Chapter 37
Industrial Uses of *Opuntia* spp. By-products

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Abstract Prickly pear cactus stems, better known as Nopal (*Opuntia* spp.), is spread around the world as feedstock. It has multiple functional compounds which could be applied in functional foods or as source of nutraceuticals. Nopal application in sugar-based confectionery, bakery and dairy products improved the quality and sensorial attributes and provided bio-functional activities. In addition to applications in pharmaceuticals industry, the stems have been used since ancient time mainly as cattle fodder, fence, to purify water and to restore or control erosion of arid and semiarid lands. As cattle fodder, solid-state fermentation of stems increased the crude protein content up to 26%. As coagulant-bioflocculant nopal biopolymers are applied to water treatment to remove turbidity, suspended solids, organic carbon, kaolin, lead, arsenic, heavy metal ions, pesticide, dyes, and bacteria. Restoration of natural ecosystems with nopal produces besides a tolerant forage to drought conditions, ecological benefits like carbon capture and decreasing the global warming. Another application of nopal is to improve house paint. It is friendly with environment and works for waterproofing. Natural dyes present in fruits, like betalains, are used as natural food colorants. The mucilage of *Opuntia* spp. has been used to fix colors of dyed fabrics. The stems and their polysaccharides could be used in (a) bio-nano-packaging for the elaboration of coatings and biodegradable-edible films to extend shelf life of fresh, frozen and processed food, and (b) vegan leather with adequate softness. The stems also could be used as a source of enzymes in the dairy sector. In construction, cactus provides benefits in adobes, mortars and concrete reinforcing steel, improves water absorption, enhances freeze-salt resistance, and delays corrosion. In restoring historical buildings and monolith, nopal is used for impregnation of minerals (consolidation). Nopal extracts, mucilage and pectin are used as redox agent to synthetized metal nanoparticles (Li, Ag, Au, hydroxyapatite and $ZnFe_2O_4$). Nopal has been assessed as resource to generate biofuels: bioethanol from lignocellulosic material, biogas from polysaccharides, biodiesel form seed oils, and electricity from nopal biogas effluent. An electrochemical cell has been fabricated using cactus stems as an electrolyte. Betacyanin from fruit and aerobic

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fermented nopal extracts showed photosensitizer properties with applications as dye-sensitized solar cell and holography. The industrial uses of *Opuntia* spp. stems are described in this chapter. The potential technological uses of these plant and its derivatives are also discussed.

Keywords Agro-industry · Waste · Soluble fiber · Pectin · Mucilage · Coagulant-bioflocculant

1 Introduction

In order to establish a relationship between scientific advances and the main investigations developed around the industrial exploitation of cactus, carried out around the world, this chapter describes the main uses and applications of nopal, as well as the results of the most outstanding investigations related to the comprehensive use of this horticultural product, which surprises us more day after day due to its multiple benefits and applications in several areas of the human development.

The use of nopal and by-products has been evidenced since pre-Hispanic times in Mexico, being a common practice in construction through its application to generate adhesion materials and paints; in water purification as a coagulating agent; and to obtain pigments present in cladodes (chlorophyll) and prickly pears (Betalains and Betacyanin).

Undoubtedly highlighting the increase in protein content (up to 26%) through solid fermentation, which strengthens the application of nopal as fodder for livestock.

It also amazing the use of biopolymers present in nopal for developing edible films and biodegradable packaging, both macro and nano structured, as well as in the green synthesis of various nanoparticles.

Likewise, in biofuels, significant progress has been made since bioethanol, biogas (methane) and electricity have been generated from cactus. The development of biofunctional foods, stands out without a doubt, it takes advantage of phytochemical content with both antioxidant and prebiotic activities present in cactus; which not only nourish but also have an impact on the oxidative status and therefore in consumer's health.

In this order of ideas, this chapter was structured as follows:

2. Fodder
3. Biological Fencing/Vegetative Barriers
4. Erosion Control
5. Water Treatment
6. Additive Used in Construction
7. Improving House Paint and General Paints
8. Nopal Mucilage in Edible Coatings and Packaging Applications
    8.1. Cactus Mucilage as a Coating Material

2 Fodder

Opuntia ficus-indica was introduces to continents in the eighteenth century by navigators with different aims: as vegetable to prevent scurvy, to make living fences, as a fodder to get carmine form cochineal, and as vegetable for human consume (Diguet, 1928). The use of *Opuntia* for livestock feeding is an ancient practice and it has spread in countries like Algeria, Argentina, Bolivia, Brazil, Chile, Colombia, Spain, Mexico, Morocco, Israel, Italy, South Africa, Tunisia, USA, Peru and other countries (Santana, 1992). In some countries, the nopal is used all year round as emergency forage during drought (Table 37.1).

Opuntia's advantages as forage include high biomass production, high efficiency in converting water into dry matter, good palatability, nutritional value, provide succulent forage during drought (evergreen), long drought resistance, tolerate severe use (high animal load), no adverse effects on animal health, low cost of establishments and maintenance, as well as soil and climate conditions adaptation (Ben Salem et al., 1996).

Due to its chemical composition, *Opuntia* does not constitute a complete food by itself, however, it is considered a good option to be used as fodder not only in arid and semiarid regions but also in stockbreeder farms throughout the year. The nopal during the dry season provides water (79–93%), 7–18% of protein (25–60 g/kg dry weight), 1.3–3% lipids (dry weight), and crude fiber 3.02–18.8% (dry base, good source of dietary fiber). The consumption of nopal as fresh food can contribute to

Table 37.1 Nopal varieties used as fodder in different countries

Country	Variety	Source
UE	*O. lindheimeri*	Merrill et al. (1980), Migaki et al. (1969)
	O. ellisiana	Han and Felker (1997)
	O. polyacantha	Shoop et al. (1977)
Brasil	Los tres cvs.	Souza (1963)
	Redonda	Metral (1965)
	Gigante	Metral (1965)
	Miúda	Metral (1965)
	IPA 20	Santos et al. (1998)
Argentina	*O. spinulifera* Salm-Dyck	Guevara and Estévez (2003)
	O. robusta	Guevara and Estévez (2003)
	Atriplex	Guevara and Estévez (2003)
Tunez	*Acacia saligna*	Guevara and Estévez (2003)
Siria	*Atriplex halimus*	Guevara and Estévez (2003)
Mexico	*Opuntia leucotricha*	Bravo and Scheinvar (1995), Elizondo et al. (1987)
	O. streptacantha	Bravo and Scheinvar (1995), Elizondo et al. (1987)
	O. robusta	Bravo and Scheinvar (1995), Elizondo et al. (1987)
	O. cantabrigiensis	Bravo and Scheinvar (1995), Elizondo et al. (1987)
	O. rastrera	Bravo and Scheinvar (1995), Elizondo et al. (1987)
	O. leptocaulis	Bravo and Scheinvar (1995), Elizondo et al. (1987)
	O. lindheimeri	Bravo and Scheinvar (1995), Elizondo et al. (1987)
	O. phaeacantha	Bravo and Scheinvar (1995), Elizondo et al. (1987)
	O. engelmannii	Lopez García et al. (2003)
	O. imbricate	Lopez García et al. (2003)
	O. microdasys	Lopez García et al. (2003)
	O. violacea (morado)	Lopez García et al. (2003)
	O. rufida (cegador)	Lopez García et al. (2003)
Ecuador	*O. engelmannii*	Flores and Reveles (2010)
	O. lindheimeri	Flores and Reveles (2010)
Sudafrica	*O. robusta*	De Kock (2003)
	O. fusicaulis	De Kock (2003)
	O. ficus-indica f. *inermis*	De Kock (2003)

35% of water demand from cattle under conditions that are not of extreme drought (Osorio et al., 2011). The minerals in nopal are calcium, potassium, magnesium, silica, sodium, and small amounts of iron, aluminum, and magnesium (Hernández-Urbinola et al., 2010).

Opuntia is a good source of water, fiber, precursors of vitamin A (29 mg carotenoids) (Rodriguez-Felix & Cantwell, 1988), and pectic substances that present a prebiotic and hypocholesterolemic effect (Guevara-Arauza & Ornelas, 2013). These chemical compounds can be beneficial to animal health.

There are some ways to increase the protein content in cactus plants including the use of fertilizers based on N and P, cloning and/or genetic modification (Gregory & Felker, 1992; Table 37.2), and solid fermentation by inoculation of prickly pear roots with nitrogen-fixing bacteria released as *Azospirillum* sp. (Caballero-Mellado, 1990). Fertilization based on the application of nitrogenous compounds can be an alternative to increase the content of crude protein. Gonzalez (1989) reported that crude protein content in fertilized cactus was close to double. The use of solid fermentation on nopal with *Aspergillus niger* developed an increase up to 12.8% of crude protein content (Oliveira, 2001), while the use of *Sacharomyces cerevisiae* reported an increase of 26% crude protein (Araújo et al., 2005). The use of acid hydrolysis (Foccher et al., 1991), and thermal pre-treatment are considered to improve the fermentation process.

Rodríguez et al. (2015) studied solid state fermentation using *Phanerochaete chrysosporium* (30 °C for 7 days at 180 rpm, fungal hydrolysis) followed by *S. cerevisiae* fermentation (37 °C for 48 h at 180 rpm), and achieved an increase in protein content from 0.042% to 26% (dry base). In addition, fungal hydrolysis generated an increase in free glucose from 8.32% to 18.9% (dry base).

Around the world (Table 37.3), as well as in Mexico, due to the need to feed cattle in the arid areas, since nineteenth century *Opuntia* has been used as fodder for livestock, mainly where the dry seasons are very long (Flores & Aguirre, 1979). In Monterrey and Nuevo León, two cities in the north of the country, farmers used to use 600 tons/day *Opuntia* to feed cattle. In Saltillo and Coahuila, 100 tons/day were used for this purpose (Granados & Castañeda, 1997).

Table 37.2 Alternatives to increase the protein content in cactus

Description	Increase up to (%)	References
Using fertilizers based on N and P	12	Gonzalez (1989)
Genetic selection	11	Felker (2003)
Inoculation with N2-fixing bacteria	9.78	Felker (2003), Mascarua-Esparza et al. (1988)
Solid fermentation	12.8	Oliveira (2001)
	26	Araújo et al. (2005), Rodríguez et al. (2015)

Table 37.3 Use of cactus as fodder on meat, milk and dual purpose production

Production	Livestock	Country	References
Meat	Cattle	Mexico	Flores and Aguirre (1979), Granados and Castañeda (1997), Lopez García et al. (2003)
		South Africa	De Kock (2003)
		EU	Felker (2003)
		Brazil	Cordeiro and Gonzaga (2003)
		Argentina	Ochoa and Barberab (2017)
		Ethiopia	
	Sheep	Mexico	Terblanche et al. (1971), Lopez García et al. (2003)
		UE	Griffiths (1905), Felker (2003)
		Chile	Riveros et al. (1990)
		WANA	Ben Salem et al. (1996), Nefzaoui et al. (1993)
		South Africa	De Kock (2003)
		Tunisia	Nefzaoui et al. (1993)
		Ethiopia	Flachowsky and Yami (1985)
	Goats	Mexico	Lopez García et al. (2003)
		Argentina	Ochoa and Barberab (2017), Guevara and Estévez (2003)
		Ethiopia	
	Rabbits	Brazil	Lukefahr and Cheeke (1990)
	Pigs	UE	Griffiths (1905)
	Oxen	UE	Griffiths (1905)
	Rams	Ethiopia	Flachowsky and Yami (1985)
Milk	Cattle	Mexico	Lopez García et al. (2003)
		Brazil	Santana et al. (1972), Lima et al. (1985), Santos et al. (1990), Lima et al. (1985)
	Goats	Chile	Azócar and Rojo (1991)
		Ethiopia	Azócar and Rojo (1991)
Dual purpose	Cattle	Mexico	González et al. (1998)
	Sheep	Mexico	González et al. (1998)
	Goats	Mexico	González et al. (1998)

The use of prickly pear as forage for cattle, sheep and goats has a significant impact by improving daily weight gain (0.1–0.6 kg/day). Supplementation with *Opuntia* increases not only milk production but also improves butter quality in terms of consistency and shelf life, as well as imparting an attractive "golden" color to the final product (González et al., 1998). Feeding sheep with *Opuntia* for to 525 days without drinking water is a resource to save animals from starvation without showing serious side effects (Terblanche et al., 1971). On the other hand, when *Opuntia* combined with corn, oats, and sorghum, it has a positive impact on the increase in weight of sheep and goats.

