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CROP ECOLOGY, CULTIVATION AND USES OF CACTUS PEAR

Final Version

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Processing and utilization of fruit, cladodes and seeds

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12 Processing and utilization of fruit, cladodes and seeds

INTRODUCTION

A Sicilian writer once called cactus pear "a treasure under the thorns" because of its immense benefits, some of which were little known before today.

In many countries – Argentina, Chile, Peru, Bolivia, South Africa, Egypt, Turkey, Ethiopia, Eritrea and other countries in South America and the Mediterranean Basin – it is traditionally the cactus pear fruit that is eaten. In Mexico, on the other hand, in addition to the fruit, the tender cladodes (*nopalitos*) are consumed. However, both fruit and *nopalitos* are perishable and processing technologies are needed to increase their shelf-life. Moreover, both fruits and cladodes contain numerous bioactive compounds which must be preserved during processing if consumers are to reap the full benefits. Cactus pear is a multipurpose fruit and a wide range of products and by-products can be derived from it. The same applies for the cladodes. Sáenz *et al.* (eds, 2006, 2013) present numerous alternatives for processing fruits and cladodes. The recent advances in this field are presented in this chapter.

CHEMICAL COMPOSITION AND BIOACTIVE COMPOUNDS

Before any raw material is processed, it is essential to understand its chemical and phytochemical composition, as well as any technological characteristics regarding the industrial process. For cactus pear, information is required about the chemical composition of the fruits, seeds and cladodes. Furthermore, a thorough understanding is required of the bioactive compounds of these cactus parts, their activities and the relative health benefits.

There has been much research on the chemical composition of the edible parts of the fruit from plants grown in different parts of the world, including Egypt, Saudi Arabia, Mexico, Chile and Argentina. There is extensive information available regarding the composition and uses of seeds as a source of oil, fibre and protein, in particular the detailed analysis of Sáenz *et al.*, eds (2006). This chapter presents the latest information on the subject.

Within the genus *Opuntia*, the most cultivated species is *Opuntia ficus-indica*, characterized by sweet and juicy fruit and pulp of different colours: white–green, yellow, orange, red or purple. The proportion of pulp in the fruit varies and the peel is generally thin. Coloured ecotypes (**Figure 1**) have a dual application: production of natural colourants (betalains); and provision of health benefits thanks to their antioxidant properties (Butera *et al.*, 2002; Galati *et al.,* 2003a; Kuti, 2004; Tesoriere *et al.*, 2005a; Stinzing *et al.*, 2005; Azeredo, 2009; Fernández López *et al.*, 2010).

Other bioactive compounds present in the fruits are vitamin C, carotenoids and dietary fibre (Morales *et al.*, 2009; Sáenz *et al.*, 2009, 2012a). Cactus cladodes have a high content of water, dietary fibre and minerals (Pimienta Barrios, 1990; Sáenz *et al.*, eds, 2006). The seeds are rich in polyunsaturated essential fatty acids such as linoleic acid (Ennouri *et al.*, 2005; Özcan and Al Juhaimi, 2011).

There are minor variations in the chemical composition of coloured cactus pear fruits; major differences are related to the pigment content. **Table 1** summarizes the ranges of certain chemical compounds and technological characteristics,

Figure 1
*Cactus pear fruits coloured ecotypes (*Opuntia ficus-indica*) (garden varieties, Antumapu Experimental Station, University of Chile, Santiago) (Photos: C. Sáenz and A.M. Fabry).*

TABLE 1 Chemical and technological characteristics of cactus pear pulp from coloured fruits

Parameters	Green cactus pear	Purple cactus pear	Yellow-orange cactus pear
pH	5.3–7.1	5.9–6.2	6.2–6.3
Acidity (% citric acid)	0.01–0.18	0.03–0.04	0.55–0.57
Soluble solids (°Brix)	12–17	12.8–13.2	13.5–14.5
Vitamin C (mg 100 g^{-1})	4.6–41.0	20.0–31.5	24.1–28.0
β-carotene (mg 100 g^{-1})	0.53	–	0.85–2.28
Lutein (μg g^{-1})	26.0	0.15	0.04
Betacyanins (mg kg^{-1})	0.1–0.8	111.0–431.0	2.4–11.0
Betaxanthins (mg kg^{-1})	0.4–3.1	89.4–195.8	16.0–76.3

Source: Askar and El Samahy, 1981; Pimienta Barrios, 1990; Sawaya *et al.*, 1983; Sepúlveda and Sáenz, 1990; Sáenz and Sepúlveda, 2001a; Sáenz *et al.*, eds, 2006; Stintzing *et al.*, 2005; Hernández Perez *et al.*, 2009b; Morales *et al.*, 2009; El Gharras *et al.*, 2006; Coria Cayupan *et al.*, 2011; Sáenz and Fabry (unpublished data).

based on values reported by several authors. Red, purple and yellow-orange cactus pears contain betalains, while red and purple contain betacyanins and yellow-orange betaxanthins (Stintzing *et al.*, 2005; Sáenz *et al.*, 2012b).

The chemical composition may vary depending on different factors:

- origin of the plants (i.e. the climate where it is cultivated);
- agronomic factors, such as cultivation, fertilization and irrigation; or
- genetic differences (Muñoz de Chavez *et al.*, 1995; Ochoa, 2008).

Cactus pear is rich in calcium, although McConn and Nakata (2004) report that calcium bioavailability might nevertheless be low, because it is present as calcium oxalate, which is not absorbed. The high potassium content and low sodium content offer clear nutritional benefits for people with kidney problems and hypertension.

TECHNOLOGICAL CHARACTERISTICS

Fruit

Besides the chemical composition and bioactive compounds, there are other characteristics to consider during processing. In general, cactus pear fruits have a high pH (5.3-7.1) and are therefore classified as low acid foods (pH ≥ 4.5); an exception is *O. xoconostle*, which has higher acidity (pH > 3.5) (Mayorga *et al.*, 1990). It is well known that heat treatment temperatures depend on the pH (Casp and Abril, 1999). For this reason, when non-acidic foods are pasteurized or canned, unless the pH is reduced (by citric acid addition, for example), a higher temperature is needed to reduce the microbial counts to a safe level compared with the treatment of acidic foods (pH ≤ 4.5). Such high temperatures (generally > 121° C) can negatively influence traits such as taste, colour and aroma. The pH and high soluble solids content of the pulp favour the growth of micro-organisms (Sáenz and Sepúlveda, 1999; Sáenz, 2000); it is, therefore, important to control heat treatments in preservation processes.

From a sensory point of view, the green fruit in some countries (e.g. Chile) has a better texture, taste (sweeter) and flavour than purple and orange ecotypes, which tend to be floury. Nevertheless, purple, red and orange fruits have great potential for processing, because the betalains contained in the colour ecotypes are more stable than the chlorophylls, with regard to both pH and heat (Merin *et al.*, 1987; Montefiori, 1990; Castellar *et al.*, 2003; Sáenz and Sepúlveda, 2001a; Sáenz *et al.*, 2012b).

Cladodes

The presence of mucilage and pectin in the cladodes influences the viscosity of some products, such as powder preparations mixed with water or juice before consumption. Both compounds are part of dietary fibre and are hydrocolloids, known for their ability to absorb and retain water. They can also be extracted and used as thickeners in foodstuffs (Sáenz *et al.*, 2003, 2004; Sepúlveda *et al.*, 2003a, 2007).

