0.5 μL of this solution was taken and 199.5 μL of water solvent was added, as well as 13 μL of Folin-Ciocalteu QP 0.2 M reagent (Sigma, F952) for the first point, with variation according to the concentration of the curve. The mixture was left in darkness for 6 minutes for the reaction to develop. Subsequently, 38 μL of 1.9 N Na_2CO_3 (Sigma, s2127) was added to each well and incubated at 40 °C for 30 min for subsequent reading. Absorbance was measured at 760 nm in a Multiskan Spectrum

microplate reader (Thermo Scientific Labsystems, USA, serial no.: 357-708179T). The polyphenol content of the *Opuntia* samples was determined using the same procedure as for the curve, replacing the stock solution with 5 μL of the extract. The results, obtained in triplicate, were calculated based on the standard curve and expressed as mg gallic acid equivalent per g of sample (mg GAE/g).

Total flavonoid content

Flavonoids were determined using an adaptation of the methodology developed by Lee *et al.* (2003), which consisted of performing a calibration curve using catechin (Sigma, 154-23-4) as a standard, dissolved in distilled water (1 mg/mL). Volumes ranging from 0 to 24 were taken and filled to 100 μL with distilled water. The *Opuntia* samples were diluted in distilled water in a 1:1 ratio. Then, 25 μL of 10% w/v NaNO_2 (Sigma, 7632-00-0) was added to 25 μL of each point on the curve and to the *Opuntia* extracts. After 5 min, 12.5 μL of $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$ (Sigma, 7784-13-6) at 10% w/v was added. After 6 min, 12.4 μL of 1.0 M NaOH was added to each sample and point on the curve. The determination was performed using a spectrophotometric procedure with a Multiskan Spectrum microplate reader (Thermo Scientific Labsystems, USA, serial number 357-708179T) at a wavelength of 490 nm. The calibration curve was used to calculate the total flavonoid content of the sample. The test was performed in triplicate; the results were expressed in g catechin/mL of extract. Subsequently, calculations were performed to obtain the mg catechin equivalent/100 g sample db.

Statistical analysis

The data obtained was analyzed using descriptive statistics with measures of central tendency and dispersion. For total, soluble, and insoluble dietary fiber, a one-way analysis of variance (ANOVA) was used, in which the independent variable was the *Opuntia* species and the response variable was the fiber content. A two-way ANOVA was used for the free radical scavenging, antioxidant activity, and total polyphenol and flavonoid content variables. The independent variables were the type of extract (aqueous or ethanolic) and the *Opuntia* species, including their two-way interaction (species \times solvent). A significant interaction indicates that the effect of extraction solvent differs across species and vice versa. When the interaction was significant ($p < 0.05$), pairwise comparisons were conducted using Duncan's multiple range test. Prior to ANOVA, normality of residuals was confirmed using the Shapiro-Wilk test, and homogeneity of variances was verified with Levene's test (both at $\alpha = 0.05$). A significance level of $\alpha = 0.05$ was applied to all tests. Analyses were performed using Statgraphics Centurion XV software.

Results and Discussion

The following discussion compares peel-specific results with published values for the same or related *Opuntia* fractions. Where reference studies used whole fruit, pulp, cladodes, or seeds rather than isolated peel, the plant fraction is indicated explicitly in parentheses. Peel-specific comparisons were preferred when available.

Table 1 shows the results obtained for fiber content in the different *Opuntia* species tested. Statistical analysis showed a significant difference ($p < 0.05$) in total dietary fiber content among the six species, with *O. robusta* showing the highest content (60.22% d.b.) compared to the other cactus species. The *Opuntia* species that showed the lowest total fiber content was *O. xocconostle* (47.58%), though this value was higher than that reported for the same species in a study done with the whole fruit, including the peel, by Arias-Rico *et al.* (2020) with 30.8%. Similarly, *O. albicarpa* (45.35%) had the lowest total

dietary fiber content compared to the other species studied, but the value obtained was higher than the 19.09–24.72% total dietary fiber reported by Manzur-Valdespino *et al.* (2022) for three cultivars of *O. ficus-indica* peel (Amaya-Cruz *et al.*, 2019). This difference is likely attributable to the air-drying (50 °C) used in that study versus the freeze-drying protocol of the present work.

Table 1. Total (TDF), insoluble (IDF), and soluble (SDF) dietary fiber content (% dry basis, d.b.) of freeze-dried peel from six *Opuntia* species.

<i>Opuntia</i> species	Total dietary fiber	Insoluble dietary fiber (%) in d.b.	Soluble dietary fiber
<i>O. albicarpa</i>	45.35 ± 0.72 ^{f*}	34.56 ± 0.61 ^e	10.79 ± 0.48 ^d
<i>O. megacantha</i>	49.84 ± 0.93 ^d	37.15 ± 0.44 ^d	12.69 ± 0.65 ^{b,c}
<i>O. ficus-indica</i>	55.73 ± 1.01 ^b	41.67 ± 0.58 ^b	14.06 ± 0.44 ^a
<i>O. xocconostle</i>	47.58 ± 0.66 ^e	35.61 ± 0.67 ^e	11.97 ± 0.37 ^c
<i>O. robusta</i>	60.22 ± 0.91 ^a	45.48 ± 0.87 ^a	14.75 ± 0.79 ^a
<i>O. undulata</i>	52.41 ± 0.77 ^c	39.39 ± 0.70 ^c	13.02 ± 0.53 ^b

*Values are means ± standard deviation (SD; n = 3 independent biological replicates). Different superscript letters within each column indicate significant differences among species ($p < 0.05$) according to Duncan's multiple range test following one-way ANOVA.

Statistical analysis showed a significant difference ($p < 0.05$) in the insoluble dietary fiber content between *O. robusta* (45.48% d.b.) and the other *Opuntia* species, with *O. albicarpa* (34.46% d.b.) and *O. xocconostle* (35.61% d.b.) showing the lowest content. However, there was no significant difference between these last two species ($p > 0.05$). In the case of *O. ficus-indica*, its peel provided a significant amount of insoluble fiber (41.67%), showing a greater impact when compared to the results obtained by Arias-Rico *et al.* (2020), who conducted a study with Wistar rats supplemented with fiber from this species for four weeks, demonstrating an acceleration of intestinal transit, likely due to the fiber's inability to dissolve in water.

The results indicated that there were no significant differences ($p < 0.05$) in soluble dietary fiber content between the species *O. ficus-indica* (14.06%) and *O. robusta* (14.75%), with the latter having the highest soluble fiber content of all the species tested. These fiber values support the use of *Opuntia* peel in the production and fortification of food products, nutraceuticals, and functional foods. *O. albicarpa* was the species with the lowest soluble fiber content (10.79%), which was consistent with the lowest percentage of insoluble fiber, meaning that this species is deficient in comparison with other *Opuntia* species.

