Perspective

Biofpr Biofuels Bioproducts & Biorefining

Toward unfolding the bioeconomy of nopal (*Opuntia* spp.)

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Abstract: Besides being a source of healthy food and water in arid and semi-arid lands, the *Opuntia* cactus plant (nopal) provides unique ecosystem services. In the last decade the plant's cladodes, fruits, flowers, and byproducts have become a source of valued bioproducts, increasingly used in the pharmaceutical, cosmetic, food, beverage, and nutraceutical industries. Following an updated examination of the new uses of nopal's biological resources, this study suggests avenues to overcome the main obstacles to unleashing the full potential of *Opuntia*'s bioeconomy. © 2019 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: *Opuntia ficus-indica*; cactus; cladode, nopal; prickly pear

Introduction

Originally from Mexico, the *Opuntia* spp. is a cactus species whose fruits (prickly pears) and stems (cladodes), traditionally used as food and water sources, are now acquiring multiple new uses in the nutraceutical, cosmetic, and personal care industries due to the remarkable properties of its main phytochemicals.[1] At the same time, 'the humble cactus'[2] is emerging as an essential crop in many areas because, 'aside from providing food, cactus also stores water in its pads, providing up to 180 tonnes of water per hectare, enough to sustain five adult cows.'[2] Accommodating > 90 wt% water in the cladodes,[3] the cactus pear is a water and livestock feed reserve that plays an important role in combatting desertification,[4] as shown, for example, by the valuable role played by the plant in fighting the recent drought in southern Madagascar.[2]

Ubiquitous in Mexico, Brazil, North African and Middle Eastern countries, South Africa, and Sicily, the *Opuntia* cactus plant (nopal) is one of the most diverse and widely distributed genera in the Americas. It includes 188 species.[5] The world's greatest diversity of cactus pear species and cultivars occurs in Mexico, which is considered one of the two centers of origin and dispersal of the genus *Opuntia*.[6] A total of 83 *Opuntia* species have been reported in Mexico,[7,8] where nearly half are native to the country.[6]

Some reports describe the presence of nopal plants in Mesoamerica since the arrival of humans 20 000 years ago, specifically in the desert and semi-desert regions, where they were important sources of food, beverages, and medicines for indigenous people. Long before the horticultural management of this plant was known, ancient Mexicans consumed it in abundance.[9] During the fifteenth and sixteenth centuries, the Spanish conquerors founded towns and communities, and created an unprecedented

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environment for small *Opuntia* horticultural systems known as 'nopaleras de solar'.

The Spanish were intrigued by one species more than any other, now known as the Indian fig cactus, *Opuntia ficus-indica*, due to its relevance in economic, religious, and social matters for the Native Americans, particularly the Aztecs. One fascinating use of *O. ficus-indica* was as a host plant for the growth of the cochineal insect (*Dactylopius* spp.), which is the source of a highly valued red dye (carminic acid).[10] Cochineal dye became the third greatest source of income for the Spanish crown in the New Spain, just after gold and silver. The successful production of cochineal dye increased its demand worldwide both in the European and Asian markets. The expansion of *Opuntia* species and cochineal production continued during the seventeenth and eighteenth centuries.[8]

During the domestication process of *Opuntia*, the continuous and systematic gathering of nopalitos and fruits favored exceptional features. It is likely that in the case of *Opuntia* fruits, known as prickly pears or 'tunas' in Spanish, this process enhanced its flavor, size, shape, and pulp texture, and decreased the seed hardness and seed quantity. Concerning 'nopalitos' (edible young cladodes), changes apparently occurred in shape, color, earliness, flavor, texture, and quantity, and quality of mucilages. This domestication process might have favored the persistence of variants of nopalitos, fruits, or both, with exceptional characteristics.[11] Thus, in Mexico there is a great wealth of *Opuntia* variants with different degrees of domestication. Many of these *Opuntia* variants have become cultivars.

In recent years, nopal has been recognized as one of the most economically important crops due to its valued nutritional, functional, and therapeutic properties, its potential in the cosmetics and bioenergy industries, its ecological applications, and for products that are of great value for current and future generations.[12] This recognition has generated a growing interest in nopal cultivation and utilization beyond conventional food and feed usages.

