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A comprehensive review of the nutritional, functional, and technological potential of prickly pear (*Opuntia ficus-indica*) in food processing

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REVIEW ARTICLE

Abstract

The exotic fruit *Opunia ficus-indica*, commonly known as prickly pear, is an underused raw material with potentially health-promoting properties. Recent research has revealed the presence of oleic acid and linoleic acid at levels that exceed 50% of the total fatty acids. A valuable amino acid profile was also found, with glutamic acid and arginine as the main compounds in the seed of the fruit. This good nutritional profile, complemented by high levels of vitamin C and abundant fiber content, make this fruit a suggestive biomaterial for industrial development purposes. Other functional compounds reported in prickly pear and with highly applicable uses are phenolic acids and betalain pigments (betacyanin and betaxanthin), which provide violet-red and yellow-orange colors to its peel and pulp, respectively. The presence of these bioactive compounds in prickly pear has led to the development of different novel food formulations with potential biological properties. However, there is still a huge margin for improving the design and production of foods using this fruit. Thus, the focus is its valorization as a highly nutritious fruit and on the use of processing of by-products as bioactive ingredients, moving toward a circular economy model.

Keywords: *Opuntia ficus-indica*; bioactive compound; polyphenol; betalain, antioxidant capacity; antimicrobial activity

Introduction

Prickly pear is a fruit of prickly pear cactus (*Opuntia ficus-indica*), which is considered to be the most economically important cactus species globally (Reyes-Agüero *et al.*, 2005). It is a shrubby plant of the Cactaceae family originally from the tropical and subtropical regions of America and the Mediterranean basin (Alves *et al.*, 2008). They are shrubs made up of fleshy segments (palms). *O. ficus-indica* has a unique morphology, standing out for its height (5–7 m), presenting stems and a crown of 1 m and 3 m in diameter, respectively. On the other hand, their seeds are pale in color and their flowers can take on various shapes, growing at the top of the cladode. The inner part (chlorenchyma) and the innermost (parenchyma) store mucilage, forming part of dietary fiber. This plant and its different parts, including cladodes, peel, pulp, and seeds (Figure 1), are used for developing novel healthy

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food items because of its nutritional characteristics as well as diverse properties, because the parts are rich in mucilage, pectins, phenolic compounds, minerals, and vitamins (Bakewell-Stone, 2023).

In relation to the opportunities that *O. ficus-indica* provides to the food industry, the utility of the cladodes has been reported as a raw material to elaborate other food products because of their potentially beneficial health properties. This part of the fruit has an oval to elongated shape with a dark green to light green color, and it is characterized by succulent stems with small spines on the surface (Farias *et al.*, 2023). Apart from the cladodes, other prickly pear by-products, such as peel and seeds, are used as novel ingredients in the development of foods and for the obtainment of high added-value phytochemicals that could be applied in the formulation of nutraceutical, cosmetic, food, and pharmaceutical products (Ramadan, 2021). Prickly pear peels have a high antioxidant capacity because of their natural antioxidant content, such as some organic acids, phenolic compounds, flavonoids, and fatty acids. The most abundant groups of chemicals are phenolic compounds and organic acids, which are represented by 14 metabolites, such as malic acid, gallic acid, (iso)citric acid, hydroxycitric acid, phloroglucinol, homocitric acid, protocatechuic acid, fumarylacetoacetic acid, dimethyl citrate, methyl gallate, 3-(4-hydroxyphenyl) propanoic acid, and ethyl gallate derivative (Sallam *et al.*, 2022).

Therefore, the incorporation of prickly pear into meat-based foods has become an increasingly popular research topic. In addition, recent studies have found that this ingredient may improve the sensory attributes of these novel food products while simultaneously mitigating oxidative processes through its potent antioxidant effects (Al-Marazeeq *et al.*, 2023; Fonsêca Dos Santos *et al.*, 2023; Parafati *et al.*, 2021; Romero *et al.*, 2021). To the best of our knowledge, no recent reviews have been published focusing on the consequences of adding prickly pear extracts in the development of novel food products. In the last 5 years, most of the works have addressed the use of these extracts as a source of bioactive compounds, discussing their advantages on human health (Silva *et al.*, 2021). For this reason, this review has incorporated the most significant results of recent original studies conducted between 2019 and 2024, highlighting the sensory and physicochemical effects on original recipe.

On the other hand, a clear and in-depth description of the outstanding nutritional and bioactive properties is also provided in an attempt to holistically display the opportunities of this underexploited cactus fruit. Therefore, this review is aimed to cover recent applications of prickly pear in the food industry as a source of nutraceuticals with potential biological activities, highlighting the uses of its different parts that provide essential nutrients. In this regard, the nutritional composition of the prickly pear fruit was addressed in depth in an attempt to display its full chemical profile.

For the discussion of the findings related to the nutritional and bioactive properties of *O. ficus-indica*, as well as its incorporation into food products, only original research studies published preferably in the last 5 years and contained in databases such as Scopus and Google Scholar were used.

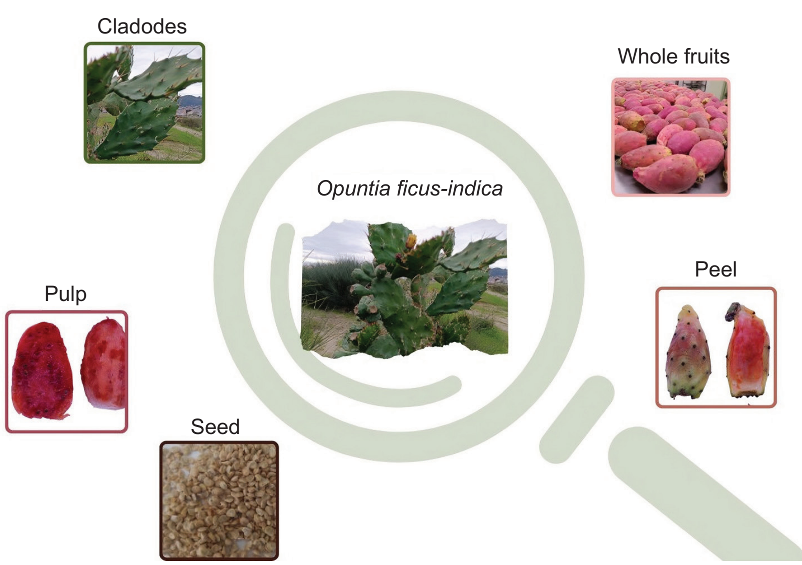

Figure 1. Different parts of prickly pear potentially usable by the industry in food processing.

Nutritional composition of prickly pear

The nutritional composition of prickly pear depends on the stage of ripening (Figure 2). As prickly pear maturity increases, the percentage of insoluble fiber (cellulose, hemicellulose, and lignin) and calcium levels increase, and the content of protein, fat, and soluble fiber (pectin, gums, and mucilage) decreases (Rodríguez-García *et al.*, 2007). According to Louppis *et al.* (2023), minerals, vitamins, and antioxidants present in the fruit have significant differences depending on geographical and botanical origin. Therefore, a high variety of chemical compounds are discovered in prickly pear matrix. Significant differences were found in important minerals, such as magnesium, calcium, and potassium, which are attributed to soil characteristics and climatic conditions of each region, which affect the amount of nutrients absorbed by the plant. Regarding vitamins, remarkable differences were found in the content of vitamin C as well as in the antioxidant power displayed.

Macronutrients

The moisture content of fresh prickly pear is high, with approximately 82% (w/w) in the pulp and whole fruit. The moisture content of the skin varies from 7.7% to 14.16%, and the seed has a moisture content of about 3.5% (Albergamo *et al.*, 2022; Choque-Quispe *et al.*, 2023; Ferreira *et al.*, 2023; Issami *et al.*, 2024). Protein content and amino acid profile of *O. ficus-indica* vary according to the ripening stage and geographical location, as certain amino acids participate in biochemical reactions related to aging. Thus, phenylalanine is involved in both enzymatic and non-enzymatic browning, while threonine and isoleucine are involved in fatty acid oxidation (Daniloski *et al.*, 2022). The seed has the highest protein concentration, reaching up to 17% (w/w) dry weight (DW) (Table 1). According to Barba *et al.* (2022) and Daniloski *et al.* (2022), main amino acids in the cladodes of *O. ficus-indica* are glutamine, valine, lysine, arginine, and leucine, with concentrations of 15.73–36.12, 7.72, 5.22, 4.81–14.62, and 2.71 g/100 g of protein, respectively. In the seeds, the predominant amino acid is glutamic acid (15–20 g/100 g of protein), followed by arginine (4–14 g/100 g of protein).

