Chapter

Valorization of Prickly Pear [*Opuntia ficus-indica* (L.) Mill]: Nutritional Composition, Functional Properties and Economic Aspects

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Abstract

Opuntia ficus-indica (L.) Mill, usually named prickly pear or nopal cactus, is the Cactaceae plant with the greatest economic relevance in the world. It is a tropical or subtropical plant, native to tropical and subtropical America, which can grow in arid and semiarid climates. Prickly pear is mainly known by its fruits, popularly named "tunas" or "figs," but their cladodes are also consumed, principally in Mexico, which is the country with the largest cultivated area and the largest producer. There is ample evidence of the health benefits of prickly pear: it shows high antioxidant activity, it is a source of nutrients and vitamins and it presents medicinal uses, among others. Furthermore, prickly pear presents other uses, including cosmetics, biofuel production, animal nutrition and soil phytoremediation.

Keywords: cactus pear, fruit, antioxidant activity, health benefits, peel, pulp

1. Introduction

Opuntia ficus-indica L. Mill, usually known as prickly pear, cactus pear or nopal, is a tropical or subtropical plant that belongs to the Cactaceae family, originally from arid and semiarid regions of America. This plant can grow in arid and semiarid climates, being the Cactaceae plant with the greatest economic relevance in the world [1]. It produces an edible and highly flavored fruit, known as "cactus pear," which is a berry with numerous seeds and thick peel, enclosing a delicately flavored pulp [2]. Their cladodes are also consumed, mainly in Mexico, which is the country with the largest area under cultivation and the largest producer [3, 4] but it is also cultivated in the United States, Spain, Italy, South Africa and Argentina, among other countries [5, 6]. Prickly pear fruit is commonly consumed in fresh, but it can also be consumed as juices, jam, syrups and other processed products. They are widely employed in Latin America. The current demand of prickly pear in Spain is increasing [4, 6].

There are ample evidences of the health benefits of consumption of prickly pear due to its source of nutrients and vitamins [4, 7, 8] and antioxidant properties due to its content of bioactive compounds [2, 9, 10]. Additionally, prickly pear presents medicinal uses: it is used in treatment of hyperglycemia and high levels of cholesterol [7, 11, 12] and its consumption is linked with lower incidence of coronary diseases and some types of cancer [8, 13], among others.

This chapter is focused on the nutritional composition, bioactive compounds and economic aspects of prickly pear fruits through a compilation and synthesis of the available studies. With this, the authors intend to contribute to the knowledge of *O. ficus-indica* and also to promote new scientific research and industrial use of this crop.

2. Nutritional composition

Table 1 shows nutritional composition of prickly pear pulp and peel. Prickly pear fruit pulp has high content of protein, lipids and moisture but low content of total fiber and ash comparing to the peel.

About sugar profile, glucose and fructose are the predominant ones in both peel and pulp. On average, fruit pulp shows high content of glucose (123 g L^{-1}) and fructose (71.7 g L^{-1}) than peel (91.0 and 52.0 g L^{-1}, respectively) [9].

Prickly pear fruit also stands out for its mineral contents. Potassium is the major macronutrient in pulp (199–410.7 mg 100 g^{-1} dw), followed by calcium (12.4–49.1 mg 100 g^{-1} dw) and magnesium (18 mg 100 g^{-1} dw). Fruit peel presents magnesium (18.6–987 mg 100 g^{-1} dw), calcium (49.04–951) and potassium (320–549 mg 100 g^{-1} dw) as the major macronutrients [14, 15]. Fruit pulp shows lower level of sodium (0.70–1.09 mg 100 g^{-1} dw) than peel (1.8–951 mg 100 g^{-1} dw) [14–16]. Iron, manganese and copper are the major microelements in fruit peel and pulp [14, 15]. The mineral pattern depends on the fruit origin and crop factors [15].

Constituents	Unit	Pulp	Peel	References
Moisture	%	90.66	88.92	[15]
Titratable acidity	g citric acid L^{-1}	0.23–1.60	0.61–3.40	[9]
Total soluble solids	° Brix	10.7–15.7	8.03–15.4	[9]
pH	—	5.41–6.01	4.83–5.59	[9]
Energy	kcal 100 g^{-1} dw	361	169	[17]
Protein	% dw	1.62	1.53	[15]
Lipids	% dw	0.56	0.32	[15]
Total fibers	% dw	4.65	5.83	[15]
Ash	% dw	2.60	3.40	[15]
Fructose	g L^{-1}	57.8–88.0	27–81.8	[9]
Glucose	g L^{-1}	103–144	57–128	[18]

Table 1.
Nutritional composition of prickly pear fruit pulp and peel.

