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Chapter 3

Traditional uses and modern applications in food systems of *Opuntia* spp.

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1 Introduction

El-Mostafa et al. (2014) and Aruwa et al. (2018) stated that *Opuntia ficus-indica* (L.) Mill. is a cactus belonging to the Cactaceae family and is the most widely cultivated species, not only in Mexico but also worldwide (Martins et al., 2023). This crop can grow in desert and semi-desert areas despite limited water, poor soils, and high temperatures (Aragona et al., 2017).

As drought has become more frequent in recent years because of climate change, this crop is an alternative for the production of high-quality food since it adapts to the lack of water because they are CAM plants (Crassulacean Acid Metabolism), which means that CO_2 fixation occurs at night, when cacti open their stomata, reducing both transpiration and water loss (Khodaeiaminjan et al., 2021). The flowers can be a source of bioactive compounds for food preservation (Ammar et al., 2012) because of the presence of red and yellow betalains and several phenolic compounds (Silva et al., 2021; Feugang et al., 2006). The fruits and cladodes can be used as food, and even possess nutraceutical due to their various components. Cladodes have fibres, carbohydrates, minerals [phosphorus

(P), magnesium (Mg), calcium (Ca), potassium (K), and some others], reducing sugars, proteins, lipids (Feugang et al., 2006; Stintzing et al., 2005) and if they are young also have chlorophyll, ascorbic acid and carotenoids. The fruits, known as prickly pears, contain fibres, sugar, amino acids, water, ascorbic acid, minerals, and antioxidants (phenols, carotenoids, flavonoids, and betalains (Silva et al., 2021; Scarano et al., 2022). The variation of the nutritional and antioxidant components of this crop depends mainly of agronomic parameters (fertilization, type of soil, irrigation type and frequency), temperatures and plant genetic (Inglese et al., 2017).

Some authors report the use of parts of the nopal or substances extracted from it as food or for obtaining other products. For example, in the confectionery industry, nopal pectin was used to create cocoa gelatin (Pilligua Piguave, 2017). The leaves (cladodes) are commonly consumed in Mexico, either cooked or as fresh vegetables, known as *nopalitos* (Dubeux et al., 2021). Third-generation snacks made with nopal and rice flours have also been developed (Anchondo-Trejo et al., 2021), and jams have been made from the pulp of the fruit (Barba et al., 2020). Alternatively, the mucilage removed from the leaves of *O. robusta* species has been used as a stabilizer produced to make mayonnaise (Bernardino-Nicanor et al., 2015), and the addition of mucilage removed from *O. ficus-indica* improved the quantities of bioactive composites in the bread (Liguori et al., 2020).

1.1 Historical Significance, Nutritional Profile and Health Benefits of *Opuntia* spp.

Nopal has been part of the Mexican history and it appears in the national coat of arms. It is part of the basic Mexican diet like beans and corn (Torres-Ponce et al., 2015).

The coasts of Mexico have marked their early beginnings with nopal, for many of the species growing there are native to Mexico. This species was used during the pre-Hispanic period by various cultures living in the region. Nopal was utilized in several ways, such as food and medicine, in construction and also for making arts. The same functions persisted during the colonial era, continuing from the time they were first observed in pre-Columbian times (Mills, 1824; Anaya-Pérez, 2001).

For ages, the species belonging to the genus *Opuntia* have been used in traditional medicine and as food because of therapeutic and nutritional properties for the control of several chronic conditions like diabetes, obesity, cardiovascular illnesses, and cancer (Santos-Diaz et al., 2017). Some of the nutritional properties provided by the fruit include low acidity (0.03-0.12%), high sugar content (12-17%), high levels of P, K and Ca, low sodium (Na) content, and a higher vitamin content compared to bananas, apples, grapes and other popular fruits (Yahia & Mondragon- Jacobo, 2011).

