The unfolding bioeconomy of nopal (*Opuntia* spp.)

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Abstract

Providing unique ecosystem services in addition to being a source of healthy food and plentiful water in semi-arid and arid regions, the *Opuntia* cactus plant (nopal) is quickly becoming a source of valued biobased products in high demand also in countries where the cactus is not harvested. Following an updated outlook on the valued new uses of nopal fruit and cladode biological resources, this study suggests avenues to overcome the main obstacles to unleashing the full potential of *Opuntia*'s bioeconomy.

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1. Introduction

Original of Mexico, the *Opuntia* spp. is a cactus species whose fruits (prickly pears) and stems (cladodes) traditionally used as a food and water source are now giving place to multiple new usages in the nutraceutical, cosmetic, and personal care industries due to the remarkable properties of its main phytochemicals.¹ At the same time, as put it by the current director of the plant production and protection division of Food and Agriculture Organization of the UN commenting the precious role played by the plant to fight the recent drought in southern Madagascar, “the humble cactus” is emerging as an essential crop in many areas since “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 up to >90 wt% water in the cladodes,³ indeed, the cactus pear is a water and livestock feed reserve already playing an important role to combat desertification.⁴

Ubiquitous in Mexico, Brazil, North African and Middle East countries, South Africa and Sicily, the *Opuntia* cactus plant (Nopal) is one of the most diverse and widely distributed genus in the Americas, which includes 188 species.⁵ The world’s greatest diversity of cactus pear species and cultivars are located in Mexico, considered one of the two centers of origin and dispersal of the genus (Márquez-Berber et al., 2012).⁶ A total of 83 *Opuntia* species have been reported in Mexico,^{7,8} where nearly half of them are endemic to it.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 XV and XVI centuries, the Spanish conquerors founded towns

and communities, and created an unprecedented environment for *Opuntia*, small 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 appreciated red dye (*i.e.*, carminic acid).¹⁰ Cochineal dye was highly valued and became the third greatest source of income for the Spanish crown in the New Spain, only 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 XVII and XVIII centuries.⁸

During the domestication process of *Opuntia*, the continuous and systematic gathering of nopalitos and fruit 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, 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, from those harvested or planted as living fences and edges of slopes of plots and those of solar, even of commercial plantations which began their establishment in the middle of XX century. Many of these *Opuntia* variants have become cultivars.

In recent years, Nopal has been recognized as one of the most economically important resources due to better valued nutritional, functional and therapeutic properties,

as well as for the potential it can have in the cosmetics and bioenergy industries, without forgetting the ecological applications and current nopal-based products 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. In brief, along with traditional use for fruit (*i.e.*, prickly pears or ‘tunas’) vegetables (*i.e.*, fresh and young cladodes known as ‘nopalitos’), and forage for livestock feed production, new and high value added usages of *Opuntia* have emerged in cosmetic, personal care, nutraceutical and pharmaceutical products, with nopal quickly becoming a source of valued bioproducts in high and rapidly growing demand also 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.

2. Cultivation, fruit and cladodes

2.1 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 plants in the wild. 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 In Morocco and Tunisia the area reaches about 150,000 ha in Morocco¹⁵ and 600,000 ha in Tunisia, where scholars have lately shown that the cladode juice is even a superior flocculant for urban wastewater treatment.¹⁶

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 (900,000)
2	Tunisia	600,000
3	Mexico	230,000 (3,000,000)
4	Morocco	150,000
5	Algeria	150,000
6	Other South American countries	75,000
7	Sicily (Italy)	8,300

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

In many countries (Table 1) several varieties are cultivated, most notably so in the country of origin, Mexico. Even France is amongst the 26 countries currently growing cactus. Sicily alone hosts 90% of Italy's cactus plantations (Figure 1) with 8,300 ha.¹⁷ Showing its dramatic potential for growth, however, one should notice that its commercial cultivation in India, the world's second most populous country, where almost 53.4 per cent land area comprises arid and semi-arid regions, is yet to start.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.