According to Regulation (EC) No. 1924/2006, prickly pear is a good source of fiber because it contains more than 3 g of fiber per 100 g of product. Other edible parts of prickly pear, such as the cladodes and skin are also declared high in fiber content because both contain more than 6 g of fiber per 100 g (Table 1). The cladode in prickly pear contains the highest amount of fiber, with 40–50% (w/w) DW of soluble fiber, comprising mucilage, gum, pectin, and hemicellulose (Daniloski *et al.*, 2022).

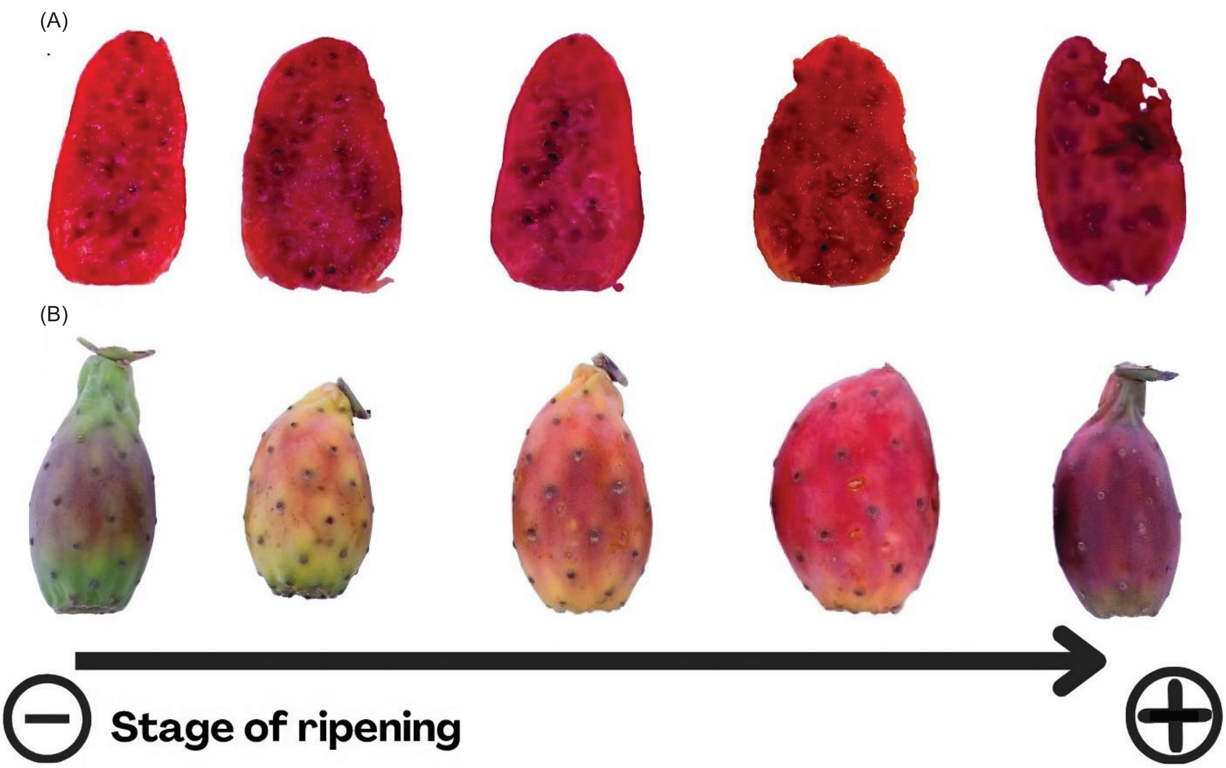

Figure 2. Different parts of prickly pear throughout the ripening process, potentially usable for the food processing industry.

The carbohydrate content in *O. ficus-indica* ranges from 60% to 70% (w/w) DW in the pulp and peel and around 45–50% in the seeds (Table 1). According to Albergamo *et al.* (2022), predominant carbohydrates in *O. ficus-indica* are monosaccharides, including glucose, galactose, xylose, arabinose, and mannose. Among all the edible parts of the plant, the pulp contains the highest levels of sugars, such as glucose (42.57 g/100 g of fruit), galactose (2.34 g/100 g of fruit), xylose (6.78 g/100 g of fruit), arabinose (13.56 g/100 g of fruit), and mannose (4.75 g/100 g of fruit). Issami *et al.* (2024) found significant differences in the levels of sugars, specifically xylose and fructose, in the peel, pulp, and seeds of prickly pear.

In general terms, prickly pear has the highest lipid content in its seeds (9.65–16.3 g/100 g), showing important levels of monounsaturated fatty acids (MUFAs) and polyunsaturated fatty acids (PUFAs), such as oleic acid (13.5–47.8 g/100 g of total fatty acids) and linoleic acid (32.7–63.8 g/100 g of total fatty acids) (Albergamo *et al.*, 2022; Issami *et al.*, 2024).

Micronutrients

Vitamins and minerals are essential micronutrients required by the human body because they are involved in numerous physiological functions. Fruits and vegetables are the foods with the highest content of these compounds, thus proving the importance of their regular intake in diet, including plant-based products. Thus, prickly pear fruit appears to be a good biological material to be consumed or used as an ingredient in food preparation, thanks to the high levels of vitamins and minerals found in its matrix. These levels depend on the part of the fruit used (peel, pulp, cladodes, or seeds) and the cultivar. The primary vitamin in prickly pear is vitamin C, also known as ascorbic acid. According to the US Department of Agriculture (USDA), prickly pear contains 14 mg/100 g DW. However, higher contents are possible, reaching up to 46 mg/100 g DW in the pulp.

The content of vitamin C is higher when the fruit is subjected to dehydration, such as after a freeze-drying process, compared to the fresh fruit (47.01 vs. 39.29 mg/100 g). This is due to the low temperature used during freeze-drying, because vitamin C is very thermolabile. Therefore, the best way to preserve bioactive compounds is avoiding the use of high temperatures, thus minimizing the deterioration of water-soluble vitamins (Alshaikhi *et al.*, 2023; Choque-Quiste *et al.*, 2023). Other vitamins present in prickly pear are vitamins B3, B6, and B9, with reported contents of 0.48, 0.32, and 0.25 mg/100 g DW, respectively (Daniloski *et al.*, 2022; El-Beltagi *et al.*, 2019).

Table 1. Proximate composition of the different parts of *Opuntia ficus-indica*.

Nutrient	Part of *O. ficus-indica*	Amount (g/100 g DW)	References
Proteins	Cladodes	1.36–10	Albergamo *et al.*, 2022; Daniloski *et al.*, 2022; Ferreira *et al.*, 2023; Guedes *et al.*, 2023; Issami *et al.*, 2024; Parafati *et al.*, 2021
	Whole fruit	0.5–1	
	Peel	1.22–8.61	
	Pulp	0.78–5.05	
	Seed	10.93–17.34	
Fiber	Cladodes	28.39–50	Albergamo *et al.*, 2022; Alshaikhi *et al.*, 2023; Daniloski *et al.*, 2022; Guedes *et al.*, 2023; Parafati *et al.*, 2021
	Whole fruit	1–2	
	Peel	12.54–58.15	
	Pulp	4.06–20	
	Seed	16.28	
Carbohydrates	Peel	62.64–75	Albergamo *et al.*, 2022; Ferreira *et al.*, 2023; Issami *et al.*, 2024; Parafati *et al.*, 2021
	Pulp	68.46–74.34	
	Seed	46.04–49.76	
Lipids	Peel	0.93–5.04	Albergamo *et al.*, 2022; Ferreira *et al.*, 2023; Issami *et al.*, 2024; Parafati *et al.*, 2021
	Pulp	1.12	
	Seed	9.45–9.65	
Ash	Cladodes	18.58	Albergamo *et al.*, 2022; Ferreira *et al.*, 2023; Issami *et al.*, 2024; Parafati *et al.*, 2021
	Peel	3.58–20.14	
	Pulp	0.28–9.48	
	Seed	1.79–4.82	

DW: dry weight.

