

Cactus Pear Fruits (*Opuntia* spp.): A Review of Processing Technologies and Current Uses[♦]

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1. ABSTRACT

Crops with additional health-promoting and nutritional benefits, such as cactus pears, are increasingly gaining momentum both for health professionals and consumers (Feugang et al., 2006). Cactus pear fruits are rich in betalains, taurine, minerals, and antioxidants, and thus fit well this trend. Hence, it is considered and are predicted a promising future crop for commercial food applications. In this light, a sound knowledge of the physical and chemical characteristics of cactus pears as well as their current and potential future uses are needed. However, data are scattered and often difficult to access. Therefore, the present review summarizes data from the literature and points out promising areas of research.

Key words: *Opuntia* spp., cactus pear, processing technologies, juice concentrate, coloring foodstuff, fruit powder

2. INTRODUCTION

The *Opuntia* cactus is a xerophyte of about 200 to 300 species and grows mainly in arid and semiarid zones. Due to their remarkable genetic variability, *Opuntia* plants show a high ecological adaptivity and can, therefore, be encountered in places of virtually all climatic conditions (Stintzing and Carle, 2005). Whereas *Opuntia* cacti originate from Mexico, they are cultivated in both hemispheres and on all continents except Antarctica (Inglese et al., 2002). Although cactus pear fruits and stems were traditionally utilized for medicinal and cosmetic purposes, as forage, building material, and as a source for natural colors (Stintzing and Carle, 2005) their use is mainly restricted to fresh fruit consumption in their countries of origin (Sáenz and Sepúlveda, 2001; Sáenz-Hernández, 1995), but are also exported to the European fresh fruit market (Mizrahi et al., 1997; Sáenz-Hernández et al., 2002). In the future, declining water resources and global desertification may even increase *Opuntia* spp. importance as an effective food production system including both fruits and vegetable parts (Stintzing and Carle, 2005).

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Stimulated by the installation of commercial production lines in Mexico, southern California (U.S.A.), and Chile, recent studies indicate that an increasing utilization of cactus-pear fruit juice, concentrates, and powders as functional ingredients for the soft drink market, including betalainic coloring foodstuffs, is expected (Castellar, et al., 2003, 2006; Stintzing et al., 2001; Stintzing et al., 2003; Moßhammer et al., 2005a; Moßhammer et al., 2006a). So, the current standard of knowledge on *Opuntia* spp. processing should be available.

3. IMPORTANT PHYSICAL AND CHEMICAL CHARACTERISTICS OF CACTUS PEAR FRUITS

The cactus pear fruit, also known as prickly pear, tuna, or fico d'india, is an oval, elongated berry of 67-216 g weight. They offer a wide spectrum of colors from white, yellow, orange, red, and purple based on betalains (Stintzing et al., 2005) and contain about 85% water, 15% sugar, 0.3% ash and less than 1% protein (Mohamed-Yasseen et al., 1996). The thick pericarp is covered with small-barbed spines hosting a juicy pulp with 150-300 nonedible seeds. The latter account for 3-7% on a weight basis, followed by the pericarp and mesocarp (36-48%) and the edible pulp (39-64%) (Felker et al., 2002; Felker et al., 2005; Gurrieri et al., 2000; Hoicke and Stintzing, 1999). Thus, cactus pear fruits may be divided into three fractions that may be exploited for commercial processing: seeds, peel, and pulp.

3.1. Seeds

3.1.1. Hydrocolloids

As reported by Habibi et al. (2005a) the polysaccharides isolated and purified from endosperm seed show the presence of either free arabinan or arabinan-rich polysaccharides attached to rhamnogalacturonan type I blocks.

3.1.2. Lipids, sterols, and fat-soluble vitamins, and proteins

According to Ramadan and Mörsel (2003a,b) total seed lipids amount to 98.8 g/kg dry weight. Major lipid acids and sterols are linoleic, palmitic as well as oleic acids and β -sitosterol with campesterol, respectively. In contrast to pulp oil, the main tocopherol was the γ -isomer, followed by α -, β -, and δ -tocopherols (Ramadan and Mörsel, 2003a,b; Sawaya and Khan, 1982; Sepúlveda and Sáenz, 1988). Tocopherols are considered effective antioxidants that prevent lipid oxidation. Thus, cactus pear seed oils should be quite stable. With regard to the lipid profile, *Opuntia* seed oil is comparable with grape seed or corn germ oil (Coskuner and Tekin, 2003; Krifa et al., 1993).

Apart from lipids, the seeds were also shown to be rich in an albumin with a molecular weight of 6.5 kDa (Uchoa et al., 1988). In general, the protein pattern of seeds appears to be a valuable marker for taxonomical studies (Carreras et al., 1997). So further studies in this area seem to be worthwhile.

3.2. Peel

In contrast to the pulp, with pH-values ranging from 5.4 to 5.8 the peel was reported to be usually more acidic (Cerezal and Duarte, 2005; Joubert, 1993; Odoux and Domínguez-López, 1996).

3.2.1. Hydrocolloids

The polysaccharides from cactus pear peel are characterized by sugar constituents typical of pectin with high and medium degrees of esterification of galacturonic acid residues (Habibi et al., 2005b; Majdoub et al., 2001).

3.2.2. Lipids, sterols, and fat-soluble vitamins

Total lipids recovered from peel amount to 36.8 g/kg on dry weight (Ramadan and Mörsel, 2003c). With linoleic, palmitic and oleic acids and with β -sitosterol and campesterol, the profile of lipids was found to be similar to that of the pulp oil (Hassanien and Mörsel, 2003; Ramadan and Mörsel, 2003a,b).

High contents of vitamin E amounting to 21.8 g/kg oil, dominated by α -tocopherol with 17.6 g/kg, were found in the lipids extracted from cactus pear peel. (Hassanien and Mörsel, 2003; Ramadan and Mörsel, 2003b).

3.2.3. Pigments

Whereas betalains impart orange, red, and purple-colored shades to peels, pigments of green-skinned cultivars consist of chlorophylls and, presumably, carotenoids. Since little is known about the pigment composition of the peel, future studies may put forward our present knowledge.

3.3. Pulp

3.3.1. Sugars and organic acids

Total soluble solids range between 12 and 17°Brix (Sáenz-Hernández, 1995), with glucose and fructose being the predominant carbohydrates in a ratio of about 1:1, depending on invertase activity (Kuti and Galloway, 1994; Sawaya et al., 1983). The high sugar content of the pulp results in sugar:acid ratios within the range of 90:1 up to 490:1, which is responsible for the bland taste and, therefore, far from a sensory pleasant ratio of 10 to 18 (Felker et al., 2005; Joubert; 1993, Odoux and Domínguez-López, 1996; Stintzing and Carle, 2006).

The high pH-value varies between 5.6 and 6.5 in fully ripe fruits (Felker et al., 2005) resulting in a very low acidity of about 0.05% to 0.18% citric acid and thus characterizes cactus pears as a low-acid food (pH > 4.5). Hence, acidification prior to thermal treatment is a prerequisite to allow pasteurization instead of more rigid sterilization, thereby retaining nutritionally important components such as betalains (Feugang et al., 2006; Piga, 2004; Stintzing et al., 2001).