Along with traditional uses for the fruit (prickly pears or 'tunas'), vegetables (fresh and young cladodes known as 'nopalitos'), and forage for livestock feed production, new value-added uses of *Opuntia* have emerged in cosmetics, personal care, nutraceutical, and pharmaceutical products. In brief, nopal is quickly becoming a source of valued bioproducts, which are also in high demand in countries where the cactus is not harvested. Following an updated outlook on the valued new uses of nopal fruit and cladode resources, this study suggests avenues to overcome the main obstacles to unleashing the full potential of *Opuntia*'s bioeconomy.

Cultivation, fruit and cladodes

Cultivation

In terms of land area occupied by cactus pears, Mexico is by far the world's leading country with more than 3 million hectares, including wild plant species. Brazil leads the world in terms of hectares (600 000) dedicated to *Opuntia* cultivation (900 000 ha including cactus plants in the wild),[13] whereas in Mexico the area occupied by *Opuntia*'s plantations currently is around 230 000 ha.[14] This area is about 150 000 ha in Morocco[15] and 600 000 ha in Tunisia, where scholars have recently shown that cladode juice is even a superior flocculant for urban wastewater treatment.[16]

In many countries (Table 1) several varieties are cultivated, most notably in the country of origin, Mexico. Sicily alone hosts 90% of Italy's cactus plantations (Fig. 1) with 8300 ha.[17] Cultivation in India, where almost 53.4% of the country's huge land area comprises arid and semi-arid regions, has been lately experimented and will likely start soon.[18]

Mexico is a world leader in the production and consumption of nopal and prickly pears due to the ancestral importance of these products for the traditional diet. The physiological and morphological characteristics of nopal plants allow them to survive in dry environments and in soils with low fertility where other crops cannot thrive.

The geographic and climate characteristics in Mexico (altitude of 0 to 2600 m above the sea level, rain up to 400 mm, temperature of 18 to 26 °C, and sandy or clay soils with high salt contents, pH of 6.5 to 8.5) are highly favorable for nopal production. In general, nopal is a traditional food in the Mexican diet (annual *per capita* consumption of 6.4 kg in 2015),[19] often eaten as a vegetable in salads, pickles, juices, sauces, jams, and as a complement in different dishes.

Table 1. Cultivated area occupied by cactus pears in the first six main *Opuntia* harvesting countries and regions.

Rank	Country	Hectares (including wild)
1	Brazil	600 000 (900000)
2	Tunisia	600 000
3	Mexico	230 000 (3000000)
4	Morocco	150 000
5	Algeria	150 000
6	*Other South American countries*	75 000
7	Italy (Sicily)	8300

Source: *International Cactus Pear Workshop: Development of a cactus pear agro-industry for the sub-Sahara Africa Region*, Bloemfontein, South Africa, 27–28 January 2015.

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Figure 1. An *Opuntia ficus-indica* plantation in San Cono, Sicily, Italy, as of May 2018. Photograph by Mario Pagliaro.

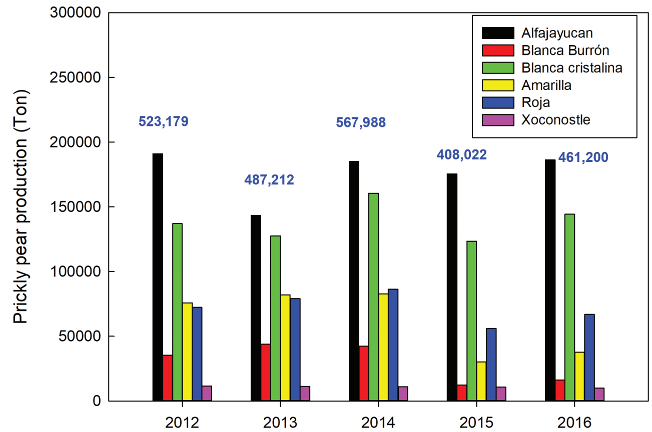

Figure 2. Production of the main varieties of prickly pears in Mexico during the period 2012–2016. The total production is shown in blue above of the bars. Source: Mexico's Ministry of Agriculture, Livestock, Rural Development, Fishing and Food (SAGARPA), 2018.

Dehydrated and ground nopal are also ingredients in the food industry to elaborate tortillas, snacks, breads, and tortilla chips, among others.