Vitamin E is another important compound in nutrition, considered a natural lipophilic antioxidant found in several natural matrices (e.g., plant-based oils). Vitamin E refers to a number of different compounds that can be classified in two groups, namely: tocopherols and tocotrienols (Torquato *et al.*, 2019). These compounds are associated with important health benefits and their primary function is to protect PUFAs from peroxidation (El Mannoubi, 2023).

Different forms and high levels of vitamin E are found in *O. ficus-indica*: γ-tocopherol is the main tocopherol reported in the seed oil and its content depends on the geographic variety, ranging from 33 to 65.45 mg/100 g of lipids. This tocopherol is also present in the peel as 3.4–6.2 mg/100 g of lipids. The pulp oil and peel contain 442 and 7.45–9.14 mg of γ-tocopherol per 100 g of lipids, respectively. On the other hand, the content of α-tocopherol in the pulp, oil and peel is between 38.5 and 84.9 mg/100 g of lipids (Alshaikhi *et al.*, 2023; El Mannoubi, 2023; Nounah *et al.*, 2021). This tocopherol is the only isomer among all tocopherols that can be strictly considered as vitamin E because it prevents its deficiency in the human body (Azzi, 2019).

The mineral content reported in *O. ficus-indica* varies significantly depending on the drying technique used, highlighting potassium (K), magnesium (Mg), and calcium (Ca) as the most abundant minerals in fresh and freeze-dried fruit. The peel is rich in K, reaching a concentration of 3578 mg/100 g, followed by Ca and Mg (3505 and 692.96 mg/100 g, respectively). These minerals are also found in the cladodes and pulp (Capar *et al.*, 2023). According to literature, the peel contains the highest amount of K (14.72 g/100 g), followed by the cladodes and pulp (10.88 and 1.86 g/100 g, respectively). On the other hand, the highest amount of Ca (approximately 4728 mg/100 g) and Mg (approximately 10,263 mg/100 g) is found in the cladodes (Table 2).

Freeze-drying of prickly pear is an interesting alternative processing method that could be used in the food industry to prepare by-products of this fruit (e.g., peel and cladodes). At the same time, its dried waste is also an important source of minerals, including K, Ca, and Mg, which add value to novel food products developed with the plant residue (Beltrá *et al.*, 2024).

Apart from the above-mentioned minerals, others, such as phosphorus (P), sodium (Na), iron (Fe), copper (Cu), zinc (Zn), and manganese (Mn), were found in the prickly pear in smaller amounts (Issami *et al.*, 2024). Bellumori *et al.* (2023) reported the presence of aluminum (Al) and barium (Ba), but in concentrations below the established safety limits safeguarding the health. These minerals are absorbed by the plant directly from the soil.

Bioactive compounds identified in prickly pear

O. ficus-indica contains bioactive compounds, such as polyphenols (e.g., flavonoids, phenolic acids, and organic acids), pigments (e.g., betalains and carotenoids), fatty acids, and amino acids, with high antioxidant activity (Sallam *et al.*, 2022; Wang *et al.*, 2023). A recent study about the metabolome of prickly pear has shown that this fruit is mainly composed of 15 fatty acids, nine flavonoids, seven phenolic acids, and seven organic acids along with one triterpenoid (Sallam *et al.*, 2022). In contrast, Capar *et al.* (2023) determined with high antioxidant activity nine bioactive compounds: two flavonoids and seven phenolic acids. Although consuming foods rich in bioactive compounds is beneficial, their absorption in the body is not guaranteed.

Although *in vivo* digestion studies display more realible results compared to *in vitro* test studies since living organisms are used, their utility is constrained due to high costs and limited scalability. *In vitro*

Table 2. Predominant mineral contents in different parts of *O. ficus-indica*.

Part of *O. ficus-indica*	Minerals (mg/100 g DW)			References
	K	Mg	Ca	
Cladode	2.35–11.642	8.8–4.728	44.2–10.263	Alshaikhi *et al.*, 2023; Beltrá *et al.*, 2024; Daniloski *et al.*, 2022; Hernández-Becerra *et al.*, 2022
Whole fruit	7.72–1647.1	0.23–98.44	0.71–1256.06	Bellumori *et al.*, 2023; Capar *et al.*, 2023; Daniloski *et al.*, 2022
Peel	63.5-3578	196–692.96	26.5–3505	Albergamo *et al.*, 2022; Bellumori *et al.*, 2023; Beltrá *et al.*, 2024; Daniloski *et al.*, 2022, 2023; Issami *et al.*, 2024
Pulp	11.1–1864.5	1.05–558.45	0.14–493.6	Alshaikhi *et al.*, 2023; Beltrá *et al.*, 2024; Daniloski *et al.*, 2022; Issami *et al.*, 2024; Louppis *et al.*, 2023
Seed	64.4–241.36	8.07–427.35	16.2–246	Albergamo *et al.*, 2022; Alshaikhi *et al.*, 2023; Bellumori *et al.*, 2023; Daniloski *et al.*, 2022; Issami *et al.*, 2024

Note. DW: dry weight.

gastrointestinal models present a more practical solution for high-throughput screening of food bioavailability. On the other hand, the antioxidant functioning of *O. ficus-indica* is evaluated by *in vitro* analysis, such as 2,2-diphenyl-1-picrylhydrazyl (DPPH), ferric reducing antioxidant power (FRAP), and oxygen radical absorbance capacity (ORAC) assays. However, during digestion, chemical compounds undergo different biotransformation reactions because of intestinal microbiota that may lead to variations in antioxidant potential. In a recent study, the metabolism of human gut microbiota significantly modified the metabolome of *O. ficus-indica*, resulting in a series of changes of its chemical profile. The absence of six compounds was noticed in the original matrix of the fruit, revealing biotransformation (Sallam *et al.*, 2022).

Prickly pear peels showed a high antioxidant ability because of their natural antioxidant content, such as some organic acids, phenolic compounds, flavonoids, and fatty acids. The most abundant groups of chemicals are phenolic compounds and organic acids, which are represented by the following 14 metabolites: malic acid, gallic acid, (iso)citric acid, hydroxycitric acid, phloroglucinol, homocitric acid, protocatechuic acid, fumarylacetoacetic acid, dimethyl citrate, methyl gallate, 3-(4-hydroxyphenyl) propanoic acid, and ethyl gallate derivative (Sallam *et al.*, 2022). In this way, peel extracts showed heterogeneous DPPH half-maximal inhibitory concentration (IC_{50}) ranging from 327.72 to 12,990 µg/mL, and an FRAP IC_{50} ranging from 302.43 to 6570 µg/mL. The data suggest that the extraction method employed could have a significant effect on the final findings (Amrane-Abider *et al.*, 2023; El Mannoubi, 2023).

Microencapsulation is a recent and modern conservation technique that is used to maintain the stable antioxidant activity of molecules, thus enhancing their preservation. The entrapment of organic compounds within a biopolymer layer favors their protection against oxidation, hydrolysis, and other degradation pathways. Fernández-Repetto *et al.* (2023) reported a decrease in moisture and hygroscopicity by microencapsulating prickly pear extracts, thus prolonging their shelf life. Interestingly, betalains and phenolic compounds exhibited significantly higher encapsulation efficiency than flavonoids.

Another way to protect molecules against damaging from external agents could be using ultrasound-assisted extraction (UAE). De Albuquerque *et al.* (2019) successfully reported the application of this emerging technology to improve and stabilize bioactive compounds in *O. ficus-indica* beverages, thus mitigating the detrimental effects of conventional heat treatment. Other emerging technologies, such as high hydrostatic pressure (HHP) and ohmic heating (OH), have been explored to better preserve bioactive compounds. Alexandre *et al.* (2021) compared the efficacy of these two techniques both individually and combined with conventional Soxhlet extraction in prickly pear peels. They found that HP and OH increased the extraction yield of total phenolics by 98–103%, compared to Soxhlet method. In addition, the antioxidant capacity using HP and OH enhanced by 35% and 65%, respectively.