Although *O. xocconostle* had one of the lowest soluble and insoluble fiber contents in this study, the results were superior to those presented by Arias-Rico *et al.* (2020), with 8.2% soluble fiber and 22.6% insoluble fiber for this same species. The difference in values was probably because the Arias-Rico study used the whole *Opuntia* fruit, while the current study used only the peel, which contains mainly complex polysaccharides (Ortega *et al.* 2025), such as fiber. Based on the results for each of the *Opuntia* species analyzed, the peel could be used as a source of fiber since, according to the FDA (2024), the recommended daily intake (RDI) associated with benefits for a healthy life is 38 g for men and 25 g for women. It could also be used as an adjunct in the clinical area as a supplement (Lambeau and McRorie, 2017) or as a food ingredient since this structural polysaccharide promotes proper digestive health, motility, and intestinal transit (Ioniță-Mîndrican, 2022).

Antioxidant capacity using DPPH

The results showed a statistically significant difference ($p < 0.05$) when the *Opuntia* species and the type of extract (aqueous or ethanolic) interacted. Figure 1 shows that, except for *O. ficus-indica*, the aqueous extracts of the other five species had a higher free radical scavenging percentage (%FRS) than the ethanolic extracts. The greatest effect caused by this extract may have been attributed to the polarity of the solvent since water has a greater interaction with the bioactive compounds present in the peels of the cacti tested. Therefore, according to the findings of Santana-Farré *et al.* (2025), the antioxidant activity could be affected by the type of solvent used in the extraction of bioactive compounds. It has been suggested that extracts with more polar solvents tend to demonstrate greater antioxidant activity compared to non-polar solvents or solvents of intermediate polarity like ethanol.

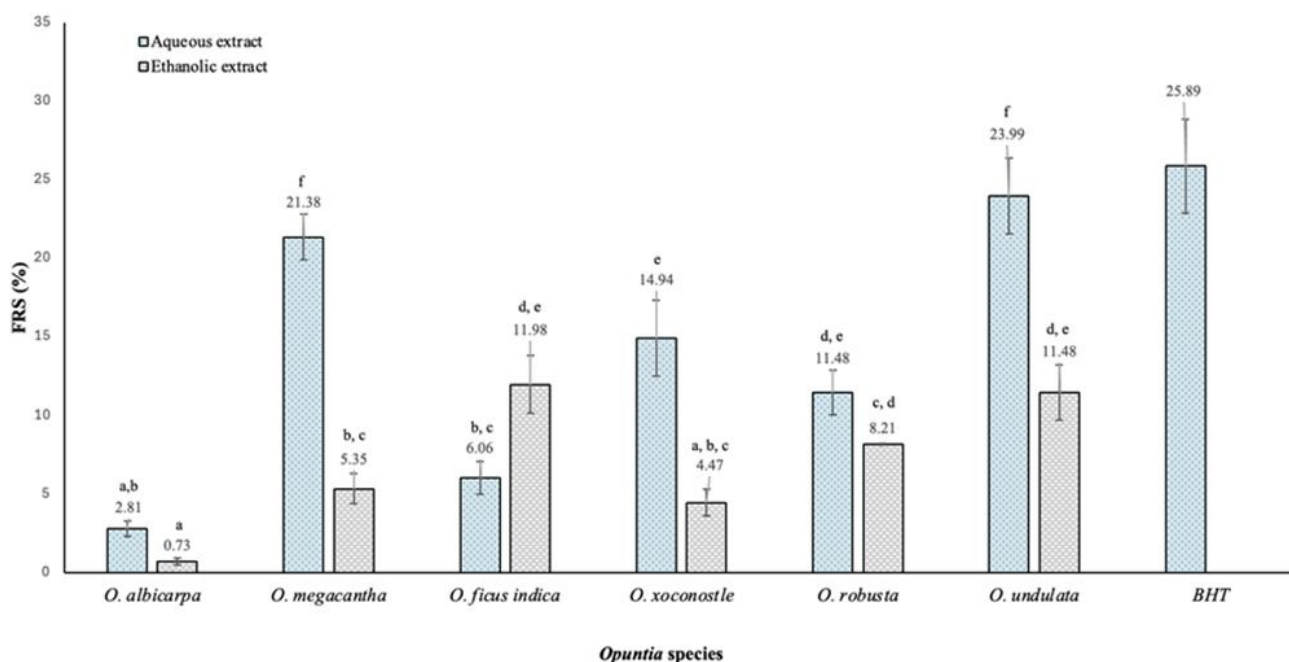


Figure 1. Free radical scavenging activity (% FRS) of aqueous and ethanolic extracts from freeze-dried peels of six *Opuntia* species, determined by the DPPH (2,2-diphenyl-1-picrylhydrazyl) method. 5 μ g BHT (butylated hydroxytoluene) was included as a positive control. Values are means \pm SD ($n = 3$). Different letters above bars indicate significant differences among species and extract types ($p < 0.05$) according to Duncan's multiple range test following a two-way ANOVA (species \times solvent interaction).

No significant differences ($p > 0.05$) were found between the values of *O. megacantha* (21.38%) and *O. undulata* (23.99%) for the aqueous extract, which were the highest of all treatments, nor was any difference observed between them and the butylated hydroxytoluene (BHT) used as a standard. The equivalence to BHT suggests that aqueous peel extracts from these two species have strong radical-scavenging capacity, consistent with *in vitro* evidence linking the antioxidant activity of *Opuntia* extracts with potential protection against oxidative stress-related damage (Muscolo, 2024).

The effect presented by *O. megacantha* and *O. undulata* was greater than that established by Alsaad and Mohammed (2021), in which ethanol was used to produce extracts from the peel of the *O. dillenii* species (20.7% FRS). This lower value of the aqueous extract and behavior is consistent with the

intermediate polarity effect presented by ethanol, as established by Santana-Farré *et al.* (2025). The study by Alsaad and Mohammed (2021) also demonstrated a 25% FRS for the pulp of *O. dillenii* fruit, which was higher than that demonstrated by the peels in both studies. This suggests that both morphological structures offer a significant antioxidant effect, confirming that the peel retains functionally relevant antioxidant activity. Recovering these compounds from agri-food waste reduces post-harvest losses while providing natural antioxidant ingredients for food and nutraceutical applications (Lee *et al.*, 2003).