The medicinal properties of plants of the *Opuntia* genus are given by their nutritional content. According to Izuegbuna et al. (2019) and Khazdair et al. (2019) paddles of *Opuntia* spp. have a great amount of minerals [Mg, K, Fe (iron) and Ca], vitamins with antioxidant functions like a β-carotene (vitamin A) in amounts comparable to spinach (*Spinacia oleracea* L.) and also an elevate content of vitamin C. Furthermore, the prickly pear shovels as food, can provide the human body with eight very important amino acids (valine, histidine, leucine, phenylalanine, threonine, isoleucine, methionine, and lysine) (Knishinsky, 2004; Koshak et al., 2021). Additionally, vegetarians people can get a substantial amount of high-quality protein from the blades (Li et al., 2020; Madrigal-Santillán et al., 2022).

The health benefits of eating *Opuntia* spp. plants are numerous and some of them are resumed in Table 1.1.

Table 1.1 Health benefits of *Opuntia* spp.

Specie	Part of the plant used	Components	Medicinal use	Reference
Opuntia spp.	Cladodes	Mucilage	Protects the gastric mucosa and inhibits necrosis development	Shirazinia et al. (2021) Silva et al. (2021) Smeriglio et al. (2021)
Opuntia spp.	Blades	A high concentration of flavonoids aids in lowering unwanted low-density lipids	Antidiabetic remedy	Prisa (2020) Medina-Pérez et al. (2019)
O. ficus-indica	Flower extract	Flavonoids	Protection of the neural system	Tsafantakis et al. (2019)

O. ficus-indica	Plant	Antioxidant capacity and taurine content	Alleviate symptoms of benign prostate hypertrophy	Fernández-López et al. (2010)
O. ficus-indica	Fruit extract	Antioxidants like vitamin C	Experiments in mice demonstrated that extract from fruit prevents the growth of ovarian, cervical, and reduces tumor development in an ovarian cancer model	Zou et al. (2005)
Opuntia spp.	Fruit	Pectin	Reduction in plasma levels (cholesterol metabolism) may help lower the body's glucose response	Stintzing & Carle (2005)
Opuntia spp.	Fruit (pulp)	Mucopolysaccharide gel	This gel can be applied in wounds reducing pain	Stintzing & Carle (2005)
Opuntia ficus-indica var. saboten	Pulp broiled	Antioxidants	Antiatherogenic effect by lowering isoprostane levels in urine, serum, and plasma; also enhances overall blood parameter levels	Lee et al. (2002) Han et al. (2001)

O. ficus-indica	Lyophilized cladodes	Glycoprotein present in mucilage	Antiulcer activity	Galati et al. (2001)
Opuntia dillenii	Fruit aqueous extract		Analgesic and anti-inflammatory properties	Loro et al. (1999)

Opuntia spp. has plenty of historical, nutritional, and medicinal importance. This hardy plant has existed within the cellular tradition for food and medicine and has been instrumental in supporting communities, mainly in arid regions around the world. With its rich nutrition, including high fiber, vitamins, minerals, and bioactive compounds, many health benefits have been credited to it. Studies have pointed out its use in cholesterol management, blood glucose management, analgesic and some others. Besides, its anti-inflammatory and antioxidant properties might be beneficial in the prevention of cancer and in the protection of the gastrointestinal tract. With so many uses, Opuntia remains an important plant for medicinal use, both traditionally and in modern medicine.

1.2 Traditional Culinary Uses of *Opuntia* spp.

Underdeveloped countries face the great challenge of feeding their growing population while respecting food security and with climate change affecting agriculture worldwide. This makes it necessary to apply more efficient agricultural technologies and search for alternative crops that can produce high yields with few resources (Mondragón-Jacobo & Méndez-Gallegos, 2018).

De Albuquerque et al. (2019) conducted a market study on the acceptance of nopal-based products in the Brazilian and Mexican populations, finding people from both countries accepted these products, even taking into account that in Brazil nopal is not part of the food traditions. The most relevant results of this study highlight that the acceptance of nopal-based products is mainly due to the functional and nutraceutical properties of the plant, besides the economic benefit that this crop can offer as an alternative in semi-arid and arid areas.