In Brazil, the use of *Opuntia* as fodder dates from the twentieth century (1915) (Pessoa, 1967); on 1932, the government established a great quantity of batch for propagation of *Opuntia* in the semi-arid northeast region of Brazil due to the drought that year (Duque, 1973). The area planted with *Opuntia* in northeast Brazil is currently estimated to over 500,000 ha. Livestock farming in this region has a dual purpose: milk and meat (cattle, sheep, and goats).

Due to nutritional deficiencies of *Opuntia* in protein (but rich in soluble carbohydrates), it is not possible its use as single feed. Therefore, Brazilian farmers integrate it with corn or silage sorghum as an integral part on livestock production systems (Melo et al., 1992; Viana et al., 1966). Santana et al. (1972), and Santos et al. (1990) showed that using *Opuntia* cv. Gigante as single forage or in mixtures greater than 73%, Holstein cows lose weight. In lactating cows, milk production and live weight gain does not show difference compared with those fed with corn silage (Santana et al., 1972) or sorghum silage (Lima et al., 1985). Feeding rabbits with *Opuntia Palma redonda* (Brazilian var.) was attractive and immoderately increased the consumption (Lukefahr & Cheeke, 1990).

In the United States of America, the use of wild varieties of *Opuntia* previously "scorched" for the feeding of oxen, dairy and fattening cattle, as well as sheep and even pigs was described by Griffiths (1905). *O. ellisiana* presented the highest efficiency in the use of water (162 kg per kg of dry matter) and water accumulation of 170 tons per ha (in Texas). By supplying 45 kg of *O. ellisiana* per animal, it is possible to satisfy the water requirements for a period of 11.8 years (4315 days).

Spineless varieties have been generated with disadvantage that they are consume by wildlife (Felker, 2003). In semi-arid areas of Santiago de Chile, the use of *Opuntia* cladodes (25%) combined with alfalfa as forage for sheep decreased water consumption up to 30% compared with those fed only with alfalfa (Riveros et al., 1990). In lactating goats feeding with diets based on *Opuntia* cladodes and alfalfa, milk production increases up to 55.4% (Azócar & Rojo, 1991).

The West Asia-North Africa region (WANA) comprises large areas with rainy winters and hot, dry summers. *Opuntia* was introduce to WANA region from Spain "moros". However, large formal plantations were not established until the 1900s (Le Houérou, 1992). Currently, the combination of spineless prickly pear (*O. ficus-indica* var. *inermis*) with cereal straw is a nutritionally satisfactory solution to keep small ruminants in arid areas of WANA region. In WANA, prickly pear is used to supplement low-quality forages such as straw supplied to sheep, managing to increase the consumption of straw in proportion to the increase in prickly pear (Ben Salem et al., 1996). In straw treated with urea or ammonia, supplementation with prickly pear up to 55% in dry basis did not developed collateral digestive disorders and provides soluble fiber necessary for better use of non-protein nitrogen in the rumen. In addition, it was achieved a digestibility of 70% of the crude protein, and up to 50% crude fiber (Nefzaoui et al., 1993). *Opuntia ficus-indica* was introduced to Ethiopia from Mexico in the late nineteenth century, and is widely distributed in the semi-arid and arid regions, covering an area of around 30,520 ha, of which 48.6% is found in wild way and 51. Four percent are cultivated.

Since nineteenth century, the nopal plantation is common and extensive. Prickly pear has been consumed by almost all domestic animals, while livestock is totally dependent on *Opuntia* during the dry season. The government support the development of *Opuntia* through two main organizations: Tigray Aid Society and the Regional Bureau of Conservation and Development of Natural Resources through which have promoted the selection, production and distribution of prickly pear varieties, the identification of diseases and the design of erosion control measures as part of its strategies (CFDP, 1994).

In South Africa, the nopal was introduced in the year 1911, and its cultivation has registered increases in production of 200–300% after the moderate application of nitrogen and phosphorous (Le Houérou, 1992; De Kock, 1980). Watering *Opuntia* without thorns is more efficient than irrigating a small area of alfalfa and generates almost twice as much forage production (De Kock & Aucamp, 1970). Cows and Sheep are fed during droughts using a silage prepared from crushed cladodes with straw in 84:16 ratio, and supplemented with molasses. Another alternative for silage, is to use *Opuntia* fruit and its cladodes ensiled with low-quality hay and supplemented with sources of protein (cottonseed, sunflower or urea), and minerals such as phosphorus and sodium (bone or salt) (De Kock, 2003). This can support dairy production in arid and semi-arid rural areas of South Africa. The most suitable supplement for feeding cladodes in South Africa is Karoo (a bush with a high protein content) or alfalfa (De Kock, 2003).

3 Biological Fencing/Vegetative Barriers

The use of various cactus species (*Opuntia ficus-indica*) as fence was described initially for Fernández de Oviedo (1526) in his work entitled "Summary of the Natural History of the Indies". This concept was supported by Benavente (1541), and López de Gómara (1552), who's often highlighting the use of cactus species as barriers or fences. Recently, in addition to their utilization as living fence to protect family household in dry regions, the nopal is used for erosion control of arid and semi-arid lands (Mondragon Jacobo & Chessa, 2013; Table 37.4).

In different parts of the world, the cactus is used as a fence. The fence plants in dry seasons are also used as forage while on summer for fruit production (Huffpost Algeria, 2015). In South Africa, cactus pear was planted as living fence and for its delightful fruit all around the arid and semiarid lands (Beinart & Wotshela, 2011). *Opuntia* spp. is also grown in Lebanon as natural fence and to produce "arak" (distilled alcoholic drink), which is characterized by its unsweetened anise-flavor. In the coastal and internal areas of Lebanon, cactus pear was initially introduced, it is destined mainly for fruit production (Chalak et al., 2012).

Sicily (Italy) is another example were cactus pear has been domestically grown since the eighteenth century. Its atypical appreciation of this plant is due to its multiple uses including fences in farming systems and emergency fodder (Barbera et al., 1991). Throughout North Africa and in parts of Italy and Spain, Torny cacti *O. ficus-indica* var. *amyclaea* (Ten.) A. Berger, var. *elongata* Shelle, and O. *violacea* Engelem var. *santa-rita* (Griffiths & Hare) L. D. Benson are used as defensive hedge for protection of gardens, orchards and olive groves. These hedges demarcate

Table 37.4 Nopal as fence

Application	Country	References
Protect and delimit grounds	Mexico	Mondragon Jacobo and Chessa (2013), Guevara-Arauza (2020)[a]
Fence	Mexico	Guevara-Arauza (2020)[a]
	South Africa	Beinart and Wotshela (2011)
	Lebanon	Chalak et al. (2012)
	Italy	Paterson et al. (2011)
	Australia	Rao et al. (1971)
	Kenya	Hosking et al. (1988)
	Nambia	Hosking et al. (1988)
	Indonesia	Chinnock (2015)
	Zimbabwe	Walters et al. (2011)
Protection of cultivars	North Africa	Griffiths (1915)
	Italy	Griffiths (1915)
	Spain	Griffiths (1915)

[a] Personal communication

boundaries, so they make an excellent fence while helping to control erosion (Griffiths, 1915).

A. subulata (Muehlenpf.), *O. elatior* P. Miller and *C. fulgida* (Engelm) F.M. Knuth var. fulgida are utilized as a living fence in Australia, Kenya, Nambia, South Africa, Spain, Indonesia and Zimbabwe (Paterson et al., 2011; Rao et al., 1971; Hosking et al., 1988; Chinnock, 2015; Walters et al., 2011). Some of the advantages to use nopal (*Opuntia* spp.) for fencing are; (a) an excellent security for crops and homes, (b) a living fence provides, and (c) restore erosioned lands. Le Houérou (1989) reported that the cost of establishing a fence using nopal is less than US$ 60/ha, while a metallic fence (four strands of barbed wire) cost about US$ 150/ha in Tunisia. The only disadvantage is the time necessary to be established for at least 2 years before it begins to function. There are alternatives to develop a fence, it is necessary to use the thickest pads from a plant, cut it and allow the scar to heal for about a week, and then plant the pads at 1.3–1.5 m spacing (White Dove Farm, 2015). Hedges and Fences of cactus can be developed by planting stems around 20–30 cm apart. The plants will grow together to form a wall of freely branching plants (3–6 m high). If the nopal is watered constantly, it can grow quickly so a fence can be stablished in as little as a 1 year. It is important to consider that spiny varieties of cactus pear or stems makes a good fence if it is compared with spineless varieties (University of California Cooperative Extension, 1989).

In landscape organization in countries or regions where no land registry exists, the nopal fences play an important role. In México the land-owners get together in "ejidos" where they agree if cactus hedges are often planted as testimony of land ownership and its register is set in the ejidal book. Additionally, nopal hedges have impact at local socio-economy in order to defending land rights and land ownership. In Tunisia planting of cactus fences on communal lands has a strong motivation and popularity due to tradition dictates that tribal land may become the property of whoever among the rightful user has established a permanent crop on it.

4 Erosion Control

Galo et al. (1985) conducted a study were re-vegetation practices on 94 plantations were assessed and they established a correlation between environmental conditions and plantation characteristics. The best response of *Opuntia* in terms of establishment were found in steppe dry climate for 1 year old sites, likewise plantations in very dry climates had higher forage yields. This effect was attributed to set of initial conditions of the plantations, particularly precipitation. López et al. (1978) showed that a combination of rest, selective removal of undesirable shrub, and protection of *O. cantabrigiensis* or *O. engelmannii* was efficient for increasing nopal biomass yield, perennial grasses and solid organic matter content. The authors reported a 76% establishment for above species of nopal. *O. engelmannii* produced the greatest biomass yield, as it has more succulent pads with few spines. Other study carried out with *O. rastrera* pointed out that the best establishment and the highest green aboveground production occurred on deep clayed load soils with slope no greater than 2% (Maldonado & Zapien, 1977).