3. Bioactive compounds

Table 2 shows the main bioactive compounds present in prickly pear fruit peel and pulp. These are betalains (betanin and indicaxanthin), flavonoids, phenolics, vitamin C and carotenoids.

Compounds	Unit	Pulp	Peel	References
Vitamin C	mg 100 g^{-1} fw	28–79.2	59.8	[2, 14, 19, 20]
Total flavonoids	mg rutin equivalents g^{-1} fw	0.2–0.7	1.4–2.8	[21, 22]
Total phenolic content	mg rutin equivalents g^{-1} fw	2–2.5	5.4–6.2	[21]
Carotenoids	μg g^{-1} fw	2.56–3.79	12.58–16.93	[2, 6]
Indicaxanthin	mg 100 g^{-1} fw	2.61–39.6	—	[19, 20]
Betanin	mg 100 g^{-1} fw	0.10–1.04	—	[20]

fw, fresh weight.

Table 2.
Principal bioactive compounds in prickly pear fruit pulp and peel.

Betalains are water-soluble pigments (containing nitrogen) that are responsible for the red or yellow color of fruits, flowers, roots and leaves of plants belonging to the order of *Caryophyllales*, in which Cactaceae plants are included. [19]. Prickly pear fruits are characterized by various colors due to the combination of two betalain pigments, the purple-red betanin and the yellow-orange indicaxanthin [20]. These compounds make prickly pear fruits a good source of bioactive compounds with antioxidant properties, which may have beneficial effects on the consumer's health [19].

Flavonoids are a group of secondary metabolites of plants implicated in fruit and flower coloration, photosensitization and energy transfer, among others. Flavonoids present high antioxidant activity that helps to neutralize damaging free radicals and to prevent oxidative stress in the human body [21, 22]. Prickly pear fruits contain more flavonoids in the peel than in the pulp and there are fewer flavonoids than phenolic compounds (**Table 2**) [21].

Vitamin C is an essential nutrient for humans that provides a high antioxidant activity and prevents against oxidative stress in humans [14, 20, 21]. The content of this vitamin depends on the cultivar among other factors, being higher in red cultivars, which show higher concentration of vitamin C than some common fruits such as apple, peach and grapes [2].

Carotenoids are organic pigments that belong to isoprenoid group and are widely distributed among fruits. They are responsible for most yellow, orange and red colors in vegetables. These pigments contribute to the appearance and attractiveness of a fruit. They can also perform as antioxidants [2, 6]. Concentration of carotenoids in prickly pear fruits is slightly lower than that reported for other fruits but it confirms the observation that yellow-colored fruits present higher concentrations than colored fruits [2].

4. (Poly)phenols and phenolic profile

Polyphenols are an important group of natural compounds, founded in plants and characterized by the presence of more than one phenol group in their structure. These molecules are considered to be of high scientific and therapeutic interest, because they help to prevent degenerative diseases, cardiovascular diseases and cancers, among others, due to their antioxidant activity [21, 23].

In general, the peel of prickly pear fruits is richer than pulp in total phenolic content [21, 24, 25] (**Table 2**). The profile of individual (poly)phenolic compounds depends on the cultivar [18]. Generally, predominant compounds in prickly pear fruit