Betalains

Betalains are nitrogen-containing water-soluble pigments specifically found in the pulp and peel, and provide the characteristic color to prickly pear. There are two types of betalains: betacyanin and betaxanthin, producing red-violet and orange-yellow colors, respectively. The peel was found richer in betacyanin whereas the pulp was richer in betaxanthin (Wang *et al.*, 2023). Variations in the betalains found in *O. ficus-indica* affect fruit color and can behave as natural food colorant, thus reducing the use of synthetic colors (Daniloski *et al.*, 2022).

The peel contains a higher concentration of betacyanins compared to betaxanthin (1.943 g/100 g vs 0.676 g/100 g) and the pulp has a higher concentration of betaxanthins compared to betacyanins (5.327 g/100 g vs 4.072 g/100 g). In terms of total betalains, the peel contains higher concentration than the pulp (247.3 vs. 161.6 g/100 g, respectively) (Wang *et al.*, 2023). Tsiailanis *et al.* (2022) characterized betalains from the prickly pear matrix, namely: indicaxanthin, isoindicaxanthin, vulgaxanthin I, dopamine-betaxanthin, phenylealanine-betaxanthin, tryptophan-betaxanthin, betanin, and isobetanin. Isoindicaxanthin was the most abundant compound, followed closely by dopamine-betaxanthin. In addition, both peel and pulp have antioxidant and antimicrobial properties because of the presence of phenolic groups and amines, providing reducing and stabilizing attributes.

Several research studies identified betalains as an antioxidant dietary cationized type with a high capacity to actively eliminate free radicals, which may help prevent cancer and cardiovascular diseases (CVDs) (Nabi *et al.*, 2023; Wang *et al.*, 2023). Similarly, betalains are claimed to have anti-inflammatory activities according to different *in vivo* assays using cell lines or animal models (Nirmal *et al.*, 2024). Apart from the biological properties, recent studies have highlighted the pigments extracted from prickly pear as antimicrobials, displaying significance degree of inhibition against Gram-positive and Gram-negative bacteria (Arslan and Altinok, 2025).

In-depth experiments showed that betalains have shown good solutions in preventing Alzheimer's disease (AD). Martínez-Rodríguez *et al.* (2024) found anti-amyloidogenic properties in up to 22 of the compounds discovered in prickly pear. The authors noted that the betalains acted against the aggregation of amyloid-Β peptides to form insoluble oligomers responsible for cognitive dysfunctioning associated with the disease. This neuroprotection was further supported by *in vivo* experiments using the nematode *Caenorhabitis elegans*. The promising evidence shown in this work against the aggregation of human amyoloid peptide by betalains could be used in the development of novel treatments for AD.

In addition to the above-mentioned properties, other potential benefits of betalain consumption could be its antihypertensive effect by lowering systolic and diastolic blood pressure, the management of dyslipidemia by reducing total cholesterol, triglycerides, and low-density lipoproteins (LDL) while increasing high-density lipoproteins (HDL), and the antidiabetic effect by decreasing blood glucose levels, improving insulin secretion, and reducing oxidative stress (Martinez *et al.*, 2024).

The extraction of pigment betalain was carried out by different methods, such as pressurized hot water by conventional heating with no isothermal conditions (90–230°C) (Ferreira *et al.*, 2023) or using ethanol dilutions (Gómez-López *et al.*, 2024). Other extraction methods were also used, which are environmentally dangerous, including methanol (El Tawil *et al.*, 2023). However, green protocols are made effective by following the current trend toward environment-friendly processes. Some novel extraction technologies applied for betalain extraction from *Opuntia* spp. include pressurized liquid extraction (PLE), ultrasound liquid extraction (UAE), or microwave (MW) extraction (Lucas-González *et al.*, 2024; Parí *et al.*, 2024; Smirani *et al.*, 2025).

Encapsulation of betalains could help in their preservation and increase the shelf life. In this regard, Mehta *et al.* (2024) reported this application after using UAE to isolate the pigments and subsequently encapsulating them with glycerol. According to the authors, the anti-inflammatory properties of betalains were preserved, having a shelf life of 4–12 months depending on storage conditions. This study showed that betalains are potential alternatives to synthetic food colorants. Moreover, Fonsêca Dos Santos *et al.* (2023) used UAE to preserve the properties and stability of betalains reduce extraction period.

Betalains can also be used in the food industry for the manufacture of smart food packaging. Halloub *et al.* (2023) employed betalains extracted from prickly pear as a pH indicator film. This technology was based on the use of betalain, cellulose, and calcium alginate molecules as a smart biomaterial to control the deterioration of salmon during storage.

Phenolic compounds

Phenolic compounds are secondary metabolites spread widely throughout the plant kingdom. They are characterized by having at least one phenol group, which is an aromatic ring attached to a hydroxyl group, and are divided in two groups: flavonoids and non-flavonoids (Elgadir *et al.*, 2023). These chemicals influence quality of the fruit by improving sensory attributes, such as color (Romero *et al.*, 2021). Predominant phenolic compounds found in *O. ficus-indica* fruit are phenolic acids p-hydroxybenzoic, cinnamic, ferulic, and caffeic. In addition, flavonoid quercetin and other phenolics, primarily phenolic acids, such as gallic acid, apigenin, syringic acid, p-coumaric acid, protocatechuic acid, vanillic acid, chlorogenic acid, and sinapic acid, were also detected (Albergamo *et al.*, 2022; Wang *et al.*, 2023).

Regarding total phenolic content, no significant differences were observed between fresh and freeze-dried prickly pear (511.06 mg of gallic acid equivalents (GAE)/100 g DW and 503.53 mg GAE/100 g DW, respectively) (Capar *et al.*, 2023). The following components of *O. ficus-indica* have the highest concentration of phenolic compounds: flowers (46.71 mg GAE/g DW), cladodes (38.04-41.12 mg GAE/ g DW), and peel (121.26 mg GAE/100 g) whereas the seeds (16.35–31.03 mg GAE/g DW) and pulp (15.22–19.02 mg GAE/100 g DW) contain the lowest concentration (Albergamo *et al.*, 2022; El-Guezzane *et al.*, 2021; Wang *et al.*, 2023).

The phenolic profile of *Opuntia* plant includes a variety of compounds, among which 40 phenolic acids were discovered, including 1 gallotannin, 3 flavanones, 8 flavanols, 18 flavonols, 3 flavononols, and 9 flavones (El-Beltagi *et al.*, 2019; Wang *et al.*, 2023). Bellumori *et al.* (2023) reported the presence of 17 phenolic compounds in prickly pear peel, highlighting the group of flavonoids. These authors also identified 9 flavonoids, 2 phenylpyruvic acids, and 3 hydroxycinnamic acids, corroborating previous findings (Amaya-Cruz *et al.*, 2019; Farag *et al.*, 2020; Melgar *et al.*, 2017). The study also revealed that the peel of *O. ficus-indica* is rich in other phenolic compounds, particularly isorhamnetin glucoside, contributing significantly to the antioxidant and anti-inflammatory properties displayed by this component of the fruit. Variations observed in the levels of these compounds were attributed to different environmental conditions and fruit maturity.

Regarding betalains, a large number of healthy properties are associated with phenolic compounds. Specifically, it has been discovered that phenolic acid fraction, abundant in prickly pear extracts, has anti-inflammatory activity and despite their diverse structure and complex mechanisms of action, they might serve as potential ingredients in the development of functional foods and drugs (Xie *et al.*, 2024). Phenolic acids are considered to be the major source of dietary antioxidants, and the phenolic hydroxyl groups attached to the ring structures of their molecules were suggested to be responsible for such antioxidant activity (Tutun and Yipel, 2024). Other potential benefits of including a source of phenolic acids, such as prickly pear, in the diet could be the prevention of CVDs (Queiroz *et al.*, 2024).

The flavonoid fraction present in prickly pear extracts has been associated with several biological properties. These compounds showed antioxant activity, helping to protect cells against the damage induced by free radicals, thus mitigating aging and associated diseases. The use of flavonoids as supplements promotes anticancer and anti-inflammatory responses, contributing positively to the prevention of several cancer types (e.g., breast, colon, liver, and lung cancers), even stopping its progression after its initiation (Pyo *et al.*, 2024).