The Mexican Ministry of Agriculture, Livestock, Rural Development, Fishing and Food (SAGARPA), through the Food, Agriculture and Fishing Information Service (SIAP), reported in 2016 a national production of 810 228 ton of nopalitos, 180 250 ton of fodder nopal and 2 454 557 ton of prickly pears, with a crop surface of 62 862.60, 84 094.50 and 262 304.64 ha for nopalitos, cladodes for cattle feed, and prickly pears, respectively.[20] According to Reyes-Agüero and Aguirre-Rivera, in Mexico there are 78 wild species of *Opuntia* (*sensu stricto*), most of them growing in the Central Mexican Plateau, a large arid-to-semiarid plateau, which extends across the states of Aguascalientes, Jalisco, Zacatecas, San Luis Potosí, Guanajuato, Querétaro, Michoacán, Mexico, Hidalgo, Puebla, Tlaxcala, Morelos, and Mexico City.[21]

Fruit

The fruit of the nopal plant, known as prickly pear, is an ovoid-spherical shape fruit. Its pulp has a large number of seeds and is protected by a peel with small prickles. The fruit weighs between 48 and 251 g, and it has recently gained attention due to outstanding nutritional and functional properties.

Among the interesting components of prickly pears are ascorbic acid (vitamin C) with levels of up to 95 mg L^{-1} of pulp, carotenoids between 2.58 and 23.70 µg β-carotene equivalents per gram of the whole fruit, phenolic compounds with levels of 22.3 to 909 mg gallic acid equivalents per liter of pulp, and high concentrations of betalains in the red prickly pear varieties.[22] When the first nopal juice launched in Arizona as a post-workout replenisher in 2013, it was the only cactus-water in the world. Within 90 days, the product was requested throughout the whole nation, and today there are more than 15 producers of 'cactus water' around the globe.[23]

The main species grown in Mexico and producers of prickly pears are *O. albicarpa, O. megacantha, O. streptacantha, O. ficus-indica, O. robusta, O. hyptiacantha,* and *O. joconostle,* with more than 102 cultivars greatly appreciated for their fruits. The main varieties of prickly pears produced in Mexico are Alfajayucan, Blanca Cristalina, Amarilla, Roja, Blanca Burron, and Xoconostle. Alfajayucan and Blanca Cristalina are the most cultivated (Fig. 2) due to their juicy fruits with light-green pulp, known as 'white prickly pears' to distinguish them from the red or purple pulp prickly pears more appreciated in the international market.

Cladodes

A large number of *Opuntia* species are suitable for consumption as fresh vegetables; however, the production of this kind of nopal relies mainly on two cultivars of *Opuntia ficus-indica* (L.) Mill., 'Milpa Alta' and 'Atlixco'.[24] In Mexico, the greatest production of nopalitos takes place mainly in the center of the country mostly in Morelos, Mexico City, Mexico and Puebla (Fig. 3). The period of maximum harvest usually takes place between April and June.

In general, nopalitos contain a high concentration of soluble dietary fiber (20 g/100 dry matter) and total carotenoids in the order of 22 mg g^{-1} dry matter, and they are a good source of antioxidants (flavonoids, free phenols) and minerals (calcium, magnesium and potassium). In relation to vitamins, nopalitos provide retinol (A), thiamin (B1), niacin (B2) and

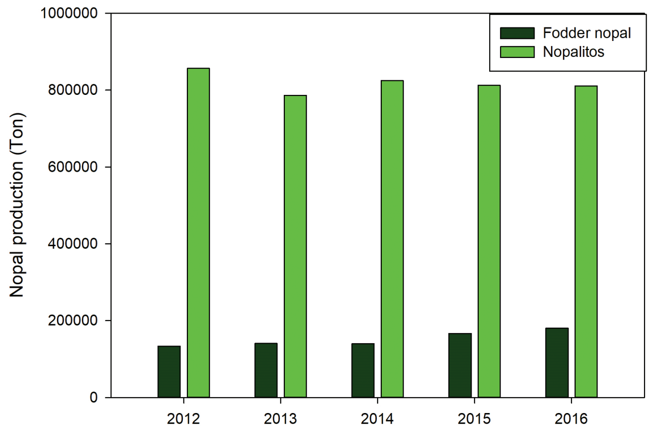

Figure 3. Production of nopal for forage and edible fresh cladodes, 'nopalitos', during the period 2012–2016 in Mexico. Source: Mexico's Ministry of Agriculture, Livestock, Rural Development, Fishing and Food (SIAP), 2018.

ascorbic acid. Nopalitos also contain amino acids such as lysine, isoleucine, threonine, valine, leucine, tryptophan, and methionine.[25] The proximate composition of cladodes from different nopal cultivars has been evaluated by many authors, and found to be often variable, probably due to different environmental conditions prevailing at the site of cultivation as well as to structural differences among these cultivars.