The chemical composition of *nopalitos* has been reported by Pimienta Barrios (1990) and Maki Díaz *et al.* (2015). As with other vegetables, there is a high content of water and fibre. Polyphenols are present and have antioxidant activity important in the diet; during preservation, however, they can cause browning due to oxidation (Rodríguez Felix, 2002). Furthermore, the acidity of *nopalitos* varies during the day – as a result of crassulacean acid metabolism (CAM) (Cantwell *et al.*, 1992) – and the optimal harvesting time must be chosen depending on the process to be applied.

Seeds

The seeds represent about 15% of the edible part of the fruit and they have a variable oil content (on average, 9.8 g 100 g^{-1} of seed) (Ramadan and Mörsel, 2003a).

Seed oil is rich in unsaturated fatty acids (Sepúlveda and Sáenz, 1988; Ennouri *et al.*, 2005; Ghazi *et al.*, 2013); it is, therefore, of interest to the pharmaceutical and cosmetic industries, for example, in Morocco and Tunisia. Given the low yield of oil from the seed, it is neither economical nor attractive as an edible oil. The presence of tocopherols, recognized as natural antioxidants, ranges from 3.9 to 50%. Matthäus and Özcan (2011) and Özcan and Al Juhaimi (2011) report that fibre and minerals are also important components in the seeds, with 12.5% crude fibre and high amounts of calcium, potassium and phosphorus, as well as other minerals. The relatively high protein content (approx. 6%) means that cactus pear seed is a source of protein for human consumption (Tlili *et al.*, 2011).

PROCESSING TECHNOLOGIES

A wide range of traditional preservation technologies can be applied to cactus pear fruit, cactus cladodes and seeds. Some technologies are described in Sáenz *et al.*, eds (2006) and some of the most innovative are described here.

Dehydrated products

Water activity (aw) is a measure of the "available water" in a food. Availability of water in plant tissues is variable, and a distinction is made between "free water" and "bound water". The proportions of free and bound water depend mainly on the food composition, as compounds such as hydrocolloids have higher water retention capacity. The mucilage present in *Opuntia* pads and fruits is an example of a hydrocolloid.

Microbial growth can be controlled by lowering a_w. The minimum a_w for microbial growth is variable. According to Roos (2007), it is > 0.90 for bacteria, 0.87-0.90 for yeast, 0.80-0.87 for moulds and 0.60-0.65 for osmophilic yeasts.

The technologies used to decrease a_w to preserve food include dehydration, concentration and freeze-drying (drying under frozen conditions); the latter combines cold with decreasing a_w to control the growth of microorganisms.

Dehydrated cactus pear products

Dehydration is one of the oldest food preservation processes. It can be done naturally – solar drying – or with equipment, such as dehydration tunnels, rollers, dryers and spray dryers. Highly controlled processes have recently been developed to produce more homogeneous and better quality dried products.

With regard to cactus pear, there have been various studies about dehydrating thin layers of pulp to prepare chewable, natural products. They are known as “fruit sheets”, “fruit leather”, "fruit bars" or “fruit rolls” and differ in thickness and moisture content: sheets are thinner and low in moisture, while bars have a high moisture content (≤ 20%). The University of Chile developed a process whereby a blend of cactus pear pulp and quince or apple pulp is used to prepare fruit rolls. Coloured ecotypes are also used to make products with a pleasant flavour and texture and attractive appearance (Sepúlveda *et al.*, 2000, 2003b) (**Figure 3**). **Table 2** shows the characteristics of certain products. All treatments contain:

- 75% cactus pear pulp;
- 25% apple pulp;
- varying amounts of sucrose (T1 and T2 = 6% and T3 = 0% sucrose and 0.01% sucralose); and
- varying amounts of flaxseed (T1 = 0% and T2 and T3 = 1%).

The total dietary fibre content of the treatments is 14.1-43.9%; the purple ecotype has a high fibre content due to its high pulp content, and sucralose (instead of sugar) is added.

The flow chart in **Figure 2** shows the various steps involved in the production of cactus pear sheets and **Figure 3** shows the cactus pear and apple pulps, as well as an oven used for drying to make the sheets.

El Sahamy *et al.* (2007a) prepared orange–yellow cactus pear sheets; they tested different drying temperatures (60 and 70 °C) and a range of ratios of sucrose (0, 1, 2, 3, 4, 5 and 10%). The prepared pulps were spread to a thickness of 10 mm and dehydrated in an air convection oven for 44 hours. The preferred sheets were those prepared with 2 and 3% sucrose.

Dehydrated products do not usually contain additives; they are, therefore, “natural products”, accepted by consumers because they are considered safe.

This simple technology, to the best of the author’s knowledge, has not been used at commercial level. While there are companies offering apple, strawberry, cherry and apricot rolls, these products are not usually 100% natural and are typically made from pear puree concentrate and artificial flavourings and colourants.

TABLE 2 Dietary fibre and total phenolics compounds in coloured cactus pear rolls mixed with apple pulp and flaxseed

Parameter/Treatment	Rolls from yellow-orange cactus pear pulp		
	T1	T2	T3
Total dietary fibre (g 100 g^{-1})	14.1 a	24.3 b	38.8 c
Total phenolics (mg GAE kg^{-1})	1 445.3 a	1 365.0 a	1 640.1 b
	Rolls from purple cactus pear pulp		
	T1	T2	T3
Total dietary fibre (g 100 g^{-1})	20.2 a	28.9 b	43.9 c
Total phenolics (mg GAE kg^{-1})	1 404.7 a	1 438.0 b	1 846.0 b

[a] GAE = Gallic acid equivalent.
Means following different letters differ at $P < 0.05$.
Source: Sáenz *et al.*, unpublished data

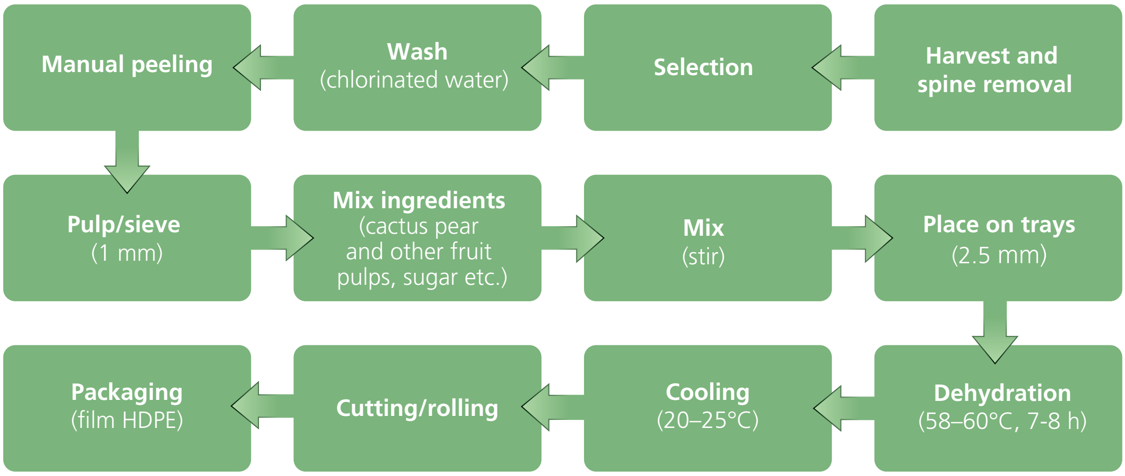

Figure 2
Preparation of cactus pear fruits rolls (adapted from Sáenz et al., eds, 2006)