Whereas citric acid (62.0 mg/100 g fruit weight) is the major organic acid in cactus pear, followed by malic acid (23.3 mg/100 g), quinic (19.1 mg/100 g), shikimic (2.8 mg/ 100 g), oxalic acids are also typical (Barbagallo et al, 1998). Isocitric, fumaric, glycolic and succinic acids were only found in traces (Askar and El-Samahy, 1981; Stintzing et al., 2001).

3.3.2. Vitamins and minerals

Significant amounts of ascorbic acid are generally found in fruits of different *Opuntia* spp. ranging from 10 to 410 mg/kg. The most common *Opuntia ficus-indica* (L.) Mill. shows ascorbic acid contents from 180 to 300 mg/kg (Piga, 2004). So, cactus pear is higher in ascorbic acid than other common fruits, such as apple, pear, grape, and banana, but other vitamins, such as carotenoids, thiamine, riboflavin, and niacine may only be found in trace amounts (Sawaya et al., 1983; Sepúlveda and Sáenz, 1990).

Cactus pear pulp is rich in calcium (up to 59.0 mg/100 g) and magnesium (up to 98.4 mg/100 g), whereas levels of sodium, potassium, iron, and phosphorus are in the typical range of fruits (Askar and El-Samahy, 1981; Stintzing et al., 2001).

3.3.3. Amino acids

The high level of free amino acids in fruits from *O. vulgaris* was first reported in 1981 (Askar and El-Samahy, 1981). In a recent study, previous data on fruit analysis could be confirmed

(Stintzing et al., 1999): Free amino acids comprised all essential amino acids. Proline was found to be the predominant amino acid in the pulp of six different cultivars ('Apastillada', 'Bianca', 'Gialla', 'Gymno carpo', 'Morado', and 'Rossa') from *Opuntia ficus-indica* fruits amounting to 883.4 and even 1929.1 mg/L followed by taurine (323.6 to 407.3 mg/L), glutamine (98.3 to 574.6 mg/L), and serine (130.6 mg/L to 392.6 mg/L) (Stintzing et al., 1999, 2003; Kugler et al., 2006).

3.3.4. Hydrocolloids

The polysaccharide fraction of cactus pear pulp was only recently reported to be composed of a complex mixture of polysaccharides of which less than 50% corresponded to a pectin-like polymer. The hydrocolloid fraction from the fruit pulp of *O. ficus-indica* fruits obtained by ethanol precipitation yielded 3.8% and contained 93.5% sugars. Whereas, after saponification, uronic acid content of 42.3% was determined; neither proteins nor nitrogen were detected. After total hydrolysis, the presence of arabinose, rhamnose, xylose, and galactose in the molar ratio of 1.0:1.7:2.5:4.1 was found. However, further studies are required to completely characterize the hydrocolloid fraction of cactus pear fruit pulp (Matsuhiro et al., 2006).

3.3.5. Polyphenols

The presence of polyphenols in the pulp has been recently reported (Butera et al., 2002; Kuti, 2004; Tesoriere et al., 2005a,b). Quercetin, kaempferol, and isorhamnetin derivatives were found to be the major flavonoids in cactus pear pulp (Kuti, 2004). However, more in-depth studies should be envisaged to fully assess the phenolic composition of cactus pear fruits neglected so far.

3.3.6. Lipids, sterols, and fat-soluble vitamins

It is well known that mesocarp or pulp of fruits generally contain very low levels of lipids ranging from 0.1 to 1.0% (Kamel and Kakuda, 2000). In cactus pear pulp oils, linoleic acid was reported the dominating fatty acid, followed by palmitic and oleic acids. Also, the polyunsaturated fatty acids γ -linolenic and α -linolenic acids were detected in higher amounts (Ramadan and Mörsel, 2003a,c). The major sterol in pulp oils was β -sitosterol followed by campesterol, together constituting about 90% of the total sterol portion. Interestingly, δ -tocopherol was the predominant vitamin E homologue, followed by α -, β -, and γ -tocopherols in far less amounts (Ramadan and Mörsel, 2003a,c).

3.3.7. Flavor compounds

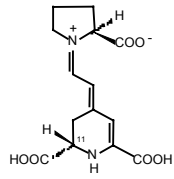
Cactus pear pulp flavor is characterized by a faint melon or cucumber-like aroma determined by alcohols and esters with 2-(*E/Z*)-2,6-nonadien-1-ol and 2-methylbutanoic acid methyl ester being the key aroma substances (Agozzino et al., 2005; Arena et al., 2001; Di Cesare and Nani, 1992; Flath and Takahashi, 1978; Weckerle et al., 2001). The flavour intensity was found to be strongest for yellow, followed by red, and, finally, white cactus pear fruits (Agozzino et al., 2005).

3.3.8. Pigments

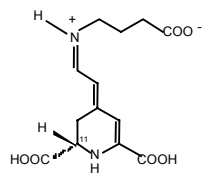
Cactus pear pulps offer different colors based on betalains covering a wide spectrum from white to purple with pigment contents of 66 to 1140 mg/kg fruit pulp (Castellar et al., 2003; Stintzing et al., 2005). Cactus pear fruits bear both yellow betaxanthins and red betacyanins (Figure 1) in betaxanthin:betacyanin ratios varying between 0 to 11.7 resulting in different color shades (Butera et al., 2002; Odoux and Domínguez-López, 1996; Stintzing et al., 2005). Interestingly, fruits solely containing betaxanthins are not yet known (Stintzing and Carle, 2006).

A compilation of relevant physical and chemical fruit characteristics is provided in Table 1.

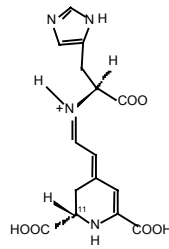
Betaxanthins
(yellow-orange)



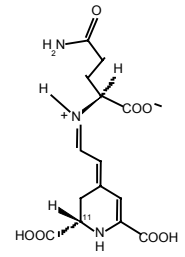
Indicaxanthin
(Proline-bx)



?-Aminobutyric acid-bx

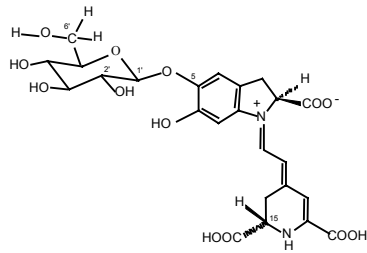


Muscaaurin VII
(Histidine-bx)

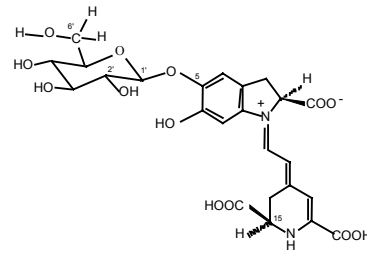


Vulgaxanthin I
(Glutamine-bx)

Betacyanins
(red)



Betanin



Isobetanin

Figure 1. Structures of major cactus pear betalains (bx = betaxanthin)

Table 1. Relevant physical and chemical characteristics of cactus pear fruits (*Opuntia* spp.)
According to: Feugang et al. (2006), Matsuhiro et al. (2006); Piga (2004);
Ramadan and Mörseel (2003a,b,c); Sáenz-Hernández (1995); Stintzing et al. (2005)

