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Review

Cactus stems (*Opuntia* spp.): A review on their chemistry, technology, and uses

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Although traditionally used as a valuable health supporting nutrient, the vegetative parts of *Opuntia* spp. plants are scarcely used in modern nutrition and medicine. While all kinds of different *Opuntia* spp. have been studied, a systematic approach regarding the inter-relationships between the composition and the pre- and postharvest conditions is still missing. Therefore, the present review compiles and discusses literature on the chemical composition of cactus stems, the knowledge on uses in food, medicine, and cosmetics. It is concluded that much research is needed to get an insight into the multitude of bioactivities reported in the traditional literature but also to take advantage of the respective constituents for food and pharmaceutical applications.

Keywords: Cactus stem / Cactus vegetable / Nopal / *Opuntia* spp. / Review

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1 Introduction

The cactus *Opuntia* (genus *Opuntia*, subfamily Opuntioideae, family Cactaceae) is a xerophyte producing about 200 – 300 species and is mainly growing in arid (less than 250 mm annual precipitation) and semi-arid (250 – 450 mm annual precipitation) zones. Due to their remarkable genetic variability, *Opuntia* plants show a high ecological adaptivity and can therefore be encountered in places of vir-

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Abbreviations: CAM, crassulacean acid metabolism; **LDL**, low-density lipoprotein

tually all climatic conditions: North, Central, and South America, the Mediterranean, North, Central, and South Africa, the Middle East, Australia, and also in India [1, 2]. Commercial cultivation is carried out in Italy, Spain, Mexico, Brazil, Chile, Argentina, and California [3]. Traditionally and still today, cactus plants serve as sources for fruits and vegetables, for medicinal and cosmetic purposes, as forage, building material, and as a source for natural colors. However, their use is still mainly restricted to the countries of origin [1, 4–8]. In the light of global desertification and declining water resources, *Opuntia* spp. is gaining even more importance as an effective food production system including both the vegetative but also the fruit parts.

Opuntia fruits, also known as cactus pears or prickly pears, are regionally consumed as fresh fruit, juice, sweets, *etc.*, but also exported for the European fresh fruit market [9, 10]. Recent investigations anticipate the use of fruit juice and fruit juice concentrate as functional ingredient for the soft drink market as well as a betalainic coloring foodstuff [11–13]. Since the mid of the 70es, the interest in cactus pads is increasing. In Mexico and South California, but also in Chile, commercial production lines have been installed with corresponding export activities.

The present contribution is covering the chemical and pharmacological properties of the constituents from *Opuntia* cactus pads, but also their current and future use in foods, pharmaceutical, and cosmetic products.

2 Biology

Though not matching with morphological criteria, the term cactus leaves is frequently used in the literature to address the flattened stem segments of the *Opuntia* plant that replace leaves in their photosynthetic function. Thus, cactus stems, cactus pads, cactus vegetable, phylloclades or cladodes are the correct terms, synonymous to nopales or pencas. The stems are composed of a white medullar parenchyma (core tissue) and the chlorophyll containing photosynthetically active parenchyma (cortex tissue). The latter is covered with spines (modified leaves) and multicellular hairs or trichomes, both forming the so-called areole, which is characteristic of members from the Cactaceae family. The subfamily *Opuntioideae* is further characterized by having short, sharp, barbed, deciduous spines, called glochids. The areoles are also the origin of the flowers, *i.e.*, short shoots with specialized leaves [14]. The glochids are composed of 100% crystalline cellulose [15]. The spines are constituted of 96% polysaccharides, which themselves divide up into 49.7% cellulose and 50.3% arabinan, the remainder being ash, fat, and waxes as well as lignin. The cellulose microfibrils of 0.4 mm length and 6–10 μm in diameter are parallely loosely imbedded in an arabinan matrix. The latter is partly present as a solid gel, partly tightly woven with the cellulose [16]. This 50 : 50 polymer was reported to be free of hemicelluloses [17]. The spines are 1–3 cm long and make up 8.4% of the total cladode weight. Their functions include mechanical protection from herbivores, reflection of light, shading of the stem, and thus reducing water loss as well as condensing fog [14].