Some applications of nopal in the food industry are:

- ✓ Third-generation snacks with nopal and rice flours: modified rice starch (by extrusion), native rice starch, xanthan gum, and nopal flour were used to prepare the food. The best result, with the highest expansion index (4.47), was obtained by using a microwave to cook snacks made with native rice, xanthan gum (0%), and nopal flour (5%) (Anchondo-Trejo et al., 2021);

- ✓ Application of the orange-yellow pulp of *O. ficus-indica* as a coloring agent in yogurt: tuna mucilage, maltodextrin (a mixture of glucose polymers appearing as a consequence of starch hydrolysis) and a mucilage-maltodextrin mixture were used to study their impact as encapsulating agents on common performance, characteristics, and stability of microparticles. *O. ficus-indica* maltodextrin and mucilage-maltodextrin mixture microparticles were found to be effective as dyes in yogurt, with both colors displaying nearly the same performance and stability. Therefore, it would be best to use nopal cladode mucilage, with the addition of maltodextrin, as an encapsulating agent for the orange-yellow pigments from tuna pulp to protect them as a yellow colorant in yogurt (Carmona et al., 2021);
- ✓ Biscuits made from nopal flour, the fungus *Pleurotus ostreatus* and amaranth: in this study, whole wheat flour was replaced in three formulations of *P. ostreatus*, nopal and amaranth flour respectively to obtain fortification cookies with a control where 100% whole wheat flour was used; one formulation contained 50% whole wheat flour-35% amaranth flour-10% nopal flour-5% *P. ostreatus* flour; the second combined 50% whole wheat flour-30% amaranth-15% nopal-5% *P. ostreatus* flour; finally, the third formulation contained 50% whole wheat flour-40% amaranth flour-5% nopal flour-5% *P. ostreatus* flour. The values obtained were highest in the treatment of cookies using the maximum level of nopal (15%), where the nutritional fiber of cookies contained 5.29% and polyphenol content was five times greater than control (Uriarte-Frías et al., 2021);
- ✓ Jams made from nopal pulp with health benefits: lactic fermentation was used to obtain the product, since it changes the levels of vitamin C, the content of phenolic composites, carotenoids and the antioxidant activity of the food, which also modulated the secretion of cytokines (proteins crucial for immune system activation) (Barba et al., 2020);
- ✓ Flour obtained from tuna shells: Bouazizi et al. (2020) used the shells of tuna (which when discarded can become an environmental problem) to obtain flour and thus

make cookies using mixtures of different weights with wheat flour and carry out studies on sensory, chemical and physical properties of the resulting doughs and cookies. Proportions of 20 and 30 g of tuna flour per 100 g were the most accepted due to their color, smell and taste.

- ✓ Biscuits made with flour from cladodes: the flour obtained from the cladodes of the nopal cactus was used to replace whole wheat flour in proportions from 0 to 100% due to their dietary fiber content (41.04%) and ash (11.9%), obtaining a quality cookie with the substitution of 25% (Nabil et al., 2020);
- ✓ Functional pasta: Several percentages (32%, 34%, 36% and 38% for 1 kg of semolina form durum wheat) of a fluid Opuntia solution (*O. ficus-indica*) were used to obtain a final product structured like dried pasta. It looked quite different from all other forms of pasta because of its near green color. Physical properties such as stickiness, hardness, and volume were similar to that of conventional pasta. The best results for the short pasta were a thickness of 1.81 mm, firmness of 70%, stickiness of 65%, yellowing index of 24.9%, and relative humidity of 12.29%. In contrast, the best results for the long pasta were a volume of 70%, firmness of 65%, stickiness of 60%, yellowing index of 24.6%, and relative humidity of 11.98% (Micale et al., 2017);
- ✓ Tuna jelly and crystallized tuna: the jelly obtained had the following composition: pH 3.07, reducing sugars 21.6%, titrated acidity 0.63% (as citric acid), soluble solids 69.2 °Brix, and humidity 23.5%. Regarding the preparation of the candied fruit (crystallized tuna), the fresh tuna was washed and separated into peel and pulp using three treatments. In the first treatment, the pulp was used with 0.2% $CaCl_2$ (calcium chloride); in the second, the pulp was used without $CaCl_2$; and in the third, $CaCl_2$ was not used, but the peel of the tuna was added. In all treatments, sucrose was added for cooking, starting with a 20% concentration, which was increased by 10% every 24 hours until a saturation percentage of 70% sugar was achieved. The treatment without $CaCl_2$ received the best ratings for the sensory qualities evaluated (aroma, color, flavor, texture, purchase intention, and international impression) (da Silva Júnior et al., 2013).