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

The geographical 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 favourable for Nopal (*Opuntia* spp.) 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 of the Mexican gastronomy. 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 ha,

84,094.50 ha 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

2.2 Fruit. The fruit of the nopal plant, known as prickly pear, is an ovoid-spherical shape fruit, its pulp has a great amount 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 components of interest of prickly pears are: ascorbic acid (vitamin C) with levels of up to 95 mg/L of pulp, carotenoids with concentrations between 2.58 and 23.70 µg β-carotene equivalents per gram of the whole fruit, phenolic compounds in 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 producer 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

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].

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 highly appreciated by their fruits. The main varieties of prickly pears produced in Mexico: Alfajayucan, Blanca Cristalina, Amarilla, Roja, Blanca Burrón, and Xoconostle. Alfajayucan and Blanca Cristalina are the most cultivated (Figure 2) thanks 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.²⁴

2.2 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’.²⁵ In Mexico, the greatest production of nopalitos takes place mainly in the center of the country mostly in in

Morelos, Mexico City, Mexico and Puebla (Figure 3). The period of maximum harvest usually takes place between April and June.

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, SAGARPA, 2018].

In general, nopalitos contain a high concentration of soluble dietary fiber (20 g/100 dry matter), total carotenoids in the order of 22 mg/g 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 ascorbic acid. They contain amino acids such as: lysine, isoleucine, threonine, valine, leucine, tryptophan and methionine.²⁶ The proximate composition of cladodes from different nopal cultivars has been evaluated by many authors, being always variable, probably due to different environmental conditions prevailing in 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 United States of America (USA), South Korea, Belgium, Japan and

the Netherlands. In 2016, 44,768 tons of nopalitos were exported, representing a value of \$14 million, 99% to the US where a large fraction of the population is of Mexican origin. A promising outlook for the nopalitos-exportation 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.²⁷

In Mexico there is a lot (and not easy to quantify) of small-scale and cottage industries making nopal-based products. Those registered as suppliers with an Internet page on the world wide web were 93 by early June 2018.²⁸ They process nopalitos and cactus fruits. Among the offered products are: 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, commercializes dried nopal powder as dietary supplements to treat diabetes, gastritis, intestinal colic, ulcers and hyperlipidaemia. The traditional use came from the ancient Mexican tribes, as documented in the Florentine codex S. XVI and by F. Hernandez.²⁹

3. Energy source

Table 2 shows that nopal biomass dwarfs other widely used plant energy sources in terms of fuel and energy produced every year per hectare cultivated.

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 (<i>Opuntia</i>)	Biogas	52,000 m ³	364,000
Sugar cane	Bioethanol	9,000 L	45,000
Corn	Bioethanol	3,200 L	16,000
Jathropa	Biodiesel	1,559 L	14,436
Palm	Biodiesel	5,550 L	51,393

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

The first biogas plant using nopal cactus as the biomass started operation, though on small scale, in Chile's Santiago in year 2000 by a company whose founder identified several important technical aspects: *i*) nopal degrades 5-10 times faster than animal manure, *ii*) fermentation takes place at slightly acidic pH (6.5-6.8) and room temperature requiring economically viable bioreactors coated inside with an epoxy resin, and no expensive stainless steel, and *iii*) the abundant nitrogen-rich water leftover of the fermentation can be used to irrigate the plantation whereas the nopal waste fiber solid residue can be used directly as fertilizer or added to compost.³⁰

In Mexico, for instance, since 2016 a *tortilla* making company (NopaliMex) uses cladode-based biogas to meet all its heat, fuel and electricity needs. In detail, the company uses two closed biodigester 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, furthermore, is cleaned of carbon dioxide and provided as compressed biomethane to modified vehicles to refuel the automotive vehicles of the company that were retrofitted to replace gasoline with biogas.³¹ The cladodes are cut before

inserting them into the biodigester in large tanks with water at 38 °C where bacteria decompose the mixture in high quality biogas (75% methane, 24% carbon dioxide and 1% minor gases and no trace of hydrogen sulfide). The heating capacity of the biogas is 7,000 kcal/m³ (8,800 kcal/m³ for 100% methane). Further treatment of the biogas thereby obtained with sulphuric acid extracts carbon dioxide, giving 96% biomethane which is used to fuel retrofitted internal combustion engine vehicles (Figure 4).