Antioxidant effect using ABTS

Figure 2 shows that there was a statistically significant difference ($p < 0.05$) when the species and the type of extract used in the study interacted. For the antioxidant activity of the six *Opuntia* species tested, the aqueous extract was greater than the ethanolic extract. However, for the *O. undulata* species, there was no significant difference ($p > 0.05$) between the two extracts; this would indicate that, regardless of the type of solvent used in the extraction, this species demonstrates a significant antioxidant effect.

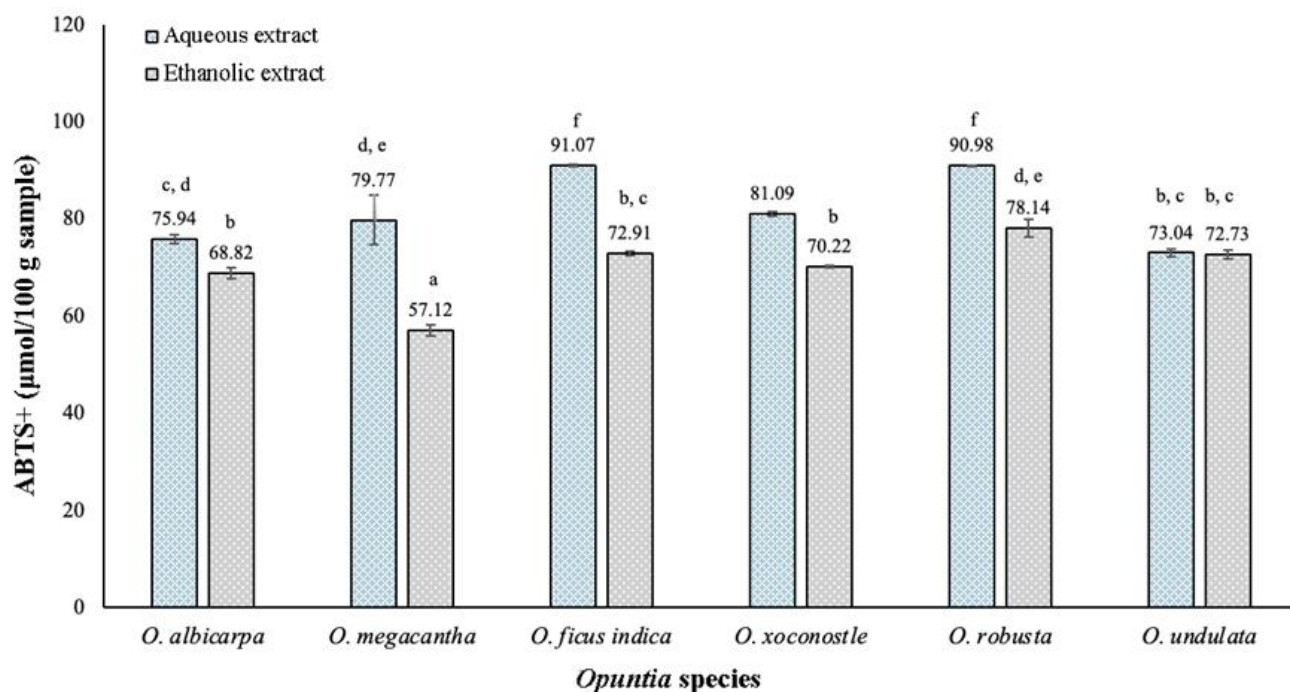


Figure 2. Antioxidant capacity ($\mu\text{mol Trolox equivalents}/100 \text{ g d.b.}$, $\mu\text{mol TE}/100 \text{ g}$) of aqueous and ethanolic extracts from freeze-dried peel of six *Opuntia* species, determined by the ABTS⁺ (2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) radical cation decolorization method. Values are means \pm SD ($n = 3$). Different letters above bars indicate significant differences among species and extract types ($p < 0.05$) according to Duncan's multiple range test following a two-way ANOVA (species \times solvent interaction).

The ability of the bioactive compounds in the aqueous extract of *O. ficus-indica* and *O. robusta* (91.07 and 90.98 $\mu\text{mol TE}/100 \text{ g}$, respectively) to neutralize ABTS⁺ radicals was statistically similar ($p < 0.05$), demonstrating the greatest antioxidant effect and coinciding with the higher fiber contents mentioned above. The variability observed in the results could be associated with how, even within the same genus, antioxidant activity can differ significantly between species. This is consistent with a study

conducted by Yeddes *et al.* (2013), who compared the antioxidant activity in the peel and pulp of three different *Opuntia* species, establishing significant differences between the samples studied. This study also suggested that antioxidant capacity is determined by factors such as the concentration of bioactive compounds, reactivity toward radicals, and the distribution and destination of radicals derived from exogenous antioxidants (Yeddes *et al.* 2013).

In the present study, ABTS antioxidant capacity ranged from 57.12 to 91.07 $\mu\text{mol TE}/100\text{ g d.b.}$ These values are lower than the 529 $\mu\text{mol TE}/100\text{ g}$ reported by Manzur-Valdespino *et al.* (2022) for *O. ficus-indica* peel, likely reflecting their use of methanol as extraction solvent. The present values did exceed those reported by Andreu *et al.* (2017) for cladodes and whole fruits (13.74–35.40 $\mu\text{mol TE}/100\text{ g}$). Seeds from different species of *Opuntia*, also considered waste, were used, showing values of 9.97–11.67 $\mu\text{mol TE}/100\text{ g}$ (Kolniak-Ostek *et al.*, 2020). Taken together, these results from different cactus structures indicate that current research has demonstrated a high antioxidant effect when using only the fruit peels. *In vitro* results revealed that *Opuntia* peels, considered a by-product, could provide a significant antioxidant effect and probable benefit to human health.

Discoloration of β -carotene

The results of the β -carotene test indicated that there was no significant difference ($p < 0.05$) between *Opuntia* species during the discoloration period. Figure 3a shows that the percentage of antioxidant activity fluctuated between 88 and 91%, indicating a high effect, even greater than that of the BHT used as a reference. It is important to mention that the persistence of the orange color during the test period is indicative of the absence of discoloration of the sample, suggesting a good antioxidant effect. In the case of the ethanolic extract, the behavior was the opposite compared to the aqueous extract since the antioxidant activity fluctuated between 15 and 20% for all species (Fig. 3b), except for *O. undulata*, which was lower (7–14%). The values were even almost half the effect evidenced by the standard (BHT), reaffirming the greater effect caused by the aqueous extract.