Culinary applications of *Opuntia* spp. have historically been more than sufficient for qualifying factors as to their cultural importance or nutritional values in all regions of the world. For centuries, prickly pear pads (nopales) and fruits (tunas) have featured on the menus of indigenous and local communities, giving them great potentials for salads, soups, drinks, and desserts. Their versatility and mild taste combine with their richly nutritious profile -high in fiber, antioxidants, and essential vitamins- to make them staples in traditional cuisines, primarily in semi-arid and arid areas of distribution because of their better adaptation to this environment. In addition to its culinary aspects, *Opuntia* spp. should be valued for its medicinal and economic importance within the broader framework of food security and sustainable agriculture. With growing attention towards functional foods and plant-based diets, the traditional uses of *Opuntia* spp. continue to resurface, offering innovative culinary applications that merge ancestral knowledge with modern gastronomy.

1.3 Sustainable and Eco-Friendly Aspects if *Opuntia* spp. in Agro- Industrial Systems: Challenges and Opportunities

The species of the genus *Opuntia* spp. can be cultivated under a series of varied agro-climatic prospects in many countries, being a crop that growth in semi-arid and arid regions with poor soils, little precipitations, high temperatures and drought (Silva & Acevedo, 1985; Timbau, 1987), conditions that currently affect modern agriculture. According to Koutroulis (2019) approximately 41.3% of Earth's terrestrial surface constitutes dry land, which supports about one third of mankind; thus, in the context of the alarming expansion of desert areas and reduced availability of water, the application of the *Opuntias* spp. as a valuable source of food is widely recognized (Taşkın & Aksoylu, 2021).

In semi-arid and arid regions, only about 15 species are extensively cultivated for their edible fruits, for vegetable use of young cladodes, and for forage from mature cladodes. Lower investments are needed on the cultivation of the species, and higher yields are obtained, compared to other crops grown in these areas, like cereals. Being an all-year-round plant would ensure a steady supply of feedstock, minimizing the costs related to silage preparation and storage (Arba, 2020).

In the regions described above, where Opuntia species reign, sustainable and economic agricultural practices become a prerequisite because of limited water availability and scarcity of nutrients in the soils (Rodríguez-López et al., 2020; Alexandre et al., 2021). This hardy crop produces sweet fruits that can be consumed fresh or used for processing. Additionally, the cladodes, which are consumed as vegetables, generate residues in the form of seeds, pulp, or peels. These residues can be converted into valuable bioproducts, such as compost, bioenergy, and biomass, contributing to waste reduction and soil fertility enhancement (Giraldo-Silva et al., 2023; Maniaci et al., 2024; Gavahian et al., 2021; Timpanaro et al., 2021).

Another uses for human food

The seeds of *O. ficus-indica* can be used for oil extraction due to their content of tocopherols, linoleic acid, vitamin E, and essential fatty acids (De Wit et al., 2021). The oil that these seeds produced is low but the properties are unique with several benefits such as antidiabetic properties, antimicrobial and antioxidant activity, cholesterol regulation, apoptotic and anti-inflammatory effects (Al-Naqeb et al., 2021). The oil obtained has a pleasing aroma and flavor, which could enhance the sensorial characteristics of foods. However, nevertheless, it is important to note that extracting this oil is challenging, with low yield and high cost; therefore, research continues, particularly focused on improving the extraction process (Al-Naqeb et al., 2023).