Among advantages of using prickly pear plantations with the aim of controlling land erosion in arid and semi-arid regions are: climatic stability, increase carbon capture, decreases the global warming, increased levels of soil fertility, stabilization of animal production and reduction of water needs of cattle (Table 37.5). However, these factors in many cases have not been evaluated, and therefore *Opuntia* plantations in various regions of the world have been economically underestimated. The

Table 37.5 Advantage of using nopal as soil erosion control agent

Advantage	Source
Direct	
Improving soil physical properties	Monjauze and Le Houérou (1965), Bariagabre et al. (2016)
Increased levels of soil fertility	Le Houérou (1994, 1996)
Regulation of surface hydrological process	Vásquez et al. (2010)
Reduction of runoff and soil loss	Vásquez et al. (2010)
Climatic stability	Le Houérou (1994, 1996)
Carbon capture	
Decreasing the global warming	
Indirect	
Deforestation control	Vázquez-Alvarado et al. (2011)
Stabilization of animal production	Le Houérou (1994, 1996)
Reduction of water needs of cattle	Le Houérou (1994, 1996)

use of cactus hedges around badlands, arid lands and stony/rocky slope have been rehabilitated in efficiently, easy, and cheap way in Tunisia and Algeria (Le Houérou, 1994, 1996).

It is important to note that in the mid-twentieth century in North Africa, diverse strategies have been implemented to reduce water and wind erosion of grasslands; reverse desertification and restore vegetation cover in arid areas, slow and direct the movement of the dunes, improve the restoration of vegetative cover and prevent erosion in those areas through the planting of prickly pear (*O. ficus-indica f. Inermis*). Wide extensions of land have been planted with *Opuntia* in Algeria, Morocco and Tunisia. It is estimated that there are 1 million ha planted with two objectives: to combat erosion and desertification of the land and to provide fodder for livestock (Nefzaoui et al., 1993).

Cactus hedges established along contours play a major role in erosion control and land-slope partitioning. Soil physical properties and organic matter content under hedges and in adjacent areas are improved. The permeability and water storage capacity of aggregates in the topsoil increase, they are more stable, less sensitive to surface crusting runoff and erosion (Monjauze & Le Houérou, 1965). Bariagabre et al. (2016) reported that soils where *Opuntia* was planted showed high levels of soil organic carbon, soil total nitrogen, soil available phosphorus, soil bulk density, soil moisture, and electric conductivity compared to adjacent open areas.

The use of vegetation patches of prickly pear in semiarid lands from central Mexico, reduced by 98% runoff, and 99% soil loss. These results indicate a positive effect of *Opuntia* patches on the regulation of surface hydrological process (Vásquez et al., 2010). The cultivation of prickly pear in arid and semi-arid lands of Mexico generated a control in soil erosion and deforestation in various regions of the country, achieving 82% of reforestation and an erosion level considered stable of 0.4 ton ha^{-1} year^{-1} (Vázquez-Alvarado et al., 2011). One of the key factors to improve soils is water infiltration. Cactus cladode extract has been assessed and showed that they have the capability to improve water infiltration in soils (Sáenz et al., 2004).

5 Water Treatment

A common practice in some countries that farmers use cactus mucilage to purify drink water (Sáenz et al., 2004). The use of nopal is an excellent alternative to reduce the use of chemical products in the treatment process of industrial wastewater (Table 37.6). The general processes use alum as coagulant, polyacrylamide (PAM) as flocculant and lime as coagulant aid. In the case of potable water treatment, aluminium sulphate and ferric chloride are used as conventional coagulants. All these chemicals can be replaced by polysaccharides obtained from nopal (Saleem & Bachmann, 2019). Approximately 10% of Latin America population, principally low-income communities, remains without access to clean water. In response to this problem, a diverse water treatment methods including bacterial

Table 37.6 Nopal as water treatment agent

Contaminant	Active component	Efficiency (%)	References
Pb^{2+}	Nopal biomass	>94	Saleem and Bachmann (2019)
Suspended solids	Cactus juice	83.3–88.7	Sellami et al. (2014)
Suspended solids	Cactus juice + lime	>90	Sellami et al. (2014)
Kaolin, arsenic, and bacteria	*O. ficus-indica* mucilage	>90	Buttice and Alcantar (2014)
Turbidity	Cladodes	98.7	Nharingo and Moyo (2016)
Heavy metals	Fruit and peels mucilage	100	Saleem and Bachmann (2019)
Bacteria (*E. coli*)	Nanofibrous membrane	100	Thomas et al. (2013)

by-products and plant-based materials have been assessed. *Opuntia ficus-indica* cactus has great potential because of its abundance, location, fast growth, and low cost.

In contaminated water, nopal (*Opuntia streptacantha*) biomass without any chemical or physical pretreatment, showed a significant Pb^{2+} removal. The maximum adsorption capacity was 0.14 mmol g^{-1} with an efficiency higher than 94% (pH 5.0 and 2.5 g L^{-1} nopal biomass). The technological implication of these results is the development of an effective and economic technology to remove Pb^{2+} from contaminated water (Miretzky et al., 2008).

Sellami et al. (2014) assessed the cactus juice compared with polyacrylamide as flocculant agent and found that depending on the wastewater's origin, the cactus juice computed removal efficiencies of 83.3–88.7% for suspended solids, and 59.1–69.1% for chemical oxygen demand. In addition, the use of cactus juice + lime enhanced the coagulation-floculation process with efficiencies greater than 90% for both suspended solids and chemical oxygen demand.

The use of nopal mucilage as flocculant agent for kaolin, arsenic, and bacteria was assessed by Buttice and Alcantar (2014), who demonstrated that mucilage from *O. ficus-indica* increases settling rates of kaolin (50 g L^{-1}) up to 12 times faster than control. So, it is a viable method for the aggregation and removal suspended acid-washed kaolin. Its efficiency combined with its abundance, low cost and accessibility become successful method for removal or reduction of suspended contaminants such as kaolin, arsenic, and bacteria.

The use of cladodes, fruit and peels mucilage and electrolytes showed maximum biosorption capacities up to 1000 mg g^{-1} for dyes and up to 2251.5 mg g^{-1} for metallic species. In addition, removal percentage computed was 98.7%, 93.6% and 100% for turbidity, chemical oxygen demand and heavy metals, respectively by coagulation-flocculation process. Polysaccharides form *Opuntia* possess multifunctional groups involved in wastewater remediation. The mechanisms associated to *Opuntia ficus-indica* flocculation-coagulation were charge neutralization and bridging effect (Nharingo & Moyo, 2016; Saleem & Bachmann, 2019). Chung-Yang

(2010) reported nopal as coagulant function by means of adsorption mechanism followed by charge neutralization or polymeric bridging effect.

Thomas et al. (2013) development a nanofibrous membrane (biodegradable water filter) based on mucilage of *Opuntia ficus-indica* and an organic polymer (chitosan, polyethylene glycol, poly lactic acid, poly vinyl alcohol) by electrospinning, which can be used in filtering contaminants from water. This invention provides sustainable technologies, environmentally friendly, non-toxic, and biodegradable methods of water treatment that are economically competitive and affordable. The electrospun nano-fibrous membrane remove bacteria (*E. coli*) form water and possess several attributes that make them very attractive in water filtration technology, these include but are not limited to, high porosity, pore sizes ranging from tens of nanometers to several micrometers, interconnected open pore structure, and large surface area per unit volume. In Mexico, the nopal juice is being researched with aim to clean wastewater generated from subway tires wash.

6 Additive Used in Construction

In construction industry recent interest has been shown in the nopal mucilage due to diversity of applications and properties as adhesive, anti-corrosive, and as additive for paints and adobe (Table 37.7). In Mexico, with a long history of using, the cactus mucilage has been applied in combination with lime as plaster on adobe or bricks walls, as well as a water barrier in stucco (Sáenz, 2013; Torres-Acosta, 2007; Torres-Acosta & Martínez-Madrid, 2005). Cladode juice was traditionally added to lime, as a practice that traced back to antiquity, as an organic adhesive to restore and protect historical buildings (Cárdenas et al., 1998). The authors assessed the addition of cactus juice up to 1.95% (extracted by boiling cladodes) to lime. The addition of cactus juice developed a drastic reduction in maximum stress and in the rate of deformation compared with control. The mechanical properties increased owing

Table 37.7 Functional properties of nopal applied in construction

Properties	Application	References
Adhesive	Mud blocks, mortars and concretes	Guillen et al. (2019), Ramírez-Arellanes et al. (2012), Pérez-Castellanos (2009)
Plaster	Adobe or bricks walls	Sáenz (2013), Torres-Acosta (2007),
Water barrier	In stucco	Ramírez-Arellanes et al. (2012), Torres-Acosta and Diaz-Cruz (2020)
Improve durability	Lime-based mortars and concretes	Torres-Acosta et al. (2005), Ramírez-Arellanes et al. (2012)
Anti-corrosive	Reinforcing steel in concrete	Pérez-Castellanos (2009), Dúran-Herrera et al. (2012), Lopéz-León et al. (2019), Martinez-Molina et al. (2016)
Resistance to erosion	Adobe bricks	Martinez-Camacho et al. (2008)

to the formation a homogeneous network in which cactus pear mucilage penetrated the calcium hydroxide without modifying the structure.

Natural polymers have been used since ancient times to improve durability of lime-based mortars and concretes. In Mexico, prickly pear mucilage has historically been used as an additive for lime mortars because it prevents rapid drying of the mortar, helping to retain the moisture it requires to set properly without cracking. Chandra et al. (1998) assessed cactus extracts in a Portland cement mortar and they found that cactus extracts increase the plasticity, improve water absorption and freeze-salt resistance of the mortar. The components of the cactus extracts (polysaccharides and proteins) interacts with calcium hydroxide produced during hydration of Portland cement to conform complexes affecting the crystallization process (Peschard et al., 2004).

Ramsey (1999) studied cladode mucilage (10%) as stabilizer for adobe construction blocks and found a lightly advantage compared them with the lime traditionally used. Probably, this result was due to the low dosage and the method used to prepare cactus mucilage as stabilizer (washing and soaking the cladodes in water for 18 days). In a similar work, Cárdenas et al. (1997) assessed the use of cladode juice in lime pastes and stated that the juice weakened the texture of lime paste.

In a study by Hernández and Serrano (2003) on the addition of lyophilized mucilage cladodes (0.5 g) to mortars (plaster, silicate sand and lyophilized cladode mucilage), they found a better compression resistance than the control mortars. Torres-Acosta et al. (2005) and Ramírez-Arellanes et al. (2012) stated that addition of cactus mucilage to cement mixes did improve the durability of the cement products. The adhesive properties of lime are enhanced, and water repellence is improved. Martinez-Camacho et al. (2008) treated adobe bricks with nopal previous immersion in alcohol-water solution, this treatment increased their resistance to erosion. The structural properties of treated material showed that nopal coats the adobe small particles, generating with this a homogeneous erosion and not selective and this impregnated material is stable up to 200 °C. This treatment aims to restore a building with cultural and historical background "*Nuestra Señora del Pilar mission*".

The addition of mucilage in lime and marble mortars improves consistency, adhesiveness, shrinkage percentage, required stirring power and supported load. The best results were obtained with marble: lime ratios of 1.5:1 and mucilage: water of 2:1. Due to its good suspension of solids, acceptable fluidity for injection, high adhesiveness and high compressive stress. This mixture represents a flexible lime and marble mortar for the consolidation of mural painting by the injection method (Pérez-Castellanos, 2009).

Mucilage from nopal is also applied in the cement industry due to the advantages it generates including reduce retraction, corrosion inhibitor, viscosity modifying agent, reduces deformity of the paste, maintaining fluidity and maintaining viscosity, it is an air entrainer, holds water longer (therefore, hydrates it longer) which aids in remote transportation (Pérez-Castellanos, 2009; Dúran-Herrera et al., 2012). Barajas et al. (2009) studied nopal gum "slobber" as a consolidant to preservation monolithic pieces through impregnation of the mineral with nopal. The use of this organic material cover the mineral particles with a smooth layer, these solutions react and lead to microporosity. León-Martínez et al. (2014) proposed the use of two new bio-polymers: nopal mucilage and marine brown alga extracts as alternative viscosity-enhancing admixtures for the production of stable, cohesive, and homogeneous pastes, mortars and self-consolidating concrete (cement-based materials). Nopal and brown alga extracts dispersions showed a shear-thinning behavior which produce a significant increase on the share viscosity and yield-stress in pastes, mortars and self-consolidating concrete, which increased with increasing brown alga extract concentration and this depend on their molecular nature.