The marked superiority of aqueous extracts over ethanolic extracts in the β -carotene discoloration assay (88–91% vs. 15–20% antioxidant activity inhibition, respectively) can be explained by the physicochemical behavior of antioxidants in emulsion systems. Frankel and Meyer (2000) described the 'polar paradox': in oil-in-water emulsions, such as the Tween 20/ β -carotene/linoleic acid system used in this assay, hydrophilic antioxidants concentrate at the oil-water interface and can be more effective than lipophilic antioxidants, which remain partitioned into the oil phase. Because aqueous extracts recover predominantly polar phenolic acids, flavonoid glycosides, and betalains, these compounds are more likely to interact at the interface of the emulsion and inhibit lipid oxidation than the less polar compounds recovered by ethanol. According to the findings by Tunç *et al.* (2025) in a study with *O. ficus-indica*, a positive correlation was observed between the high percentage of β -carotene and the antioxidant effect presented by the *Opuntia* fruit. This could be extrapolated to the current study with *O. ficus-indica* peels and other species since there was no statistically significant difference ($p > 0.05$), validating the functional effect of the carotenoid present in this by-product.

The high content of β -carotene found in the aqueous extract of the peels of the six species evaluated suggests a possible clinical application due to the beneficial effects associated with this compound. β -carotene is the main carotenoid that acts as a precursor to vitamin A and plays an important role in preventing certain diseases, including neurodegenerative disorders, heart disease, and lung cancer (Tunç *et al.* 2025). Accordingly, the results obtained from the DPPH and ABTS⁺ assays, which show

remarkable antioxidant activity, support the possible protective effects of β -carotene against the development of cancer.

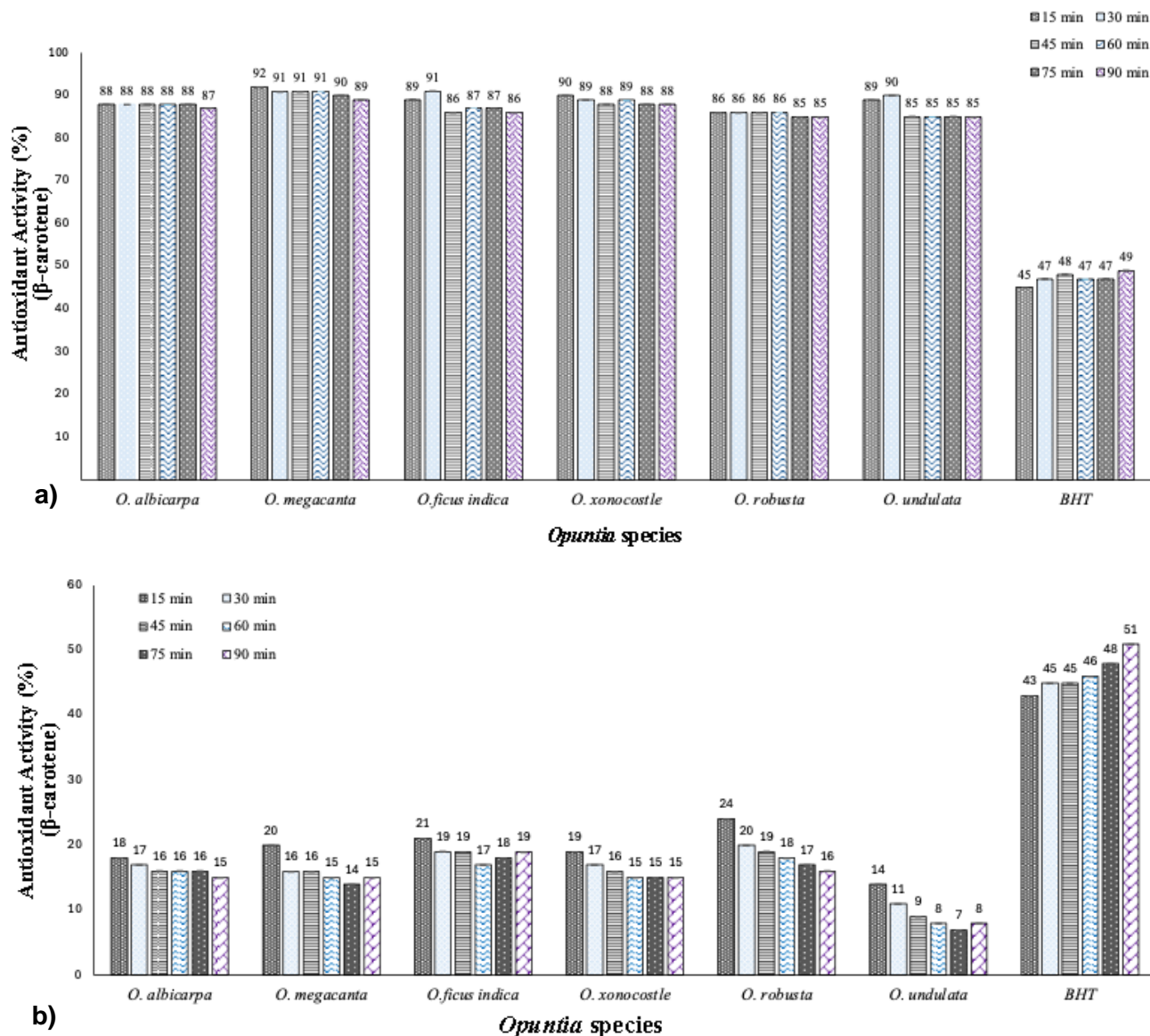


Figure 3. Oxidative discoloration inhibition of β -carotene (%AA, antioxidant activity) by (a) aqueous and (b) ethanolic extracts from freeze-dried peel of six *Opuntia* species, measured at 450 nm over 90 min. 5 μ g BHT was included as a positive control. Values are means \pm SD ($n = 3$); error bars are not visible at this scale due to low inter-replicate variability ($SD < 1\%$). No significant differences were found among species for the aqueous extract ($p > 0.05$); for the ethanolic extract, *O. undulata* showed significantly lower inhibition compared to the remaining five species ($p < 0.05$), according to Duncan's multiple range test.

Polyphenols content

The total phenol content present in the six different species studied can be seen in Figure 4. Statistically significant differences ($p < 0.05$) were found when the type of extract and the six *Opuntia* species interacted. Aqueous extracts showed higher total polyphenol content compared to the

ethanolic extracts, with the latter showing no statistically significant difference between the *Opuntia* species ($p > 0.05$). The ethanolic extracts showed no significant interspecific differences in polyphenol content, indicating that ethanol was an ineffective solvent for extracting these compounds from the peel matrix. The higher polyphenol recovery in aqueous extracts is consistent with the polar nature of the predominant phenolic acids and flavonoid glycosides in *Opuntia* peels, as well as the known association between dietary fiber and bound phenolic compounds. Bound phenolics, which are covalently linked to cell wall polysaccharides and are more accessible with aqueous or alkaline extraction, can account for up to 24% of total phenolics in plant matrices (Acosta-Estrada *et al.*, 2014). This may particularly apply to high-fiber species such as *O. robusta*, where a larger fraction of polyphenols may be bound to the fiber matrix. The solvent-dependent difference has been further attributed to extraction conditions, solvent type, and sample characteristics (Chaves *et al.*, 2020).