Ali et al. (2020) reported that the inclusion of ground roasted prickly pear seeds in bread resulted in significant improvements in increased contents of fiber, ash and fat, antioxidant activity, and phenolic compounds. According to authors, sensory characteristics of the supplemented bread remained unchanged at levels of up to 6%, but higher levels would result in an undesirable product.

Powdered cladodes (5%) of *O. ficus-indica* were used as a substitute for wheat flour in bread production, offering potential health benefits due to the increase in phenolic and antioxidant compounds, while maintaining certain sensory properties unchanged (Msaddak et al., 2017).

Several pigments extracted from this cactus are used as natural food dyes. The red pulp from *O. ficus-indica* was used to obtain an encapsulated powder as a natural colorant to add to extruded cereals, and its effects on the physicochemical properties of the food were studied. Different concentrations of prickly pear powder (2.5%, 5.0%, and 7.5% w/w) were mixed with corn semolina. Two moisture levels (22% and 100%) were used for extrusion, and the resulting extruded cereals were analyzed for their physical, chemical, and sensory characteristics. The results showed a negative impact on texture and density but a positive effect on water absorption and expansion indices. Regarding the sensory results, the extruded cereal made from a mixture of 2.5% red prickly pear powder and corn semolina was the most accepted by consumers (Ruiz-Gutiérrez et al., 2017). Another study used freeze-dried orange-yellow *O. ficus-indica* fruit as an ingredient to produce corn- and rice-based snacks, incorporating it before the extrusion process at concentrations of 0%, 2%, 6%, and 10%. The results showed that even at the lowest concentration (2%), the sensory profiles remained similar to those of the fresh fruit before freeze-drying, and the total flavonol content in the final product remained unchanged after cooking (Moussa-Ayoub et al., 2015).

Functional beverages are consumed not only for hydration but also for their nutritional benefits, which contribute to human health. As previously mentioned in this chapter, *Opuntia* spp. provide significant health advantages, driving their increasing use in functional beverage production. In this regard, El-Sayed & Ramadan (2020) found that incorporating 20% cactus pear pulp into a fermented rice milk beverage enhanced its antioxidant properties while maintaining probiotic viability for up to 12 days at 5°C. Likewise, a wine made from *O. ficus-indica* fruit juice and lantana (*Lantana camara*) showed improvements in various parameters, including color, total phenol content, and sensory quality, while preserving acidity, sulfite, and methanol levels within marketable wine standards (Tsegay & Gebremedhin, 2019).

<u>Uses as forage</u>

Cactus crops have a high water content in their cladodes as part of their physiological composition, making them highly valuable for animal hydration in arid and semi-arid regions (Arba, 2020). For this reason, numerous studies have examined the impact of *Opuntia* spp. cladodes as fodder on livestock productivity and rumen function (Inácio et al., 2020; Morshedy et al., 2020). In Mexico, pregnant ewes (in their last trimester of gestation) were fed natural or protein-enriched *Opuntia* cladodes to assess their milk production and the birth weight and growth of their lambs. Results showed no significant differences in the evaluated parameters when comparing *Opuntia* forage with alfalfa hay. However, lambs that consumed both forms of *Opuntia* (with and without protein) were heavier than those fed only alfalfa hay. These findings are particularly relevant in semi-arid and arid regions where forage availability is mainly limited by water scarcity (Reyes et al., 2020). In Brazil, a study examined the influence of cactus silage at three different inclusion levels (0%, 21%, and 42%) on lamb meat quality and carcass characteristics. The highest weight gain was observed in animals fed with 42% cactus forage, along with a reduction in saturated fatty acids and an increase in rib eye area (do Nascimento Souza et al., 2020).