Compound	Pulp [18]	Peel [18]	Pulp [5]	Peel [5]	Pulp and peel [26]
Protocatechuic acid-hexoside	x	x			
Piscidic acid			x	x	x
Caffeic acid 4-O-glucuronide					x
4-Hydroxybenzoic acid derivative			x	x	
p-Coumaric acid 4-O-glucoside					x
Myricetin-hexoside	x	x			
Ferulic acid derivative	x	x			x
Ferulic acid-hexoside	x	x			
Guaiacyl(t8-O-4)guaiacyl-hexoside	x	x			
Sinapic acid-hexoside	x	x			
Syrinigyl(t8-O-4)guaiacyl	x	x			
Quercetin-hexoside-pentoside	x				
Quercetin-rhamnose-hexoside-rhamnose		x			
Rutin-pentoside		x			
Syrinigyl(t8-O-4)guaiacyl	x				
Kaempferol-di-rhamnose-hexoside		x			
Kaempferol-glucosyl-rhamnoside			x	x	x
Kaempferol 3-O-(2”rhamnosyl-galactoside)7-O rhamnoside					x
Taxifolin					x
Isorhamnetin-rhamnose-rutinoside	x	x			
Isorhamnetin glucosyl-rhamnosyl-rhamnoside			x	x	
Isorhamnetin glucosyl-pentoside			x	x	
Isorhamnetin glucosyl-rhamnoside			x	x	x
Quercetin-hexoside-pentoside	x	x			
Isorhamnetin derivative	x	x			
Dihydrosinapic acid hexoside	x	x			
Quercetin-3-O-rutinoside (rutin)		x	x	x	
Secoisolariciresinol-hexoside	x	x			
Quercetin-hexoside	x	x			
Kaempferol-rutinoside		x			
Syringaresinol	x	x			
Naringenin-hexoside	x	x			
Isorhamnetin-rutinoside	x	x			
Isorhamnetin-3-O-glucoside					x
Isorhamnetin diglucoside					x
Isorhamnetin-C-hexoside		x			
Eucomic acid					x

Compound	Pulp [18]	Peel [18]	Pulp [5]	Peel [5]	Pulp and peel [26]
Naringin	x	x			
Guaiacyl(8-O-4) syrinigyl (8-8) guaiacyl-hexoside	x	x			
Feruloyl derivative	x				
Trihydroxy-methoxy-flavonol	x	x			

Table 3.
Phenolic compounds found in prickly pear fruit peel and pulp in the most recent studies.

pulp and peel are ferulic acid and derivatives, isorhamnetin and derivatives, sinapic acid and derivatives, and quercetin and derivatives [5, 18, 24]. Other compounds found in these botanical parts are kaempferol, myricetin, luteolin, catechin, naringin and syringaresinol, among others [5, 18, 24].

The presence of the phenolic compounds in prickly pear fruit peel and pulp, due to its antioxidant activity, makes this fruit an important product that can contribute to prevent human degenerative diseases such as cancer, diabetes, hypercholesterolemia, arteriosclerosis or cardiovascular and gastric diseases [21, 25]. **Table 3** shows some compounds found in the most recent studies [5, 18, 26] about phenolic profile of prickly pear fruit peel and pulp.

5. Sugars and organic acid composition

Citric and malic acids are the major organic acids present in prickly pear fruit pulp and peel. Other organic acids, such as oxalic, tartaric, quinic, shikimic and fumaric acids, are present in traces. Citric acid ranges from 1.60 to 3.20 g L^{-1} in fruit peel and shows values from 0.30 to 1.61 in pulp g L^{-1} [9]. Malic acid shows concentrations between 1.04 and 2.20 g L^{-1} in peel and 1.20 and 2.10 g L^{-1} in pulp. However, cladodes show higher values of these acids (71.8 g L^{-1} of malic acid and 37.7 g L^{-1} of citric acid) and also contain succinic acid (43 g L^{-1}) [9]. This is due to the CAM metabolism of *O. ficus-indica*, especially in the cladodes. Organic acids are accumulated in the vacuole during night and suffer a reciprocal reserve carbohydrates accumulation during the daytime phase [27].

Organic acids in fruits are in lower concentration in comparison with cladodes; however, fruits, especially pulp, are characterized by high sugar content. Some authors [9] studied the concentration of glucose and fructose in fruits and their results show that glucose predominates over fructose in both fruit peel and pulp (123 g L^{-1} of glucose and 91 g L^{-1} of fructose in pulp versus 91 g L^{-1} of glucose and 52 g L^{-1} of fructose in fruit peel). However, other studies [28] show that glucose, fructose and sucrose concentration is higher in fruit peel than in pulp. These results indicate that concentration of sugars may depend on the cultivars.

Sugar concentration in prickly pear fruit makes it a good source of energy and a natural source of sweetness for food preparations. Besides, fructose contributes to the typical sweet taste of this fruit, due to its high wetness compared with glucose and sucrose [29].