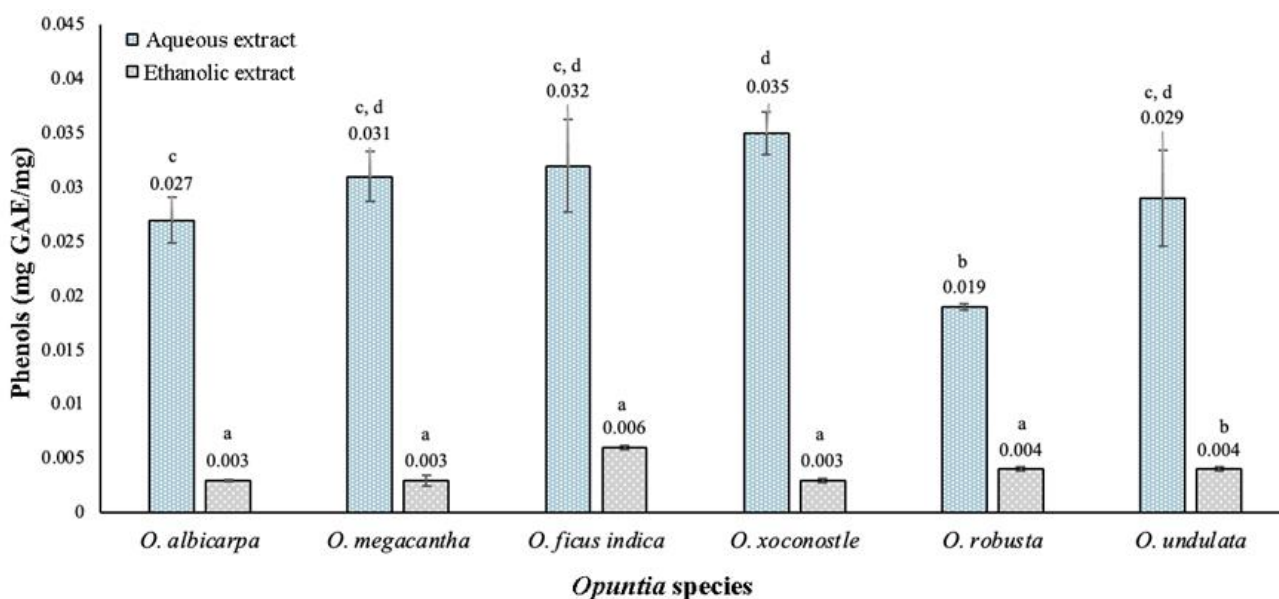


Figure 4. Total polyphenol content (mg gallic acid equivalents per gram dry basis, mg GAE/g d.b.) of aqueous and ethanolic extracts from freeze-dried peel of six *Opuntia* species, determined by the Folin-Ciocalteu method. Values are means \pm SD ($n = 3$). Different letters above bars indicate significant differences among species and extract types ($p < 0.05$) according to Duncan's multiple range test following a two-way ANOVA (species \times solvent interaction).

The phenol content of the aqueous extract of the six species evaluated (19-35 mg GAE/g d.b., converting from the reported mg GAE/mg units) were comparable to those reported by Amaya-Cruz *et al.* (2019) for three cultivars of *O. ficus-indica* peel (8.62–12.28 mg GAE/g d.b.) and higher than those reported by Valencia-Áviles *et al.* (2024) for the ethanolic extract of *O. streptacantha* peels (0.019 mg GAE/mg and 0.014 mg GAE/mg with the aqueous extract of the same plant structure). These results revealed that the *Opuntia* species in the current study probably had a higher content of bioactive compounds compared to the metabolites found in the peels of *O. streptacantha*.

The statistical results confirmed that there was no significant difference ($p < 0.05$) in the aqueous extracts between the species *O. megacantha*, *O. ficus-indica*, *O. undulata*, and *O. xocconostle*, the latter demonstrating the highest content of this compound. The presence of phenols, including the *O. xocconostle* extract (0.035 mg GAE/mg of sample), was lower compared to that found by Reis *et al.*

(2017), who found average values of 0.063 mg GAE/mg and that by Tunç *et al.* (2025), with values averaging 0.068 mg GAE/mg. These variations are likely due to the current study using only the fiber, whereas the reference studies used the whole fruit with the peel, in addition to using organic solvents such as methanol and hexane to obtain the extract. Polyphenols, secondary metabolites present in certain species of the *Opuntia* genus, protect plants against oxidative stress and may also prevent certain diseases in humans (Reis *et al.*, 2017). Therefore, the findings in *Opuntia* species are significant because, in addition to being obtained from a waste product, they may have important applications in the food industry and in the health sector.

Total flavonoid content

Statistical analyses showed a statistically significant difference ($p < 0.05$) when the type of extract and the *Opuntia* species tested interacted (Figure 5). Variability in the results was observed. For the aqueous extract, the highest flavonoid content was found in the *O. undulata* species (16.02 mg CE/100 g); however, there was no significant difference with the ethanolic extract (16.37 mg CE/100 g). In the case of the ethanolic extract, the highest content was found in the species *O. ficus-indica* (17.39 mg CE/100 g), which was the sample with the highest flavonoid content among the six species and both extracts. This variability is consistent with broad interspecific differences in flavonoid content documented across *Opuntia* species and cultivars (Amaya-Cruz *et al.*, 2019; Ramírez-Ramos *et al.*, 2018; Tunç *et al.*, 2025), which reflect the influence of species identity, planting location, fruit pigmentation, and growing conditions on the qualitative and quantitative flavonoid profile.