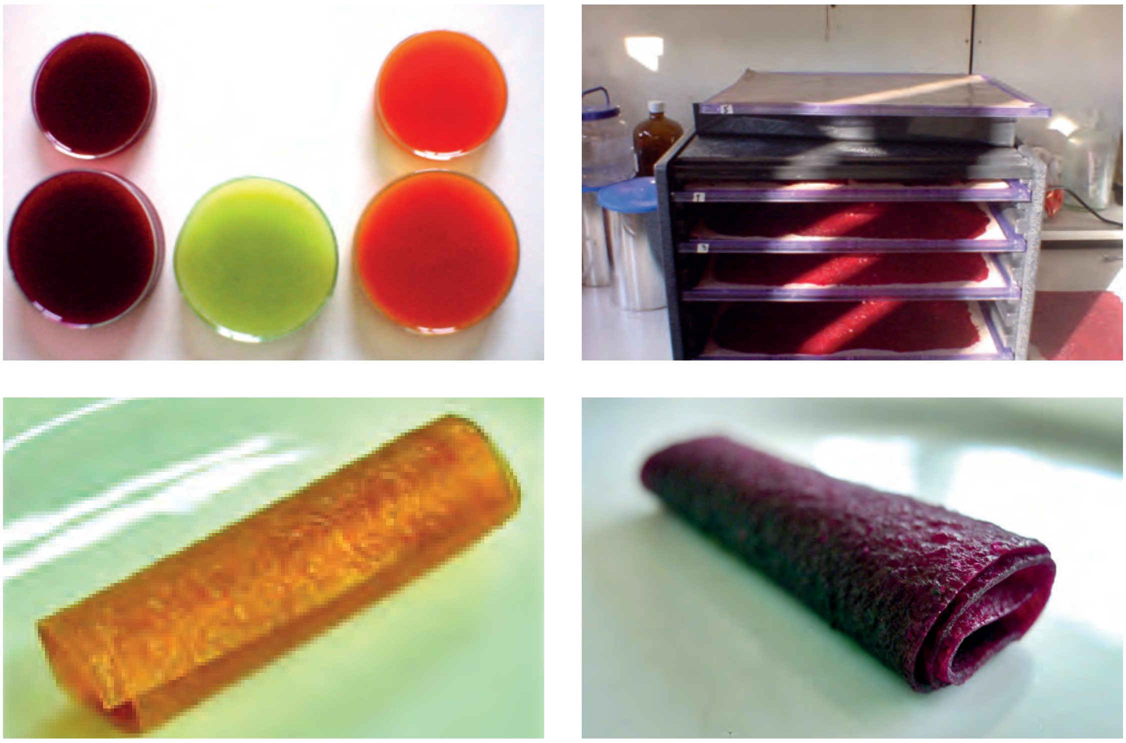

Figure 3
Cactus pear and apple pulps; electric tray drier; rolls from coloured ecotype (Photos: C. Sáenz and A.M. Fabry)

The quality of such products could be easily improved by using coloured cactus pear pulp to prepare a more natural and healthier product.

Dehydrated cladode products

The dehydration options for cladodes are different from those for cactus pear fruits. The cladodes are not dehydrated for direct consumption, but are transformed into powders (Sáenz *et al.*, 2010) with a high content of dietary fibre. This powder can be used to make cookies (blended with wheat flour), puddings and – in some countries, in particular Mexico – breakfast cereals or tortillas. It can also be used in the production of food supplements (capsules, tablets etc.).

Rodríguez García *et al.* (2007) observed that during the development of young cladodes, insoluble fibre increases (from 29.87% in a 60-g cladode to 41.65% in a 200-g cladode), while soluble fibre decreases (from 25.22 to 14.91%, respectively). Ayadi *et al.* (2009) prepared powder using 2-3-year cactus pads; the total dietary fibre was 51.24%, of which 34.58% insoluble fibre and 12.98% soluble fibre.

This powder can make a nutritional contribution to several food products by increasing the daily dietary fibre intake. Inclusion of the powder in foods, however, implies certain technological challenges, as some aspects of taste and texture require improvement (Sáenz *et al.*, 2002b, c; Ayadi *et al.*, 2009). For example, heat treatments result in a herbaceous aroma and flavour, and the mucilage present in the cladodes produces texture defects (Sáenz *et al.*, 2012a). The research of Sáenz *et al.* (2012a) resulted in a purified natural dietary fibre with > 80 g 100 g^{-1} of total dietary fibre and 20-22 g 100 g^{-1} of soluble dietary fibre, one of the scarcest types of fibre present in vegetables. Purification results in an increase in total dietary fibre, a decrease in the green colour of the powder and a decrease in the total phenolic compounds, in particular when cladodes are washed at high temperatures. This purification process is promising and could result in more widespread use of cactus cladode powder as a food additive, especially in markets where consumers are not familiar with the herbaceous flavour of cactus cladodes and therefore are less accepting. Further research is required to obtain a powder rich in dietary fibre, low in flavour and colour and with high antioxidant capacity for use as an ingredient in new food formulas.

Cactus pear concentrates

The range of concentrated products derived from cactus pear includes syrups, jams and concentrated juices (Sáenz, 2000). Morales *et al.* (2009) developed dessert sauces (toppings) from coloured ecotypes with excellent results, preserving both their attractive colour and their functional compounds. Vacuum concentration was used on mixtures of cactus pear pulp with sugar (22.0-30.25%), fructose syrup (13.75-22.0%), glucose (11.0-19.25%), citric acid (0.14%) and modified starch (1.5%). These attractive products may be used in a range of different dishes (**Figure 4**). **Table 3** lists bioactive compounds present in two coloured toppings.

A wide variety of cactus-pear-based foods are manufactured (Sáenz *et al.*, eds, 2006). Companies use the Internet to advertise different ways of eating and enjoying cactus pear fruit products, offering concentrated products, such as jams, syrups and candies. The information available online suggests that these are mainly artisanal and small-scale companies.

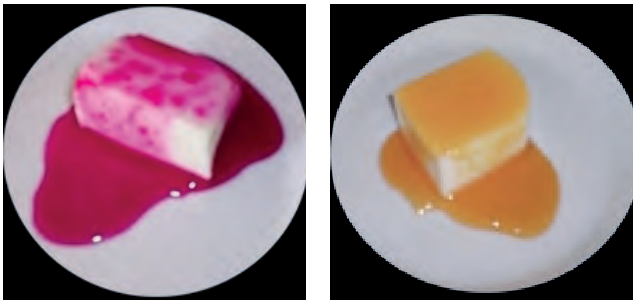

Figure 4
Coloured cactus pear toppings on a milk dessert. (Photos: C. Sáenz and M. Morales)

TABLE 3 Bioactive compounds in coloured cactus pear toppings

Bioactive compound	Purple cactus pear topping	Yellow-orange cactus pear topping
Carotenoids (µg g^{-1})	0.186 ± 0.001	0.021 ± 0.001
Total phenolics (mg GAE $litre^{-1}$)[a]	350.50 ± 15.25	131.48 ± 5.72
Betalains	81.06 ± 1.83	63.80 ± 1.86
Betacyanins (BE mg kg^{-1})[b]	66.09 ± 1.03	0.92 ± 0.00
Betaxanthins (IE mg kg^{-1})[c]	14.97 ± 1.53	62.88 ± 1.86

[a] GAE: gallic acid equivalent; [b] BE: betanin equivalent; [c] IE: indicaxanthin equivalent (Morales *et al.*, 2009).