The intake of flavonoids could modulate the activity of intestinal microbiota by exerting antimicrobial or prebiotic effects against pathogenic bacteria. In particular, quercetin molecule induces modulation in unbalanced intestinal microbiota in mice supplemented with a high-fat diet (Porras *et al.*, 2017). Phenolic compounds can be extracted through multiple procedures. Most of them, including hydro-distillation, maceration, and Soxhlet extraction, are based on a liquid–liquid extraction method, which is now less used due to a large number of drawbacks, such as high solvent consumption, slow operation period, low extraction yields, use of toxic compounds, and deterioration of target compounds (Edo *et al.*, 2024). Therefore, now environment-friendly alternatives are applied.

The UAE technology was reported to recover good amount of phenolic acids and flavonoids (10–12 mg GAE/g DW) in the peel of prickly pear by reducing the temperature of solvent ethanol–water at 50°C (Parí *et al.*, 2024). A similar finding was reported when HHP and OH were used with ethanol at 30/70% and 40/70%, extracting up to 98% and 103% of phenolic compounds, respectively, more than by using the Soxhlet method (Alexandre *et al.*, 2021). Therefore, green extraction technologies could serve as viable alternatives to conventional ones for phenolic recovery from prickly pear matrices, although other issues, such as cost-effectiveness and scalability, must be considered.

Fatty acids

More than 80% of the fatty acids in prickly pear seed oil are unsaturated, with linoleic (32.7–63.8%) acid and oleic (13.5–47.8%) acid being the most representative compounds of PUFAs and MUFAs, respectively (Nounah *et al.*, 2024). Linoleic acid is the most abundant fatty acid found in this part of the fruit and is related to several health benefits. Thus, a diet rich in linoleic acid is found to reduce the risk of CVDs and metabolic syndrome (Jackson *et al.*, 2024). In addition, physiologically important fatty acids, such as arachidonic acid, eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA), are produced from omega-6 fatty acids, the group of linoleic acid (Waehler, 2023; Wang *et al.*, 2023).

Of the total fatty acids contained in the seed, 15% belong to the group of saturated fatty acids (SFAs), with palmitic acid and stearic acid being the prominent ones (10.1–12.92% and 3.1–6.1%, respectively) (Table 3). Nounah *et al.* (2024) identified 11 triglycerides in *O. ficus-indica*, highlighting palmito-dilinoleic (PLL), oleo-dilinoleic (LLO), and trilinoleic (LLL), primarily composed of unsaturated fatty acids (linoleic acid and oleic acid), with a content of 19.9–24.3%, 17.8–19.12%, and 17.3–21.28% of total lipids, respectively. The geographical origin of the seeds had little influence on these levels. It is interesting to note that the composition of fatty acids in cactus fruit seeds varies with seasons. Specifically, oleic acid, palmitic acid, and stearic acid are present at higher levels in June whereas linoleic acid is more prevalent in August. Moreover, several factors, such as variety of prickly pear, geographic location, methods and solvents used for oil extraction, cultivar, degree of ripeness, and timing of the harvest, can impact the fatty acid content in prickly pear cactus fruit seeds (Issami *et al.*, 2024).

According to Sallam *et al.* (2022), long-chain fatty acids, such as oleic acid and linoleic acid, decreased by addition of gut microbiota to prickly pear extract, while short-chain fatty acids increased due to bacterial fermentation. This indicates that the composition of intestinal microbiota influences the production of short-chain fatty acids after consuming prickly pear, and is associated with better intestinal health.

Biological activities of prickly pear and their application in food processing

Apart from modifying sensory attributes, the inclusion of bioactive compounds of *O. ficus-indica* can provide a series of positive effects on the human body, such as antimicrobial, antioxidant, anti-inflammatory, neuroprotective, and anticancer effects, as well as exerting a protective action on the cardiovascular system and counteracting metabolic alterations caused by diabetes (Albuquerque *et al.*, 2020). All these potential effective impacts are shown in Table 4. In addition, *O. ficus-indica* has shown a great potential as an ingredient to be included in the recipes of a wide range of food products, as shown in Table 5.

Table 3. Fatty acids in different parts of *Opuntia ficus-indica*.

Fatty acid	Part of fruit	Amount (% of total fatty acids)	References
Lauric acid C12:0	Cladode Peel	1.33 0.7–1.97	Daniloski *et al.*, 2022; El Mannoubi 2023
Myristic acid C14:0	Cladode Peel Pulp Seed	1.96 1.95–3.3 1.09 0.04–0.05	Daniloski *et al.*, 2022; El Mannoubi 2023; Nounah *et al.*, 2024; Romero *et al.*, 2021
Palmitic acid C16:0	Cladode Whole fruit Pulp Peel Seed	13.9 22.74–25.08 16.83 21.53–25.92 10.1–12.92	Albergamo *et al.*, 2022; Daniloski *et al.*, 2022; El Mannoubi 2023; Issami *et al.*, 2024; Nounah *et al.*, 2024; Romero *et al.*, 2021
Stearic acid C18:0	Cladode Pulp Peel Seed	3.33 4.96–7.14 2.65–3.52 3.1–6.1	Albergamo *et al.*, 2022; Daniloski *et al.*, 2022; El Mannoubi 2023; Issami *et al.*, 2024; Nounah *et al.*, 2024; Romero *et al.*, 2021
Arachidic acid C20:0	Pulp Peel Seed	0.15–1.22 0.01–0.42 0.08–0.4	Albergamo *et al.*, 2022; El Mannoubi 2023; Issami *et al.*, 2024; Nounah *et al.*, 2024; Romero *et al.*, 2021
Behenic acid C22:0	Peel Seed	0.5–2.97 0.04–0.2	Daniloski *et al.*, 2022; El Mannoubi 2023; Issami *et al.*, 2024; Nounah *et al.*, 2024
Lignoceric acid C24:0	Peel Seed	0.4–1.29 0.02–0.03	Daniloski *et al.*, 2022; El Mannoubi 2023; Issami *et al.*, 2024
Palmitoleic acid C16:1*n*-7	Cladode Peel Pulp Seed	0.24 1.1–3.81 0.9 0.04–1	Albergamo *et al.*, 2022; Daniloski *et al.*, 2022; El Mannoubi 2023; Issami *et al.*, 2024; Nounah *et al.*, 2024
Oleic acid C18:1*n*-9	Cladode Peel Pulp Seed	11.2 1.03–24.1 19.81–23.2 13.5–47.8	Albergamo *et al.*, 2022; Daniloski *et al.*, 2022; El Mannoubi 2023; Issami *et al.*, 2024; Nounah *et al.*, 2024; Romero *et al.*, 2021
Elaidic acid C18:1*n*-9	Seed	0.01–0.3	Issami *et al.*, 2024; Nounah *et al.*, 2024
Vaccenic acid C18:1*n*-7	Seed	4.3–5.2	Nounah *et al.*, 2024
Gadoleic acid C20:1*n*-9	Peel Pulp Seed	1.05 0.2 0.2–0.4	Albergamo *et al.*, 2022; Nounah *et al.*, 2021
Gondoic acid C20:1*n*-9	Peel Pulp Seed	1.05 0.25 0.05–0.42	Albergamo *et al.*, 2022; Issami *et al.*, 2024
Linoleic acid C18:2*n*-6	Cladode Peel Pulp Seed	32.8–34.9 28.97–47.8 28.21–48.9 32.7–63.8	Albergamo *et al.*, 2022; Daniloski *et al.*, 2022; El Mannoubi 2023; Issami *et al.*, 2024; Nounah *et al.*, 2024; Romero *et al.*, 2021; Wang *et al.*, 2023
Linolenic acid C18:3*n*-3	Cladode Peel Pulp Seed	33.2 9.27-11.44 3.26-18.2 0.2–0.3	Albergamo *et al.*, 2022; Daniloski *et al.*, 2022; Nounah *et al.*, 2024; Romero *et al.*, 2021
SFAs	Peel Pulp Seed	23.42–39.52 21.94 14.12–1	Albergamo *et al.*, 2022; El Mannoubi 2023; Nounah *et al.*, 2024

(*continues*)

Table 3. Continued.