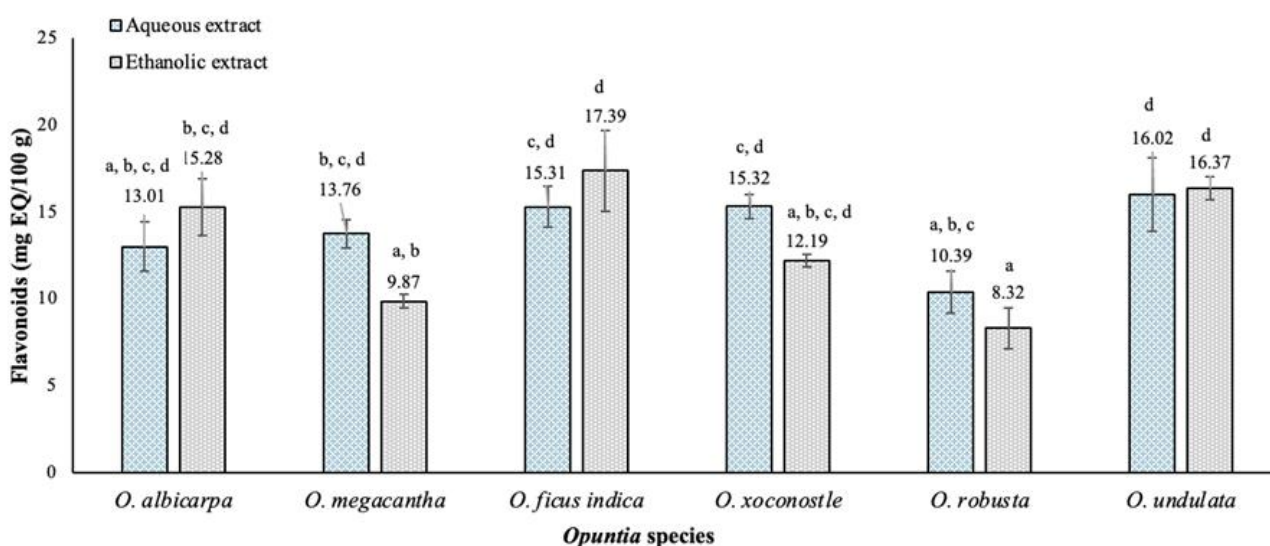


Figure 5. Total flavonoid content (mg catechin equivalents per 100 g d.b., mg CE/100 g d.b.) of aqueous and ethanolic extracts from freeze-dried peel of six *Opuntia* species, determined by the aluminum chloride colorimetric method. Values are means \pm SD ($n = 3$). Different letters above bars indicate significant differences among species and extract types ($p < 0.05$) according to Duncan's multiple range test following a two-way ANOVA (species x solvent interaction).

Ethanolic extracts showed higher flavonoid content than aqueous extracts in most species. This trend is in line with what is established by Chaves *et al.* (2020) regarding the efficiency of the solvent used in the extraction of phenolic compounds such as flavonoids. This research indicated that, for this determination, solvents such as ethanol tend to extract compounds such as flavonoids more efficiently

than water, due to the intermediate polarity of alcohol and its ability to form hydrogen bonds with the solute.

The overall flavonoid content in the present study ranged from 8.32 to 17.39 mg CE/100 g, which was consistent with that reported by Ramírez-Ramos *et al.* (2018) in a study of the fruits and peels of eleven varieties of *Opuntia* sp., where these researchers demonstrated a flavonoid content that fluctuated between 1.34 and 27.27 mg QE/100g. The results of the present study were close to those evidenced by Tunç *et al.* (2025), who demonstrated a flavonoid content ranging from 5.11 to 30.80 mg QE/100 g present in the *Opuntia* fruits evaluated. The results of both studies lend greater relevance to the current study considering that, although the peels are a by-product, the flavonoid content was like that found in the whole fruit, revealing the importance of using certain plant components that are considered waste.

These findings could also be compared with other by-products, such as *Opuntia* seeds. Research conducted by Kolniak-Ostek *et al.* (2020) showed a fluctuation in total flavonoid content from 0.069 to 0.266 mg QE/100 g; these results indicate that the seeds apparently have a lower flavonoid content compared to *Opuntia* peels. This could further enhance the effect of the peels evaluated, making them a potential candidate for application in the food industry as a functional food or nutraceutical, as well as in the health sector as a possible complement to patented treatments.

Conclusions

The peels of six species of *Opuntia* (*O. albicarpa*, *O. megacantha*, *O. ficus-indica*, *O. xocostle*, *O. robusta*, and *O. undulata*) are a viable and largely underutilized source of dietary fiber and bioactive compounds. This study provides the first systematic comparison of peel phytochemistry across these six species using both aqueous and ethanolic extractions and demonstrates significant species \times solvent interactions for all bioactivity variables. *O. robusta* and *O. ficus-indica* stood out for their high total, soluble, and insoluble fiber content, making them strong candidates as functional fiber ingredients for food fortification and gastrointestinal health applications. The polyphenol and flavonoid content, combined with strong radical-scavenging activity in several species, supports the use of these peels as natural antioxidant ingredients. *In vitro* evidence from the present study aligns with the functional properties reported for other *Opuntia* fractions and by-products.

Antioxidant activity showed that aqueous extracts generally performed better than ethanolic extracts, in several cases matching or exceeding BHT, the synthetic reference antioxidant. This behavior highlights the efficiency of water as a green solvent for the extraction of bioactive compounds, promoting sustainable and safe strategies for applications in foods intended for human consumption. The variability observed between species and types of extract shows that species selection matters: the best candidate for fiber enrichment (*O. robusta*) is not the same as the best for antioxidant applications (*O. megacantha*, *O. undulata*), which has practical implications for ingredient sourcing. Using peel by-products opens concrete opportunities for developing new functional ingredients, dietary supplements, and plant-based food products enriched with *Opuntia* peel fractions.

ETHICS STATEMENT

Not applicable. This study did not involve human participants, human data, human tissue, or animals.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF SUPPORTING DATA

All data generated or analyzed during this study are included in this published.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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AUTHOR CONTRIBUTIONS

I.S.-C.: Conceptualization, Methodology, Formal analysis, Investigation. D.B.-A.: Methodology, Data Curation, Writing - Original Draft, Writing - Review & Editing. L.A.C.-G.: Methodology, Data Curation, Writing - Original Draft, Writing - Review & Editing. C. J.-M.: Plant material, Methodology, Validation, Visualization. J.V.-P: Methodology, Writing - Review & Editing, Funding acquisition. S.G.-T.: Conceptualization, Supervision, Methodology, Project administration.