Cactus pear sweet gels

Research by the author's group at the University of Chile has recently led to the development of cactus pear sweet gels using the pulp of different coloured ecotypes to exploit the attractive pigments (Sáenz and Fabry, unpublished data). These products – obtained evaporating the pulp and adding gelling agents such as pectin – have proved very popular with small farmers in arid zones of Chile, where there are shortages not only of water, but of electric power. These sweet gels are made with available technologies, enabling small farmers to add value to their cactus pear production. The flow chart in **Figure 5** shows the different stages in the production of sweet gels from cactus pear.

These cactus pear sweet gels are made with:

- seedless cactus pear pulp (1 000 g);
- sugar (760 g)
- pectin (52 g) – another gelling agent (e.g. carboxymethyl cellulose – CMC) could be tried, or a mixture of fruit pulps rich in pectin (e.g. quince); and
- citric acid (16 g) – or substituted with lemon juice.

Figure 6 shows cactus pear sweet gels made by small farmers in the village of Codpa (Arica and Parinacota, Chile) in a workshop led by our group. The village is located in Camarones, in the middle of the Tarapacá Desert in the north of Chile – an area with water and electric energy restrictions and

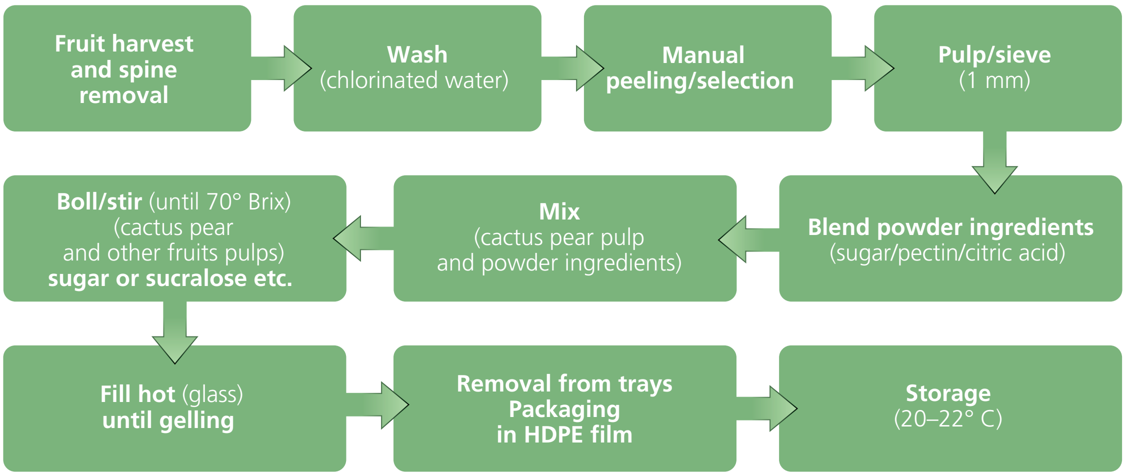

Figure 5
Preparation of cactus pear sweet gels

Figure 6
Cactus pear coloured sweets made in a workshop in the north of Chile (Photos: C. Sáenz and A.M. Fabry)

where cactus pear grows as an alternative crop.

Recently, Sáenz and Fabry (unpublished data) developed cactus pear pulp gummy confections, mixing a fine screened pulp (2.5 litres) with unflavoured gelatin (0.45 kg), water (2 litres) and sugar (1.5 kg) (**Figure 7**).

The final product has a brilliant and attractive appearance (**Figure 8**) and a high sensory acceptance. The colour parameters of purple gummy confections are L = 5.6, a* 30.0, b* = 9.0, C* = 31.3 and hab = 16.6, corresponding to a dark purple colour. Despite the soluble solids content of 56.5° Brix, the product shows a high a_w (0.92). For this reason, to ensure a good shelf-life, the use of preservatives (e.g. sodium benzoate and potassium sorbate) is recommended.

Nopal jams

The preparation of jams combines heat treatments with a decrease of a_w (and sometimes also of pH to enable less severe thermal treatment). There are different jams and syrups on the market in several countries (Sáenz *et al.*, eds, 2006). One innovative product, for which technology was recently transferred to small farmers in the north of Chile, is cladode and lemon jam: nopal jam. To remove the excess mucilage affecting the texture, the cladodes are pre-treated with $Ca(OH)_2$. This pre-treatment may be avoided if the cladodes have a low mucilage content. The flow chart in **Figure 9** describes the steps involved in the preparation of nopal jam.

Nopal jam represents a new alternative for processing cladodes. The jam can be eaten with crackers and baked goods, or served with meat and other dishes (**Figure 10**).

Figure 7
Preparation of cactus pear gummy confections

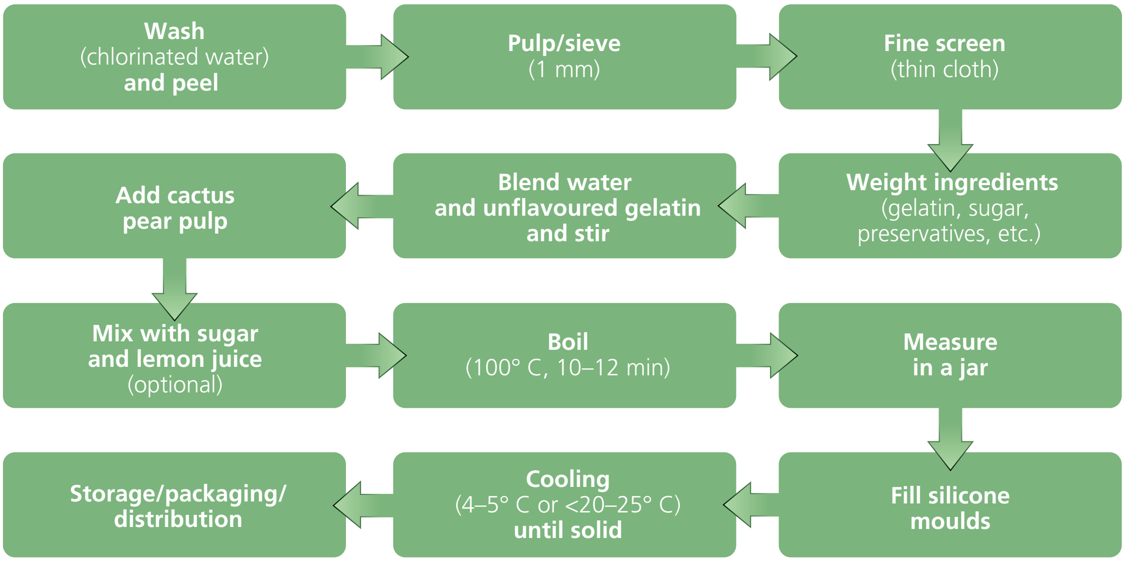

Figure 8
Gummy confections made from purple cactus pear, yellow–orange cactus pear and a mixture of both (Photo: C. Sáenz and A.M.Fabry)

