Viewpoint

Opuntia ficus-indica seed oil: Biorefinery and bioeconomy aspects

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In this study, we offer a perspective written from a biorefinery viewpoint aimed at expanding the cactus peer seed oil market and utilizations. Besides antioxidant and skin and hair hydrating action which make it suitable as a valued cosmetic ingredient, the oil contained in the seeds of *Opuntia ficus-indica* and *Opuntia dillenii*, rich in unsaturated fatty acids, also shows anti-inflammatory properties which offer significant potential as functional ingredient of nutraceutical and food supplement products.

Practical applications: The outcomes of the study will be useful in progressing the expansion of the emerging bioeconomy, especially in *Opuntia* producing countries.

Keywords: Antioxidant / Anti-inflammatory / Opuntia ficus-indica / Prickly pear

Received: January 6, 2017 / Revised: January 24, 2017 / Accepted: February 2, 2017

DOI: 10.1002/ejlt.201700013

1 Introduction

Commonly known as prickly or Cactus pear, *Opuntia ficus-indica* (OFI) is a perennial plant specie belonging to the *Cactaceae* family whose fruits and leaves (cladodes) afford a number of phytochemicals of significant nutraceutical importance [1]. Native to North America's arid regions, particularly Mexico and the arid regions of the United States, it was brought to Europe and then to Africa and Asia, and showed remarkable ease of adaptation to other arid climates.

Thanks to its shallow roots spreading horizontally the plant is able to withdraw water from the soil resulting in high water utilization efficiency [2], eventually making the cactus pear a true reservoir of water, accommodating 87–88% water in the cladodes. As suggested by Snyman, the cactus pear as a crop is underestimated and more attention should be given to *Opuntia* species, as a feed reserve for livestock and as a means to combat climate change and desertification [3].

Mexico, Morocco, Brazil, South Africa, Argentina, the US, China, and several other countries and regions host *Opuntia* plantations, including Sicily with 7400 hectares [4]. In Mexico, *nopal* (the prickly pear cactus) has been part of the diet, as well as of traditional medicine, for several thousand years [5].

Today, it is well known that cactus pear fruits are rich in antioxidant vitamin C (20–40 mg/100 g) [6] and sterols [7], as well as anti-inflammatory betalain pigments [8] (particularly indicaxanthin) [9], and biophenols, imparting them with neuroprotective, antiulcerogenic and hepatoprotective properties [10]. In addition, the fruits are a source of nutritionally relevant compounds such as aminoacids, polyunsaturated fatty acids and essential minerals (especially calcium, potassium, and magnesium).

The cactus pear contains a large number of seeds (about 0.24 g/g). The chemical characterization of the cactus pear seed oil, concluding that the lipid was a good potential source of edible oil for human or animal consumption, was published by researchers in Saudi Arabia in 1982 [11]. The article initially attracted limited attention, with only 6 citations between 1982 and 1999; [12] but in the subsequent decade (2000–2009) the study of Sawaya and Khan received 24 citations, reflecting the increasing interest for the health benefits of using natural products, with another 28 citations between 2010 and 2016.

Yet, we had to wait until 2016 for the first systematic study on the effect of cultivar, season and locality on lipid content and fatty acid composition of the oil [13]. Today, the

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OFI oil, still extracted in limited amount, is used in several top cosmetic products for skin and hair treatment. However, the relevance of health benefits broaden the application areas of cactus pear oil well beyond cosmetics. In this study, we offer a perspective into a valued lipid mixture written from a biorefinery viewpoint aimed at enhancing and improving the extraction of this bioderived oil, especially in the producing countries.

2 Seed and oil composition

Even if the cultivars of OFI exhibit considerable morphological variations, the percentage of seeds per gram of pulp is relatively constant (0.24 seeds/g pulp) [13]. The main component of the seed is cellulose (45.1 wt%), followed by lipids (23%). Apart from cellulose and lipids, the seeds are also rich in albumin protein with 6.5 kDa molecular weight, and proanthocyanidins (oligomeric flavonoids of catechin and epicatechin and their gallic acid esters) with strong antioxidant activity [14]. Minerals and sulphur amino acids are also present [15].