In the 2010–2016 period, the sales of nopalitos to the foreign market reached 25 countries, including the USA, South Korea, Belgium, Japan, and the Netherlands. In 2016, 44 768 tons of nopalitos (a value of about $14 million) was exported from Mexico, most of which (99%) went to the USA where a large fraction of the population is of Mexican origin. A promising outlook for nopalitos exports is envisaged: in 2015 the exported volume of the vegetable was 25.9% higher than the previous year and in 2016 it had an additional 5% increase.[26]

In Mexico, there are a lot of small-scale and cottage industries that manufacture nopal-based products. Of these, 93 had registered as suppliers with an Internet page by early June 2018.[27] They process nopalitos and cactus fruits. The products processed in these home factories include fresh nopal, jams, confitery, pickles, snacks, tortillas, juices, nopal flour recommended to prepare juices, smoothies, tortillas, bakery and pastry, and cosmetics, among others, either for national consumption or for exportation. Nearly 30% of the companies that supply nopal products commercialize dried nopal powder as dietary supplements to treat diabetes, gastritis, intestinal colic, ulcers, and hyperlipidemia. They were traditionally used by the ancient Mexican tribes, as documented in the Florentine codex S. XVI and by Hernandez.[28]

Energy source

Table 2 shows that nopal biomass enhances the use of plant sources as biofuels and green energy products, such as bioethanol and biodiesel.

The first biogas derived from nopalitos materials was produced in 2000 by a Chilean, Santiago-based company. Although the production was on a small scale, the biogas produced had important technical and industrial characteristics:[29] (i) nopal degrades five to ten times faster than animal manure, (ii) fermentation takes place at a slightly acidic pH (6.5–6.8) and at room temperature, requiring economically viable bioreactors internally coated with an epoxy resin, and no expensive stainless steel, and (iii) the abundant nitrogen-rich water leftovers from fermentation can be used to irrigate plantations whereas nopal waste fiber solid residues can be used directly as fertilizer or compost.

In Mexico, for instance, since 2016, a tortilla-making company (NopaliMex) has used cladode-based biogas to meet all its heating, fuel, and electricity needs. The company uses two biodigestor tanks where cladodes from its 70 ha cactus plantation are biodigested anaerobically to produce biogas and fertilizers (nitrogen-rich water and humus). Part of the biogas is cleaned of CO_2 and is provided as compressed biomethane to modified vehicles to refuel the automotive vehicles of the company that were retrofitted to replace gasoline with biogas.[30] The cladodes, cut into small pieces, are inserted into the biodigestor (a large tank with water at 38 °C where bacteria decompose the mixture into high-quality biogas, composed of 75% methane, 24% carbon dioxide, and 1% minor gases, and no trace of hydrogen sulfide). The heating capacity of the biogas is 7000 kcal m^{-3} (8800 kcal m^{-3} for 100% methane). Additional treatment with sulfuric acid can be performed to remove carbon dioxide and produce a high-quality biomethane (up to 96% purity), which is used to fuel retrofitted internal combustion engine vehicles (Fig. 4).

Table 2. Nopal biomass compared to other plant biomass in terms of fuel and energy produced.

Crop	Fuel	Amount (volume/ha year)	Energy (Mcal/ha year)
Nopal (Opuntia)	Biogas	52 000 m^3	364 000
Sugar cane	Bioethanol	9000 L	45 000
Corn	Bioethanol	3200 L	16 000
Jathropa	Biodiesel	1559 L	14 436
Palm	Biodiesel	5550 L	51 393

Source: L. Kleiner, *Chile: Nopal Cactus as Biomass for Alternative Energy*, Elqui Global Energy, Providencia Santiago (Chile), 2013.

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Figure 4. The 8 t closed tank anaerobic digester at Nopalimex, a company in Mexico's Michoacán central State. Reproduced from Ref. 30, with kind permission.