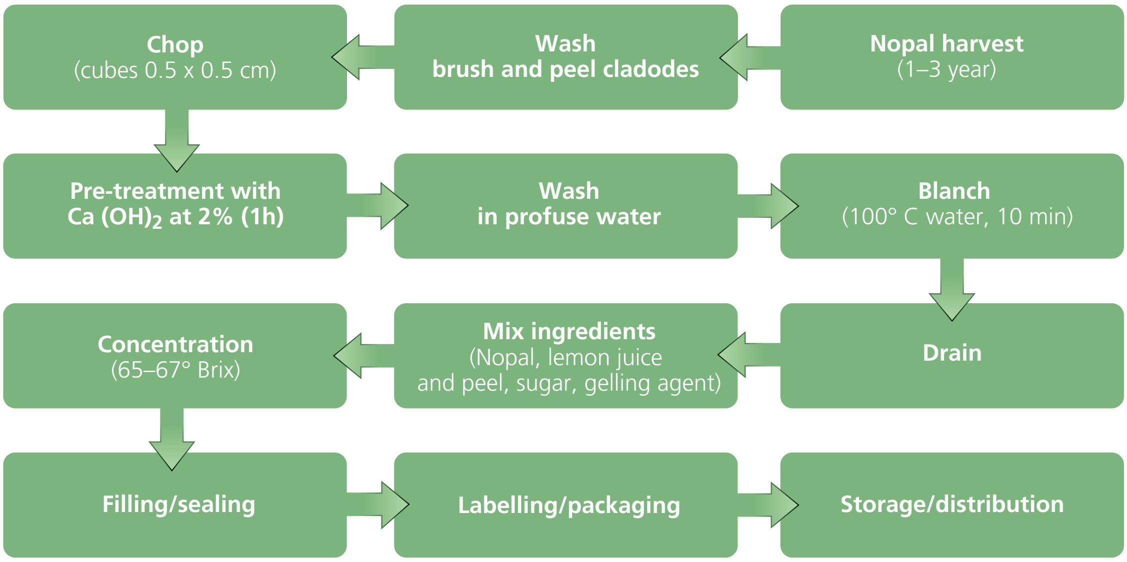

Figure 9
Preparation of nopal jam (cladode and lemon) (Modified from Sáenz et al., eds, 2006)

Figure 10
Cladode and lemon jam (Photos: C. Sáenz and A.M.Fabry)

Cactus pear juices

The pasteurization of cactus pear juice made with green fruit has produced unsatisfactory results, due to the unpleasant colour and aroma changes that occur during the process. On the other hand, purple cactus pear juice blended with other juices (e.g. pineapple) might represent an interesting alternative (Sáenz and Sepúlveda, 2001a). However, acidity is a potential issue: the addition of organic acid to increase acidity facilitates the heating process but can modify the taste, while consumers generally prefer cactus pear juices with the original acidity of the fruit, similar to that of the fresh fruit (Sáenz and Sepúlveda, 1999). El Samahy *et al.* (2007a) studied the production of pasteurized and sterilized cactus pear juices, adjusting the pH and adding preservatives in some treatments (sodium benzoate). Colour changes were observed at high temperatures, but microbiological stability was achieved in all the treatments. Baccouche *et al.* (2013) produced different formulations of a cactus pear beverage made with whey; it was pasteurized at 80° C for 20 minutes, and the physical stability was assessed after 40 days at 5° C. The authors observed an increase in sedimentation and turbidity (Nephelometric Turbidity Unit – NTU) during storage, and a decrease in colour, probably due to the Maillard reaction.

De Wit *et al.* (2014) made juices from eight cactus pear cultivars, with different fruit colours: one *O. robusta* cultivar ('Robusta', purple) and seven *O. ficus-indica* cultivars ('Berg' × 'Mexican', pink; 'Fusicaulis', green-white; 'Meyers', red; 'Algerian', red; 'Santa Rosa', orange; 'Skinners Court', green–white; 'Morado', white). The juices were pasteurized (60 °C for 10 minutes). The authors reported that the heat treatment had an unfavourable effect on the flavour of the juice and, for some of the cultivars (i.e. 'Santa Rosa'), pasteurization caused the cactus pear and melon taste of the fresh juice to turn bitter and astringent.

An example of a commercial product is a drink made from coloured cactus pear concentrate, water and natural flavouring. This product is available in the United States market, packaged in 1-litre Tetra Pak and sold for approximately US$6 litre^{-1}.

Cladode juices and nectars

Rodríguez (1999) reported various formulations of a drink made from tender cladodes, which were blanched at 95° C, liquefied and filtered. For the best results, the liquid was diluted 30% with water, the pH was adjusted with citric acid (to reach pH 3.5) and aspartame was used as a sweetener (1 g 335 ml^{-1}). The product was pasteurized at 76° C for 15.2 minutes, with mild loss of heat-sensitive nutrients and other compounds.

Recent years have seen an increase in the supply of cladode juices and nectars, mainly sold in Mexico. The process for obtaining cactus pad juice is as follows:

- Remove spines from the cladodes.
- Cut into pieces.
- Grind using industrial or domestic equipment (blender).
- Add water to facilitate the process.
- Filter the liquid to separate the solids.

Cladode juice is produced by several companies in Mexico, and mixed juices are also made, combining cladodes with orange, pineapple, guava or celery; the juices are available in the domestic market and for export. Another product sold in the Mexican market is "nopal water", a drink made with cactus cladodes juice and sugar, usually produced on a small scale. Other products include cladode syrups, made from a base of sucrose syrup (55-75° Brix) with the addition of cladode juice. In Texas (United States of America), a company produces blackberry and blueberry syrups with added cactus mucilage.

Canned *nopalitos* (tender cladodes)

Canning and pasteurization technologies are widely adopted in the manufacture of various products made from *nopalitos*. In Mexico, for example, pickled or salted tender cladodes (*nopalitos*) have been available on the market for many years. (Corrales García and Flores Valdez, 2003). Detailed descriptions of the preparation of pickled *nopalitos* and *nopalitos* in brine, among others, are given in Sáenz *et al.*, eds (2006).

Frozen products

Freezing is widely adopted for food preservation. More than any other method, freezing allows the taste, texture, and nutritional and functional features to be preserved. Techniques, such as cold air tunnels (-40 °C) or spraying liquid nitrogen (-196° C), are widely used in the food industry to improve the quality of the final product. The faster the freezing, the smaller the ice crystals formed and the better the product quality achieved. Freezing combines the effects of low temperature (microorganisms cannot grow, chemical reactions are reduced, and cellular metabolic reactions are delayed) with a decrease in water activity (a_w) (Casp and Abril, 1999; Vieira, 1996; Delgado and Sun, 2000). However, experiments on cactus pear have not yet yielded good results (Sáenz *et al.*, eds, 2006). Several studies indicate that freezing technologies could achieve better results with cactus pear pulps, rather than whole, half or sliced fruits. Defrosting – regardless of the type of cut (whole, halves or slices) – presents some problems, with excessive mucilage drip after defrost, resulting in an unpleasant appearance. This happens even when individually quick frozen (IQF) technologies are adopted, involving freezing temperatures close to -40° C.