Fatty acid	Part of fruit	Amount (% of total fatty acids)	References
MUFAs	Peel Pulp Seed	3.25–16.21 25.05 16.9–40.2	Albergamo *et al.*, 2022; El Mannoubi 2023; Guetarni *et al.*, 2024; Nounah *et al.*, 2024; Wang *et al.*, 2023
PUFAs	Peel Pulp Seed	53.87–60.45 52.93 16.69–61.71	Albergamo *et al.*, 2022; El Mannoubi 2023; Guetarni *et al.*, 2024, Wang *et al.*, 2023

Notes: SFAs: saturated fatty acids; MUFAs: monounsaturated fatty acids; PUFAs: polyunsaturated fatty acids.

Table 4. Bioactive compounds in *O. ficus-indica* and their biological activities.

Bioactive compound		Biological activities	References
Flavonoids	Quercetin	Antioxidant Anti-inflamatory Antimicrobial Antidepressant action Antihyperglycemic Neuroprotective Anticancer	Ali *et al.*, 2022; Elkady *et al.*, 2020; Gade *et al.*, 2010; Gómez-Maqueo *et al.*, 2019; Ogidi and Ajoko, 2024; Park *et al.*, 2010
	Kaempferol	Antidepressant action Anti-inflamatory Anticancer	Ali *et al.*, 2022; Gómez-Maqueo *et al.*, 2019; Park *et al.*, 2010
	Isohamnetin	Anti-inflamatory Anticancer Antimicrobial Antihyperglycemic	Elkady *et al.*, 2020; Gómez-Maqueo *et al.*, 2019
	Rutin	Anticancer	Önem *et al.*, 2022
Phenolic acids	Piscidic acid	Antioxidant Antimicrobial	Alexandre *et al.*, 2021
	Gallic acid	Antioxidant Antihyperglycemic Anti-inflamatory Anticancer Neuroprotective	Andreu *et al.*, 2018; Gómez-Maqueo *et al.*, 2019; Ogidi and Ajoko. 2024
	Protocatechuic acid	Antioxidant Antimicrobial Anti-inflamatory Anticancer	Song *et al.*, 2020
	Ferulic acid	Anti-inflamatory Neuroprotective	Ogidi and Ajoko, 2024; Zeghbib *et al.*, 2024
	2,5-dihydroxybenzoic acid	Anti-inflamatory	Zeghbib *et al.*, 2024
	p-coumaric acid	Anti-inflamatory	Zeghbib *et al.*, 2024
	4-hydroxybenzoic acid	Anti-inflamatory	Zeghbib *et al.*, 2024
Vitamin	Ascorbic acid	Antioxidant Antihyperglycemic	Chavez-Santoscoy *et al.*, 2009; Gómez-Maqueo *et al.*, 2019
Fiber	Pectine	Antihyperglycemic	Albuquerque *et al.*, 2020
Carotenoids	–	Anticancer	Wang *et al.*, 2023
Betalains	–	Antioxidant Antimicrobial Anti-inflamatory Anticancer Cardioprotective	Gengatharan *et al.*, 2015; Smeriglio *et al.*, 2019

Table 5. Incorporation of *O. ficus-indica* in different food matrixes.

Type of food	Part of *O. ficus-indica*	Food product	Level of inclusion	Remarkable outcomes	References
Meat	Pulp	Beef patties	1%	• No difference in color between patties enriched with *n*-3 fatty acids and those containing red prickly pear pulp. • Values of TBARs were below 1.5 mg MDA equivalent/kg of fat (15 days) using orange and red varieties, unlike the control batch (>3 MDA equivalent/kg of fat). • Higher pulp content, higher WHC, and hardness. • Color scored highest using the orange variety. • Overall, the red variety was more accepted for incorporation.	Romero *et al.*, 2021
	Cladodes	Burgers	5%, 10%, and 15%	• Decreased hardness with 10% addition al lower springiness and cohesiveness with 15%. • Higher WHC and lower cooking loss with 15% addition. • Greater acceptability at a 5% of incorporation. • Decrease of TBARs values adding cladodes at 10%.	Fonsêca Dos Santos *et al.*, 2023
		Chicken and beef burgers	1, 3, and 5%	• Lower cooking losses with 3 and 5% of inclusion. • Decrease in TBARs values with increase in ingredients. • Higher fiber content as addition increases. • Improved sensory quality using 5% addition.	Al-Marazeeq *et al.*, 2023
	Pulp	Beef burgers	5%	• No difference in color. • Lower L* values. • Increased hardness. • Inhibition of TBARs, presumably because of the presence of alginate in encapsulated samples. • Consumer satisfaction unaffected.	Parafati *et al.*, 2021
	Cladodes	Viena sausages	2%, 4%, and 6%	• Lower L* and a* values and higher b* values with 6% addition. • The hardness increased with the addition of up to 4% and decreased with 6%. • Lower consumer acceptance as incorporation increases. • No differences between the control group and the one added with 2%.	Diego-Zarate *et al.*, 2021
Meat analogue	Whole fruit	Patties	1%, 2%, and 3%	• Decrease in color (a* and b*) as fortification increases. • Optimal blend with 3% prickly pear cactus, 1% mugwort, and 1% sweet pumpkin powder.	Choi *et al.*, 2024
Fermented beverage	Pulp	Milk-based fermented beverage	5%, 10%, 15%, and 20%	• Higher acceptance adding 5%. • Increased antioxidant capacity. • L* values increased and a* and b* values decreased during storage because of oxidation and degradation of prickly pear pigments. • No detection of coliforms, molds, and yeasts during storage.	Vachhani *et al.*, 2023
Sweets	Pulp and peel	Gummies	1–2 drops	• Same visual acceptability between the control gummies and those with encapsulated ingredient. • Anti-inflammatory and non-cytotoxic properties exhibited *in vitro* by encapsulated betalains. • Less *in vitro* pigment loss by encapsulated betalains, compared to conventionally extracted betalains.	Mehta *et al.*, 2024

(*continues*)

Table 5. Continued.

Type of food	Part of *O. ficus-indica*	Food product	Level of inclusion	Remarkable outcomes	References
Pastry product	Peel	Cookies	3% and 6%	• No difference in color. • Higher hardness with 6% addition. • 50% less hardness with a 3% addition than with 6%. • Less water absorption and slower dough formation. • Higher color score with 6% addition. • Positive score (6.5–8.25) for the samples added with the peel but fewer than the controls.	Hussain *et al.* 2022
Bakery product	Pulp	Cake	1%, 2%, 5%, 10%, and 15%	• Flours of red and green varieties are rich in dietary fiber (40.16–52.23%). • Red variety flour showed better WHC and swelling capacity (6.37 g/g and 4 mL/g) than the green one. • Green variety flour presented a higher gelation point (14%). • Cakes with up to 10% of flour tasted better and showed improved texture. • Greater acceptance of cakes made with green variety flour than with red variety.	Kallel *et al.*, 2024
		Biscuits	4%	• Increased WHC and OHC. • Elevated levels of crude fiber, total phenolics, and flavonoids. • Enhanced antioxidant capacity. • The bulk density and swelling of the flour remained unaffected.	Mahloko *et al.*, 2019

Notes: TBARs: thiobarbituric acid-reactive substance; MDA: malondialdehyde; WHC: water-holding capacity; OHC: oil-holding capacity.

Antimicrobial activity

Natural compounds with antimicrobial properties offer a potential avenue to combat the growing threat of antimicrobial resistance, which has been aggravated by the overuse of synthetic antimicrobial agents. Several findings on this topic are discussed, establishing prickly pear as an extract with potential antimicrobial properties. *O. ficus-indica* is a natural antimicrobial that inhibits the growth of bacteria, viruses, fungi, and protozoa through mechanisms different from those of conventional antimicrobials (Vaou *et al.*, 2021).