Another company, a cement manufacturer called Cruz Azul, is using biogases produced by fermentation of nopal cladoes mixed with cow dung to operate its 1 MW-thermoelectric power unit fully.[31] The company has achieved a reduction of 40% in its significant electricity costs. In general, however, the energy efficiency of nopal fermentation assessed on the basis of the energy return on energy invested (EROI) is 8.14 in the worst scenario, but it may easily reach 12.41 when an organic farming system is used coupled to a closed digestate storage tank.[32]

Biotechnological applications

Opuntia's cactus fruits and cladodes both offer a number of phytochemicals with important nutraceutical properties.[1] The edible tender cladodes, 'nopalitos' of the *Opuntia* species, contain structural polysaccharides like pectins, mucilages, hemicelluloses, and cellulose. These polysaccharides are the main components of dietary fiber and they already have a wide range of nutraceutical and food applications. Today's global concerns about maintaining a healthy lifestyle drive an increasing demand for dietary fiber and bioactive compounds, which are increasingly used as functional ingredients in processed foods and pharmaceutical and personal care products. Several studies have supported the traditional use of nopal in Central Mexico and have found evidence of the anti-hyperglycemic, antioxidant, antiulcerogenic, and hypolipidemic activities of polysaccharides and phytochemicals from cladodes of *Opuntia*.[33–35]

Cladode powder, furthermore, is used to make several cosmetic and personal care products such as skincare and make-up products. These protect skin cells by limiting the formation of free radicals, decreasing the production

Figure 5. The solar dryer and the dehydrated cladodes obtained in San Cono, Sicily, since May 2018. Reproduced from Ref. 37, with kind permission.

of melanin caused by ultraviolet light, and by limiting the production of cytokines by epidermis cells. For instance, one recent clinical trial carried out with a concentration of 0.1% of 100% cells in powder[36] resulted in a 31% reduction in the total surface of face wrinkles, a 14% decrease of melanin rate formation (decreasing pigmentation) and an 18% reduction in UV-induced oxidation (along with an increase of the skin immune defense system). Traditionally, nopal flour has been obtained by direct sun drying of cactus cladodes, sliced and left in the open environment for several days, followed by grinding the dehydrated cladodes and sieving.

Providing a case study that is generally applicable in all the world's semi-arid regions where the plant is increasingly harvested, scholars in Italy recently reported the successful use of solar air heating and ventilation to dehydrate *Opuntia ficus-indica* cladodes.[37] The dehydrated cladodes and the ground nopal cladodes dried in this way retain their natural green-yellow color (Fig. 5), opening the route to functionalized foodstuffs and nutraceuticals, personal care, and cosmetic products of even higher efficacy and broader scope.

Several research groups across the world have studied and reported the extraction and characterization of mucilages and pectins from the cladodes and peels of prickly pears. Research has clearly shown that these substances may be valorized as novel thickening, gelling, emulsifier, and film-forming agents in foods, cosmetics, pharmaceutical and personal-care products, also as novel bioplastics and biomaterials for food packaging materials and biomedicine.[38–41]

The first study suggesting the use of *O. ficus-indica* (OFI) peel as a source of pectin for use as thickening material goes back to 1994,[42] when scholars in Italy discovered that hot acid extracted OFI pectin had a galacturonic acid content of 64%, and a low degree of methoxylation (10%). Being inedible, the peel is removed from the fruit in all companies selling packaged fresh fruits as well as from those producing jams and fruit juice. The production of waste *Opuntia* peel is thus significant, with most peel currently used as animal feed, and a smaller fraction feeding methanogen bacteria in anaerobic digestors. Ten years' later, scholars in Morocco and in France reported the first structural analysis of the pectic material contained in the OFI peel.[43]

After 10 years, Rodríguez-Hernández and co-workers in Mexico,[44] relying again on conventional hydrolytic extraction in hot acidic (pH = 4) water, reported that pectin extracted from the peel of *Opuntia albicarpa Scheinvar 'Reyna'* fruit has a low methoxyl content (30.7%) and high molecular weight ($M_w = 10.16 \times 10^5$ g mol^{-1} versus $M_w = 76 \times 10^3$ g mol^{-1} for lemon pectin). This provides the pectin from *Opuntia* peel with the ability to form soft and elastic gels with a clear viscoelastic properties denoting gel-like behavior (Fig. 6).

In general, the *O. ficus indica* fruits are a source of nutritionally relevant compounds such as aminoacids, essential minerals including calcium, potassium, and magnesium, vitamin C (20–40 mg/100 g),[45] and sterols.[46] Other high-valued bioactive compounds from prickly pears, with a variety of biotechnological applications, are betalain pigments, which consist of two main groups: betacyanins (red) and betaxanthins (yellow). These could have good industrial and food applications because they could replace artificial dyes, which cause allergic disorders and are carcinogenic.