Ice creams made from coloured cactus pear pulps can be found in very few countries and may be an interesting alternative for the use of pulps or concentrates. El Samahy *et al.* (2009) studied ice cream made with the addition of concentrated red cactus pear pulp (30°Brix); a 5% addition of pulp was found to be the most acceptable. The author's research group is currently conducting experiments with this attractive product.

OTHER TECHNOLOGIES

Fermentation

Fermentation is one of the oldest food preservation techniques and has been used with cactus pear to obtain various products. *O. streptacantha* (cactus pear 'Cardona') has been used to produce alcoholic beverages in Mexico since the pre-Hispanic period; the most traditional drink made with the juice of this species is *colonche* (Corrales García and Flores Valdez, 2003; Diaz, 2003).

Flores (1992) experimented with *O. streptacantha* and *O. robusta* to make a wine and a distilled alcohol. A wine of 11.6 °GL was obtained from juice concentrate (20 °Brix) using *O. streptacantha*; the distilled alcohol reached 56.2 °GL. The two species, *O. streptacantha* and *O. robusta*, produced alcohol with similar characteristics and a pleasant fruity aroma.

Another product with interesting potential is vinegar and some manufacturing experiences are worthy of note. Pérez *et al.* (1999) prepared vinegar from orange cactus pear using two types of substrate for acetic fermentation: must with previous alcoholic fermentation (13.5° GL) and cactus pear juice with added sugar (22° Brix). *Acetobacter pasteurianus* was used in the first case, *Acetobacter xylinum* in the second. Both vinegars obtained presented an intense yellow-amber colour, clean and bright, with a fresh and acetic acid smell.

Prieto *et al.* (2009) studied the development of balsamic-type vinegars from coloured cactus pear juices; the resulting products had an attractive colour, pleasant aroma and good sensory acceptability (**Figure 11**).

Membrane technologies

Membrane separation technologies have been increasingly used in the food industry in the last 25 years. Today their use is widespread and adopted for a range of purposes, including cold pasteurization, juice clarification and bioactive compound concentration (Cissé *et al.*, 2011; Rai *et al.*, 2006; Todisco *et al.*, 2002). Membrane technologies have advantages over other separation technologies (traditional filtration and concentration):

- Operation at low temperatures (15-35° C) – consequently affordable (low energy consumption) and degradation of heat-sensitive compounds is avoided.
- No use of chemicals (filter aids or enzymes) – unlike in filtration or traditional separation (Cassano *et al.*, 2010).

In membrane separation technologies, the membrane (ceramic or polymer) acts as a barrier: it allows only certain components in a mixture to pass and retains others. The flow of these substances is determined by various driving forces, including: pressure, concentration and electric potential. This selectivity means, for example, that it is possible to enrich a flow with one or more substances present in the feed. Two flows emerge from the feed: permeate (or filtrate) and retentate (or concentrate). The retentate contains substances that do not cross the membrane, while the permeate is rich in substances that pass through (Raventós, 2005). The selectivity depends on the size of the pores in the membrane and the chemical affinity between the membrane and the substances (Cheryan, 1998; Raventós, 2005).

Membrane technology processes used in the food industry include: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). RO is known for its effectiveness in desalinating seawater. Initial research on cactus pear juice focused on the application of MF and UF – the methods normally used in juice clarification. Cassano *et al.* (2007) experimented with cactus pear cv. 'Gialla' (yellow-orange) and combined membrane technologies with concentration by osmotic distillation (OD); they used low temperatures and preserved the organoleptic, nutritional and sensory characteristics of cactus pear juice. The concentration process (OD) resulted in 61° Brix and a good balance of betalains.

Cassano *et al.* (2010) later compared the performance of MF and UF in the physicochemical composition of yellow cactus pear juice. In both processes, the solids suspended in fresh juice were completely removed and a clarified juice obtained, and the betacyanins were retained. This retentate, rich in betalains, could be pasteurized and added to a juice concentrate to prepare, for example, pulpy juices, ice cream, jellies or infant formula (Cassano *et al.*, 2010).

Figure 11
Balsamic-type vinegars from coloured cactus pear juices (Photo: C. Sáenz)

The research group of the authors of this chapter recently used this technology to separate or concentrate betalains from purple cactus pear MF, UF and NF (Cancino, Robert and Sáenz, unpublished data). Thanks to the avoidance of high temperatures, there was no degradation of the pigments, and the betalain extracts obtained were free of mucilage and had a reduced content of low molecular sugars. **Table 4** shows the characteristics of purple cactus pear pulp: prediluted (P), ultrafiltered (UF) and nanofiltered (NF). The ultrafiltered and nanofiltered extracts were, as expected, fully clarified solutions (0 NTU), in comparison with the prediluted pulp (2 453 NTU), which contained mucilage. In the UF, the betacyanin content (247.9 mg BE litre^{-1}) was similar to that of P; however, in the NF, the betacyanin values (216.3 mg BE litre^{-1}) were lower than those in P and UF, taking into consideration that the pulp (feed) is diluted.

Cassano *et al.* (2010) obtained the highest betalain values with UF (32.8 mg BE litre^{-1}). The polyphenol content was concentrated in both membrane processes (UF and NF). Cassano *et al.* (2010) – applying UF to cactus pear cv. 'Gialla' and using other membranes and process conditions – reported lower values of total polyphenols (552.17 mg

TABLE 4 Physical and chemical characteristics of prediluted pulp, ultrafiltered and nanofiltered extract from purple cactus pear

Parameter	P	UF	NF
Total sugars (%)	13.2 ± 0.0 b	9.2 ± 0.3 c	17.5 ± 0.1 a
Turbidity (NTU)	2453 ± 64 a	0.00 ± 0.00 b	0.00 ± 0.00 b
Betacyanins (mg BE litre^{-1})	254.0 ± 0.2 a	247.9 ± 4.3 a	216.3 ± 7.0 b
Betaxanthins (mg IB litre^{-1})	85.4 ± 0.1 b	88.6 ± 1.2 a	79.1 ± 2.6 c
Total phenolics (mg GAE litre^{-1})	534.8 ± 4.4 b	659.7 ± 5.0 a	673.5 ± 13.5 a
Colour			
L	12.5 ± 0.9 c	17.8 ± 0.1 b	19.3 ± 0.03 a
C*	48.0 ± 1.7 c	59.3 ± 0.1 b	62.4 ± 0.1 a
H_{ab}	25.9 ± 1.0 c	30.3 ± 0.1 b	31.4 ± 0.1 a

P = pulp; UF = ultrafiltered pulp; NF = nanofiltered pulp; BE = betanin equivalent; IE = indicaxanthin equivalent; GAE = gallic acid equivalent.
Different letters in rows: means statistical differences (Tukey $p < 0.05$).
Source: Cancino, Robert and Sáenz (unpublished data).

GAE litre^{-1}). The results obtained for the different extracts (P, UF and NF) are due to the membrane pore size, as well as the chemical affinity between the membrane and the interaction between the different compounds and the membrane.

These kinds of products open new possibilities for the production of colourants from cactus pear. However, further research is required to improve the pigment concentration and other properties of the extracts.