6. Volatile compounds

Volatile compounds influence the sensory quality of fruits. Their aromas are formed from a complex group of chemical substances such as aldehydes, alcohols, ketones, terpenes and esters, among others. These compounds usually show a low concentration in fruits and their variability depends on cultivar, climatological conditions, maturity and storage conditions, among other factors [30]. In prickly pear fruit pulp, the content of these compounds varies from 3.33 mg 100 g^{-1} to 14.86 mg 100 g^{-1} [31].

Even though prickly pears have no strong aroma, up to 61 compounds have been identified [32]. In a recent research [31], the studied cultivars showed aldehydes and terpenes as the most numerous compounds. Both chemical groups and alcohols were the most abundant compounds. However, other studies reported alcohols [32–34] and esters [35] as the most numerous and abundant compounds. Some predominant compounds are D-limonene (citrus notes), 2,6-nonadienal (vegetable notes), nonanol (green, melon and fatty attributes), 2-hexenal (almond, apple green, sweet and vegetable notes), and 1-hexanol (green and sweet notes), among others [31–33].

Although prickly pear fruits are highly valued for their health-promoting benefits, sensory analysis is needed to complete the knowledge of aroma of this fruit and the effect of the cultivar [31].

7. Fatty acids

The consumption of monounsaturated and polyunsaturated fatty acids (MUFAs and PUFAs, respectively) has been stated to provide health benefits. It also contributes to the improvement of various health conditions regarding obesity, cardiovascular diseases, diabetes mellitus and even some types of cancer [13, 36].

Prickly pear fruit pulp and peel showed important percentages of MUFAs and PUFAs. In fruit pulp, MUFAs ranged from 16.9 to 40.2% (as % of total of fatty acid profile) and PUFAs ranged from 35.2 to 53.9%. Fruit peel showed slightly lower values of MUFAs (6.90–31%) but higher ones in PUFAs (37.0–63.2%) [37]. Furthermore, prickly pear seed oil showed high percentages of PUFAs, recorded at levels between 57.90 and 63.29%, and MUFAs, ranged from 19.81 to 23.30% [38].

The most abundant compounds in fruit pulp, peel and seed oil were linoleic (C18:2), oleic (C18:1) and palmitic (C16:0) acids [15, 37]. Prickly pear fruit peel showed higher percentages of linoleic acid than fruit pulp (41.2 and 29.2% respectively), but pulp presented higher percentages of oleic acid than peel (26.8% in pulp and 14.4% in peel). Both peel and pulp showed similar percentages of palmitic acid [37].

8. Health benefits: antioxidant activity

Antioxidant activity is one of the major mechanisms by which fruits and vegetables provide health benefits. Fruits and vegetable are also able to inhibit excessive oxidation due to free radicals, which are in the form of reactive oxygen species [9]. Prickly pear is rich in antioxidant product, containing phenolic compounds, carotenoids, betalains and vitamin C, all of which could be directly responsible for the health benefits [39]. Antioxidant activity in prickly pear fruit and peels may be affected by environmental factors, cultivar, genetic diversity, phenotype, agronomic practices, environmental and climatic conditions and processing of the fruit, among others [40]. Besides, the processing method and the extraction solvent affect antioxidant activity of *O. ficus-indica* extracts [26].

Antioxidant activity can be measured by different methods depending on the various mechanisms of antioxidant action. For example, some authors [2, 6, 8–10, 26, 41] studied antioxidant activity by DPPH, $ABTS^{\cdot+}$, FRAP and ORAC methods. DPPH method consists in the elimination of DPPH radical by antioxidant

Method	Unit	Pulp	Peel	References
ABTS	mmol Trolox kg^{-1} dw	6.40–30.6	14.7–36.9	[9]
	μmol Trolox g^{-1} fw	6.70	—	[10]
DPPH	mmol Trolox kg^{-1} dw	58.4–60.1	54.8–59.6	[9]
	μmol Trolox 100 g^{-1} fw	108.85–122.47	141.60–141.80	[6]
FRAP	mmol Trolox kg^{-1} dw	15.0–32.3	40.2–116	[9]
	μmol Fe (II) g^{-1} dw	18.42–137.65	58.70–175.44	[26]
ORAC	mmol kg^{-1} fw	3.68–8.16	—	[41]
	μmol Trolox g^{-1} fw	26.3	—	[2]

dw, dry weight; fw, fresh weight.