A total of 24 known and unknown betalains were identified in ten Mexican prickly pears studied, and the betalain content in *O. robusta*, a purple-colored prickly pear, was comparable to that found in red beet (*Beta vulgaris* L. ssp.).[47] Anti-inflammatory betalain pigments, particularly betanin and indicaxanthin,[48] are abundant in *Opuntia ficus-indica* fruits giving them neuroprotective, antiulcerogenic, and hepatoprotective properties.[49]

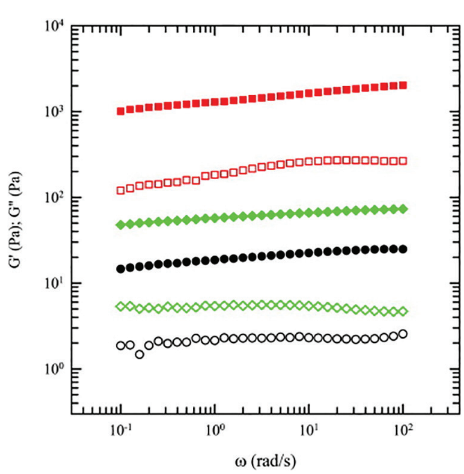

Figure 6. Variation of storage modulus (G′, filled symbols) and loss modulus (G″, open symbols) with angular frequency for 4 g kg^{-1} prickly pear pectin with: 0.25 mmol L^{-1} $CaCl_2$ (circles), 0.50 mmol L^{-1} $CaCl_2$ (diamonds) and 0.75 mmol L^{-1} $CaCl_2$ (squares). Reproduced from Ref. 44, with kind permission.

Lately researchers in Italy and Portugal reported the successful extraction of pectin and natural red pigment from the peel of white and red OFI fruits harvested in Sicily using mild microwave-assisted hydrodiffusion and hydrodistillation (Fig. 7).[50] The new process directly affords high-quality pectin and betanin in aqueous solution from which they are readily isolated.

A comprehensive review of safety, antioxidant activity, clinical efficacy, and bioavailability of plant betalains recently proposed the first human daily intake of betanin and indicaxanthin at 100 and 50 mg, respectively.[51] Labeled E 162, as an approved food additive in the European Union, betanin is a valued violet-red betacyanin that colors food without altering the flavor.[52] The latter property, adding to pigment stability at pH between 3 and 7 and to its exceptionally high free radical-scavenging activity,[53] makes it particularly well suited for use in processed food products such as beverages, confectionary, bakery, ice cream, and dairy products.

Although containing a smaller amount of betanin (50 mg kg^{-1} for OFI versus 300–600 mg kg^{-1} for red beet roots),[54] sourcing this important colorant from *Opuntia* in addition to current industrial practice to extract the pigment from red beet (*Beta vulgaris* L.)[53] would provide significant advantages. Unlike the red beetroot which slowly supplies its high betanin content after 2 years of cultivation, the *Opuntia* plant is ubiquitous and produces numerous fruits twice a year between (in the northern hemisphere) mid-June and late November.

The *O. ficus indica* seed oil is rich in unsaturated fatty acids, exerting unique skin and hair hydrating action, and it contains the highest amount of vitamin E available in any beauty oil on the market. It also has antioxidant and anti-inflammatory properties, which provide it with significant potential as a functional ingredient of nutraceutical and food-supplement products.[55] The oil, extracted from seeds of two Mexican varieties of cactus pear (green: *O. albicarpa* and red: *O. ficus indica*), has an appreciable amount of unsaturated fatty acid, linoleic fatty acid being the predominant one (65–67%), and this oil has the potential to be used as a natural antioxidant and antimicrobial agent in the food, cosmetic, and pharmaceutical industries.[56]

The seed oil of *O. ficus indica* grown in Sicily is similar to that of fruits grown in Tunisia, where it is nowadays a primary source of wealth in the North African country. It is produced by a dozen companies in Tunisia, which buy