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References

- Acosta-Estrada, B.A., Gutiérrez-Urbe, J.A. and Serna-Saldívar S.O. 2014. Bound phenolics in foods, a review. *Food Chemistry*. 152:46-55. <https://doi.org/10.1016/j.foodchem.2013.11.093>
- Alaiz, M., Girón-Calle, J., Garzón, A., Castro, C., Drago, S., Jimenez-Martínez, C. and Vioque, J. 2025. Total and free amino acids composition of the peel and pulp from the fruits of seven Mexican *Opuntia* species. *International Journal of Food Properties*. 28(1):2512952. <https://doi.org/10.1080/10942912.2025.2512952>
- Alsaad, A. and Mohammed, L. 2021. Study of the antioxidant activity of cactus (*Opuntia dillenii*) Fruits (Pulp and peels) and characterization of their bioactive compounds by GC-MS. *Basrah Journal of Agricultural Sciences*. 34(2):204-219. <https://doi.org/10.37077/25200860.2021.34.2.16>
- Alshaikhi, A., Alzahrani, M., Hazzazi, J., Kurdi, J. and Ramadan, F. 2023. Nutritional aspects, bioactive phytochemicals and biomedical traits of *Opuntia* spp.: current trends and applications. *Journal of Umm Al-Qura University for Applied Sciences*. 10(2):367-378. <https://doi.org/10.1007/s43994-023-00101-1>
- Amaya-Cruz, D.M., Pérez-Ramírez, I.F., Delgado-García, J., Mondragón-Jacobo, C., Dector-Espinoza, A. and Reynoso-Camacho, R. 2019. An integral profile of bioactive compounds and functional properties of prickly pear (*Opuntia ficus indica* L.) peel with different tonalities. *Food Chemistry*. 278:568-578. <https://doi.org/10.1016/j.foodchem.2018.11.031>

- Andreu, L., Nuncio-Jáuregui, N., Carbonell-Barrachina, Á.A., Legua, P. and Hernández, F. 2017. Antioxidant properties and chemical characterization of Spanish *Opuntia ficus-indica* Mill. cladodes and fruits. *Journal of The Science of Food and Agriculture*. 98(4):1566-1573. <https://doi.org/10.1002/jsfa.8628>
- Arias-Rico, J., Del Socorro Cruz-Cansino, N., Cámara-Hurtado, M., López-Froilán, R., Pérez-Rodríguez, M, De Cortes, M., Sánchez-Mata, M., Jaramillo-Morales, O., Barrera-Gálvez, R. and Ramírez-Moreno, E. 2020. Study of xoconostle (*Opuntia* spp.) powder as source of dietary fiber and antioxidants. *Foods*. 9(4):403. <https://doi.org/10.3390/foods9040403>
- Aruwa, C., Amoo, S. and Kudanga, T. 2018. Opuntia (Cactaceae) plant compounds, biological activities and prospects – A comprehensive review. *Food Research International*. 112: 328-344. <https://doi.org/10.1016/j.foodres.2018.06.047>
- Bhardwaj, A., Thakur, B. and Aljulaih, A. 2025. Recent advances in valorizing agricultural waste: a sustainable approach. *Waste and Biomass Valorization*. <https://doi.org/10.1007/s12649-025-03419-5>
- Chaves, J., De Souza, M., Da Silva, L., Lachos-Perez, D., Torres-Mayanga, P., Da Fonseca Machado, A., Forster-Carneiro, T., Vázquez-Espinosa, M., González-De-Peredo, A., Fernández-Barbero, G. and Rostagno, M. 2020. Extraction of flavonoids from natural sources using modern techniques. *Frontiers In Chemistry*. 8:507887. <https://doi.org/10.3389/fchem.2020.507887>
- Corral-Martínez, J., Mascorro-Gallardo, J., De la O J., López-Reynoso, J. and Valadez-Moctezuma, E. 2025. Transcriptomic analysis of the development of *Opuntia albicarpa* fruits in relation to carbohydrate metabolism and flavonoid biosynthesis. *Journal of the Professional Association for Cactus Development*. 27. <https://doi.org/10.56890/jpacd.v27i.590>
- El-Beltagi, H., Ahmed, A., Mohamed, H., Al-Otaibi, H., Ramadan, K. and Elkatry, H. 2023. Utilization of prickly pear peels flour as a natural source of minerals, dietary fiber and antioxidants: Effect on cakes production. *Agronomy*. 13(2):439. <https://doi.org/10.3390/agronomy13020439>
- Floegel, A., Kim, D., Chung, S., Koo, S. and Chun, O. 2011. Comparison of ABTS/DPPH assays to measure antioxidant capacity in popular antioxidant-rich US foods. *Journal of Food Composition and Analysis*. 24(7):1043-1048. <https://doi.org/10.1016/j.jfca.2011.01.008>
- Food and Drug Administration (FDA). 2024. The nutrition facts Label.
- Frankel, E.N. and Meyer, A.S. 2000. The problems of using one-dimensional methods to evaluate multifunctional food and biological antioxidants. *Journal of the Science of Food and Agriculture*, 80(13):1925–1941. [https://doi.org/10.1002/1097-0010\(200010\)80:13<1925::AID-JSFA714>3.0.CO;2-4](https://doi.org/10.1002/1097-0010(200010)80:13<1925::AID-JSFA714>3.0.CO;2-4)
- Garzón, A.G., Cian, R.E., Jiménez-Martínez, C., Girón-Calle, J., Vioque, J. and Drago, S.R. 2025. Effects of gastrointestinal pH on the bioactivity of fruit peel extracts rich in betalains and polyphenols from six *Opuntia* species. *International Journal of Food Science and Technology*. 60(2):vvaf180. <https://doi.org/10.1093/ijfood/vvaf180>