Parameter	
<i>Weight</i> [g]	67 to 216
<i>Seeds</i>	<i>3 to 7% of fresh weight</i>
Number of seeds/fruit	150 to 300
Hydrocolloids (endosperm)	arabinans, rhamnogalacturonans
Total lipids [mg/kg]	98.8 (on dry weight basis)
Main lipids	linoleic, oleic, palmitic acids
Main sterols	β -sitosterol, campesterol
<i>Peel</i>	<i>36 to 48% of fresh weight</i>
Color	green, orange, red, purple
Hydrocolloids	pectin-like composition
Total lipids [mg/kg]	36.8 (on dry weight basis)
Main lipids	linoleic, oleic, palmitic, γ -linolenic, α -linolenic acids
Main sterols	β -sitosterol, campesterol
Vitamins (in oil)	vitamin E
<i>Pulp</i>	<i>39 to 64% of fresh weight</i>
Color	white, yellow-orange, red, purple
Main pigments	indicaxanthin (proline-betaxanthin), γ -aminobutyric acid-betaxanthin, muscaaurin VII (histidine-betaxanthin), vulgaxanthin I (glutamine-betaxanthin), betanin, isobetainin
Pigment content [mg/kg]	66 to 1140
pH	5.6 to 6.5
Main acid	citric acid
Total titratable acids [g/L]	0.5 to 1.1
Total soluble solids [%]	12 to 17%
Main sugars	glucose, fructose
Total sugar contents [g/L]	100 to 130
Sugar:acid ratio	90:1 to 450:1
Main amino acids	proline, taurine, glutamine, serine
Main minerals	calcium, magnesium
Main vitamin	vitamin C
Main phenolics	quercetin, kaempferol, isorhamnetin
Hydrocolloids	complex mixture of rhamnogalacturonan and at least 50% nonpectic substances
Main lipids	linoleic, palmitic, oleic, γ -linolenic, α -linolenic acids
Main sterols	β -sitosterol, campesterol
Total lipids [mg/kg]	8.7 (on dry weight basis)
Main aroma compounds	2-(<i>E/Z</i>)-2,6-nonadien-1-ol, 2-methylbutanoic acid methyl ester

4. CACTUS-PEAR FRUIT-PROCESSING TECHNOLOGIES AND CURRENT USES

Cactus pear fruits play an important role in human diet in their countries of origin, such as Mexico or Chile, where peeled fresh fruits are commonly consumed at home, in vegetarian restaurants, or in local health-food stores (Pimienta-Barrios, 1994; Sáenz and Sepúlveda, 2001). Recently, a couple of reviews pointed out the high nutritional value of cactus pear fruits (Feugang et al., 2006; Piga, 2004; Sáenz, 2000; Stintzing et al., 2001). The late discovery of their nutritive value may explain that no commercial juice products are available at industrial level and processing of cactus pear fruits in general has only been scarcely investigated (Joubert, 1993; Sáenz and Sepúlveda, 2001). Because cactus pear fruits are susceptible to rapid microbial spoilage, especially by yeasts and mesophilic bacteria, feasible transformation and preservation processes are a prerequisite to prevent postharvest losses.

4.1. Seeds

Seeds were separated from pulp using a pulper (Sawaya and Khan, 1982). After washing with water, the seeds were ground to pass a 20 mm sieve. Ground seeds were extracted for 36 hours with petroleum ether in a soxhlet extractor. After removal of the solvent in a rotary evaporator oil yield amounted to 136.0 g/kg from the total seed fraction. In a more recent study, lipids isolation from ground lyophilized seeds was carried out using a chloroform/methanol extraction procedure. Afterwards the solvent was separated in a rotary evaporator to yield 98.8 g oil/kg seeds (Ramadan et al., 2003a).

However, the methods so far described for oil extraction from cactus pear seeds and peels are only suitable for analytical purposes and may not be considered for industrial processing. Thus adequate technologies remain to be established.

4.2. Peel

Since the peels of cactus pear fruits are normally not eaten and are difficult to separate from the pulp, low interest in cactus pear fruit peel processing is understandable.

However, in a recent work two new products containing ground peels were elaborated (Cerezal and Duarte, 2005). Whereas for the first, a mixture of ground cactus pear skins, pulp, and sucrose was used to obtain a concentrated sweet product, the second consisted of ground peels, sucrose, and pectin and was addressed as "*marmalade*". While different concentrations of preservatives and acids were tested for the first product, for the latter a formulation exhibiting 63% TSS (total soluble solids), a pH of 4.0 with potassium sorbate preservation was suggested. The optimum composition for the first product comprised 3 parts of pulp and 1 part of peels with the addition of phosphoric acid and sodium bisulphite.

Peels may also be used for oil recovery as recently proposed by Ramadan et al. (2003b), yielding 36.8 g oil/kg peel.

4.3. Pulp

Because the pulp is the most valuable edible part of the cactus pear fruit, it is considered the most interesting fruit portion for food processing. However, for many potential customers of cactus pear products their large number of seeds is an insurmountable obstacle to their purchase (Thomas, 1998). Therefore, seed separation is a prerequisite to obtaining an attractive product from cactus pear pulp.

4.3.1. Traditional products

Traditional preservation procedures still applied today, especially in Mexico, were originally developed for wild species (*O. streptacantha* and *O. robusta*). They include tuna “cheese” (*queso de tuna*), a dried product obtained by further concentration of a toffee-like viscous cactus fruit preparation (*melcocha*) enriched with raisins, nuts, and pine nuts to improve flavour and taste (Sáenz-Hernández, 1995; Ortiz-Laurel and Mendez-Gallegos, 2000). An investigation on cactus pear pulp processing into so-called fruit sheets was reported by Sepúlveda et al. (2000), when quince and cactus pear pulps were blended at a ratio of 25:75 to obtain a natural alternative to sweets. *Colonche* is another traditional product. This low-alcohol drink is obtained through fermentation of cactus pear pulp and juice in wooden barrels (Sáenz, 2000). However, both products are produced at cottage industry-scale and mainly consumed fresh after production.

4.3.2. Minimally processed products

Piga et al. (2000, 2003) achieved a shelf-life extension of cactus pear by minimal processing of the fruits. Manually peeled fruits from *Opuntia ficus-indica* cv. ‘Giulla’ were placed in polystyrene trays and sealed with polyolefinic films. Both chemical and sensory attributes of these minimally processed fruits were retained for 8 days at 4°C storage. A similar approach was followed by Saézn et al. (2001) when fruit texture was maintained in ethylene-vinyl acetate (EVA) bags over 7 days at 5°C. A very recent investigation proposed modified atmosphere packaging at 4-8°C up to 7 days, thus reducing microbial spoilage through the action of mesophilic bacteria such as *Staphylococcus* spp., *Enterobacter* spp., or *Leuconostoc mesenteroides* as well as yeasts (Corbo et al., 2004).

4.3.3. Jams, syrups, canned, and frozen products

Sawaya et al. (1983) reported the manufacturing of cactus pear jam at pilot plant-scale with added dates. In this work, sugar:pulp ratio, acidifying agents (type and quantities), pectin dosage, flavoring, dates:prickly pear pulp ratio, and the effect of fruit blanching on jam quality were studied. In all trials, pH was adjusted to 3.2 using different aqueous organic acid solutions. The best sensory results were obtained using the following recipe: pulp:sugar ratio of 60:40, addition of 1.25% pectin, citric acid or a combination of citric and tartaric acids (1:1), with a ratio of 20% dates. Most preferred flavors were cloves, grapefruit, orange and almond.