Díaz-Blanco et al. (2019) based on the result obtained by Dúran-Herrera et al. (2012) stated that nopal mucilage can delay the corrosion of reinforcing steel in concrete. This natural additive at concentration 1:3 was able to delay the onset of corrosion and protect the reinforcing steel with an efficient of 86%, acting as a retardant of the setting of the concrete, as a result of maintain a corrosion rate between negligible and low throughout the test period. They also affirmed that nopal mucilage within the concrete matrix maintains the ideal conditions for the steel to acquire a state of passivation.

Lopéz-León et al. (2019) evaluated the mucilage from *Opuntia strpetacantha* (0.5 g) as a corrosion-resistant hybrid coating of rebars through immersion for 24 h in a 3.5 wt% NaCl solution. The mucilage hybrid coating enhanced corrosion protection due to the homogeneity of the mucilage in the coating. Thus, it has favorable properties as a barrier due to its ability to obstruct the diffusion of aggressive species by trapping them in a coating structure, which avoid their adsorption on the metallic surface, acting as a corrosion inhibitor due to its semipermeable behavior, where only water molecules flow through its pores.

A clear example about the benefices of nopal in construction is the development of a mud block using ecological materials like soil mixtures, cellulose (recycled paper), and *Opuntia ficus* extract (mucilage) as a binder. The soil and the wastepaper are grinding down to a particle size smaller than 3 mm, the mixture is hydrated, and its pH was adjusted (<8) trough addition of lime. Follow by a stabilization that contributed to the cementation of particles and the subsequent addition of mucilage; the components are homogenized until moldable pasta is obtained. This is emptied into molds and left to dry for 9 days. The mud blocks showed a compressive strength higher 76 kg/cm^2 than non-structural conventional bricks 60 kg/cm^2, and structural conventional bricks 70 kg/cm^2. In addition, not only moisture absorption is reduced by up to 30%, but also the organic brick weight up to 25% were computed. Moreover, at a 10% lower cost since no firing is required without generating CO_2, the production times are shorter, mitigation of climate change, fewer worker diseases and mitigation of climate change. So, this kind of material promotes the conservation of natural resources and reduce the environmental impact (Guillen et al., 2019).

A developed research by Torres-Acosta and Diaz-Cruz (2020) showed that nopal derivatives (exudate nopal mucilage and cooked nopal mucilage) may act as clogging sponge-like biopolymer within the cement matrix pores, stopping water and chloride transport into concrete. Exudate nopal mucilage exhibited improved durability index values up to 20% (total voids percentage/effective porosity decreases and saturated electrical resistivity/compressive strength increase), and rapid chloride permeability index was improved up to 30%. For its part, cooked nopal mucilage produced superior improvements to the control mixture between 20% and 40%. On the other hand, addition of dehydrated nopal powder did not improve substantially concrete durability performance, except chloride transport: additions <2% decreased rapid chloride permeability index value up to 10%.

7 Improving House Paint and General Paints

The mucilage's from nopal had a traditional use for improving house paint in some countries (Sáenz et al., 2004). Studies are under way on the use of cladode extracts as an additive which function as adhesives in paints (Sáenz, 2013). In Mexico, small pieces of nopal pads are mixed with lime solutions to improve the quality when this solution are used to pain walls or fences. In this process, mucilage give fixing properties. Other example is "*Ecopal*" a multipurpose paint made form slime of prickly cactus, limonene solvent and polystyrene, it is friendly with environment and also works for waterproofing (Vargas, 2015).

8 Nopal Mucilage in Edible Coatings and Packaging Applications

By definition edible films and coatings are primary packaging materials, they are able to preserve foodstuffs and extend their shelf life, based on polymeric matrixes directly applies on the foodstuffs surface or between constituents by immersion, spraying, electro-spraying, which is followed by drying. Generally, these films and coatings are developed from biopolymers and enriched with different kind of additives as essential oils, plant extracts, enzymes and probiotics providing biological and functional properties such as antioxidants and antimicrobial activities. The advantage of biopolymer-based material over polyolephine-based materials are their sustainability and safer for human health (Gheribi & Khaoula, 2019).

Nowadays, edible coatings and films have been projected as operative solution to prevent physical and nutritional quality foods losses. This is no new, cellulosic and waxy coatings were used in the mild-twentieth century to reduce weight loss and develop the shine and brilliance of fruit and vegetables (Hassan et al., 2018). The advantage of use edible coating in horticultural products and perishable food stuffs is the coatings acts as a modified atmosphere system or packaging in which the metabolism is reduced as a result to the change in the micro-environment generated between the product tissue and the thin layer coating development high CO_2 and H_2O vapor levels and low O_2 levels. This reduction in metabolism, also decreases the respiration rate and deteriorative reactions like browning after like reflection on surface or physical damage generated by instability of phenolic compounds or enzymatic activity such as oxidase and peroxidase. Coatings acts like a selective barrier to gases and water transfer by slowing foodstuff dehydration maintaining its turgor. The change in atmosphere (high CO_2 levels, and low O_2 levels) decrease the growth of spoilage and pathogenic microorganism without affecting color, taste or smell of the coated product (Guevara-Arauza, 2010).

Cactus mucilage is consider a trendy versatile biopolymer, eco-friendly, available, and profitable alternative to petroleum-based materials (Valdés & Garrigós, 2016). Also, this biopolymer is one of the most abundant carbohydrate in cactus plant and it is consider a valuable raw material for added-value biomolecules with various industrial applications (Ochoa & Barberab, 2017). This polysaccharide has been used as polymeric matrix and reinforcing or blending agent for development of bio-composite materials and as a green material that could be applied in biomedical, construction, furniture and packaging industries (Kumar et al., 2017, 2018). The mucilage content in cladodes is higher in older cladodes and increases as a response to drought in order to preserve the plant. It is more abundant in cactus cladodes (19–24% dry weight) than in fruit peels (4.1%), fruit pulp (3.8%) and flowers (18.3%) (Habibi et al., 2004; Matsuhiro et al., 2006; Ammar et al., 2015).

Cactus mucilage is a branched heteropolysaccharide (about 33–55 sugar residues) with high molecular weight conformed mainly of arabinose, galactose, xylose, and rhamnose with slight variations in the content. It has the ability to swell when dissolved in water and to form colloidal and viscous suspensions (Sepúlveda et al., 2007). Consider as hydrocolloid, *Opuntia ficus-indica* mucilage has great water-holding capacity, which permit to the plant growing under water-stress conditions, playing an important role in the physiology of the plant (Sáenz et al., 2004). Mucilage extraction yields depend on the plant organ, the cactus species, and the extraction method. Furthermore, the extraction parameters deeply influence the extraction yield (Sepúlveda et al., 2007). Due to its properties, cactus mucilage can be used as a reinforcement agent in polymeric matrices, to develop edible films and coatings as well as to form bio-composites when it is blended with other polymers and it can be consider eco-friendly material (Del-Valle et al., 2005; Gheribi et al., 2019a, b; Lopez-Garcia et al., 2017; Guadarrama-Lezama et al., 2018).

8.1 Cactus Mucilage as a Coating Material

Cactus mucilage has been effectively used as a coating material for highly perishable horticultural and minimally processed products (fresh cut or sliced ones; Table 37.8). Del-Valle et al. (2005) used cactus mucilage for first time on strawberries. This treatment showed better firmness than control and enhanced resistance to mechanical damage during storage and, thereby, reduce economic losses. Furthermore, the color of coated strawberry was maintained for 5 days and their sensory attributes were preferred over uncoated ones during storage period.

Oluwaseun et al. (2014), used cactus mucilage-based coating on papaya fruits extend their shelf life and reported that ripening was delayed during storage at room

Table 37.8 Application of nopal based edible films and coatings on horticultural products

Horticultural product	Total shelf life (days)[a]	Increase in shelf-life (days)[a]	References
Strawberries	14	5	Del-Valle et al. (2005)
	21	12	Ruiz-Hernández (2009)
Blackberries	10	6	Najera-García et al. (2018)
Papaya	21	7	Oluwaseun et al. (2014)
Pineapples	28	9	Trevino-Garza et al. (2017)
Sliced pineapple	6	5	Zambrano et al. (2017)
Mango	16	4	Girma et al. (2019)
Sliced mango	9	6	Alikhani (2014)
Kiwifruit slices	12	5	Allegra et al. (2016)
Figs	14	7	Allegra et al. (2017)
Guava	16	4	Zambrano et al. (2018)
Yam	10	6	Morais et al. (2019)
Tomatoes	21	13	Bernardino-Nicanor et al. (2018)
	30	19	Olicón-Hernández et al. (2020)
Loquat fruits	35	30	Kahramanoğlu (2020)
Fresh cut potatoes	5	5	Wu (2019)
Roasted peanuts	29.5	21	Mestrallet et al. (2009)

[a]Compared with control

temperature as a result of change in its internal atmosphere. Also, aerobic psychrotrophic and mesophilic bacteria counts decreased from 11 to 4–6 CFU/g and from 9 to 4–6 CFU/g, respectively. Similar results reported the efficacy of cactus mucilage coatings for reducing microbial growth (Trevino-Garza et al., 2017; Allegra et al., 2017).

For their part, Trevino-Garza et al. (2017) applied bio-composites materials of mucilage/chitosan coatings on fresh-cut pineapples and found that it is effective to protect the product and extending its shelf life by 6 days in comparison with control (uncoated ones). Coated fruit exhibited higher firmness than uncoated ones after 18 days of storage at 4 °C. The coatings act by decreasing water vapor transmission rate and weight loss by almost 10%. The results indicated that the coating delayed respiratory metabolism reactions. Besides, coating significantly reduce *Listeria monocytogenes* and *Salmonella typhi* counts. They also reported marked reduction on yeast and mold, total aerobic, and psychrotrophic counts for uncoated fruits compared with coated ones from 6.6 to 3–5 UFC/g; 4.7 to 3.6–4 UFC/g; 4.1 to 2.4–3.8 UFC/g respectively, at the end of storage of 4 °C. The authors did not take in consideration the modified atmosphere created by coating and attributed the reduction in microbial growth to antimicrobial effect of chitosan and low storage temperature (4 °C).

In another research, Allegra et al. (2017) showed that *Opuntia ficus-indica* mucilage-based coating applied in breba figs significantly lowered the growth of

Enterobacteriaceae compared with uncoated ones. However, the coating did not induced any microbial growth inhibition in other kind of microorganism throughout storage period at 4 °C. Zegbe et al. (2015) applied edible films to coat guava fruit and found that color, firmness, soluble solids, and dry matter concentrations were maintained throughout room temperature storage. But, the incorporation of plasticizers (glycerol and polyethylene glycol) in edible film formulation increased fruit weight loss. Mucilage from *Opuntia elatior* Mill used for coating guava fruits affected significantly firmness, pH, titratable total acidity, total soluble acids, and sensory attributes (Zambrano et al., 2018),

Tomatoes coated with mucilage from *Opuntia Robusta* maintained their firmness and showed a reduction on weight loss. However, lycopene content remained higher in uncoated tomatoes after 21 days of storage (Bernardino-Nicanor et al., 2018). Morais et al. (2019) applied a composite from cactus mucilage and cassava starch to minimally processed Yam and found that mucilage coated product showed lower weigh loss than roots coated with the composite mucilage-starch. They also found an increase in polyphenol content, likely synthetized as a defense mechanism against browning reactions occurring in minimally processed yam. In general, the use of nopal mucilage as a coating material reinforce firmness, brings better appearance, extended shelf life of cactus mucilage-coated products and preserving their quality attributes. Even though mucilage and partially Tween 20 addition increased yeast growth, their levels were still below the threshold for yeast spoilage at the end of storage period.