OTHER PRODUCTS

Cactus pear colourants

Natural colourants – in particular, red and purple – are highly appreciated by consumers since synthetic red colourants used as additives in food have been restricted by official regulations in the European Union and the United States of America because of the possible adverse effects on human health (Tsuda *et al.*, 2001). Therefore, there is a growing interest in new, natural red pigment sources and their potential application in foods.

Red and purple cactus pear ecotypes have a variable betalain content in both the pulp and peel (Odoux and Domínguez López, 1996; Sepúlveda *et al.*, 2003c). This pigment is commercially obtained from red beetroot and is widely used in the food industry. Its use in food is permitted by both US and EU legislation (Sáenz *et al.*, 2009). The red beet extract (rich in betalains) is used mainly to colour food, such as dairy products, confectionery, ice cream, desserts, beverages and sausages. However, it has some disadvantages: an earth-like flavour, imparted by geosmin and 3-*sec*-butyl-2 methoxypyrazine, and high nitrate levels. Red or purple cactus pears are, therefore, an interesting alternative as a source of betanin for the production of food colourants (Sáenz *et al.*, 2009; Castellar *et al.*, 2003) (**Figure 12**).

The use of a purple concentrate cactus pear juice as food colouring for dairy products (e.g. yogurt) was studied some years ago (Sáenz *et al.*, 2002d; Sepúlveda *et al.*, 2002, 2003c). Topics including pigment purification and stability, crucial for application in industry, are currently being addressed.

Castellar *et al.* (2008) obtained a betalain concentrate by fermentation (*Saccharomyces cerevisiae* var. Bayanus AWRI 796) of *O. stricta* juice. The final product had 9.65 g betanin litre^{-1}, pH 3.41, 5.2° Brix and a viscosity of 52.5 cP.

Other studies focused on dehydration of cactus pear pulp by spray-drying or freeze-drying to obtain colourant powders. Mosshammer *et al.* (2006) adopted lyophilization and spray-drying with maltodextrin as carrier (18-20 dextrose equivalent [DE]) to dehydrate *O. ficus-indica* cv. 'Gialla' juice; they reported high betalain retention (≤ 90%) for both kinds of powder. Similarly, various species of purple cactus pear *(O. stricta, O. streptacantha, O. lasiacantha*) were spray-dried, using maltodextrin as drying carrier (10, 20 DE). Diaz *et al.* (2006) observed that after 24 weeks at 25° C, the powder retained 86% of the original content of betanin. Obón *et al.* (2009) used glucose syrup (29 DE) and reported that after 1 month stored at room temperature, the colour powder retained 98%. Rodríguez Hernández *et al.* (2005) observed that


Figure 12
Purple cactus pear fruits and microparticles (Photos: C. Sáenz and P. Robert)

cactus pear powder, when reconstituted, presented a slightly different colour from the fresh juice.

Betalain stability is affected by several factors: pH, water activity, exposure to light, oxygen, enzyme activity and, above all, temperature (Azeredo, 2009; Herbach *et al.*, 2006; Castellar *et al.*, 2003). A technology – microencapsulation – is available to stabilize the pigments (Sáenz *et al.*, 2009, 2012b; Gandía Herrero *et al.*, 2010; Vergara *et al.*, 2014; Robert *et al.*, 2015).

Microencapsulation is a technique involving the introduction of bioactive compounds (solid, liquid or gaseous) into a polymeric matrix to protect them from the environment, interaction with other food components or controlled release (Yáñez Fernández *et al.*, 2002). Microencapsulation by spray-drying is the most widely used technique: it obtains a powder of low water activity, enabling easier transportation, handling and storage and ensuring microbiological quality (Hayashi, 1989).

Vergara *et al.* (2014) combined membrane technology (to separate betalains) and microencapsulation (to protect them), obtaining a healthy colourant that can be used in the food industry. Gomez (2013) studied the microparticle betalains stability in soft drinks, comparing microparticles from cactus pear pulp, and ultrafiltered and nanofiltered extracts; he concluded that the stability of betalains is affected both by their source (pulp or extract) and by the encapsulating agent used. Betalains from cactus pear pulp are more stable in soft drinks, probably thanks to the mucilage. Alfaro (2014) applied purple cactus pear pulp microparticles in yogurt, and reported that after 45 days' storage, 60% of betalains were retained.

There has been relatively little research to date on the encapsulation of betalains from cactus pear (*O. ficus-indica*) (Sáenz *et al.*, 2009; Vergara *et al.*, 2014; Pitalua *et al.*, 2010; Gandía Herrero *et al.*, 2010; Robert *et al.*, 2015; Otárola *et al.*, 2015). Further investigation is required.

Extruded products

Extrusion cooking is a high-temperature short-time (HTST) technology. While there has been little relative study in cactus pear and cladodes, this technology is widely applied in food processes, such as breakfast cereals, salty and sweet snacks, baby foods and snack foods. Food materials are plasticized and cooked, combining moisture, pressure, temperature and shear. The factors affecting product quality include extruder type, screw configuration, speed, temperature and feed rate, as well as the composition of the raw material and the type of food ingredients used (Singh *et al.*, 2007; El Samahy *et al.*, 2007b).

El Samahy *et al.* (2007b) studied cactus pear rice-based extruded products – an innovative option for production of a new value-added snack based on cactus pear pulp concentrates. In this study, orange-yellow and red cactus pear pulps were concentrated (40° Brix), added to rice flour and the blend put in a single-screw extruder. Different formulations (varying the ratio of rice flour and cactus pear pulp concentrate) were tested. Substitution levels of 5% and 10% of concentrated cactus pulps gave the best results for extruded products with good functional, nutritional and sensory characteristics. The poor sensory attributes of the formula without cactus pear pulp were significantly improved by adding cactus pear concentrates.

Sarkar *et al.* (2011) extruded cactus pear pulp (yellow variety) with rice flour. The authors tested different solids ratios (rice flour solids : puree solids – 6 : 1, 8 : 1 and 10 : 1). The blends were dried in a twin-screw extruder. The results revealed that some characteristics, such as porosity, decreased when the fruit solid level increased.

Cactus pear pulp has potential for the production of extruded products; further study is required to better understand the behaviour of cactus pulp in this process and to improve characteristics of the products obtained.

Hydrocolloids (mucilages) from cladodes

Hydrocolloids are polysaccharides with variable complexity, generally used in the food industry as additives to provide viscosity to, for example, beverages, puddings and salad dressings. They include cactus mucilage, a polysaccharide-type arabinogalactan present both in cactus pads and in cactus pear fruits (Sáenz *et al.*, 2004; Matsuhiro *et al.*, 2006). The mucilage has an important physiological role in the *Opuntia* species as it has a high water retention capacity (Nobel *et al.*, 1992). It can be extracted from the matrix (cladodes or fruit peel) with water, and precipitated with ethanol; or other techniques can be adopted, such as pressing (Sepúlveda *et al.*, 2007). In general, the extraction yields are low (≤ 2% fresh weight [FW]), but they nevertheless offer an interesting prospect, considering that the cladodes (pads) are usually pruning residues and are available throughout the year. Various extraction methods have been reported using different solvents to precipitate the mucilage, such as ethanol, isopropyl alcohol and acetone (Rodríguez González *et al.*, 2014; Cai *et al.*, 2008; Sepúlveda *et al.*, 2007; Yahia *et al.*, 2009; Medina Torres *et al.*, 2000). Some studies have researched the application of this hydrocolloid in fruit nectars to replace other thickeners normally used in the food industry (e.g. CMC) (Sepúlveda *et al.*, 2003a, 2004).