Capar *et al.* (2023) determined the antimicrobial activity of prickly pear by inhibiting different pathogenic microorganisms, such as *Bacillus cereus*, *Escherichia coli* 0157:H7, *Staphylococcus aureus*, *Saccharomyces cerevisiae*, and *Candida albicans* by using ampicillin as a control. The results showed that fresh fruit had the highest antimicrobial capacity, followed by freeze-dried fruit. This property is correlated with antioxidant capacity and betalain pigment content. Thus, the higher the antioxidant capacity, the higher the antimicrobial activity, because antioxidants act as antimicrobials through membrane interaction, DNA gyrase inhibition, and metal cleavage (Capar *et al.*, 2023; Palmeri *et al.*, 2020). Guetarni *et al.* (2024) observed that Gram-positive bacteria were more susceptible to the antimicrobial activity of *O. ficus-indica*, compared to Gram-negative bacteria. This dissimilarity is attributed to structural differences in the cell walls of these two groups of bacteria.

El-Beltagi *et al.* (2019) reported that prickly pear pulp and peel extracts showed a great antimicrobial activity against Gram-positive bacteria, specifically *S. aureus* and *B. cereus*, Gram-negative bacteria, such as *E. coli* and *Salmonella* typhimurium, and fungi (e.g., *Aspergillus niger* and *C. albicans*). This antimicrobial activity was found to be higher in the peel than in the pulp, and ethanol was highlighted as the most effective solvent for extraction. Antimicrobial activity could be attributed to the presence of different bioactive compounds, such as sterols, flavonoids (myricetin, quercetin, rosmarinic acid, naringenin, and kaempferol), tannins, phenols (vanillic acid and p-coumaric acid), and alkaloids, in prickly pear extract.

Iftikhar *et al.* (2023) determined that hydroethanolic extracts of the cladodes, pulp, and whole fruit of prickly pear cactus inhibited the growth of *Salmonellatyphi*, *Helicobacterpylori*, *S. aureus*, and *E. coli*. The highest inhibitory activity was observed against *S. aureus*, while the lowest was against *Salmonellatyphi*, which was consistent with literature, indicating a higher sensitivity of Gram-positive bacteria to the antimicrobial action of prickly pear, compared to Gram-negative bacteria.

The cladodes showed significantly lower minimum inhibitory concentration, compared to the pulp and whole fruit. The seed oil of *O. ficus-indica* exhibited broad-spectrum antimicrobial activity against a wide range of microorganisms, including Gram-positive (e.g., *S. aureus* and *Listeria monocytogenes*) and Gram-negative bacteria (e.g., *E. coli* O58:H21 and O157:H7 and *Pseudomonas aeruginosa*) as well as the fungus *C. albicans*. Interestingly, no significant differences in antimicrobial activity were found between the green and red prickly pear varieties (Ramírez-Moreno *et al.*, 2017).

Antioxidant capacity

Fruits are one of the main sources of active antioxidants in the diet, known to serve as a strategy to protect the body against oxidative stress induced by substances, both endogenous and exogenous (Siddeeg *et al.*, 2021). On the other hand, the ability of food to act as an antioxidant is determined by the nature and amount of natural compounds contained in its matrix. Many of these compounds belong to the group of polyphenols and exhibit different antioxidant activities, which could be linked to their structure, stability, bioavailability, and food matrix (Lang *et al.*, 2024).

The antioxidant activity or capacity, depending on whether a single compound or a group of compounds is present, is commonly measured by a wide range of known methods, such as DPPH, ORAC, or FRAP. In this regard, Romero *et al.* (2021) investigated the antioxidant activity of antioxidants in the pulp of freeze-dried prickly pear, comparing different varieties: orange and red prickly pear. Total phenolic content ranged from 15.22 to 19.02 mg of GAE/g DW, displaying the orange variety the highest content of antioxidants. In contrast, antioxidant capacity, analyzed by DPPH test, varied from 3.51 to 4.97 mg of ascorbic acid equivalent/g DW. Specifically, high antioxidant activity was observed in the red prickly pear variety. This finding was linked to the ability to scavenge radicals, even though this variety does not show the highest content of phenolic compounds.

Prickly pear peel extracts exhibited higher antioxidant capacity compared to the pulp, with significantly greater concentrations of total phenols, including flavonoids (36.69 vs. 13.99 mg quercetin/g DW) and tannins (25.98 vs. 3.6 mg tannic acid/g DW). However, the content of total alkaloids was similar in both pulp and peel extracts (2.44 vs. 2.50 g/100 g DW). Regarding the content of anthocyanins, the pulp extract had a higher content than the skin extract (471.41 vs. 56.73 mg of cyanidin-3-glucoside equivalent/100 g) (El-Beltagi *et al.*, 2019). In a recent study, the antioxidant effect of adding different concentrations of prickly pear flour to the diets of old mice was studied. The results showed a direct relationship between reduction of lipid peroxidation in brain tissue and increase in the concentration of *O. ficus-indica* in rodents' diet. Additionally, the content of MDA decreased with increase in the concentration of *O. ficus-indica* (Moura *et al.*, 2023).

Anti-inflammatory effect

A large number of plant extracts have demonstrated the ability to counteract pro-inflammatory events because of the presence of various chemical compounds with suggested biological activities (Gonfa *et al.*, 2023). Some recent studies have reported anti-inflammatory activities in different extracts of *O. ficus-indica* fruit tissues, with different compounds being involved in such biological action. Zeghbib *et al.* (2024) found anti-inflammatory ability of different extracts from *Opuntia* spp., identifying several compounds, namely 4-hydroxybenzaldehyde, 4-hydroxybenzoic, ferulic, p-coumaric, and 2,5-dihydroxybenzoic acid, responsible for inactivating the nuclear factor kappa B (NF-κB) signaling pathway and suppressing the expression of pro-inflammatory cytokines. Other compounds, such as (+)-pinoresinol, catechol, and vanillic acid, were also implicated in this preventive action. Ammam *et al.* (2023) reported anti-inflammatory properties of *O. ficus-indica* cladode extracts by decreasing carrageenan-induced paw edema in Wistar rat models and dextran-induced inflammation as well as analgesic activity by observing reduced pain.

Prickly pear polysaccharides were also reported to prevent pro-inflammatory processes. Murad *et al.* (2023) observed that polysaccharides from peel extract might exert up to 77.77% anti-inflammatory activity by inhibiting the heat-induced albumin denaturation. The use of this natural extract at 150 μg/mL could significantly inhibit inflammation than using 85 μg/mL of diclofenac sodium, a standard drug frequently administered for this purpose (Murad *et al.*, 2023). In this sense, anti-inflammatory drugs could be associated with adverse effects that trigger harmful reactions in the body.

In an interesting approach utilizing prickly pear tissues in medical applications, Naselli *et al.* (2024) successfully implemented a potential drug delivery system based on vesicles derived from the juice of this fruit, which showed anti-inflammatory properties by decreasing the expression of pro-inflammatory cytokines (interleukin-1 beta [IL-1β] and TNF-α) and, conversely, increasing the expression of anti-inflammatory cytokines (Interleukin 4 [IL-4] and IL-10). This next-generation natural carriers could be of great help in the treatment of inflammation-related disorders and wound-healing.

Neuroprotective properties

Recent research has focused on the use of plant phytochemicals, such as phenolic compounds, including flavonoids, to protect neurons against damage induced by pathogenic causes that leads to neurodegenerative diseases (Ogidi and Ajoko, 2024). In AD, there is a loss of neurons in the central nervous system (CNS), causing severe dysfunctioning. Inhibition of cholinesterase enzyme has been reported to promote neuroprotective effects, and based on this finding, several inhibitor drugs, such as tacrine, donepezil, rivastigmine, and galantamine, have been developed as a primary treatment in affected patients (Moreira *et al.*, 2022). Therefore, Chafaa *et al.* (2024) assessed the aptitude of prickly pear nutraceuticals to delay the action of cholinesterase, including both acetylcholinesterase (AChE) and butyrylcholinesterase (BChE), nonspecific cholinesterase enzymes. The authors noted that both fruit seed oil and the resulting hydroethanolic extract from the pressed cake were able to inhibit the activity of aforementioned enzymes. The ability of several phenolic compounds, such as gallic acid, chlorogenic acid, and ferulic acid, and flavonoids quercetin and myricetin, to induce the inhibition of cholinesterase might be behind these outcomes. Similarly, Murad *et al.* (2023) reported anticholinesterase activity in *O. ficus-indica* polysaccharides, reaching 42.02% inhibition with 100 µg/mL, only 17.48% less than by using donepezil (a standard anticholinesterase drug) with the same concentration, thus demonstrating a clear anti-AD effect. Experts on the matter identified polysaccharides as memory enhancers and protectors of regenerative capacities, both qualities attributed to glucose. This monosaccharide is crucial for brain functioning, and its combination with others, such as galactose and mannose, results in a powerful factor for the treatment of AD (Murad *et al.*, 2023).