Figure 4. The 8 tonne closed tank anaerobic digester at Nopalimex, a company in Mexico's Michoacán central State. [Reproduced from Ref.31, with kind permission].

Another company that currently generates power from biogas obtained via anaerobic fermentation of nopal cladodes (mixed with cow dung),³² is the cement manufacturer “Cruz Azul” in the state of Aguascalientes operating a 1 MW thermoelectric power unit entirely fuelled by biogas. The company has achieved a reduction of 40% reduction in its significant electricity costs. In general, indeed, the energy efficiency of nopal fermentation assessed using the energy return on energy invested (EROI) is 8.14 in the worst scenario, but may easily reach a value of 12.41, adopting organic farming system coupled to a closed digestate storage tank.³³

4. Biotechnological Applications

Both *Opuntia*'s cactus fruits and cladodes afford a number of phytochemicals of significant nutraceutical importance.¹ The edible tender cladodes, 'nopalitos' of *Opuntia* species contain structural polysaccharides like pectins, mucilages, hemicelluloses and cellulose. These polysaccharides are the main components of dietary fiber already have a wide range of nutraceutical and food applications as today's global concern about maintaining a healthy lifestyle drives increasing demand dietary fiber and bioactive compounds are widely used as functional ingredients in processed foods, pharmaceutical and personal care products. Several studies have supported the traditional use of nopal in Central Mexico and have found evidences of the anti-hyperglycemic, antioxidant, antiulcerogenic and hypolipidemic activities of polysaccharides and phytochemicals from cladodes of *Opuntia*.^{34,35,36}

The cladode powder, furthermore, is used to formulate several cosmetic and personal care products such as skincare and make-up products as it protects skin cells by limiting the formation of free radicals, decreasing the production of melanine caused by UV, and by limiting the production of cytokins produced by aggressed epidermis cells. For instance, one recent clinical trial carried out with a concentration of 0.1% of 100% cells in powder,³⁷ led to a 31% reduction of the total surface of face wrinkles, a 14% decrease of melanin rate formation (decreasing pigmentation) and a 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 of general applicability in all world's semi-arid regions where the plant is increasingly harvested, scholars in Italy lately reported the successful use of solar air heating and ventilation to dehydrate *Opuntia ficus-indica* cladodes.³⁸ For the

first time, the dried cladodes and the ground dehydrated nopal cladodes retain their natural green-yellow color (Figure 5) due to β -carotene and chlorophyll, opening the route to functionalized foodstuff and nutraceutical, personal care and cosmetic products of even higher efficacy and broader scope.

Figure 5. The solar dryer installed in San Cono, Sicily.
[Photograph of Vincenzo Morreale, reproduced with kind permission].

Several research groups across the world have studied and reported the extraction and characterization of mucilages and pectins from 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.^{39,40,41,42}

The first study suggesting the use of OFI peel as a source of pectin to be used as thickening material goes back to 1994,⁴³ when scholars in Italy found out that hot acid extracted OFI pectin had a galacturonic acid content of 64%, and a low degree of methoxylation (10%). Being not edible, 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.⁴⁴

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 mM CaCl_2 (circles), 0.50 mM CaCl_2 (diamonds) and 0.75 mM CaCl_2 (squares). [Reproduced from Ref.45, with kind permission].

Another ten years, and Rodríguez-Hernández and co-workers in Mexico,⁴⁵ relying again on conventional hydrolytic extraction in hot acidic ($\text{pH} = 4$) water reported that pectin extracted from the peel of *Opuntia albicarpa Scheinvar* 'Reyna' fruits has a low methoxyl content (30,7%) and high molecular weight ($M_w = 10.16 \times 10^5 \text{ g mol}^{-1}$ vs. $M_w = 76 \times 10^3 \text{ g mol}^{-1}$ of lemon pectin) which imparts the *Opuntia*'s peel pectin the ability to form soft and elastic gels with a clear viscoelastic properties denoting a gel-like behavior (Figure 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 ($20\text{-}40 \text{ mg}/100 \text{ g}$)⁴⁶ and sterols.⁴⁷ Other high valued bioactive compounds from prickly pears with diverse biotechnological applications are betalain pigments, conformed

by two main groups; betacyanins (red) and betaxanthins (yellow), which could have a great industrial and food applications because they could replace artificial dyes that cause allergic disorders and are carcinogenic.