According to Nipane et al. (2021), edible spineless cacti thrive in semi-arid and arid regions and tolerate high soil salinity levels better than most crops. For this reason, they serve as an alternative forage crop for livestock, allowing the efficient use of vacant land while also providing a source of filtered water through their moisture-rich cladodes. Several studies have explored the use of spineless cacti as forage. In one study, lambs were fed fresh spineless nopales at varying ratios (0 to 450 g kg^{-1} DM), with results showing that the highest inclusion level (450 g kg^{-1} DM) enhanced nutrient utilization, improved microbial efficiency, and consequently promoted lamb growth (Cardoso et al., 2019). Similarly, Alhanafi et al. (2019) reported a 16% reduction in lamb water intake when their diet included a combination of nopal cladodes and spineless nopal (at a ratio of 1.7:1), replacing 60% of barley grass and 16% of the concentrate mix (based on DM), compared to the control group.

A summary of this section is provided in Table 1.2.

Table 1.2 Other applications of *Opuntia* sp. for human and animals

Species	Part of the plant used	Uses/ applications	References
O. ficus-indica	Seeds	Oil extraction	Al-Naqeb et al. (2023); Al-Naqeb et al. (2021); De Wit et al. (2021)
O. ficus-indica	Seeds	Flour production from roasted prickly pear seed for bread	Ali et al. (2020)
O. ficus-indica	Fruit (20% of the pulp).	Fermented rice milk beverage	El-Sayed & Ramadan (2020)
Opuntia spp.	Cladodes	Forage on livestock productivity and rumen function	Inácio et al. (2020); Morshedy et al. (2020)
O. ficus-indica	All crop	Cactus silage (42%) to increased lamb meat quality	do Nascimento Souza et al. (2020)
O. ficus-indica	Spineless cladodes	Forage for lambs with and without protein	Reyes et al. (2020)
Saltbush (*Atriplex halimus* L.) and cactus (*Opuntia ficus-indica*)	Cladodes and spineless nopal	Lamb diet	Alhanafi et al. (2019)

Nopalea cochenillifera Salm Dyck	Fresh Spineless cactus	Lamb diet (450 g kg^{-1} dry matter)	Cardoso et al. (2019)
O. ficus-indica and *L. camara*	Juice from the fruit	Wine	Tsegay & Gebremedhin (2019)
O. ficus-indica	Cladodes as powder (5%)	Bread	Msaddak et al. (2017)
O. ficus-indica	Fruit	The red pulp was used to obtain an compressed powder as a natural colorant to add to extruded cereals at 2.5%	Ruiz-Gutiérrez et al. (2017)
O. ficus-indica	Freeze-dried orange-yellow fruit	Corn and rice-based snacks	Moussa-Ayoub et al. (2015)

With its resilience to extreme conditions and efficient water use, along with multiple economic benefits, *Opuntia* spp. represents a potential mega-resource for sustainable and eco-friendly agro-industrial applications. Its value extends beyond soil conservation, carbon sequestration, and bioproduct generation to its role in human and animal nutrition. Advancing research, innovation, and policy support could pave the way for *Opuntia* spp. to become a key player in sustainable agriculture and industry.

Conclusions

Having played a significant role in traditional food systems for centuries, *Opuntia* spp. remains highly valued in arid and semi-arid regions for its resilience and nutritional benefits. Traditionally considered a staple food, it provides an array of bioactive compounds, minerals, and vitamins that contribute to human health and well-being. With its antioxidant, anti-inflammatory, and metabolic benefits, *Opuntia* spp. is recognized as a functional food, generating growing interest in modern diets.

Traditional culinary knowledge regarding *Opuntia* spp. remains relevant in modern food applications, with its cladodes (nopales) and fruits (tunas) being used both fresh and in processed forms. The potential of Opuntia in beverages, jams, flours, and functional food products highlights its versatility in innovative food technology.

From an agro-industrial perspective, *Opuntia* spp. stands out as a sustainable crop requiring minimal water and inputs, offering diverse applications in food, forage, and bio-based industries. Its role as animal feed further supports its alignment with circular economy models, reducing environmental impacts and improving resource efficiency.

However, significant challenges lie ahead for the full integration of *Opuntia* spp. into global food systems, such as scaling up processing, developing supply chains, and raising consumer awareness. With further research, technological advancements, and policy support, *Opuntia* spp. has the potential to become a major contributor to sustainable and resilient food production.

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