The amount of oil extracted from *Opuntia ficus-indica* seeds greatly varies depending on the variety and its geographic origin: 7.3–9.3% depending on the variety for OFI grown in Algeria [16], through 13.6% of seed weight for Morocco pears [17] and up to 14.4% in fruits of Turkish origin [18].

Unsaturated linoleic acid is the dominating fatty acid, but the composition varies with ripeness degree. For example, analysis of fruits grown in Morocco (Table 1) shows that linoleic acid (58.79%) is followed by saturated fatty palmitic acid (11.18%) and stearic acid (1.50%) [19].

The results reported by Sawaya and Khan in 1982 for fruits grown in Saudi Arabia were similar: Linoleic acid: 63%, palmitic acid: 12%, and stearic acid: 2.8%, but monounsaturated oleic acid (8.8%) was also detected [11].

Table 1. Fatty acids, sterols, and vitamin E in the total lipid composition of prickly pear seed oil grown in Morocco (Adapted from Ref. [19], with kind permission)

Lipid composition	Concentration (%)
Lipids	
Linoleic C18:2	58.79
Palmitic C16:0	11.18
Stearic C18:0	1.50
Sterols	
β-sitosterol	21.93
Campesterol	3.75
Stigmasterol	1.64
Vitamin E	
γ-tocopherol	1.23

Morocco's results are also in agreement with those obtained with fruits grown in Tunisia (linoleic acid: 56.6%, palmitic acid: 12.24%, stearic acid: 3.69%) harvested in three consecutive seasons (2007, 2008, and 2009) [20], even though in the Tunisian fruits a substantial amount of monounsaturated fatty acids (ca. 26%) is also present. However, linolenic and oleic acids were not detected in Morocco's seed oils due to the lower degree of maturity of the fruit, as a rapid increase in monounsaturated fatty acid content is observed toward the end of fruit maturation process. Accordingly, high content (ca. 20%) of monounsaturated acids was found, again, in cactus pear fruits purchased from a local market in Germany (i.e., several days or weeks after harvesting) [21]. Also, see values for oleic acid for fruits harvested in South Africa at odor-break stage [13].

Remarkably, no differences in fatty acid composition between the 3 harvesting years was observed for the prickly pears collected in Tunisia [20], while a noticeable difference was obtained for biophenols, in agreement with their secondary metabolite nature which makes them highly dependant on seasonal variations in climatic conditions [22].

Tocopherols are particularly abundant in the cactus fruit seed oil. The sterol marker is β-sitosterol, which comprises about 72% of the total sterol content, whereas α- and δ-tocopherol are among the main components, amounting to about 80% of the total vitamin E content (Table 2) [23].

In 2013, Larbat et al. first reported the biophenolic profile of *Opuntia ficus-indica* seed oil [16]. Out of eight compounds detected in significant amounts, highly beneficial hydroxycinnamic acid esters such as the sucrose ester of ferulic acid (feruloyl-sucrose) and di-glucose ester of sinapic acid (sinapoyl-diglucoside), were the main biophenols identified, though in glycoside form. Remarkably, the team found a high correlation between phenolic content in the defatted seed extracts and the antioxidant activity, with samples presenting the highest antioxidant activity also having the highest phenolics contents. A similar correlation has been recently found by de Wit and coworkers studying the oils obtained in South Africa from seven cactus pear varieties of *Opuntia ficus-indica* and *Opuntia robusta*, who found that three fatty acids (stearic acid, oleic acid, and behenic acid)

Table 2. Sterols and fat-soluble vitamin profile of cactus pear (Opuntia ficus-indica L.) seed and pulp oils (Adapted from Ref. [23], with kind permission)

Compound	Seed oil (g/kg)	Compound	Seed oil (g/kg)
Campesterol	1.66	α-Tocopherol	0.056
Stigmasterol	0.30	β-Tocopherol	0.012
β-Sitosterol	6.75	γ-Tocopherol	0.330
β-Carotene	0.047	δ-Tocopherol	0.005
Vitamin K_1	0.525	Total vitamin E	0.403

are significantly correlated with the oxidative-stability index [24].