A total of 24 known/unknown betalains were identified in 10 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.).⁴⁸ Anti-inflammatory betalain pigments, particularly betanin and indicaxanthin,⁴⁹ are abundant in *Opuntia ficus-indica* fruits imparting them with neuroprotective, antiulcerogenic and hepatoprotective properties.⁵⁰

In 2017, scholars 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, Italy, via mild microwave-assisted hydrodistillation and microwave-assisted hydrodiffusion (Figure 7).⁵¹ The new process is carried out in water only, without the aid of any chemical, and directly affords the polysaccharides and the natural dyes in solution.

Figure 7. Top: OFI red fruits (*left*) and mixed red and white fruits (*left*). Fresh fruits from Sicily, treated as received; Bottom: The Ethos X extractor (*left*) whose vessel was filled with milled OFI peel (*middle*) affording the aqueous extract (*right*). [Reproduced from Ref.51, with kind permission].

A comprehensive review of safety, antioxidant activity, clinical efficacy and bioavailability was lately concluded proposing the first human daily intake of betanin and indicaxanthin at 100 and 50 mg, respectively.⁵² Labelled E 162 as approved food additive in the European Union, betanin is a valued violet-red betacyanin which colors food without altering the flavor.⁵³ The latter property, adding to the pigment stability at pH between 3 and 7, makes it particularly well suited for use in processed food products such as beverages, confectionary, bakery, ice cream and dairy products.

Though containing a lesser betanin amount (50 mg/kg for OFI vs. 300-600 mg/kg for red beet roots)⁵⁴ sourcing this important colorant from *Opuntia* in addition to current

industrial practice to extract the pigment from the roots of red beet (*Beta vulgaris* L.),⁵⁵ would provide significant advantages. Contrary to the red beetroot which slowly affords its high betanin content after two years of cultivation, for example, the *Opuntia* plant is ubiquitous and gives numerous fruits twice a year between mid June and the late November.

Additionally, rich in unsaturated fatty acids exerting unique skin and hair hydrating action, the *O. ficus indica* seed oil, containing the highest amount of vitamin E available in any beauty oil on the market, has antioxidant and anti-inflammatory properties which offer significant potential as functional ingredient of nutraceutical and food supplement products.⁵⁶ 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 acids, the linoleic fatty acid being the predominant (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.⁵⁷ 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 where it is produced by a dozen companies in Tunisia which buy about 2,500 tons of organic prickly pears from 800 farming companies.⁵⁸ Bottled in 10 or 20 mL small bottles, the oil is sold on international markets at >€1,000/L (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 comprises significant amounts of other unsaturated fatty acids showing highly beneficial health properties.⁵⁹

5. Removing the obstacles to *Opuntia*'s bioeconomy

After decades in which the nopal plant has been an undervalued crop, the *Opuntia* cactus is increasingly being adopted in arid and semi-arid countries as a true sustainability tool aiding to reduce pressure on water and soil sources. Besides use as a food of high nutritional value and a water source, its cladodes, fruits and by-products can be used to produce valued bioproducts. It is now clear that nopal, its fruits, cladodes and by-products including the fruit peel, can be used in the production of bioproducts including, among others, pectins, mucilages, antioxidants, betalains, 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 we suggest avenues to overcome the four main obstacles on the path to shape a wealthy and diffuse bioeconomy of *Opuntia*.

5.1 Facing lack of adequate investment. Research on novel nopal-based products is currently slowly triggering the development of biotechnological industries establishing and contributing to the progress of *Opuntia* bioeconomy in the main countries where nopal is cultivated. In spite of the growing interest in the functional properties of polysaccharides (mucilages, pectins) and phytochemicals from *Opuntia*, however, in Mexico and in other nopal-harvesting countries there is a lack of research and technology-driven industries to isolate and formulate said functional bioproducts.⁶⁰ There is therefore a need to attract investors and young talented managers and researchers.

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

second main need, *i.e.* solving the knowledge gap on nopal's bioproducts and their growth potential.