Table 4.
Antioxidant activity of prickly pear fruit pulp and peel by different methods.

compounds present in the extracts, which determines its ability to capture radicals. The ABTS method captures the cationic $ABTS^{\cdot+}$ radical. FRAP method measures the ability to reduce Fe^{3+} in the sample. ORAC method measures the ability of the sample to scavenge peroxyl radicals.

Table 4 shows the antioxidant activity of *O. ficus-indica* depending on the method and the part analyzed (pulp and peel). The scavenging activity of DPPH, $ABTS^{\cdot+}$ and FRAP methods is higher in fruit peel. This trend can be observed in other fruits like pomegranate [42], guava fruit [43] and berries [44]. The consumption of fruits with high antioxidant activity, such as prickly pear fruits, is related to preventing degenerative diseases such as cancer, diabetes, hypercholesterolemia, arteriosclerosis or cardiovascular and gastric diseases [21, 25].

9. Processed products

One of the oldest ways to preserve highly perishable fruits is through different processing systems. Although it is necessary to do more research in preservation of prickly pear fruit and use it out of the harvest period, there are some processed products obtained from prickly pear fruit. The main ones are juices and nectars, marmalades and jams, dehydrated sheets, sweeteners, alcohol and wines [29, 45].

Juices and nectars from prickly pear fruit are mostly water. They contain appreciable amounts of sugars, vitamins and mineral salts (mainly potassium, calcium and sodium). They also are a good source of bioactive substances such as phenolic compounds, betalains, vitamin C and β-carotene. These products show different percentages of fruit pulp (15–75%), citric acid (0.3%), sucrose and water [45, 46].

Marmalades and jams are usually prepared from ripe fruits with high sugar content. In their manufacturing, it is important to control the sugar/pulp ratio, type and quantities of acidifying agents and the percentage of added pectin (thickening agent). Prickly pear fruit pulp already contains pectin, responsible for the viscosity of the pulp, which is a positive element toward the production of juices, marmalades and jams [45, 47].

Regarding prickly pear dehydrated sheets, there are different formulations and methods for their elaboration, mixing pulp in different sucrose ratios (0–10%). The thickness of the sheets is usually 5–15 mm. The preparations need to be spread and then dried at 60–70°C for at least 44 hours. Some authors mix prickly pear pulp with other fruits, like quince or melon pulps [45, 48, 49].

Sweetener liquid preparation from prickly pear fruit pulp implies enzymatic clarification of pulp juice, its decoloration and its vacuum concentration until 60°Brix (56% of glucose, 44% of fructose approximately). The obtained product shows a density and water activity similar to that of honey and marmalades and its characteristics are similar to other sweetener liquids currently marketed [45, 50].

Alcoholic beverages from *O. ficus-indica* are less known than those from other processed products. Some authors, for obtaining prickly pear wine, inoculated their juice with *Saccharomyces cerevisiae* and added SO_2 (10 mg L^{-1}) and citric acid for obtaining a pH 3.3, and then performed fractional distillation [51]. Besides, prickly pear fruit pulp can be added to other alcoholic beverages such as yakju, increasing the levels of alcohol, sugars and antioxidant activity [52].

Prickly pear seed oil is another potential product that can be obtained during fruit processing. Linoleic acid is the main fatty acid, and the percentages of PUFAs and MUFAs reach 63.29 and 23.30%, respectively [38]. Besides, other physical and chemical characteristics, such as refractive index, iodine number and saponification number, make it similar to other vegetable oils such as corn or grape seed oil [45].

1. Economic evaluation of prickly pear fruit production

Nowadays, *O. ficus-indica* cultivation is developed in at least 18 countries in arid and semiarid areas. The extension of this crop is more than 100,000 ha [53]. This does not include naturalized plants or plants cultivated for home consumption.

Prickly pear has been used since the sixteenth century as an important subsistence crop in many communities of Africa, Asia, Europe and America, although fruit consumption remains limited to local ethnic markets and there is little export. Only Mexico, Italy, Chile, South Africa and Argentina produce cactus pear in a commercial way [3].