Allegra et al. (2016) packed kiwi fruit slices coated only with cactus mucilage or with mucilage-Tween 20, under passive atmosphere at 5 °C for 12 days. Slices treated only with mucilage retained the highest firmness and showed significant beneficial effects on the visual and flavor score of the kiwi-fruit slices until the end of the shelf life period. In addition, both treatments allowed to generate a significant higher firmness and lower weight loss than untreated slices, until 5 days of shelf life. Even though mucilage and partly tween 20 addition increased yeasts growth, their levels were still below the threshold for yeast spoilage at the end of the monitoring period.

Mangoes (*Mangifera indica*) coated with Aloe gel (50%) and cactus mucilage (75%) in combination and/or alone retard chemical and quality deterioration and keep good appearance up to 16 days of storage (Girma et al., 2019). Aloe gel had significant effect on all sensory attributes, while cactus only on color, appearance and over all acceptances. Alikhani (2014) treated sliced mangoes by coating with *Opuntia* mucilage and rosemary oil microencapsulated then were overwrapped using PVDC film and finally stored at 6 °C. This treatment inhibits the decay incidence and slowed microbial growth. In addition, the loss of ascorbic acid, changes in color, activity of peroxidase enzyme were retarded. The author conclude that the use of cactus mucilage effectively prolong the quality attributes and extend the storage life of sliced mango up to 9 days.

Ruiz-Hernández (2009) applied three different kind of coatings on strawberry: (a) “MAG” mucilage (4%), olive oil (1%) and glycerol (1%); (b) “MPG” mucilage (4%), polyethylene glycol (1%), and glycerol (1%); and (c) “C” chitosan (1%), acetic acid (2.5%), and olive oil (0.6%). The coated product was packed in perforated glass polystyrene and stored at refrigeration throughout 21 days. The coats applied to strawberry kept the firmest and sensory characteristics. By its part MAG and C treatments kept the color for long time. In addition, the strawberry coated with a layer of the MAG formulation was the one with the least weight loss at the end of the storage period. The C treatment delayed mold and yeast growth. Besides, MAG films showed both the lowest water vapor permeability (2.02–4.21 g m^{-2} h mmHg) and the O_2 permeability (13.1 mL m^{-2} h^{-1} Pa^{-1}), while C films were more lightly, resistant and stronger despite to show the lowest thickness (34.2–48.9 μm) compared with mucilage formulated films (92.3–167.2 μm). The author conclude that mucilage coating applied to strawberry is a good treatment to keep shelf life.

Olicón-Hernández et al. (2020) designed an edible film based on cactus mucilage (20%), chitosan (2%), and glycerol (3%) as an alternative against fungi infections on horticultural products. This film showed a strong antifungal effect against *Rhizopus stolonifer in vitro* and *in situ* condition increasing the shelf life of tomatoes. The resulting film was homogenous, flexible, luminous, slightly dark and cumulative viscosity.

Zambrano et al. (2017) evaluated the effect of cactus mucilage (10% and 20%, w/v) as edible coating on cut pineapple physicochemical, sensory and quality parameters. Cactus mucilage helped to reduce the detrimental effect caused by minimal processing of fresh cut pineapple. The sliced pineapple (1 cm thick) were treated with sodium hypochlorite then immersed in a solution of mucilage for 1 min, finally were stored at 6 °C for 7 days. The coating was effective in retarding the weight loss and firmness. Thus, judges had preference coated samples at the end of storage for taste, color, texture and appearance attributes.

Kahramanoğlu (2020) assessed four different cactus mucilage based biomaterials on the postharvest life and storage quality of loquat (*Eriobotrya japonica Lindl.*) fruits var. 'Morphitiki'. The author found that cactus mucilage extract (CME), CME + *Nigella sativa* oil, CME + propolis extract, CME + cinnamon oil treatments were effective in maintaining the postharvest quality of loquat fruits by reducing weight loss, positively affecting fruit firmness, preventing fruit browning and reducing decay incidence. Besides, 0.5% *Nigella sativa* oil (Ns) or 0.5% propolis extract (PEx) treatments can be used to store loquat fruits with acceptable quality for up to 35 day at 4 °C.

Najera-García et al. (2018) mixed mucilage from *O. heliabravoana Scheinvar* and thermoplastic starch to produce an edible coating that applied to blackberries. After 10 days of storage, the coated fruits did not show significant different from those of the control on the physicochemical variables. Nevertheless, the microbial growth of coated blackberries was significantly lower than that of the uncoated fruit.

Mestrallet et al. (2009) applied *Opuntia ficus-indica* and algarrobo (*Prosopis* spp.) pod syrup coatings on roasted peanuts stored at 23 °C for 112 days. The product was more resistant to lipid oxidation and development of rancid flavor, so the stability of roasted peanuts was improve through preventing loss of their sensory and nutritional quality. The prickly pear coating showed higher antioxidant activity.

Therefore, its addition as coating provided protection against lipid oxidation. After 20.7 days of storage at 23 °C, peroxide value in roasted peanuts coated with prickly pear syrup reached 10 meq O_2/kg, while in roasted peanuts without treatment this value was reached in only 8.5 days.

Aquino et al. (2009) applied a combination of cactus mucilage (35 mPa) blended with citric acid (1%), and sodium bisulphate (500 ppm) as coating to inhibit the browning process during the drying (50 °C and air velocity of 2 m s^{-1}) of banana Roatán (*Musa Cavendish*) (5 mm thickness). The treatment applied to bananas formed and edible coating on the surface of sliced bananas that gives shine and diminished the browning of bananas during drying.

8.2 Cactus Mucilage as a Film Packaging Material

Biodegradable edible films made up from natural polysaccharides are trendy due to over accumulation of solid wasted and their impact on environment. On the other hand, their potential industrial applications is as an excellent alternative to overcome the above problems. In the last decade, cactus mucilage from different plants and varieties has been used to developed standalone and composite bio-based films with unique properties. Between the outstanding raw materials are *Balangu*, cactus, chia, *Dracocephalum moldavica* seeds, flax, quince, and okra fruit. Being non-toxic and intended for human consumption are other advantages of this films. The main process to perform this kind of biodegradable based-mucilage film are based on thin polymeric layers formed by a dry (extrusion) or humid (casting) procedure (Gheribi et al., 2018; Jouki et al., 2014; Dick et al., 2015; Karami et al., 2019; Sadeghi-Varkani et al., 2018; Beigomi et al., 2018; Cotrim et al., 2016).

Espino-Díaz et al. (2010) studied the effect of calcium on developed cactus mucilage-based films using glycerol as plasticizer and found that between pH 4 and pH 8, films were elastic but strong enough to be characterized. The values of tensile strength (TS), elongation at break (EB) and water vapor permeability (WVP) for these mucilage films were 0.95 MPa, 24% and 98–147 g mm/m^2 day kPa,

Table 37.9 Mechanical and barrier properties of mucilage based films

Tensile strength (TS; MPa)	Elongation break (EB; %)	Water vapor (g mm/m^2 day kPa)	References
0.95	24	98–147	Espino-Díaz et al. (2010)
>1	33	63.8	Gheribi et al. (2018)
0.5–2.7	NR	20.22–180.40	Lira-Vargas et al. (2014)
1.65	14	NR	Gheribi et al. (2019b)
30–50	10–70	$0.852–3.066 \times 10^{12}$	Dominguez-Martinez et al. (2017)
4.44	NR	1.41	Gonzáles et al. (2019)
0.25–0.36	NR	6.55	Salinas-Salazar et al. (2015)

NR not reported

respectively (Table 37.9). The films color varied from light yellow to yellow-green at low and high pH values, respectively. Chroma values were higher in mucilage films at high pH values without calcium. Color saturation was influence by pH and calcium content.

Gheribi et al. (2018) assessed the effect of different plasticizers on edible films developed using cactus mucilage and reported that sorbitol-plasticized films showed the best TS and WVP, while polyethylene glycol (PEG) 400 plasticized films showed the highest glass transition temperature 49 °C and thermal stability up to 171 °C. In addition, glycerol plasticized films had TS > 1 MPa, EB 33%, and WVP 63.8 g mm/m^2 day kPa. Comparing, the films developed by Gheribi et al. (2018) had higher TS and EB values than those performed by Espino-Díaz et al. (2010). On the other hand, WVP value for Gheribi et al. films was lower than Espino-Diaz et al. films.

8.3 Development of Composite Materials Using Cactus Mucilage

Composite materials using cactus mucilage (0.5%), gelatin (0.25–0.5%), and beeswax (0.25–0.5%) plasticized with glycerol were produced by Lira-Vargas et al. (2014). The developed composites had intermediate to high roughness. The addition of beeswax increased the lumpiness and decreased the transparency of composite film. The ternary blend showed an increased TS (0.5–2.7 MPa), and decreased water vapor ($13–116 \times 10^{-12}$ mol m/s m^2 Pa), O_2 ($3–14 \times 10^{-12}$ mol m/s m^2 Pa), and CO_2 ($3–9 \times 10^{-12}$ mol m/s m^2 Pa) permeability. Despite of improving the mechanical and barrier properties, the ternary composites characteristics are still poor, which limit their practical and industrial application.

Gheribi et al. (2019b) developed a composite conformed by cactus mucilage and polyvinyl alcohol (PVA). The optimal blend was the composite at 80:20 (mucilage:PVA). The authors showed that PVA inclusion increased TS (165%), EB (14%), and the water contact angle (24%), confirming an improvement on physical, mechanical, thermal and barrier properties of mucilage-PVA films. In another research, the properties of ternary composites made of chitosan, PVA, and cactus (*O. tormentosa*) mucilage (10%) were studied by Dominguez-Martinez et al. (2017). The inclusion of mucilage contributed to composites stability and homogeneity with lower TS values (30–50 MPa), EB values (10–70%) and higher WVP values (852–3066 mL/mm^2 day Pa) and water uptake than neat PVA and chitosan films.

Guadarrama-Lezama et al. (2018) developed a binary-composite made of citric pectin and cactus mucilage at different proportions and showed that films microstructure was compact, smooth and homogeneous even at high concentrations (>12%) with increased thermal stability and decreased water vapor permeability and solubility. Lopez-Garcia et al. (2017) assessed the chemical, thermal, and mechanical properties of composited films based on starch-chitosan-PVA-mucilage

Opuntia joconostle composite throughout two methods, the direct incorporation of mucilage and the addition of water ethanol extracted mucilage. The first treatment caused microphase separation in the film network, while the second treatment had no clear microphase separation (aggregation), this means that the film components were homogeneously dispersed in extracted mucilage and indirectly-added mucilage. Films developed adding directly mucilage showed mechanical properties slightly lower than films with extracted mucilage.