Joubert (1993) canned hand-peeled cactus pear fruits of five different cultivars in acidified sucrose syrup (20% TSS) at 100°C for 15 min. Softening of the fruits was observed with increasing processing times. However, by addition of 0.25% CaCl₂ to the syrup, texture was improved. Canned fruits stored for 22 months were still firm and retained their shape, but a color loss was observed for yellow- and orange-colored cultivars. In addition, the canned fruits developed a gherkin jam-like uncharacteristic flavor, not further closely characterized.

In another study (Cerezal and Duarte, 2004), peeled cactus pears were canned in glass-jars after addition of pasteurized syrup consisting of water, sucrose, sodium bisulphite (0, 50 and 100 ppm), calcium chloride (120 ppm), potassium sorbate (1000 ppm), ascorbic acid (500 ppm), phosphoric and citric acids to reach a pH of 4.0 to 4.2. Evaluating color, opacity, texture, and taste, best results were obtained without bisulphite using a mixture of phosphoric and citric acids.

As an alternative preservation method, freezing of slices and quarters of peeled and unpeeled fruits using a fluidized bed tunnel at -40°C was reported by Sáenz (1995, 2000). However, upon defrosting, higher drip losses and significant texture losses were registered, rendering this approach unsatisfactory.

4.3.4. Purée, juice, and juice concentrates

Fruit processing into purée and juice production are the most important technologies. Preservation of characteristic nutrients, taste, flavor as well as color, long shelf-life, easy handling, and convenience, make juice a valuable and attractive product for both customers and the food industry. Moreover, the multiple functional properties of cactus pear fit well with the recently upcoming demand for health-promoting foods and natural ingredients (Stintzing et al., 2000; Piga, 2004). In addition, diversity of colors based on betalain pigments is considered the most striking feature of cactus pears (Stintzing and Carle, 2006). With pigment contents of up to 1140 mg/kg fruit pulp (Castellar et al., 2003; Stintzing et al., 2005), cactus pears deserve being considered for fruit coloring purposes.

Despite the high potential of cactus pear, reports on pulp and juice processing are scarce and, so far, only a few studies were carried out at laboratory scale.

First investigations on cactus pear juices were performed by Espinosa et al. (1973). The authors acidified cactus pear juice with lemon juice to reach a pH-value of 4 prior to pasteurization at 80°C over 20 min. However, juice preservation failed since the heated product was still susceptible to acetic acid fermentation. Joubert (1993) evaluated laboratory-scale juice extraction and filtration using five different cactus pear cultivars grown in South Africa ('Direkteur', 'Frusicaulis', 'Gymno carpo', 'Morado', and 'Skinner's Court'). However, the juices were still cloudy after paper filtration which was assumed to be caused by pectins and arabans. Additionally, heat degradation of indicaxanthin was evaluated spectrophotometrically with losses amounting to 20% and 40% upon a thermal treatment for 30 min at 70°C and 90°C, respectively. In 1993, Sáenz studied pasteurization and concentration of juices from green cactus pears. Objective color measurements showed a lightness (L^*) decrease associated with a loss of green hue upon thermal treatment. Additionally, darkening was observed for concentrates stored at room temperature. In a further study, Sáenz and Sepúlveda (2001) added pineapple juice, citric acid, water, and sugar to minimize cactus juice viscosity and to lower pH, thus reducing the risk of microbial spoilage.

The first commercial interest in the potential of cactus pear was expressed by D'Arrigo Brothers (Castroville, CA, USA) who developed a process particularly designed for purée manufacture from red cactus pears (Thomas, 1998). While a red cactus pear purée with considerable suspended solids is being sold in commercial quantities by Vita Pakt of Covina (Covina, CA, USA), as of yet no clear juice or concentrate is being sold commercially (Sáenz and Sepúlveda, 2001).

Only recently, the potential of cactus pear for natural coloring was demonstrated (Moßhammer et al., 2005a). A betalain-based coloring foodstuff from red and yellow-orange cactus pears (*Opuntia ficus-indica* cv. 'Gialla' and cv. 'Rossa') was obtained at pilot-plant scale simply by applying unit operations typical of conventional fruit-juice production. Complete separation of the peels from the pulp and removal of seeds were achieved by carborundum peeling of frozen fruits and subsequent straining through a finisher. Earlier attempts applying lye-peeling with a boiling solution of 18% NaOH resulted in severe flesh damage and were thus judged unacceptable (Joubert, 1993). For improvement of filterability, different enzyme preparations were tested to degrade the pectic-like substances (Moßhammer et al., 2005a). To ensure optimum pH conditions for enzymation, and to avoid deteriorative sterilization, strained pulp was acidified with citric acid to pH 4. Enzymatic pulp maceration was carried out for two hours at 40°C. Subsequently, the juice was heated to 92°C to inactivate enzymes prior to filtration and rapidly cooled to room temperature using a tubular heat exchanger. After filtration, the clarified

juice was pasteurized at 92°C in an HTST system (Actijoule[®]), bottled under steam injection and cooled to room temperature (Figure 2). Altogether, clarified juices with an attractive visual appearance, good microbial stability, and an overall juice yield of 37% was obtained.