Mexico is the world's largest producer of prickly pear, accounting for 45% of world production [3, 4]. Other important producing countries of prickly pear are Italy (12.2%) and South Africa (3.7%). The rest of the production is in Argentina, Chile, Bolivia, Peru, Colombia, United States of America, Morocco, Algeria, Libya, Tunisia, Egypt, Jordan, Pakistan, Israel, Greece, Spain and Portugal [3, 4].

Regarding Mexico, the planted area covers around 50,000–70,000 ha and the gross annual production is 300,000–500, 000 tones. It is the fifth fruit crop in the country and about 20,000 families obtain some income from cactus pear cultivation. Vegetable production, featured by small plots of land cultivation, supposes an additional 12,000 ha of cultivated area [54]. In this country, the cultivation of prickly pear presents the advantage that it produces employment and income in areas where few other crops can be produced [55].

Italy is the second world producer and the principal world exporter of cactus pear, mostly concentrated (96%) in Sicily with 7000–8300 ha producing about 78,000–87,000 tones per year [55]. South Africa's 1500 hectares produces about 15,000 tones. Other countries where cactus pear is cultivated are South Africa (1500 ha, 15,000 tones of fruit production), Argentina (1650 ha), Brazil (500,000 ha), Chile (934 ha), Peru (5000 tones of fruit production) and California (120 ha) [4]. However, it is difficult to quantify areas and production of prickly pear crop because it is a crop with low economic and social importance in most of the countries, so that there are not consistent economic data about it [4].

In Mexico, the main producer, the average production is approximately 12.8 t ha^{-1} (400 crates), which are sold at an average price of 3.2 euros each crate. This gives a total of 1280 euros per hectare, and the profit is approximately 340 per hectare, because the costs of tools, weeding, pruning, fertilization, fumigation, harvest and transport, among others [56]. In the case of Italy, the average production is approximately

15.1 t ha^{-1}, the incomes are 5.71 euros per hectare on average and the average profit per hectare is 1658.88 euros [55, 57]. In Spain, average production per hectare is 234 t ha^{-1}, and the average price is 1.42 euros per kilogram. Prices depend on the moment of the season and go from 1.8 euros per kilogram to 1.05 euros. This implies an average income of 555, 254.7 euros per hectare. So, average profit is 545, 801 euros per hectare.

Besides, prickly pear fruits show a high amount of compounds with biofunctional, nutraceutical and cosmetic properties, above crops like *Opuntia joconostle*, *Ziziphus jujube, Stenocereus pruinosus, Stenocereus stellatus* and *Punica granatum* [58–61]. However, no economic value analysis of the cactus pear cultivation based on obtention of these biofunctional, medicinal, nutraceutic and cosmetic compounds has been done. These compounds reach a value in the marketplace of 213.68 € per 20 mg in the case of kaempferol or 204.53 € per 10 mg in the case of isorhamnetin, and both are present in prickly pear fruit, among others.

10. Other aspects

Besides the health benefits of fruit consumption, *O. ficus-indica* presents other multiple applications in different areas:

- There are studies about the antigenotoxic capacity of the cladodes against mycotoxin zearalenone (mycotoxin F-2, produced by some species of *Fusarium*) in mice [62, 63].

- Cladodes of *O. ficus-indica* could be used to produce biofuels, specifically bioethanol and biogas [64, 65].

- Due to its clotting power, cladodes could be used as a natural coagulant to remove turbidity and color in raw waters, with a yield of 65 g of coagulant per kg of cladodes [66].

- Some studies showed that supplementing the feeding of goats with cladodes and fruit peels may be an important resource to reduce their water intake, without detrimental effects on digestion, growth and meat quality [67, 68].

- Pigments of red and purple prickly pear cultivars could be used in food industry as additives in products like sweets, desserts and dairy products. These additives were obtained by microencapsulation technique of betalains [69, 70].

- Due to its Crassulacean acid metabolism (CAM), *O. ficus-indica* has been studied for its ability of endure prolonged drought and CO_2 uptake, which can help to mitigate effects caused by desertification and global climatic change [71, 72].

- *O. ficus-indica* could be used in phytoremediation of contaminated soils with Se, Pb and other contaminant substances [73, 74].

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