The antioxidant activity of OFI seed oil is actually so high that, if added in 5 g/L amount, the oil extract acts as an environmentally friendly corrosion inhibitor for steel immersed in a solution of hydrochloric acid (1 M) [25]. Adding to the economic and practical value of the oil, it is the presence of the above mentioned antioxidants that stabilizes the oil preventing oxidative damage of the PUFA residues whose high level of unsaturation would lead to a quick oxidation and deterioration.

3 Uses and benefits

Likewise to Argan oil widely used in cosmetics for its restorative and antiaging properties for hair, skin, and nails, OFI seed oil possesses hydrating and anti-aging properties. The high amount of the polyunsaturated ω-6 fatty acid, linoleic acid, in the triglyceride backbone favors deep and quick penetration through dermal layers, stimulating cell renewal. Oleic and stearic acid help in moisturizing the skin and stimulate collagen production, whereas palmitic acid reinforces the skin's healthy barrier function, preventing wrinkles. Like Argan oil, once adsorbed the oil promotes antiaging via free radical scavenging, reducing redness. However, since OFI oil generally contains 150% more vitamin E than Argan oil, the effect is more pronounced and its duration longer. The first cosmetic companies selling the cactus pear oil advertise it as "an excellent source of essential fatty acids (approximately 83%), especially linoleic acid (63%), tocopherols (1000 mg), betalains, Vitamin K, amino acids and trace elements" [26]. The oil, furthermore, is also used to moisturise hair and promote keratin regeneration, eventually bringing back the shine and strength of the hair.

Due to the high contents of PUFA, amino acids, particularly proline and taurine, and minerals such as calcium and magnesium, if available in large amounts at lower cost, OFI seed oil could also be used as ingredient for sport and energy drinks [27].

The oil shows also remarkable anti-inflammatory activity due to β-sitosterol [28]. Oils containing polyunsaturated fatty acids and antioxidants (tocopherols, polyphenols, and carotenoids, etc.) prevent diabetes complications, and may even inhibit the disease's development [29]. In mice, the OFI oil clearly shows protective effects against chemically induced (alloxan) diabetes mellitus [30]. In detail, it acts by quenching free radicals produced by alloxan and inhibiting tissue injuries in pancreatic β-cells. In a clinical study with 29 patients administered with 250 mg of *nopal*, it significantly reduced both total and LDL-cholesterol and reduced platelet proteins [31], whereas HDL cholesterol and triglyceride levels were not affected.

4 Extraction and market

The OFI oil is currently mainly extracted in Morocco via cold pressing. The process takes up to 3–4 days yielding a oil with very limited oxidation retaining most of the flavor, aroma, and nutrients. The seeds are isolated from the washed peeled fruits via mechanical sieving. Hence, the oil is obtained pressing the seeds through a hydraulic press. In general, one litre of cactus seed oil requires approximately half a tonne fruit which partly explains the high cost of the oil.

Most of the oil on the market is obtained in Morocco where annual production of "Barbary fig fruit" was reported to exceed 1.2 million tonnes from 150 000 hectares of plantations mostly in the southern regions as early as of 2011 [32], when the country began programs to further expand *Opuntia* cultivation in arid land owing to UN funding.

Similar plans are underway in Mexico, where *nopal* covers about 3 million hectares, mostly in the form of wild cactus (mainly in Zacatecas, State of México, and Hidalgo) [33], and in Brazil, which has the largest planted area of cactus pear in the world with the cultivation of approximately 600 000 hectares, mostly *Opuntia* and *Nopalea* cultivars [34].