Anticancer effect

Research related to the antiproliferative and cytotoxic effects of *O. ficus-indica* extracts on different cancer cell lines has shown restrictive effects against cell replication. In particular, peel and cladode extracts have been recently acknowledged for their exhibited anticancer activities, potentially serving as nutraceuticals in experimental therapies. When human liver and breast cancer cells were exposed to a methanolic extract of prickly pear peel, anti-proliferative properties were revealed with the respective IC_{50} of 2.00±0.19 and 3.85±0.24. Rutin, the major peel compound reported, was apparently responsible from this result by inhibiting C-C motif chemokine ligand 18 (CCL18, a chemokine). This flavonoid exhibited good binding affinity toward the aforementioned small cytokine used to investigate antiproliferative activity (Önem *et al.*, 2022). Other prickly pear peel extracts obtained in a similar study also showed anti-tumoral activity, reducing the viability of MCF-7 human breast cancer cells in a concentration-dependent manner. A 53% reduction in cell viability was reported after a 72-h incubation with 400 µg/mL of cyclohexanone extract recovered from fruit peel. Compounds identified in the extracts, such as quercetin, kaempferol, and rutin, could be the cause of this activity, as suggested by Ali *et al.* (2022) based on previous findings.

Prickly pear cladodes were also successfully tested for anticancer activity in different human cell lines. D'angeli *et al.* (2024) reported a strong cytotoxic effect on human mucoepidermoid pulmonary carcinoma cells when exposed to a cladode extract obtained with acetone (120 µg/mL), significantly affecting cell viability, with a >50% reduction after 48 h of incubation. This extract also remarkably reduced cell life by inducing apoptotic phenomena, especially at 80 µg/mL. Similarly, lymphoblast cell activity was reduced by using ethanolic extracts of *O. ficus-indica* cladodes, exhibiting potent antiproliferative properties with IC_{50} 44.67 µg/mL after 48 h in case of spiny cladodes and 44.11 µg/mL for spineless cladodes, both types causing cell apoptosis and leading to loss of mitochondrial membrane potential and cellular malfunctioning (Öncül *et al.*, 2024). This outcome might contribute to the development of effective natural drugs to combat leukemia myeloid disease.

Impact on cardiovascular health

Cardiovascular diseases, which affect the heart and blood vessels, have a substantial incidence and mortality rate, being the leading cause of deaths worldwide. This health condition is a consequence of other disorders, such as hypertension, coronary heart disease (CHD), cerebrovascular disease, heart failure, etc. (Gaidai *et al.*, 2023). Natural plant-based products have shown cardio-protective effects, exhibiting antioxidant, anti-hypercholesterolemic, anti-ischemic, and platelet aggregation inhibitory properties, and therefore are potentially effective for managing CVDs (Singhai *et al.*, 2024).

According to a recent research on the subject, the fruit of *O. ficus-indica* could provide effective cardiovascular protection, and this is supported by the results obtained from the experiments conducted in *in vivo* models. Safaeian *et al.* (2024) tested the effect of *O. ficus-indica* fruit extracts on the prognosis of mice induced with epinephrine cardiac injury. After dietary administration, animals' electrocardiographic, biochemical, histopathological, and oxidative stress parameters were alleviated, especially at high anthocyanin concentrations. In a similar study, but with human models, Di Folco *et al.* (2023) evidenced amelioration in the patients affected by mild hypercholesterolemia after supplementation with prickly pear cladode extract, containing 75% pectins and mucilages, and bergamot fruit extract.

The levels of analyzed metabolic parameters, such as LDL cholesterol, total cholesterol, and triglycerides, decreased significantly by up to 23.4%, 12.6%, and 18.2%, respectively, differing approximately between 3% and 8%, compared to the control group. On the other hand, HDL cholesterol increased by around 25% (3.5% more than the control group), demonstrating a rapid nutraceutical activity by certain compounds found in these matrices (e.g., flavonoids, soluble fibers, plant sterols, and thiamine). However, the apparent activity of prickly pear matrix compounds against CVD symptoms in diagnosed patients may be ineffective, compared to healthy individuals. Gouws *et al.* (2022) observed no differences in triglycerides between the control and treatment groups when consuming prickly pear juice after eating a high-fat muffin (50-g fat).

Influence on diabetes mellitus

The anti-diabetic effects demonstrated by prickly pear fruit in different studies were related to its matrix composition, particularly richness in phenolic compounds. Thus, according to Mohammed *et al.* (2025), the presence of these molecules, including flavonoids, would be related to the inhibition of the enzymes α-amylase and α-glucosidase, both implicated in the breakdown of carbohydrates, thus decreasing blood glucose levels. Albuquerque *et al.* (2020) previously associated this improved carbohydrate metabolism with the polyphenolic composition of this fruit. In the same manner, Juárez-Flores *et al.* (2025) used this reasoning to explain reduced glucose levels observed in the blood of hyperglycemic Wistar mice after feeding the animals with *O. ficus-indica* juice.

Phenolics were identified as potential agents responsible for reducing carbohydrate absorption and regulating the activity of certain enzymes involved in glucose metabolism.

In addition, the amount of soluble fiber present in the juice was highlighted as an anti-glycemic substance, also contributing to reducing cardiovascular risks and regulating body weight, ultimately improving the sensitivity of insulin receptors. In this regard, the complex polysaccharide pectin, abundantly found in plant foods, and in prickly pear fruit, has been linked to effective control of blood glucose levels (Albuquerque *et al.*, 2020). The use of *O. ficus-indica* fruit extracts in the development of potential drugs to address the symptoms of diabetes might help to relieve the potential adverse effects of commercial treatments, such as metformin, including weight gain, gastrointestinal discomfort, hypoglycemia, and liver problems. Conversely, no harmful consequences for the human body are associated with the consumption of prickly pear (Aidan and Mckay, 2025).

Conclusion

O. ficus-indica exhibits high potential as a valuable food ingredient because of its nutritional characteristics, presenting a high content of dietary fiber, vitamins, minerals, and antioxidants that contribute to the overall health and well-being. Beyond its nutritional health benefits, prickly pear is a biological raw material rich in bioactive compounds, such as polyphenols and betalains. These compounds are responsible for multiple bioactivities, also acting as colorants in the case of betalains, with potential applications in the food industry. Extraction of bioactive compounds from *O. ficus-indica* is crucial to ease their incorporation into food matrices and maximize the prickly pear benefits. Various extraction methodologies, such as UAE and other sustainable green technologies, are used currently to obtain high-quality and pure extracts to be applied in the development of novel food products. On the other hand, encapsulation technology might contribute to improving this task by protecting and stabilizing bioactive compounds from the prickly pear matrix, thus extending their bioavailability.

In summary, *O. ficus-indica* is a nutritious food that offers a significant amount of bioactive compounds, serving as an attractive raw material for the diversification of meat and other food products because of the greater amount of bioactive compounds present in its different parts. Little research has been done on this fruit and its applications in the food industry. Therefore, there is a large knowledge gap to be filled in order to obtain high-quality products to meet consumer expectations. Promoting prickly pear as a day-by-day fruit could be a good starting point for increasing its popularity in the food market, giving it greater visibility as a nutritious food. Prickly pear has significant potential in the food industry due to its potential bioactivity. However, this remains to be corroborated in in vivo models. Using processing by-products as healthy ingredients could increase the market value of this little-known fruit while simultaneously creating a business model based on the circular economy.

Data Availability Statement

No new data were created.

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Authors' Declaration

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AI Declaration Statement

The authors declare that the content of this work is original and has not been assisted by any AI.

Author Contributions

Laura Moraga-Babiano: writing—original draft preparation; Rubén Agregán and Noemí Echegaray: writing—review and editing; Rubén Domínguez-Valencia, Mirian Pateiro, and José M. Lorenzo: supervision.

Conflicts of Interest

The authors declared no conflict of interest.

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