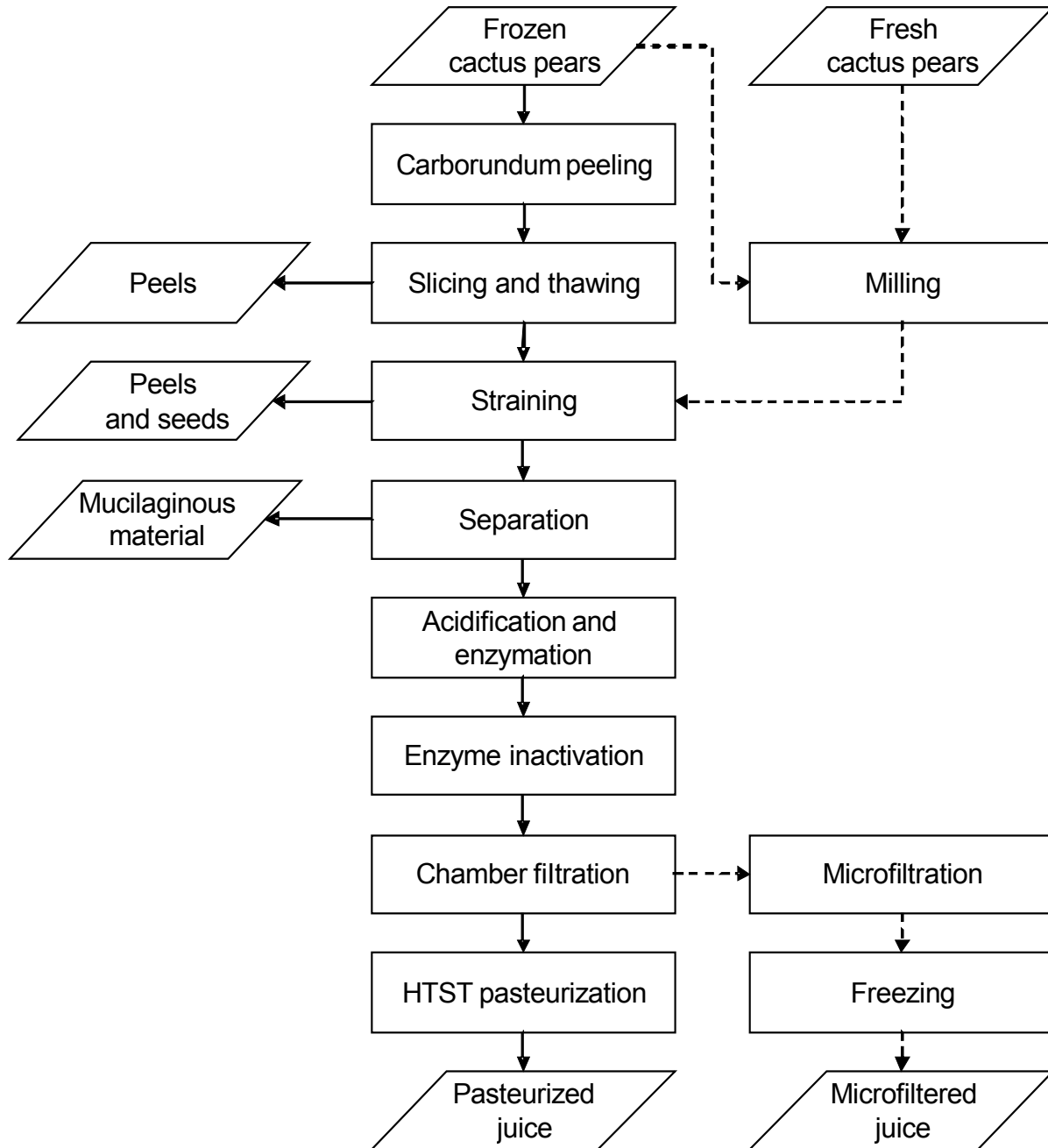


Figure 2. Production scheme of pilot-plant-scale cactus-pear juice manufacturing (modified after Moßhammer et al., 2005a; Moßhammer et al., 2006a)

Upon pasteurization, color losses of 6-13% and 2-6% were observed for betaxanthins and betacyanins, respectively. While lightness (L^*) and chroma (C^*) increased during processing for both cultivars, hue angle (h°) remained unchanged for the yellow cultivar 'Gialla', but a slight shift towards red was observed for the red cultivar "Rossa" after pasteurization (Moßhammer et al., 2005a). Additionally, proline contents were determined upon processing and found to be a sensitive indicator for indicaxanthin degradation because proline was released by indicaxanthin degradation upon thermal treatment (Figure 3). Interestingly, despite high contents of amino acids and reducing sugars, neither Maillard browning nor HMF formation were observed.

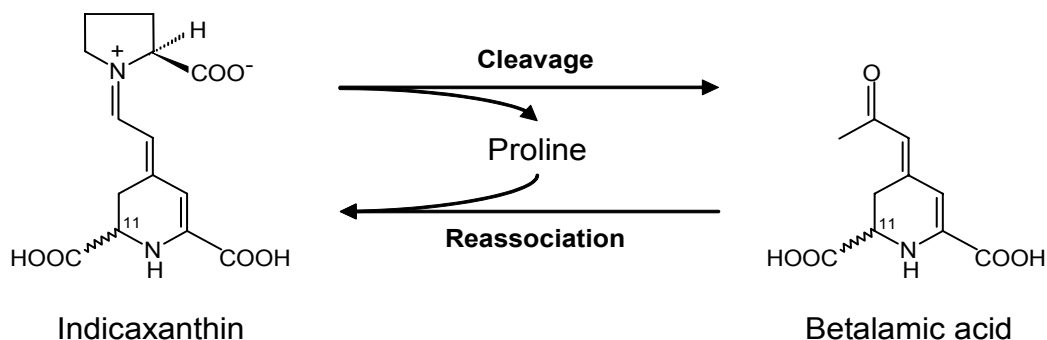


Figure 3. Thermal degradation and reassociation of indicaxanthin

A considerable improvement of this process (Moßhammer et al., 2005a) was achieved through replacing carborundum peeling of frozen fruits by grinding the fresh fruits (Moßhammer et al., 2006a; Figure 2). Thus, an easier handling of industrial processing and increased juice yields were achieved. Moreover, processing fresh instead of frozen cactus fruits would be more economical. However, milling of fresh instead of thawed cactus pears required a different enzyme preparation for complete degradation of pectic-like substances. It is assumed that through freezing and thawing the physicochemical characteristics of the pectic substances were altered, thus requiring a different enzymation strategy. Furthermore, replacing pasteurization by cold-sterile microfiltration (0.2 μm) resulted in identical betalain retentions and, additionally, complete haze separation. This process was even suitable to obtain juice concentrates and fruit powders both at laboratory and pilot-plant scale, respectively (Moßhammer et al., 2006a; Figure 4). Acceptable overall pigment retentions of 71 to 83%, combined with the retention of the initial color properties after reconstitution of semiconcentrated and concentrated preparations, proved the viability for industrial cactus pear juice processing. Despite high contents of reducing sugars and amino acids, only minor Maillard browning effects were found for concentrates produced by evaporation at pilot-plant scale. In particular, basically early Maillard reaction products detectable between 340 and 360 nm were registered. Moreover, indicaxanthin:isindicaxanthin ratios were shown to be a good indicator of heat exposure, being even more sensitive than the respective betanin:isobetanin ratios.

4.3.5. Dehydrated products

Dehydration presents an alternative to cactus pear juice and jam processing. Dried products may open new options for industrial applications (i. e., soups, fruit or cereal bars, dessert preparations, instant dishes, or chocolates). However, studies on drying cactus pear fruit and its juice are very limited.

Recently, convective solar drying of prickly pear fruit slices was proposed by Lahsasni et al. (2004a,b). Cut cactus pear fruits from Morocco were dried in an experimental solar dryer varying drying air temperatures from 50 to 60°C and flow rates from 0.0227 to 0.0833 m³/s, relative humidities from 23 to 34%, and solar radiation intensities between 200 and 950 W/m², respectively. Drying temperature was found to be the decisive factor in controlling the drying rate.

Rodríguez-Hernández et al. (2005) studied the suitability of cactus pear juice (*Opuntia streptacantha*) to produce spray-dried fruit powders. Drying was performed in a laboratory spray-dryer using inlet temperatures between 205 and 225°C, and compressor air pressures of 0.1 to 0.2 MPa, respectively. Commercial maltodextrins (10 and 20 dextrose equivalents, DE) were used as carrier agents at two levels, i.e., 18 and 23%. The authors obtained lower moisture contents in powders using maltodextrin 20 DE as compared to maltodextrin 10 DE. Interestingly, the effect of maltodextrin type on the hygroscopicity was found to be insignificant. However, pressure and maltodextrin concentration significantly affected water uptake capacity. Minimal moisture contents and hygroscopicity were obtained at 205°C and 0.2 Mpa, whereas maximum vitamin C retention (45 to 50%) was achieved at 0.1 MPa and 205°C. Noteworthy, cactus pear juice was not very sensitive to color deterioration under the drying conditions applied (Rodríguez-Hernández et al., 2005). Whereas lightness (L*) was not affected by spray-drying, a*-values increased and b*-values decreased as compared to fresh juice, resulting in total color changes of $\Delta E^* = 6.7$ to 9.8. In order to obtain a relatively stable product retaining its high quality, the following values were recommended: inlet temperature, 215°C; pressure, 0.15 Mpa; maltodextrin 10 DE concentration, 20.5%.