Guillaume in France and Harhar et al. in Morocco recently concluded that cactus-seed oil "seems to be ready to spread over the cosmetic-ingredient market," despite "very little scientific studies supporting its biological properties" [35]. So far, the market is a small niche of the beauty oil market. Highlighting its benefits, in 2015 a reputed fashion magazine wrote that prickly pear oil was a "natural ingredient on the rise that does everything Argan oil does, but better" [36].

Argan oil is one of the most expensive vegetable oils on account of limited supply and high demand. A similar situation might soon be faced by prickly pear seed oil. The 4835 tonnes global Argan oil market (in 2014) is expected to reach almost 20 000 tonnes by 2022, growing at almost 20% annual rate from 2015 to 2022 [37].

A quick review of online prices for OFI oil carried out at the end of 2016 showed its high economic value with 15 mL directly sold for £20 by a Moroccan factory (The Opuntia Company), or 30 mL sold at €61.50 by another company based in the same country (Argan Oil Direct). Asked to comment on this nascent market, Guillaume offered insight:[38]

> «Since a "Cactus oil Federation" not yet exists, market figures are difficult to get. Each producer or country of production is keeping its numbers or use them as communication tools meaning that the real accuracy is doubtful. The cosmetic and personal care industry is following the market evolution, waiting for a true start that it is also a question of enhanced market offer and marketing activities».

In summary, (i) the abundant availability and the low cost of the OFI fruit, (ii) the growing global demand for "naturals" in cosmetics, wellbeing, medicine, sport, and personal care, coupled to the (iii) remarkable biological, nutritional, antioxidant, and anti-inflammatory properties, support the viewpoint that the essential seed oil of *Opuntia* cactus could become one of the most valued products of the nascent bioeconomy.

5 Outlook and conclusions

Already used in several top cosmetic products and beauty treatments in luxury spas, the OFI oil will shortly be produced in significantly larger amount for applications well beyond cosmetic, to become an important new ingredient in nutraceutical, food supplement, sport drink and food products. It is likely that in place of conventional cold pressing, new extraction techniques will emerge capable to afford the oil in shorter time and higher yield but still producing no waste solvents or other potentially polluting or toxic residues. For example, recent results showed that *Opuntia stricta* seed oil extracted with supercritical CO_2 has more than 2.25 times higher phenolics content when compared to the oil extracted using *n*-hexane [39].

It is likely, we argued in this study, that the oil will follow a path similar to that of Argan oil. However, whereas Argan is only grown in southern Morocco, cactus is ubiquitous in warm countries so that, once seed oil extraction factories will be installed in the main producing countries, the *Opuntia* oil production will largely exceed that of Argan oil. Furthermore, once these factories will be operational, also the fruits of wild prickly pear, available at no other cost than that of harvesting, will be used as raw material, as the seed oil of *Opuntia dillenii* is of even higher quality, being comprised almost entirely of PUFAs and containing higher tocopherol amounts [40].

Mexico and Brazil, by far the largest producers of cactus, will enter the marketplace as basically all parts of the plant including the cladodes and the fruit peel are excellent raw materials for a variety of biomaterials and bioproducts including valued pectin which, indeed, was lately found by scholars in Mexico to be of particularly high quality having a low degree of esterification [41], which makes it ideal as food and medical hydrocolloid.

In a positive feedback loop, the increased availability of the oil will then foster new research carried out in partnership between the bioeconomy companies and local research centres aimed at identifying new applications. Eventually, the old Cactus plant from which the Aztecs extracted a milky juice to make ointments used to treat burns, wounds and edema, will become a key ingredient of important nutraceuticals in a typical case of innovation guided by the past which has been a constant driving force of the central science: Chemistry.

We thank Professor Dominique Guillaume, Laboratoire de Chimie Thérapeutique, University of Reims, for helpful correspondence. This article is dedicated to Prof. Adriana I. Rodríguez Hernández, Universidad Autónoma del Estado de Hidalgo, for all she is doing to progress the bioeconomy of Opuntia ficus-indica in Mexico.

The authors have declared no conflict of interest.

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