The mucilage has also been tested as an edible coating to protect fresh fruits. Del Valle *et al.* (2005) used mucilage as edible film to increase the shelf-life of strawberries stored at 5° C, reporting that the fruits maintained their texture and flavour and no deterioration occurred after 9 days of storage. This edible film could provide an alternative for the preservation of different fresh fruits, such as berries. However, application to different products is a challenge, because the respiratory rate of each type of fruit must be taken into account. Aquino *et al.* (2009) used a mucilage solution blended with different citric acid and sodium bisulphite concentrations to inhibit the browning of banana slices during the drying process. The authors reported that a combination of 500 ppm sodium bisulphite and citric acid (1%), following treatment in the mucilage solution (35 mPas), inhibited browning and made the banana slices shinier.

Recently, Medina Torres *et al.* (2013) and Otárola *et al.* (2015) reported that mucilage can be used as an encapsulating agent for bioactive compounds, gallic acid and betalains; this points to new opportunities in the industrial sector. Sáenz *et al.* (2009) also reported this behaviour in a study of the encapsulation of betalains from purple cactus pear fruits.

Lira Ortiz *et al.* (2014) extracted low methoxyl pectins from *O. albicarpa* Scheinvar skin, and discovered its potential for use in the food industry as a thickening and gelling agent – the latter when calcium ions were added. The authors obtained a yield of 98 g kg^{-1} of dry matter.

Seed oil

Cactus pear fruits contain variable amounts of seeds, but they are usually present in a high proportion (10-15 g 100 g^{-1}). In most cactus pear fruit processes, the seeds are separated from the pulp, resulting in large quantities of discarded seeds that become an environmental waste problem. For this reason, in recent decades, researchers in different countries have studied the seed composition and sought different possible uses for the seeds.

Sawaya *et al.* (1983) studied the seed composition and its potential utilization in animal feed. They reported 16.6% protein content, 17.2% fat, 49.6% fibre and 3.0% ash. The mineral content is high in sodium (67.6 mg 100 g^{-1}), potassium (163.0 mg 100 g^{-1}) and phosphorus (152.0 mg 100 g^{-1}).

Cactus pear seed oil is edible; it could be another nutritive and functional product of potential interest to the food industry, but perhaps not for direct consumption (as indicated below). The oil is usually extracted in research using organic solvent (4.4-14.10%) (Sawaya and Khan, 1982; Sepúlveda and Sáenz, 1988; Ennouri *et al.*, 2005; Becerril, 1997; Tlili *et al.*, 2011; Ouerghemmi *et al.*, 2013; Chougui *et al.*, 2013), depending on factors such as growing conditions, variety and fruit maturity (Özcan and Al Juhaimi, 2011). Use of a cold press to obtain the seed oil was only reported by Gharby *et al.* (2015) from Morocco, with a yield of 6-7%. This type of extraction is more environmentally friendly as it avoids the use of organic solvents.

Yields of edible oils are 6-17%, which, in terms of waste stream, compares reasonably with other commonly used seed oils. The production of cactus pear seed oil as edible oil is only viable with integrated processing, using all parts of the plant (Sáenz *et al.*, eds, 2006).

Cactus pear seed oil is rich in unsaturated fatty acids and has a high linoleic acid content (57.7-73.4%) and low linolenic content. **Table 5** shows the percentages of the main seed oil fatty acids.

The oil has a high unsaturated fatty acid content, as well as other healthy compounds, such as sterols, tocopherols, vitamin E, β-carotene and vitamin K (Ramadan and Mörsel, 2003a; Kouba *et al.*, 2015). Phenolic compounds were reported by Tlili *et al.* (2011) and Chougui *et al.* (2013): respectively, 61 mg GAE 100 g^{-1} and 268 mg 100 g^{-1}, expressed as rutin equivalent. The researchers in Mexico and Taiwan reported higher figures (Cardador Martínez *et al.*, 2011). Further research is required before definitive conclusions can be drawn.

These and other physical and chemical properties, including refractive index, iodine index and saponification number, highlight the similarity between cactus pear seed oil and other edible vegetable oils, such as corn oil or grape seed oil. Oil extraction yields are low

TABLE 5 Fatty acid content (%) in cactus pear seed oil (*Opuntia ficus-indica*) from different countries

Fatty acid	Countries						
	Morocco [a]	Turkey [b]	South Africa [a]	Tunisia [a,c,g]	Germany [d]	Chile [e]	Algeria [f]
Palmitic (C16 : 0)	11.9	10.6-12.8	13.7	12.2-12.7	23.1	16.2	13.1
Stearic (C18 : 0)	3.4	3.3-5.4	3.38	3.2-3.9	2.67	3.3	3.5
Oleic (C18 : 1n-9)	21.3	13-23.5	15.7	16.4-22.3	24.1	19.9	16.3
Vaccenic (C18 : 1n-7)	–	5.1-6.3	–	4.8	–	–	5.3
Linoleic (C18 : 2n-6)	60.8	49.3-62.1	64.38	53.5-60.6	32.3	57.7	61.8

[a] Gharby *et al.* (2015); [b] Mattháus and Özcan (2011); [c] Tlili *et al.* (2011); [d] Ramadan and Mörsel (2003a); [e] Sepúlveda and Sáenz (1988); [f] Chougui *et al.* (2013); [g] Ouerghemmi *et al.*, 2013.

compared with other common edible seed oils; cactus pear seed oil could nevertheless be used in the food industry as a fat replacer in special confectionery products. However, pharmaceutical and cosmetics uses offer more and better alternatives. In this context, cactus pear seeds also contribute with essential oils, a group of compounds used mainly in the pharmaceutical field. Ouerghemmi *et al.* (2013) reported that essential oils comprise, among others, terpenes, esters and aldehydes, and the yield for cactus pear seeds is close to 4%.

In recent years, other applications have emerged, in particular for cosmetics; this industry has exploited the oil's characteristics (polyunsaturated fatty acid content, tocopherols, sterols, phenolics) and in countries such as Morocco a promising industry has emerged. There are several cooperatives and private companies that extract this oil for cosmetic purposes, and at least 20 producers of cactus oil exist (Abderrahman Ait Hamou, ANADEC, Morocco, personal communication). The industry extracts the oil by cold press – an environmentally friendly process that avoids the use of solvents (Berraaouan *et al.*, 2015; Gharby *et al.*, 2015). Before the oil is extracted by cold press, the seeds must be separated using a special machine (**Figure 13**).

CONCLUSION

There are a vast array of alternatives for processing the fruits, cladodes and seeds from *Opuntia* plants. In general, the technologies used are available to many small-scale agro-industries that could take advantage of this new raw material to diversify their production. When, on the other hand, the aim is the creation of new agro-industries for cactus pear processing, investment is required and must come from governments, NGOs or other sources. In some countries, a cooperative model could be promoted. The immense variety of cactus pear products and by-products can bring huge benefits to many people, in particular those living in arid and semi-arid zones of the world.

Figure 13
Seed separator (Photos: A. Ait-Hamou)