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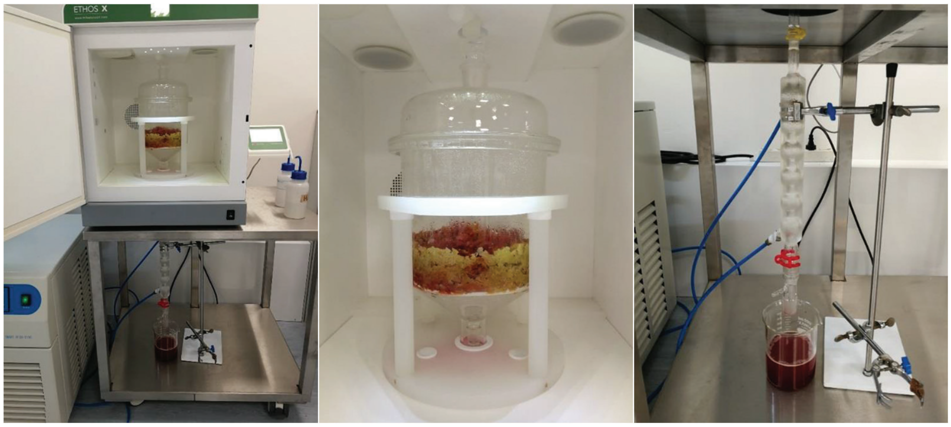

Figure 7. The milled peel of *Opuntia-ficus indica* red and white fruits in the vessel of a microwave extractor (Ethos X, *left*); and the red aqueous extract upon irradiation and extraction (*right*). Reproduced from Ref. 50, with kind permission.

about 2500 tons of organic prickly pears from 800 farming companies.[57] Bottled in small 10 or 20 mL bottles, the oil is sold on international markets at a price of > €1000 L^{-1} (the production of a liter of oil of prickly pear requires 30 kg of seeds). Like the oil obtained in Tunisia, the Sicilian oil has a higher vaccenic acid content, but it contains significant amounts of other unsaturated fatty acids presenting highly beneficial health properties.[58]

Removing the obstacles to *Opuntia*'s bioeconomy

The *Opuntia* cactus is increasingly being adopted in arid and semi-arid countries as a sustainability tool to reduce pressure on water and to protect soil (the cactus roots in dry lands crucially mitigate the intensity of sandy and dust storms). Besides its uses as a food of high nutritional value and a water source, the nopal cladodes, fruits, and flowers can be used to produce valued bioproducts including pectins, mucilages, antioxidants, betalains, and polyunsaturated fatty acids as bioactive compounds for food, cosmetic, pharmaceutical and personal-care products, biomaterials for edible food-packaging materials and biomedicine (drug-delivery systems). In the following paragraphs, we suggest some approaches for overcoming four main obstacles to an efficient culture of *Opuntia* and enhancing its bioeconomy value.

Lack of adequate investments

Research on the development of nopal biotechnological industries and an *Opuntia*-based bioeconomy is currently slow in *Opuntia*-producing countries. Despite growing interest in the functional properties of cactus polysaccharides and phytochemicals, there is still a lack of effective research and technology-driven industries to isolate, process and package functional bioproducts from nopal in Mexico and other nopal-producing countries,[59] suggesting the need for new investments and a focus on these research areas.

Governments and producer associations in all main nopal-growing countries should take action, first, to identify the most convenient and promising applications of *Opuntia*'s bioproducts. Once a lucrative market with potential for prolonged growth is identified, investments will follow quickly, as shown, for example, by the global success of cactus water, started in Arizona in 2013, and now sold across the world.[23] This brings us to the second main need, namely solving the knowledge gap regarding nopal's bioproducts and their growth potential.

Removing knowledge barriers

Noting, in late 2017, that 'hydrocolloids are not commodities'[60] and that the hydrocolloid sector was 'doing little to communicate about the ingredients with consumers', Seisun, one of the world's leading experts in the food hydrocolloids market, commented that the nutritional and nutraceutical advantages of hydrocolloids had only recently been discovered and that there was still much to be learned about them.

These arguments closely echoed related analyses suggesting that there was an urgent need for all countries to establish new bioeconomy research and educational institutes capable of deploying more useful and sound research, education, and policy advice in the crucially important bioeconomy and solar energy fields.[61] Such institutes would (i) shape the new bioeconomy and energy professionals, (ii) undertake growth-driven research aimed at the practical application of breakthrough solutions, (iii) develop best practice through international cooperation, and (iv) provide sound advice to policymakers and investors.

The extraction of pectin from nopal and prickly pears could be an alternative way to obtain high added-value products from nopal and prickly pears, taking into account the large volumes of byproducts during the harvesting stage. Currently obtained from dried lemon peel and from apple pomace,[62] pectin is the food and dairy beverage hydrocolloid preferred by consumers, and its growing use has created a global shortage that has driven up prices and lengthened delivery time.[63] Sourcing it from prickly pear peel, rather than from citrus peel, would help to solve prolonged availability issues with dried citrus crops from Argentina.