In a very recent study, spray-drying of yellow-orange cactus pear (*Opuntia ficus-indica* cv. 'Gialla') juice concentrate and freeze-drying of single-strength juice were investigated (Moßhammer et al., 2006a; Figure 4). For this purpose, a mixture of 1 part concentrate (65% TSS) and 1.5 parts of maltodextrin (DE 18-20) dissolved in 1 part of H₂O was dried using a laboratory-scale spray dryer at 165°C and 90°C for inlet and outlet temperatures, respectively. For freeze-drying experiments, a mixture of 5 parts of microfiltered juice and one part of maltodextrin (18-20 DE) were dried in a laboratory freeze dryer at 25°C until constant weight (72 h). Whereas vitamin C losses of 50 to 55% upon spray drying were in agreement with the results of Rodríguez-Hernández et al. (2005), freeze drying entailed a minor vitamin C loss of only 10%. Ninety-six percent of total betalains were retained after spray-drying and total color changes ($\Delta E^* = 2.3$) were marginal. Overall appearance was more affected by freeze-drying ($\Delta E^* = 6.4$), particularly caused by a lightness decrease with an overall betalain retention of 93%. Despite high amounts of reducing sugars and amino acids, only minor Maillard browning was found for the freeze-dried powder.

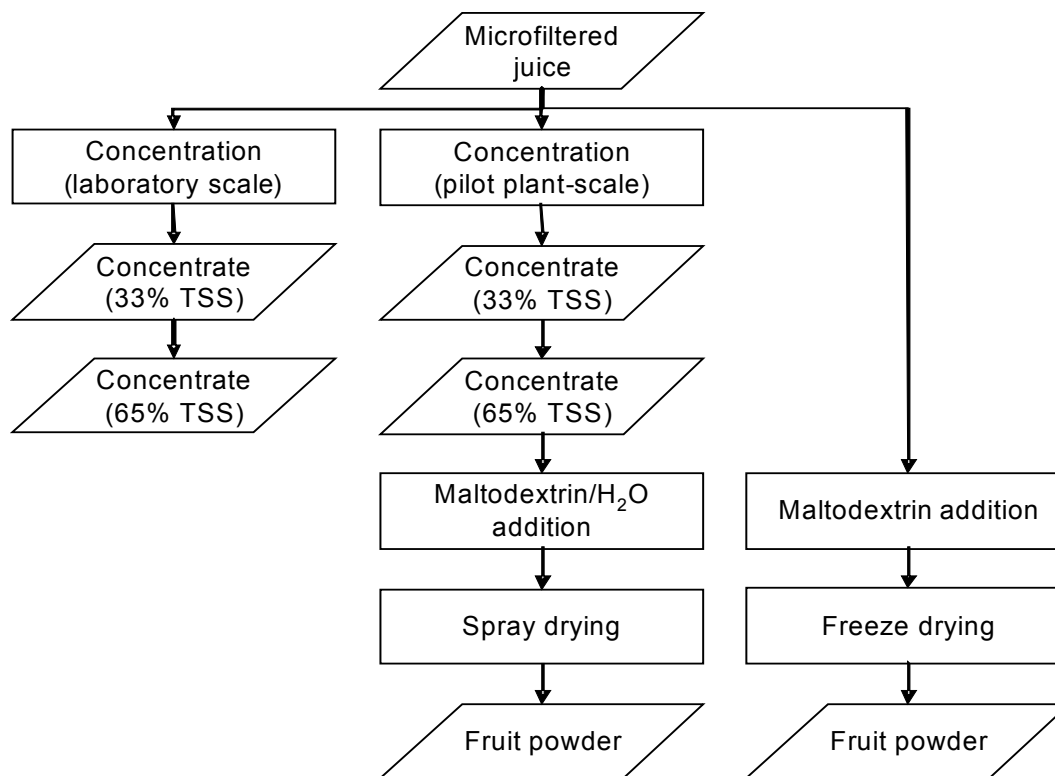


Figure 4. Production scheme of juice concentrate and fruit-powder manufacture from cactus-pear juice (modified after Moßhammer et al., 2006a)

4.3.6. Alcoholic beverages

Because small-sized cactus pear fruits are unsuitable for the fresh-fruit market, their processing into alcoholic beverages was performed (Bustos, 1981). Cactus pear juices containing 10 mg/L SO₂ with and without addition of citric acid were inoculated with the *Saccharomyces cerevisiae* Montrachet strain yielding 3.9 to 7.3 g/L alcohol. By subsequent fractionated distillation, a pure alcohol displaying typical cactus pear aroma was obtained.

Lee et al. (2000) fermented various mixtures of diluted cactus pear juices and grape juices to produce alcohol. Fermentation was carried out using *S. cerevisiae* after SO₂, Na₂SO₃, and tartaric acid addition. Interestingly, maximal alcohol concentrations were obtained for 100% grape juice (9.6%), while high cactus juice proportions resulted in lower ethanol yields.

In another study using *S. cerevisiae* as the fermentation organism, 95.54% conversion of fermentable sugar was achieved with an ethanol yield of 55.3 mL/L (Turker et al., 2001). The pigment degradation was found to be 17% at the end of the fermentation process. This may be due to β-glucosidase activities of the yeasts cleaving the red glycosides betanin and isobetanin into their corresponding highly labile aglycons (Figure 5).

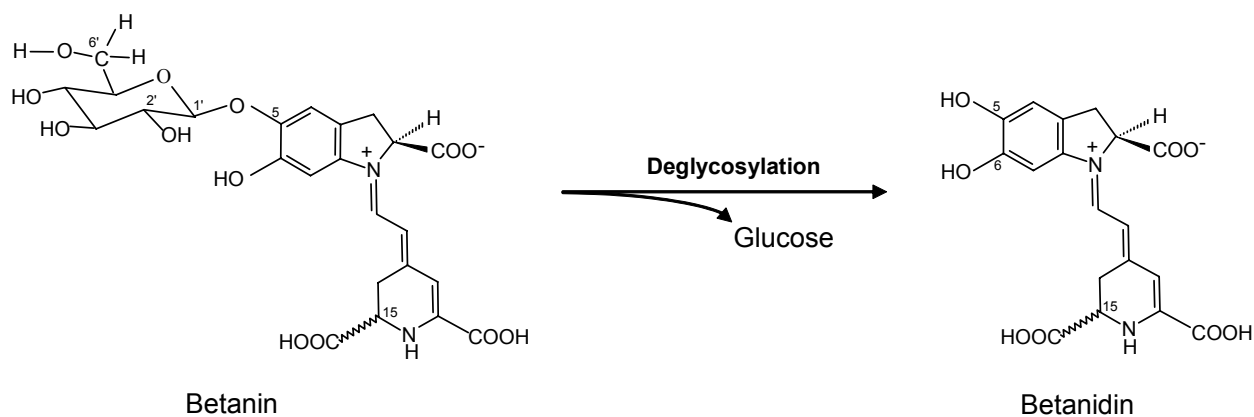


Figure 5. Deglycosylation of betanin

4.3.7. Liquid sweetener

The use of cactus pear to obtain a natural liquid sweetener was studied by Sáenz et al. (1998). For this purpose, whole fruits were processed in a screw press. After enzymatic treatment of the resulting pulp using a pectinolytic enzyme preparation with high arabinase activity, the juice (16.5% TSS) was filtered and decolorized with activated carbon. Concentration to 60% TSS was performed in a laboratory scale vacuum rotary evaporator at 40°C. The resulting product had a light golden-yellow-color and exhibited a similar sweetness of 67 relative units as compared to glucose syrup with a value of 65.5.