Cactus mucilage from *Cereus hildmannianus* fruits (widespread cactus in Brazil) was applied by Damas et al. (2017) to develop glycerol-plasticized edible films with interesting functional properties. Similarly, Gheribi et al. (2019b) used a prickly pear peel for the extraction of mucilage that further used to develop flexible and cohesive films with a smooth surface and good thermal stability.

Ayquipar-Cuellar et al. (2020) developed various films using agro-industrial wastes in specific prickly pear peel mucilage, potato husk starch, glycerine, and vinegar (acidifying) with the aim to be applied in horticultural products. All edible films showed good barrier properties and thereby very low permeability. In addition, cactus mucilage and glycerine contents led to films with higher thickness, opacity, moisture and water retention capacity, while potato starch content influences the percentage of water solubility.

An intelligent packaging was developed based on incorporation of betalain (0.25, 0.50 and 1.0 wt% on starch basis) from red pitaya (*Hylocereus polyrhizus*) peel extract in a starch/polyvinilo alcohol matrix. The use of betalain extract (1.0 wt%) in films allowed to monitor the freshness of shrimp, as a result of a visible color change due to the accumulation of volatile nitrogen compounds (ammonia) during the spoiling process as a result of color change under alkaline conditions. The extract addition improved, not only the compactness mechanical, antioxidant, and antimicrobial potential of the films, but also enhanced water vapor barrier and ultraviolet-visible light barrier ability (Qin et al., 2020).

Scognamiglio et al. (2020) blended cactus mucilage in gel form with a self-produced thermoplastic potato starch (TPS), and glycerol (30%). Three methods of extraction were compared bare maceration, mechanical blending, and mechanical blending plus maceration. The last process allowed to get the high extraction yield and the larger deformation of the samples with respect to the control. The authors also reported that the mechanical properties were not completely satisfactory since the effect of calcium and magnesium contained in the mucilage did not improve the rigidity of TPS films.

Gonzáles et al. (2019) successfully fabricated edible films containing mucilage from different Nopal cultivars (Villanueva, Jalpa, and Copena F1). The edible films developed with Copena F1 showed the lower water vapor permeability (1.63×10^{-11} g m^{-1} s^{-1} Pa^{-1}), high solubility (81.2%), and high resistance (4.44 N mm^{-1}). The characteristics in color, yellowness index, transparency (3.81); and light transmission rate (48.9%) allow their use for foods susceptible to light exposure, with better visual effect.

Due to importance related with cactus mucilage properties researches have explored the development of edible coatings and films with the main goal to apply this to horticultural products. Salinas-Salazar et al. (2015) characterized films based on *Opuntia ficus-indica* mucilage (0.5% w/v), beeswax (0.5%, w/v), and gelatin (0.5%, w/v) and found that this kind of films had the lowest water vapor permeability (7.578 × 10^{-11} g/m s Pa). Edible films with 1.5% (w/v) gelatin, and 0.5%, 1% and 1.5% (w/v) of mucilage had the best mechanical properties (0.25–0.36 MPa). Orozco (2017) developed and characterized films based on cactus mucilage (5%) + citric pectin (2%), and glycerol (5 mL). Ayquipa (2018) characterized films performed with prickly pear peel mucilage, potato peel glycerol, and vinegar. The author coincide on the fact that this sort of films may be useful for application in the preservation of fruit.

Overall, cactus mucilage films exhibited unique properties; however, barrier properties are inferior to polyoleophine-based films (conventional plastic materials), which limit their industrial application. Cactus mucilage is compatible with many biodegradable polymers such as PVA, chitosan, starch, and citric pectin, which may lead to countless industrial applications.

9 Nanoparticles and Nanocomposites Based on *Opuntia ficus-indica*

Recently, organic nanoparticles, as for example cellulose, pectin and mucilage, are being synthesized due to its importance in diverse areas such as in food and pharmaceutical industries, and in packaging technologies. Their more relevant characteristics are availability, functionality, easy synthesis, properties, low cost, high biodegradability, biocompatibility, and high strength. As a result, biopolymer nanofibers are being used as reinforcement material in electronic devices medicines, and many other products. However, the use of spherical nanoparticles has not widely been applied in the industry at present. It is important to highlight that dimensions of nanoparticles depend on numerous factors that include the source from the cellulose was obtained and the precise preparation conditions among others.

9.1 Cellulose Nanoparticles from Opuntia *spp.*

Malanine et al. (2005) obtained nanocomposite materials prepared from *Opuntia ficus-indica* cladodes and model amorphous matrix composed of an aqueous suspension of a copolymer of styrene and butyl acrylate. In combination, the highly reactive surface of the cellulosic filler which presenting a high density of hydroxyl groups, the resulting possibility of entanglements, and the very high aspect ratio of the filler, generated a high performance material.

Marin-Bustamante et al. (2017) used the waste generated from de-thorning process of nopal (40,000 tons/year) to generate a new biodegradable nanoparticles

Table 37.10 Green synthesis of nanoparticles from or using cactus components

Source	Nanoparticle	Applications	References
Cladodes	Cellulose	Reinforcement material	Malanine et al. (2005)
Thorns	Cellulose	Reinforcement material	Marin-Bustamante et al. (2017)
Pectin	$Ca_{10}(PO_4)_6(OH)_2$	Bone regenerating material	Gopi et al. (2015)
	CdS	Treatment of cancer cells	Kandasamy et al. (2019)
		Detection of cancers and other diseases	
		Anti-bacterial and fungal activities	
Extracts	Au/Li	Periodontal disease	Alvarez-Bayona et al. (2019)
	$ZnFe_2O_4$	Oxidation of glycerol to formic acid	Kombaiah et al. (2017)
	ZnO	Absorb ultraviolet light in sunscreen	Francisco-Escudero et al. (2017)
	Ag	Antimicrobial activity	Silva-de Hoyos et al. (2012), Ledezma et al. (2014), Baylon et al. (2015)

taking advantage of its huge amount of hemicellulose and cellulose. The size of developed cellulose nanoparticles were ranged from 24 to 122 nm. They concluded that cellulose nanoparticles from nopal thorn could be used as reinforcement material in various industries (Table 37.10).

9.2 *Green Synthesis of Nanoparticles Using Cactus Pectin*

Green chemistry throughout the use of biomolecules from plants, alga, fungi, bacteria, yeast, waste materials have been used to eliminated the use or generation of hazardous substances in the design, manufacture and applications of chemical products. The use of catalysts (polysaccharides, enzymes etc.) in place of physical and chemical reagents improve atom efficiency, reduces the cost of synthesis, free of chemical contaminants, and are safe and eco-friendly. These biomolecules play an active role in the formation of nanoparticles, through biogenic reduction of metal precursors, the nature of biological entities in different concentrations influence the shape and size, acting as driving force for the synthesis of nanoparticles.

Biogenic reduction is a “Bottom Up” approach similar to chemical reduction where a reducing agent is replaced by extract or molecules of natural or waste products with inherent stabilizing growth terminating and capping properties. The biomedical applications including bio-imaging, drug delivery, biosensors, and gene delivery. Gopi et al. (2015) developed hydroxyapatite nanoparticles (25 nm) using pectin extracted form peels of prickly pear as template for the synthesis. The nanohydroxyapatite particles were pure, low crystalline and showed potential antimicrobial activity. The *in vitro* apatite formation showed an enhanced bioactivity, so the synthesized nanoparticles can act as a better bone regenerating material in the field of biomedicine. Kandasamy et al. (2019) described the green synthesis of CdS nanoparticles (spherical shaped, $d_{50} = 9.56$ nm) using *Opuntia ficus-indica* fruit sap as a green template with extrinsic crystallite size control in the quantum confinement range.

9.3 Green Synthesis of Nanoparticles Using Cactus Extracts

Alvarez-Bayona et al. (2019) reported the success in synthesis of Au/Li nanoparticles using extracts form *Opuntia ficus-indica* through green synthesis. Kombaiah et al. (2017) reported the synthesis of spherical $ZnFe_2O_4$ nanoparticles through green synthesis using *Opuntia* extract. The synthetized Zinc ferrites nanoparticles were used in the catalytic reaction for the oxidation of glycerol into formic acid with a good catalytic performance and better selectivity of formic acid throughout the reaction. Francisco-Escudero et al. (2017) applied aqueous extracts of *Opuntia amyclaea* to promote the biorreduction of metal ions and as a particle stabilizing agent in the biosynthesis of zinc oxide nanoparticles (bio-conductors). The developed zinc oxide nanoparticles showed submicron sizes with hexagonal structure. It did not show antibacterial activity (40μL from a 1628μg/mL solution) against *Escherichia coli* and *Staphylococcus aureus* due probably to the encapsulation of polysaccharides and mucilage proteins employed. The pH was critical in order to obtain NPs-ZnO free of $Zn(OH)_2$ with low particle size.

Silva-de Hoyos et al. (2012) prepared stable silver nanoparticles (23 nm) in a colloidal aqueous solution by the chemical reaction of silver nitrate ($AgNO_3$) and *Opuntia ficus-indica* aqueous extract, which function as both, reducing and stabilizing agent. Concentration of reducing agent and temperature during the process can control the size and morphology of nanoparticles. Ledezma et al. (2014) synthesized silver spherical nanoparticles (4–28 nm, an average size 10 nm) using nopal extracts as reducing agent and poly (PVA) as stabilizing agent. Silver nanoparticles were incorporated into PVA nanofiber (250 nm) by electrospinning process. Ag nanoparticles/nanofibers at 50 and 20 ppm concentrations showed antimicrobial activity against *Escherichia coli*, *Staphylococcus aureus* and *Aspergillum niger*.

Baylon et al. (2015) correlated the chemical composition, reducing sugar and phenol compounds content, with the reduce capacity of metallic ions in order obtain silver nanoparticles. They assessed seven wild and two domestic strains of nopal *Opuntia* spp. and found significant differences in the content of this compounds in all nopal strains analyzed. The freeze-dried extracts were used to reduce an $AgNO_3$ solution to obtain Ag-nanoparticles. The authors reported that Milpa alta, Copena, and Xoconostle extracts strains showed very high reduction rates (high nanoparticles yield), while tuna cardona and blanca, as well as rastrero nopal extracts showed from moderate to very slow reduction rates.

10 Bioenergy from Cactus

Faced with the challenge of responding to the world wide needs in the search for new energy sources, the nopal (*Opuntia* spp.), as a result of their chemical composition and their metabolism characteristics, presents advantages in relation to other species given that its high productive efficiency, wide adaptation range, fast growth and low input requirements which allow their grown in marginal and semiarid and arid lands. Cacti have been proposed as an energetic resource. Likewise, the bioenergy from cactus biomass is considerable inexhaustible, clean, sustainable, and constitutes an energy option viable, since from its stems and fruits it is possible to obtain biogas, biodiesel and bioethanol or semi-finished products that can be used directly (Table 37.11).