Adopting clean technologies

Whatever the bioproduct or the mixture of bioproducts derived from *Opuntia*, today's and tomorrow's nopal-based bioeconomy companies will need to adopt clean production technologies. This is not just to align the sale of health-beneficial products with the uptake of environmentally friendly production processes; it is mainly because clean production technologies afford better bioderived products. Hence, for instance, instead of using pectin extraction with hot acidic water, as is done at most pectin plants across the world, which inevitably also produces large amounts of acidic wastewater requiring expensive treatment, companies extracting pectin from the peel of prickly pear fruits will use new, waste-free extraction technologies directly. Some recent green extraction methods like extraction with water, ethanol, or steam targeting pectin and dietary fibers from cladodes and fruits of *Opuntia* have been reported.[64] Microwave-assisted[65,66] and ultrasound-assisted[67] extractions are amid the methods studied most. The mechanical extraction of *O. ficus-indica* seed oil intensively carried out in Tunisia is another example. These processes do not necessarily need to be advanced technologies. What is relevant is that the extraction technology should afford clean and integral bioproducts ready to be commercialized as such, or formulated as ingredients in functional products for manifold applications.

Communicating the bioproduct value to consumers

Nopal-derived bioproducts belong to natural hydrocolloid, natural antioxidant, natural colorant, and natural cosmetic oil markets. All the latter markets are growing, driven by new applications and by replacement of the corresponding synthetic counterparts. Yet, getting back to Seisun, who was finding that innovation within the hydrocolloid sector was minor, consisting mostly of incremental product-line extensions and differentiation,[60] today's and tomorrow's nopal-bioeconomy companies need to be aware that promoting innovation in this (and in related) market, will require knowledge-based communication efforts similar to those regularly undertaken by the omega-3 global industry.[68]

In other words, research-driven nopal bioeconomy companies will need to employ adequately educated managers, able to communicate, creatively and adequately, the value of their ingredients and bioproducts to consumers and, more generally, to their customers. It is relevant to notice here how, to sell 'cactus water' in United Kingdom where most people have never seen this exotic fruit from semi-arid and arid areas of the world, one company incorporates an educational component, which includes someone donning an 8 ft prickly pear cactus outfit and strolling the streets of London handing out samples to citizens and answering questions.[23]

Outlook and conclusions

Several outcomes originate from this study devoted to unfolding nopal bioeconomy. First, the fact that such a bioeconomy already exists is illustrated by the 80 million EUR *O. ficus-indica* seed oil market in Tunisia (90% of which is devoted to export), or by the fact that cactus water has become a sport drink competing with coconut water across > 10 000 shops in the world in less than 5 years.

Similarly, gone are the 2004 days in which Stintzing and Carle were finding that the vegetative parts of *Opuntia* spp. plants were 'still scarcely used in modern nutrition and medicine'[25] calling for new research 'to get an insight into the multitude of bioactivities reported in the traditional literature but also to take advantage of the respective constituents for food and pharmaceutical applications.'[25]

In general, we find that the nopal-bioeconomy meets the three visions of the bioeconomy (biotechnology, bioresources, and bioecology) that co-exist in in the research literature.[69] Biotechnology, through research and application, upgrades the biological raw materials of *Opuntia* and creates new value streams, whereas the cultivation of nopal bioresources promotes numerous ecological services including the promotion of the biodiversity, and prevention of soil degradation and water supply in arid and semi-arid areas (bio-ecology). From this viewpoint, nopal bioeconomy companies, instead of focusing on the functional properties of their products only, will learn instead to master and communicate the wider consequences of using their products in terms of environmental, social and economic benefits.

On an industrial scale, the bio-based economy is a qualitative and long-term transformational process, largely representing a knowledge-based economy,[70] creating additional demand for educated professionals and new revenues for farmers. What has changed in the last two decades, making it feasible from a technical viewpoint, is the efficiency of the new green chemical and physical processes with which the biological resources are isolated and processed, some of which were briefly reviewed in this account.

With *Opuntia* cactus, the financial investments required to start bioeconomy productions are relatively small, and return on investment is quick. What is required mostly is to remove the knowledge barriers and to uptake clean production technologies directly. This study suggests avenues to tackle these issues at the dawn of a new sector of the bioeconomy: that of the *Opuntia* cactus originating from Mexico more than 20 000 years ago.

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