5. IMPACT OF THERMAL TREATMENT AND STORAGE ON COLOR OF CACTUS PEAR JUICES

The different color shades based on betalains are considered the most striking feature of cactus pears for use as natural colorants in the food industry (Stintzing et al., 2005) and temperature can be regarded the most crucial factor on betalain stability both during food processing and storage (Herbach et al., 2006). Therefore, the following chapter will give an overview on studies dealing with color changes during thermal treatment and illuminated or dark storage, respectively.

5.1. Heat stability of cactus pear pigments

Merin et al. (1987) studied color stability of betacyanins at pH 4.4 from cactus pear at different temperatures using absorption spectra to monitor color changes. The degradation rates were found to depend on both temperature and pigment concentration. As confirmed more recently by Lee et al. (2000), Son and Lee (2004), and Moßhammer et al. (2006b), color degradation was higher at elevated temperatures and slower for higher concentrations, respectively (Table 2). Neither the presence of oxygen nor ascorbic acid (0.1% dosage) had significant impact on the thermostability of the pigments. Moreover, Lee et al. (2000) observed a stronger betalain loss upon heating at lower pH-values of 4.0 and 3.2 (Table 2). Studies on heat stability of indicaxanthin at pH 6.4 in orange-colored juices from *Opuntia ficus-indica* cv. 'Gymno Carpo' were carried out by Joubert (1993) using absorption spectra to monitor pigment loss. As reported for betacyanins (Merin et al., 1987), absorbance of indicaxanthin decreased steadily with increasing temperature and heating time (Table 3). The same relation was observed by Turker et al. (2001) upon heating of fermented yellow-orange cactus pear juice (Table 3).

Table 2. Heat stability of cactus pear betacyanins

Reference	Heated material	pH	Heating period [min]	Temperature [°C]	Pigment retention [%]
Merin et al. (1987)	pigment solution ¹	4.4	182	50	50
	pigment solution ¹	4.4	64	70	50
	pigment solution ¹	4.4	12	90	50
	concentrated pigment solution ¹	4.4	990	50	50
	concentrated pigment solution ¹	4.4	100	70	50
	concentrated pigment solution ¹	4.4	23	90	50
Lee et al. (2000)	diluted filtered juice ²	3.2	15	85	18
	diluted filtered juice ²	4.0	15	85	43
Son & Lee (2004)	diluted filtered juice ²	4.0	20	80	78
Moßhammer et al. (2006c)	centrifuged juice ³	4.0	60	75	43
	centrifuged juice ³	4.0	60	85	12
	centrifuged juice ³	4.0	60	95	0
	centrifuged juice ³ + 0.1% isoasc ⁴	4.0	60	75	89
	centrifuged juice ³ + 0.1% isoasc ⁴	4.0	60	85	68
	centrifuged juice ³ + 0.1% isoasc ⁴	4.0	60	95	31

¹ from *O. ficus-indica* cv. 'Gymno Carpo'

² from *O. ficus-indica* var. *saboten* MAKINO

³ from *O. ficus-indica* cv. 'Gialla'

⁴ isoasc = isoascorbic acid

Table 3. Heat stability of cactus pear betaxanthins

Reference	Heated material	pH	Heating Period [min]	Temperature [°C]	Pigment retention [%]
Joubert (1993)	diluted filtered juice ¹	6.4	30	70	80
	diluted filtered juice ¹	6.4	30	90	60
Turker et al. (2001)	fermented juice ²	5.0	30	50	96
	fermented juice ²	5.0	30	70	85
	fermented juice ²	5.0	30	90	30
Moßhammer et al. (2006b)	centrifuged juice ³	4.0	60	85	40
	centrifuged juice ³ + 0.1% asc ⁴	4.0	60	85	46
	centrifuged juice ³ + 1.0% asc ⁴	4.0	60	85	42
	centrifuged juice ³ + 0.1% isoasc ⁵	4.0	60	85	51
	centrifuged juice ³ + 1.0% isoasc ⁵	4.0	60	85	49
	centrifuged juice ³ + 0.1% citr ⁶	4.0	60	85	29
	centrifuged juice ³ + 1.0% citr ⁶	4.0	60	85	40
	centrifuged juice ³	6.0	60	85	70
	centrifuged juice ³ + 0.1% asc ⁴	6.0	60	85	61
	centrifuged juice ³ + 1.0% asc ⁴	6.0	60	85	58
	centrifuged juice ³ + 0.1% isoasc ⁵	6.0	60	85	70
	centrifuged juice ³ + 1.0% isoasc ⁵	6.0	60	85	69
	centrifuged juice ³ + 0.1% citr ⁶	6.0	60	85	79
	centrifuged juice ³ + 1.0% citr ⁶	6.0	60	85	71
	pigment solution ³	4.0	60	85	6
	pigment solution ³ + 0.1% asc ⁴	4.0	60	85	12
	pigment solution ³ + 1.0% asc ⁴	4.0	60	85	12
	pigment solution ³ + 0.1% isoasc ⁵	4.0	60	85	12
	pigment solution ³ + 1.0% isoasc ⁵	4.0	60	85	12
	pigment solution ³ + 0.1% citr ⁶	4.0	60	85	12
pigment solution ³ + 1.0% citr ⁶	4.0	60	85	15	
Moßhammer et al. (2006c)	centrifuged juice ³	4.0	60	75	58
	centrifuged juice ³	4.0	60	85	25
	centrifuged juice ³	4.0	60	95	0
	centrifuged juice ³ + 0.1% isoasc ⁵	4.0	60	75	70
	centrifuged juice ³ + 0.1% isoasc ⁵	4.0	60	85	40
	centrifuged juice ³ + 0.1% isoasc ⁵	4.0	60	95	15

¹ from *O. ficus-indica* cv. 'Gymno Carpo'² from *O. ficus-indica* (wild-growing cultivar)³ from *O. ficus-indica* cv. 'Gialla'⁴ asc = ascorbic acid⁵ isoasc = isoascorbic acid⁶ citr = citric acid