- Hui, X., Wu, G., Han, D., Gong, X., Wu, X., Tang, S., Brennan, M. and Brennan, C. 2021. The effects of bioactive compounds from blueberry and blackcurrant powder on oat bran pastes: enhancing *in vitro* antioxidant activity and reducing reactive oxygen species in lipopolysaccharide-stimulated Raw264.7 macrophages. *Antioxidants*. 10(3):388. <https://doi.org/10.3390/antiox10030388>
- Ioniță-Mîndrican, C., Ziani, K., Mititelu, M., Oprea, E., Neacșu, S., Moroșan, E., Dumitrescu, D., Roșca, A., Drăgănescu, D. and Negrei, C. 2022. Therapeutic benefits and dietary restrictions of fiber intake: a state-of-the-art review. *Nutrients*. 14(13):2641. <https://doi.org/10.3390/nu14132641>
- Kolniak-Ostek, J., Kita, A., Miedzianka, J., Andreu-Coll, L., Legua, P. and Hernandez F. 2020. Characterization of bioactive compounds of *Opuntia ficus-indica* (L.) Mill. seeds from spanish cultivars. *Molecules*. 25(23):5734. <https://doi.org/10.3390/molecules25235734>
- Lambeau, K. and McRorie, J. 2017. Fiber supplements and clinically proven health benefits: How to recognize and recommend an effective fiber therapy. *Journal of the American Association of Nurse Practitioners*. 29(4):216-223. <https://doi.org/10.1002/2327-6924.12447>
- Lee, K., Kim, Y., Lee, H. and Lee, C. 2003. Cocoa has more phenolic phytochemicals and a higher antioxidant capacity than teas and red wine. *Journal of Agricultural and Food Chemistry*. 51(25):7292–7295. <https://doi.org/10.1021/jf0344385>
- Madane, P., Das, A., Nanda, P., Bandyopadhyay, S., Jagtap, P., Shewalkar, A. and Maity, B. 2019. Dragon fruit (*Hylocereus undatus*) peel as antioxidant dietary fiber on quality and lipid oxidation of chicken nuggets. *Journal of Food Science and Technology*. 57(4):1449-1461. <https://doi.org/10.1007/s13197-019-04180-z>
- Manzur-Valdespino, S., Arias-Rico, J., Ramírez-Moreno, E., Sánchez-Mata, M. de C., Jaramillo-Morales, O.A., Angel-García, J., Zafra-Rojas, Q.Y., Barrera-Gálvez, R. and Cruz-Cansino, N. del S. 2022. Applications and pharmacological properties of cactus pear (*Opuntia* spp.) peel: A review. *Life*. 12(11):1903. <https://doi.org/10.3390/life12111903>
- Marco, G. 1968. A rapid method for evaluation of antioxidants. *Journal of the American Oil Chemist's Society*. 45(8):594-598. <https://doi.org/10.1007/BF02668958>
- Milán-Noris, A., Chavez-Santoscoy, R., Olmos-Nakamura, A., Gutiérrez-Urbe, J. and Serna-Saldívar, S. 2016. An extract from prickly pear peel (*Opuntia ficus-indica*) affects cholesterol excretion and hepatic cholesterol levels in hamsters fed hyperlipidemic diets. *Current Bioactive Compounds*. 12(1):10-16. <https://doi.org/10.2174/1573407212666151231183553>
- Moussaoui, B., Rahali, A., Bouamar, S. and Riazi, A. 2020. Biological properties of betalains extracted from inermis nopals of Algerian *Opuntia ficus indica* (L.). *South Asian Journal of Experimental Biology*. 10(4):234-242. [https://doi.org/10.38150/sajeb.10\(4\).p234-242](https://doi.org/10.38150/sajeb.10(4).p234-242)
- Muscolo, A., Mariateresa, O., Giulio, T. and Mariateresa, R. 2024. Oxidative Stress: The role of antioxidant phytochemicals in the prevention and treatment of diseases. *International Journal of Molecular Sciences*. 25(6):3264. <https://doi.org/10.3390/ijms25063264>
- Ortega, C., Loza, S., Gómez, D., Ochoa, C. and Aparicio, X. 2025. Chemical and antioxidant analysis of peels from two red-purple cactus pears (*Opuntia streptacantha*) from Altos Norte of Jalisco, Mexico. *Journal of the Professional Association for Cactus Development*. 27:81-101. <https://doi.org/10.56890/jpacd.v27i.568>

- Prosky, L., Asp, N., Schweizer, T., DeVries, J. and Furda, I. 1988. Determination of insoluble, soluble and total dietary fiber in foods and food products: interlaboratory study. *Journal of the Association of Official Analytical Chemists*. 71(5):1017-1023. <https://doi.org/10.1093/jaoac/71.5.1017>
- Ramadan, M., Ayoub, T. and Rohn, S. 2021. *Opuntia* spp.: Chemistry, bioactivity and industrial applications. Springer. <https://doi.org/10.1007/978-3-030-78444-7>
- Ramírez-Ramos, M., Medina-Dzul, K., García-Mateos, R., Corrales-García, J., Ybarra-Moncada, C. and Castillo-González, A. 2018. Nutraceutical components, antioxidant activity and color of eleven varieties of prickly pear (*Opuntia* sp.). *Journal of Applied Botany and Food Quality*. 91:211-218. <https://doi.org/10.5073/10.5073/JABFQ.2018.091.028>
- Reis, C., Gouveia, C., Vitorino, M., Gazarini, L., Ribeiro, M. and Peres, M. 2017. Bioactive compounds and morphology in *Opuntia* spp. fruits from Portuguese ecotypes. *Bulgarian Journal Agricultural Science*. 23(6):929-938.
- Santana-Farré, R., Buset-Ríos, N. and Makran, M. 2025. Antioxidant potential of *Opuntia dillenii*: A systematic review of influencing factors and biological efficacy. *Nutraceuticals*. 5(3):22. <https://doi.org/10.3390/nutraceuticals5030022>
- Shimada, K., Fujikawa, K., Yahara, K. and Nakamura, T. 1992. Antioxidative properties of xanthan on the autoxidation of soybean oil in cyclodextrin emulsion. *Journal of Agricultural and Food Chemistry*. 40(6). <https://doi.org/10.1021/JF00018A005>
- Sikiru, S., Abioye, K., Adedayo, H., Adebukola, S., Soleimani, H. and Anar, M. 2024. Technology projection in biofuel production using agricultural waste materials as a source of energy sustainability: A comprehensive review. *Renewable And Sustainable Energy Reviews*. 200:114535. <https://doi.org/10.1016/j.rser.2024.114535>
- Tunç, Y., Yaman, M., Yılmaz, K., Khadivi, A. and Mishra, D. 2025. Biochemical, nutritional, and nutraceutical properties of cactus pear accessions. *Scientific Reports*. 15(1):19755. <https://doi.org/10.1038/s41598-025-04726>
- Valencia-Avilés, E., Zamora-Vega, R., Tranquilino-Rodríguez, E., Martínez-Flores, H., Rodiles-López, J. and Castillo-Garibay, I. 2024. Antioxidant evaluation of extracts from the peel of the prickly pear cactus *Opuntia streptacantha*. *Journal of Food and Nutrition Research*. 12(10):438-445. <https://doi.org/10.12691/jfnr-12-10-6>
- Yeddes, N., Chérif, J., Guyot, S., Sotin, H. and Ayadi, M. 2013. Comparative study of antioxidant power, polyphenols, flavonoids and betacyanins of the peel and pulp of three Tunisian *Opuntia* forms. *Antioxidants*. 2(2):37-51. <https://doi.org/10.3390/antiox2020037>
- Zenteno-Ramírez, G., Juárez-Flores, B., Aguirre-Rivera, J., Monreal-Montes, M., Mérida- García, J., Pérez Serratos, M., Varo-Santos, M., Ortiz-Pérez, M. and Rendón-Huerta, J. 2018. Juices of prickly pear fruits (*Opuntia* Spp.) as functional foods. *Italian Journal of Food Science*. 30(3). <https://doi.org/10.14674/IJFS-921>