5.2 Removing knowledge barriers. Noting in late 2017 that “hydrocolloids are not commodities”⁶¹ and that the hydrocolloid sector was “doing little to communicate about the ingredients with consumers”, Seisun, one of the world's leading experts in food hydrocolloids market, was adding:

“One area of innovation concerns the physiological function of hydrocolloids, many of which are either soluble or insoluble. The nutritional and nutraceutical benefits of hydrocolloids have only just begun to be discovered. They can do much more than simply viscosify, gel and suspend. Much has yet to be learned and understood.”⁶¹

These arguments echo closely related analyses suggesting the urgency for all countries to establish new bioeconomy research and educational institutes capable to deploy sound and more useful research, education and policy advice in the crucially important bioeconomy and solar energy fields.⁶² Such institutes will *i*) shape the new bioeconomy and energy professionals, *ii*) undertake growth-driven research aimed at practical application of breakthrough solutions, *iii*) develop best practices through international cooperation, and *iv*) provide sound advice to policy makers and investors.

Getting back to pectin, its extraction from nopal and prickly pears prickly pears could be an alternative to obtain high added-value products from nopal and prickly pears, taking into account the high volumes of by-products during the harvesting stage. Currently obtained from dried lemon peel and from apple pomace,⁶³ 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.⁶⁴ Sourcing it from prickly pear peel, rather than from citrus peel, would help to solve prolonged availability issues with dried citrus crop from Argentina.

5.3 Adopt clean technologies. Whatever the bioproduct or the mixture of bioproducts derived from *Opuntia*, today's and tomorrow's nopal-based bioeconomy companies will adopt clean production technologies. This not only to align the sale of health-beneficial products with the uptake of environmentally-friendly production processes, but mainly because clean production technologies afford better bioderived products. Hence, for instance, instead than using pectin extraction with hot acidic water as done at most pectin plants across the world, which inevitably produce also large amounts of acidic wastewater requiring expensive treatment, companies extracting pectin from the peel of prickly pear fruits will directly use new, waste-free extraction technologies. As shown by the mechanical extraction of *O. ficus-indica* seed oil intensively carried out in Tunisia, these processes do not necessarily need to be advanced technologies. What is relevant is that they afford clean and integral bioproducts ready to be commercialized as such or formulated as ingredients in functional products for manifold applications.

5.4 Communicate 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, 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.⁶⁵ In other words, research-driven nopal bioeconomy companies will employ adequately educated managers able to creatively and adequately communicate to value of their ingredients and bioproducts to consumers and, more in general, 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 leading company incorporates an educational component which includes someone donning an 8-foot prickly pear cactus outfit and strolling the streets of London handing out samples to citizens and answering questions.²³

6. Outlook and conclusions

Several outcomes originate from this study devoted to the unfolding nopal bioeconomy. First, the fact that such bioeconomy already exists is rendered by the 80 million EUR market of *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 five years.

Similarly, gone are the 2004 days in which Stintzing and Carle were finding that “the vegetative parts of *Opuntia* spp. plants was still scarcely used in modern nutrition and medicine”²⁶ 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”.²⁶

In general, we find that the nopal-bioeconomy meets the three (biotechnology, bioresource and bioecology) visions of the bioeconomy co-existing in the research literature.⁶⁶ Biotechnology, through research and application, upgrades the biological raw materials of *Opuntia* creating new value streams, whereas the cultivation of nopal bioresource promotes numerous ecological services including promotion of the biodiversity, 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 rather learn to master and communicate the wider consequences of using their products in terms of environmental, social and economic benefits.

On industrial scale, the bio-based economy is a qualitative and long-term transformational process largely representing a knowledge-based economy,⁶⁷ 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 are 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 mostly required is to remove the knowledge barriers and uptake directly clean production technologies. This study suggests avenues to tackle these issues on 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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joconostle and *O. lasiacantha* with five cultivars each; *O. chavena* with seven cultivars; *O. hyptiacantha* and *O. streptacantha* with 12 cultivars each; *O. ficus-indica* with 15 cultivars; *O. albicarpa* with 22 cultivars, and *O. megacantha* up to 34 cultivars.

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