In a very recent study, the impact of added ascorbic, isoascorbic, and citric acids on heat stability of cactus pear betalains at pH 4 and pH 6, respectively, has been investigated (Moßhammer et al., 2006b). Also, the influence of matrix compounds such as sugars, organic acids, amino acids, and pectic substances on pigment stability were assessed. The authors reported that heat stability of both betaxanthins and betacyanins was improved by the addition of the organic acids (Table 2, Table 3). Additionally, matrix compounds were found to have a positive effect on betalain stability. Consequently, the so-called matrix index was introduced, expressing the protective potential of individual food components on color (Moßhammer et al., 2006b). Interestingly, the stabilizing effects of the additives under investigation were less pronounced in matrix-free pigment preparations as compared to cactus pear juice. In general, betaxanthins were more stable after heating at pH 6, whereas betacyanins exhibited improved heat stability at pH 4. Moreover, the formation of 2-decarboxy-betainin (Figure 6) upon thermal treatment of yellow-orange cactus pear juice being more pronounced at pH 4 as compared to pH 6 was reported for the first time. In another study (Moßhammer et al., 2006c) the pigment stabilizing effect was associated with an improved overall color retention of both betaxanthins and betacyanins by isoascorbic acid addition (0.1%). While the indicaxanthin:isoindicaxanthin ratio changed upon thermal treatment of yellow-orange cactus pear juice (Moßhammer et al., 2006ab), most recent findings (Moßhammer et al., 2006c) demonstrated a good correlation of indicaxanthin:isoindicaxanthin ratios and overall color retentions of heated cactus pear juices. Therefore, this ratio was suggested to be a valuable indicator of thermally treated cactus-pear products, allowing calculation of the initial betaxanthin content at the same time. Furthermore, depending on the particular heating conditions, 2-decarboxy-betainin was observed to occur in small amounts, which could be inhibited by isoascorbic acid dosage (0.1%).

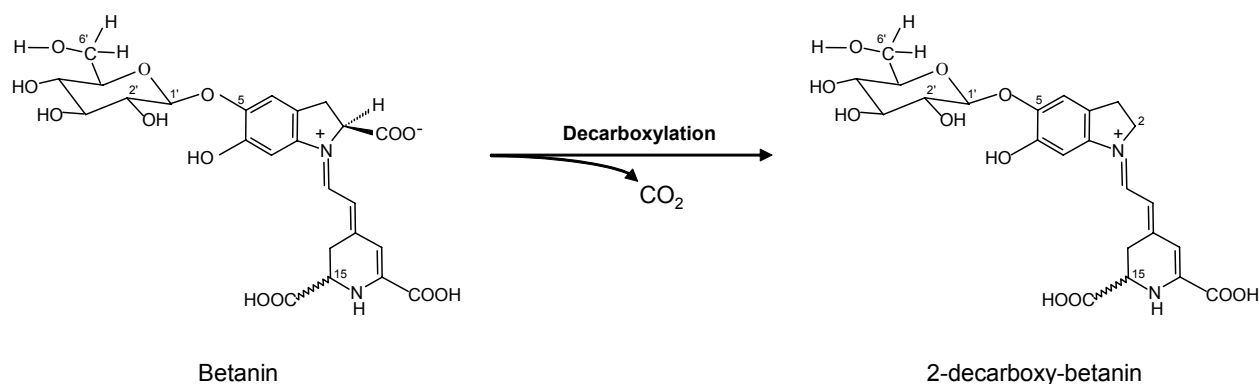


Figure 6. Heat-induced formation of 2-decarboxy-betainin

5.2. Storage stability of cactus pear pigments

According to Sáenz et al. (1993), storage of concentrate from green cactus pear was accompanied by decreasing lightness (L^*), chroma (C^*) and b^* -values, and by an increase of the a^* -values. Additionally, a color shift from greenish to yellow-red caused by chlorophyll degradation was observed upon storage at elevated temperatures.

In a very recent study, chromatic changes of yellow-orange cactus-pear juice stored up to six months with and without isoascorbic acid addition both in darkness and under illumination were monitored (Moßhammer et al., 2006c). All samples investigated exhibited a lightness (L^*) decrease that was ascribed to degradation products of ascorbic acid as earlier reported for other fruit juices (Wong et al., 1992). In addition, decreases of chroma (C^*) and slight changes

of the hue angle (h°) were observed. Analogously to heated cactus pear juices, an improved color stability was achieved by isoascorbic acid addition resulting in prolonged half-life times for both betaxanthins and betacyanins, respectively (Table 4).

Table 4. Storage stability of cactus pear betacyanins and betaxanthins (Moßhammer et al., 2006c).

Additive	Storage	Pigments	Half-life time $T_{1/2}$ [months]
without additive	dark	betaxanthins	1.1
without additive	dark	betacyanins	1.2
0.1% isoasc ¹	dark	betaxanthins	2.6
0.1% isoasc ¹	dark	betacyanins	3.6
without additive	light	betaxanthins	0.7
without additive	light	betacyanins	1.0
0.1% isoasc ¹	light	betaxanthins	0.8
0.1% isoasc ¹	light	betacyanins	1.3

¹ isoasc = isoascorbic acid

6. CONCLUSIONS AND OUTLOOK

While the market potential of plain *Opuntia* juices is considered fair due to their faint flavor and high sugar:acid ratio, their utilization as a functional additive or for food coloring appears to be more promising. Due to the high contents of amino acids, particularly proline and taurine, and minerals such as calcium and magnesium, cactus pear juices are considered a valuable ingredient for sports and energy drinks (Reyner and Horne, 2002; Seidl et al., 2000). Due to the broader range of color shades and the absence of peatiness, nitrate accumulation as well as risk of microbial carry-over (Stintzing et al., 2001), cactus pears present an advantageous alternative to red beet which is the only commercially exploited betalain source, so far. With a high coloring power at near neutral pH where anthocyanin-based preparations fail, cactus pear concentrates may be suitable for coloring yoghurts, ice creams, and fruit preparations. Fruit and cereal bars, chocolates, instant products, and even meat substitutes might be further applications. As recently demonstrated, the production of tailor-made hues ranging from bright yellow to red-purple through blending differently colored cactus juices may be a further promising feature for industrial applications (Moßhammer et al., 2005b). Moreover, cactus-pear juice is considered a valuable source for enhancing color of fruit-juice blends, such as orange-apple juice blends (Moreno-Alvarez et al., 2003). In addition to their use as colorants, the recently reported effects of betalains on human health (Butera et al., 2002; Feugang et al., 2006; Gentile et al., 2004; Tesoriere et al., 2004) may open broader applications. Furthermore, the untapped potential of the hydrocolloid fraction and polyphenolics of both cactus-pear fruit pulp and peels remains to be evaluated both from a nutritional and a technological point of view. Moreover, because of its high glucose and fructose contents, cactus pear is considered a potential raw material for the manufacture of high fructose glucose syrup (HFGS; Hamdi, 1997). Due to consumers' restrictive attitude towards genetically modified food ingredients, HFGS from cactus pear may present a natural alternative to high-fructose corn syrup (HFCS) from corn. Finally, for complete exploitation of the fruit, seeds may be used for oil extraction (Ramadan and Mörsel, 2003a; Stintzing, Schieber and Carle, 2000).

Hitherto, the main limitation of broader commercialization of cactus-pear derivatives is the current market prices and the lack of know-how in cactus pear fruit processing. On the other hand, cactus pears are already available for commercial exploitation and enlarging acreages is feasible on a short-term basis. Selection and breeding programs should, therefore, be encouraged. Due to the continuing downturn of cochineal production, conversion of *Opuntia* plantations for fruit production seems to be attractive. Because *Opuntia* is characterized by a high water-use efficiency, it does not require special climatic conditions. The plant grows on marginal soils with poor texture and low pH levels at the same time exhibiting the highest biomass production rate of all overground plants (see Stintzing and Carle, 2005 and references therein). Therefore, cactus-pear fruits are a promising plant with a big potential for breeders, agriculturists and food technologists alike.

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