10.1 Bioethanol

Sanchez et al. (2009) carried out different hydrolysis pretreatments [S1-hydrolyzing fresh cladode with boiling hydrochloric acid 1 M (30 min) or S2-with concentrated sulphuric acid (96%) and autoclave at 121 °C for 20 min] and conditions of process (4 or 5 days of retention time at 25 or 30 °C) in order to determine the best procedure to obtain the maximum ethanol concentration using the yeast *Saccharomyces cerevisiae* throughout fermenting non-cellulosic carbohydrates from prickly pear

Table 37.11 Nopal as source of biofuels

Bioethanol	**Production**[a]	**Fermentation yield (%)**[b]	**References**
	6041.5 mg	41	Sanchez et al. (2009)
	19.5 g L^{-1}	66	Kuloyo et al. (2014)
	20.6 g L^{-1}	70	Kuloyo et al. (2014)
	12.9 g L^{-1}	49	López-Domínguez et al. (2019)
	1490–1875 L ha^{-1} $year^{-1}$	NR	Santos et al. (2016)
Biogas (Methane)	**Production**	**Variety; Density (plants/ha)**	
	1860 m^3	*O. ficus-indica*; 20,000	Krümpel et al. (2020)
	1791 m^3	*Euphorbia tirucalli*; 266,667	Krümpel et al. (2020)
	281–382 mL g^{-1} VS^{-1}	*Opuntia*; NR	Lueangwattanapong et al. (2020)
	3717 m^3 ha^{-1} $year^{-1}$	Prickly pear; NR	Santos et al. (2016)

NR not reported

[a] Concentrations were below the desired level (5%) that considered as economically feasible

[b] Respect to initial sugar content

cladodes. Although considerable concentrations of ethanol were reached (6041.5 mg ethanol which means 41% of fermentation yield respect to initial sugar content) by S2 treatment, these concentrations were far below the desired level (5%) that considered as economically feasible.

In another study, Kuloyo et al. (2014) assessed the effects of limited aeration on the fermentation profiles, sugar utilization, and ethanol production using enzymatic hydrolysate of pretreated cladodes of *Opuntia ficus-indica* as feedstock. Ethanol concentrations up to 19.5 g L^{-1} (66%) and 20.6 g L^{-1} (70% of the theoretical yield on total sugar in the hydrolysate) were obtained in oxygen limited cultures with *Kluyveromyces marxianus* and *Saccharomyces cerevisiae*, respectively. These ethanol concentration represent almost double compared to non-aerated cultures in which similar ethanol yields were reported through fermentation procedures using *K. marxianus* and *S. cerevisiae* at 30 and 40 °C. Not only ethanol yield by *K. marxianus* was enhanced, but also the utilization of galactose, xylose and arabinose. Besides, the authors reported an improvement in ethanol concentration obtained by fermentation of cladodes of 1.4% (w/v) respect to that reported by Retamal et al. (1987) who reported 1.2% (w/v) of ethanol production using fruits and cladodes. However, further bioprocess development (deal with viscosity and increase the fermentable carbohydrate concentration in the hydrolysate) is required to obtain an economically viable ethanol concentration of at least 4% (w/v) (Wingren et al., 2003) from this lignocellulosic feedstock.

López-Domínguez et al. (2019) evaluated ethanol production using cladodes flour (20%) as unique carbon source and two wild microorganism *Acinetobacter pittii* isolated from decaying cladodes at conditions of 37 °C and pH 6.5 for both total cellulases (0.67 IU/mL) and endoglucanase (0.23 UI/mL), respectively, and *Kluyveromyces marxianus* isolated from termite stomach for 4 h at 40 °C and pH 5.5 as conditions to obtain the maximum alcohol production (12.9 g/L). Based on their results, the authors suggest the use of *A. pittii* to develop the hydrolysis of carbohydrates and then, the use of *K. marxianus* for alcoholic fermentation in a simultaneous or semi-simultaneous process.

10.2 Biogas Production (Methane)

Ramírez-Arpide et al. (2018) assessed that nopal (*Opuntia ficus-indica* (L.) Mill.) could be used for biogas production by co-digestion with dairy cow manure. The authors took in consideration the fact that the last one is the second largest source of greenhouse gas emissions in dairy farms. Additionally, a life cycle assessment was carried out to evaluate the environmental impact and energy balance of biogas production associated with the process to evaluate the feasibility of using nopal as biogas source. The authors compared an organic farming system and a conventional farming system. Biogas production and yield data obtained in a 10 L anaerobic digester showed that the energy return on invest for biogas production ranges from 8.1 to 12.4. Organic farming system decreased the environmental impact by 22.5%

in the global warming potential category but increases the acidification potential and eutrophication potential impact category values by 47.2% and 45%, respectively, while covering the digestate tank results in 2.3% reduction in global warming potential and 1.7% reduction in photochemical ozone creation potential.

It is important to highlight that gas production from nopal cladode and dairy cow manure co-digestion and digestate management offers cleaner energy production since the global warming potential has a lower value than that reported for similar feedstocks. The use of these two biomasses combines the strengths of a plant that accumulates biomass efficiently and the reduction of greenhouse gas emissions by using one of the main wastes in dairy production.

Krümpel et al. (2020) studied the potential of intensive cultivation of *Opuntia ficus-indica* and *Euphorbia tirucalli* under various planting densities on marginal land blocks (900 m^2) and compared the specific methane production of their biomass. The results showed that high density planting did not negatively affect the plant growth and biomass production. During 4 months growth time, the plantation at the highest density of *Opuntia ficus-indica* 20,000 plants/ha of marginal land was able to generate a methane yield of approximately and 1860 m^3. This methane production was higher than 1791 m^3 generated in the case of *Euphorbia tirucalli* at 266,667 plants/ha.

Lueangwattanapong et al. (2020) reported that methane yield (281–382 mL/g VS) of five selected crassulacean acid metabolism (CAM) species from the five different genera (*Agave*, *Ananas*, *Euphorbia*, *Kalanchoe*, and *Opuntia*) were equivalent to that of the maize. Therefore, CAM plants could represent viable new feedstocks for biogas production. *Agave angustifolia* Haw. generated the highest methane yield of all CAM species. It is important to highlight that batch assays were performed using sludge and rumen fluid as inocula under uncontrolled pH at 39 °C. So, rumen fluids could play an important role in the hydrolysis step.

Lower lignin in CAM plants as compared to maize resulted in a faster volatile fatty acid (VFA) production suggesting that CAM plants may be viable as bioenergy crop. Santos et al. (2016) reported that compared with other crops, prickly pear showed high potential for methane production (3717 m^3 ha^{-1} year^{-1}) being comparable to traditional energy crops. In contrast, the ethanol yield potential (1490–1875 L ha^{-1} year^{-1}) was lower compared to traditional biomass sources (sugarcane and sugar beet for example).

11 Nopal as Source of Electricity

Deshpande and Joshi (1994) fabricated an electrochemical cell using cactus stem as an electrolyte. The authors studied the discharge characteristics and found that at a current drain of 100 φA, the cell gives an optimum energy density of 175 mW h kg^{-1}. The power generated by these cells is enough to run piezoelectric buzzer and a LCD calculator for a few hours.

Kamaraj et al. (2019) focused their work on spending biomass effluent made with prickly pear cacti mixed with cattle dunk waste (80:10) to improve resource utilization, reduction of the waste stream and further energy production through microbial fuel cells (MFCs) system. The design of a modified clay cup (*cantarito*) microbial fuel cell (C-MFCs) improved applying commercial acrylic varnish (AV) on the internal side (In-C-MFCs), external side (Out-C-MFCs) and both sides (Both-MFCs) of the clay cup to digest the biomass effluent from nopal biogas. The maximum volumetric power density were 1841.9 mW/m^3, 1023.7 mW/m^3, and 448.9 mW/m^3 for Both, Out, and In-C-MFCs, respectively. The produced methane by decomposition of biomass effluent was used for fuel and burned to generate enough electricity in this case to power a 4-digits clock with two Both-C-MFCs connected in series for 29 days. The acryloyl group in varnish could favor the performance of C-MFCs, this theory is supported by the fact that control experiment (C-MFC without applied varnish) did not show a stable potential as a consequence a poor performance. Additionally, metagenomics studies reveal the diversity of the microbial community at the initial and final stage of MFC operation. The microbial diversity including members of the phyla *Actinobacteria*, *Bacteroidetes*, *Firmicutes*, *Proteobacteria*, *Synergistetes* and candidate division TM7 was found. Interestingly, the microbial analysis revealed that Rhizobiales and Bdellovibrio were significantly more abundant in Both-C-MFCs.

Apollon et al. (2020) explored the application of plant microbial fuel cell (P-MFC) in arid or semi-arid areas using four *Opuntia* species for the generation of sustainable electricity via plant-based biobattery design under open environment and unsaturated water conditions. The authors constructed a Novel vertically integrated plug-in ceramic stick based P-MFCs, this could reduce the usage of the topsoil surface and aid the possible potential of scale-up design. For a long operating time (30 days), the results showed an average power density of 103.6 mW m^{-3} with reactors using *Opuntia albicarpa*, followed by *Opuntia ficus-indica* (10.63 mW m^{-3}) > *Opuntia robusta* (7.46 mW m^{-3}) > *Opuntia joconostle* (0.46 mW m^{-3}), with 1000 Ω resistance. Higher total electricity production of 285.12 J was achieved in *Opuntia albicarpa* over 4 weeks. In addition, the energy generation of 3.66 W h m^{-2} was achieved in this study. Notably, *Opuntia ficus-indica* and *Opuntia albicarpa* species showed a significant height in the first 2 months (P-value < 0.05). The authors concluded that: this finding opened the avenue for the electricity generation impact on plant growth. The P-MFC also shows the potential to be used in a semi-arid area.

12 Nopal Used in Solar Cells and Halographic Materials

Olivares-Pérez et al. (2012) described the use of 0.8 mL fermented nopal (*Opuntia ficus-indica*) extracts mixed with 2.5 mL polyvinyl alcohol (PVA-matrix), deposited by a gravity technique on a glass substrate, as a recording medium to be applied in holographic grating, written by a He-Cd laser (442 nm). The nopal extract used was generated through the degradation of pectic substance and chlorophyll by natural processes of fermentation through sugars and alcohols. Despite temperature has an important role in the decomposition rates of chlorophyll and mucilage through pheophytins reactions, the fermentation was developed at room temperature, a process in which is highly likely that the Mg atoms in most chlorophyll nucli are substituted by Fe^{2+} generating a dark brown color from the chlorophyll fermented mucilage. The authors demonstrated the presence of Fe-pheophytin, together with a mixture of combination of many other mineral ions responsible for the photosensitivity of the material. Previous studies have written holograms with Fe (III), which makes a transition to Fe (II) for recording an image. Even though the PVA film with the fermented extract is dried to form a photosensitive emulsion, the extract is strongly affected by the environmental conditions, which determine the speed of the aging process of the photosensitive film (oxidation). The photosensitive material developed behaved well, under normal laboratory conditions (room temperature 20 °C, relative humidity 40%) has the property of self-developing, is easy to handle, has a low cost, low toxicity and showed adequate properties for building transmission holographic gratings. Besides, the holographic elements constructed from this material have a diffraction efficiency of approximately 32.3% to first order at the Bragg angle.

Ganta et al. (2017) developed a dye-sensitized solar cell (DSSC) using as sensitizers natural dyes (chlorophyll and anthocyanin adhesion promoters) extracted from the cladode of prickly pear (*Opuntia ficus-indica*), the gel of Aloe Vera (*Aloe barbadensis miller*), and the combination of cladode and Aloe Vera extracts on side-by-side configuration. These adhesion promoters helped in efficient adsorption of plant dyes onto the TiO_2 film, leading to photoelectric conversion. The photoelectrochemical performance of DSSCs revealed a open circuit voltages (Voc) ranged from 0.440 to 0.676 V. Fill factors (FF) were greater than 40%, short-circuit photocurrent densities (Jsc) oscillated from 0.112 to 0.29 mA/cm^2 and the highest conversion efficiency of 0.74% was reported for the Cladode DSSC due to the presence of stronger adhesion promoters in the chlorophyll dye, providing a better charge transfer. Moreover, the authors overcome the problem in mixing the dyes by designing a DSSC using two dyes on a side-by-side configuration (conversion efficiency of 0.50%). Due to their low production cost, simple and energy-efficient assembly method, and environmental friendliness, this natural plant bases dyes as sensitizers of DSSCs are promising (Ganta et al., 2017).

Purushothamreddy et al. (2020) explored prickly fruit extracts as a photosensitizer in DSSC and confirmed the presence of betacyanin in the extract and hydroxyl groups anchoring onto the TiO_2 surface. Reflectance edge of TiO_2 is red-shifted upon the adsorption of natural dye. The fabricated DSSC had a conversion efficiency (η) of 0.56% with high fill factor (FF) of 0.85, open-circuit voltage (V_{oc}) of 0.56 V, and short circuit-current density (J_{sc}) with 1.17 mA/cm^2.

13 Bio-Functional Foods

The demand of functional and probiotic foods is on the rise and there is always a quest to develop array of the products rather than the traditional products. Prickly pear stem (nopal) has been used in folk medicine and a raw material since ancient times. Stems have been proved to possess components with valuable biological activities. Nowadays, people consume food not only to cover the nutritional requirements, they also demand for healthy, natural and convenient food that show biological activities. The addition of mucilage from nopal to food products could generate functional food (Table 37.12).

Table 37.12 Nopal based biofunctional foods

Product	Biofunctionality	Compounds related	References
Tortillas	Prebiotic activity	Soluble fiber (mucilage and pectin)	Guevara-Arauza et al. (2011)
	Improve oxidative status	Flavonoids (Quercetin; dihydroquercetin)	
	Antioxidant activity	Chlorophyll, betacyanins; betalain	
	Improve digestive system	Insoluble fiber (cellulose and lignins)	
	Improve immune system	Soluble fiber consumed by acidolactic bacteria	
Bread rolls	Prebiotic activity	Soluble fiber (mucilage and pectin)	Guevara-Arauza et al. (2015), Guevara-Arauza et al. (2012)
	Antioxidant activity	Chlorophyll, betacyanins; betalains	Guevara-Arauza et al. (2011), Bouazizi et al. (2020)
Juice and beverage	Antioxidant activity	Flavonoids, chlorophyll, betacyanins; betalain	Panda et al. (2017)
Ice cream	Prebiotic activity	Soluble fiber (mucilage and pectin)	Guevara-Arauza et al. (2012)
	Antioxidant activity	Chlorophyll, betacyanins; betalain	Perez-Navarro (2016)
	Improve digestive system	Insoluble fiber (cellulose and lignins)	Guevara-Arauza et al. (2011)
	Improve immune system	Soluble fiber consumed by acidolactic bacteria	El-Samahy et al. (2009)
Salami	Antioxidant activity	Betalain pigments	Kharrat et al. (2018)
	Prebiotic activity	Soluble fiber (mucilage and pectin)	

13.1 Tortillas

Guevara-Arauza et al. (2011) studied the bio-functional effects of nopal supplemented products, tortillas and bars (filled with prickly pear fruit jam) and reported that these kind of products have suitable physicochemical characteristics to be marketed. Interestingly, a high content of bioactive components (i.e., dietary fiber and polyphenols) were achieved in the products. Daily supplementation with nopal-based tortilla over 21 days, improved the oxidative status of healthy humans. Experimental evidence showed increased levels of trolox equivalent antioxidant capacity (TEAC, 1.47 mmol/L), phenolics (7.67 mg QE/L) and vitamin C (77.91μmol/L) in volunteer's plasma after intake and the decreased oxidative status in plasma lipids (MDA levels), as well as lower concentrations of the main antioxidant agent in the oxidized form in erythrocytes (GSSG). In addition, a diminution of glucose (4.43 mmol/L), cholesterol (total 4.27 mmol/L, and LDL, 1.96 mmol/L), and triglycerides levels (1.54 mmol/L) were detected, which together reduce the risk of various chronic diseases. The relative low levels of antioxidants provided by the nopal-based products can not generate the observed effects by themselves. Therefore, other compounds with antioxidant activity present in nopal and compounds of the formulation should be involved in the observed findings. The author concluded that the intake of nopal-based tortillas with high content in fiber and antioxidants could help to improve the overall oxidative status in humans, which can reduce the risk of some chronic diseases. In addition, these products showed suitable physicochemical characteristics to be marketed (Guevara-Arauza et al., 2011).

13.2 Bread Rolls

Guevara-Arauza et al. (2015) assessed the addition of total fiber (TF), insoluble fiber (IF), and soluble fiber (SF) from nopal to wheat flour to make bread rolls. The rheological properties of dough as well as quality, texture, sensorial and physical characteristics of the crumb rolls produced were evaluated. The storage (23.5 MPa) and loss modulus (11.9 MPa) for SF-dough were the lowest indicating that a less visco-elastic behavior was obtained. Polarized light microscopy showed that a more homogeneous size and a better distribution of starch granules were developed into SF-dough. Crumb hardness (3.25–4.78 N) and chewiness (0.31–0.81 N) of SF-rolls were lower than the control experiment (3.99–5.81 N and 0.35–1.01 N, respectively). Springiness for all treatments was constant (1.0) compared with the control (1.02–0.87) for 2 days of storage. The lowest cohesiveness values (0.24–0.14) were computed by IF treatment for a similar storage time. The specific crumb volume increased by 12.46%, 9.03%, and 1.10% by the addition of SF, TF and IF, respectively. The lowest rate of staling was shown by SF-rolls (0.199), and it was followed by TF (0.296), IF (0.381) and control (0.458) treatments. As a result, the highest scores on quality (9.3 out of 10) and sensorial attributes (from 8.9 up to 9.7) were assigned to SF-rolls. The authors concluded that the addition of soluble fiber produced the softest dough. Therefore, a less visco-elastic behavior was obtained and a better distribution of starch granules was developed into SF dough. These results agreed with crumb texture profile analysis, where the lowest hardness and chewiness were shown by SF-roll crumb. In addition, rolls formulated with SF showed the lowest rate of staling, had excellent bread acceptability and showed an increase in specific volume. On the other hand, the addition of total fiber and insoluble fiber developed harder dough than the control experiment, accordingly higher crumb hardness and chewiness were recorded. These improvements on rolls may be considered additional to the nutritional benefits of nopal soluble fiber which has been shown. It has prebiotic activity (Guevara-Arauza et al., 2012), so further studies should be addressed in order to determine the possible bio-functionality of these rolls.

Bouazizi et al. (2020) did successfully integrate prickly pear peels flour “PPPF” (20 g/100 g) as key ingredient in biscuits formulation. The main bioactive compounds in prickly pear biscuits are betalains (2776 mg/100 g d.w.), fibre (20.70 g/100 g d.w.), and considerable ash levels (14.57 g/100 g d.w.). The authors highlight the improving on technological properties such as the aptitude to kneading, the flavor retention, and the antioxidant capacity after addition of PPPF. Likewise, the acceptance sensory test showed that biscuits prepared with 20 g/100 g and 30 g/100 g PPPF computed the better score for smell, colour and overall acceptability.

13.3 Juice and Beverage

Panda et al. (2017) prepared a prickly pears-lacto juice by fermenting the juice of prickly pears as substrate (diluted by appropriate factor) with strain *Lactobacillus* fermentum ATCC 9338. The overall acceptability of developed product was recommended by sensory panelist. The composition and properties of lacto-juice were: ascorbic acid, 6 mg/100 mL, DPPḤ (2,2-diphenyl-1-picrylhydrazyl) scavenging activity, 105μMTE (micro molar trolox equivalent)/mL; total soluble solids, 5.9°Brix; total sugar, 1.75 g/100 mL; reducing sugar, 0.20 g/100 mL; pH, 4.1; titratable acidity, 1.7 g tartaric acid/100 mL; lactic acid, 0.32 mg/100 mL; and phenol, 0.41μg/mL. The authors highlighted the disintegration during the course of probiotic fermentation of some risky organic compounds such as 4h-Pyran-4-one, 3,5-dihydroxy-2-methyl; furfuryl alcohol; 2-propenenitrile, 2-(acetyloxy); 2,2-diethyl-3-methyloxazolidine; acetaldehyde and furan present in the fresh fruit juice.

13.4 Ice Cream

Guevara-Arauza et al. (2012) reported that mucilage (MO) and pectic-derived (PO) oligosaccharides from prickly pear stems could act as prebiotic. The research indicates that a mixture of MO treatment enhanced lactobacilli growth up to 23.8%, while PO increased the bifidobacteria population by 25%. Furthermore, the addition of MO produced a slight decrease in *enterococci*, *enterobacteria*, *staphylococci*, and *clostridia* of about 4%. Increased levels of the short-chain fatty acids (SCFA) were attained in the cultures at rates of 35% and 16% in response to MO and PO treatments, respectively. Propionic acid (propionate) and butanoic acid (butyrate) production increased at least 50% throughout MO and PO treatments. A decrease in the ammonium level of 11.5% was produced by MO treatment.

Some attempts were done to incorporate prickly pear pulp to ice cream and water ice. Perez-Navarro (2016) incorporated orange and purple prickly pear pulp to ice cream (25% and 20%) and water ice (40% and 35%). In these products, the total betalain content was 635 mg L^{-1} and 990 mg L^{-1} for prickly pear pulp, 46.93 mg L^{-1} and 96.23 mg L^{-1} for water ice, and 20.4 mg L^{-1} and 39.5 mg L^{-1} for ice cream added with orange and purple prickly pear pulp, respectively. The Trolox equivalent was 860 and 1213 for prickly pear pulps, 65.3 and 56.6 for water ice, and 60.2 and 39.5 (μmol Eq Trolox 100 mL^{-1}) for ice cream formulated with orange and purple, respectively. In addition, the overrun was 18.1% and 7.53% for water ice, and 30.2% and 16.9% for orange and purple ice cream, respectively. About sensory product acceptation, the orange ice cream was the most preferred.

El-Samahy et al. (2009) tested the addition of red cactus pear (*Opuntia ficus-indica*) concentrate up to 30°Brix and four levels (0%, 5%, 10%, and 15%) to basic ice cream mix (0.5% gelatin, 8% fat, 10.5% milk solids non-fat (MSNF), and 16% sucrose). The rheological properties of all ice cream mixes before and after aging showed that the flow behavior of mixes is non-Newtonian besides being pseudoplastic behavior. While specific gravity and weight per gallon of resultant ice cream samples increased by increasing of added pulp. Sensory evaluation of ice cream samples showed that sample with 5% cactus was very desirable and very close to control sample.

13.5 Salami

In order to replace some synthetic additives by a natural extract from red prickly pear (*Opuntia stricta*) in salami, Kharrat et al. (2018) added 2.5% of prickly pear extract (PPE), as natural colorant and antimicrobial agent in salami formulation. They found a decrease in hardness and chewiness of the formulated salami. The sensory panel appreciated more the color, taste and texture of salami prepared with 2.5% PPE. Moreover, PPE inhibited bacterial growth in salami stored at 4 °C, over 30 days. Prickly pear extract (PPE) displayed a strong antioxidant and antimicrobial activities associated likely to its high level of phenolics (152.2μg QE/mg PPE), flavonoids (370.6μg GAE/mg PPE) and carbohydrates content (18.8%) that composed mainly of galactose, rhamnose and galacturonic acid. Overall, the betalain pigment, carbohydrate and phenolic compounds present in PPE could be used as a natural colorant, antioxidant and antimicrobial agent without change of the sensory characteristics in meat products.

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