3 General composition and chemistry of cactus stems

Cladode composition varies depending on the edaphic factors at the cultivation site, the season and the age of the plant [18–20] accounting for the considerable variations in published data. Therefore, the respective nutrient contents vary both among species and varieties and should not be taken as absolute values. The composition of de-barbed cladodes has been investigated by [21]. In 100 g dry matter, 19.6 g ash, 7.2 g lipids and waxes, 3.6 g lignin, 21.6 g cellulose, and 48 g other polysaccharides were found, while crude proteins were not assessed. Other authors [1, 9, 18–20, 22] reported 64–71 g carbohydrates, 18 g fibers, 19–23.5 g ash, 1–4 g lipids, and 4–10 g proteins, the latter consisting of 1–2 g digestive proteins. On a fresh weight basis, these values translate into 3–7 g carbohydrates, 1–2 g minerals, 0.5–1 g proteins, 0.2 g lipids, and 1 g fibrous substances per 100 g plant material [20, 23]. Younger cladodes show higher carbohydrate, protein, and water contents. Interestingly, fertilization low in nitrogen led to an increase in the crude protein content, while for use as feed for lactating cows, nitrogen doses of 224 kg/ha were recommended. Phosphate supplementation of 112 kg/ha improved the low phosphate content of the cladodes [22]. During growth, the fibrous framework decomposed in the core but developed in the cortex. In total, however, proteins and fibers decreased with age. Typically, the juice from nopales exhibited a pH of 4.6 with 0.45% titratable acids and 6.9 g/100 g dry matter [20, 22, 24].

The high calcium and fiber contents are worth mentioning. Based on their composition pattern, cladodes are judged more valuable than lettuce, but less nutritive than spinach

Table 1. Mean chemical composition of despined *Opuntia* sp. cladodes[a)]

	Dry matter basis (g/100 g)	Fresh weight basis (g/100 g)
Water	–	88–95
Carbohydrates	64–71	3–7
Ash	19–23	1–2
Fibers	18	1–2
Protein	4–10	0.5–1
Lipids	1–4	0.2

[a)] According to [1, 9, 18–20, 22, 23]

[19, 22]. The water content of 88 – 95% makes cladodes a low-calorie food with 27 kcal/100 g [25]. The respective compound classes summarized in Table 1 are discussed below. Since, to the best of our knowledge, there is no report on the volatile constituents of cactus pads, only the non-volatile constituents will be considered.

3.1 Low-molecular-weight compounds

3.1.1 Minerals

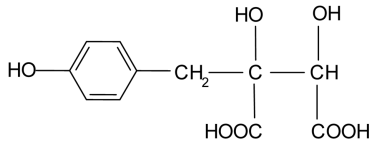
Potassium is the main mineral amounting to about 60% of the total ash content (166 mg/100 g fresh weight), followed by calcium (93 mg/100 g fresh weight), sodium (2 mg/100 g fresh weight), and iron (1.6 mg/100 g fresh weight) while magnesium was not detected [26]. In more recent studies, the mineral composition was reported to be 50, 18 – 57, and 11 – 17 mg/100 g dry weight for potassium, calcium, and magnesium, respectively, followed by manganese (62 – 103 μg/g), iron (59 – 66 μg/g), zinc (22 – 27 μg/g), and copper (8 – 9 μg/g) on a dry weight basis [18, 27]. Again, these values should be considered approximate numbers since the mineral contents vary with species, site of cultivation, and the physiological state of the cladode tissue. As will be discussed later, calcium is playing a crucial role in water retention of succulent tissues.

3.1.2 Sugars

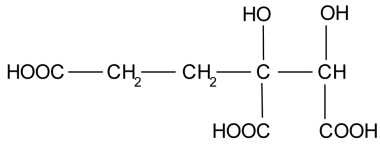
The free sugar content was reported to reach 0.32 g/100 g fresh weight [26]. In another study the reducing sugar fraction was reported to be 0.64 – 0.88 g/100 g dry weight increasing with development but also varying with species [20].

3.1.3 Organic acids

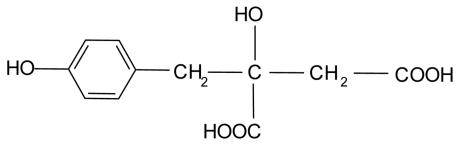
Teles *et al.* [28, 29] have reported malonic acid and citric acid contents of 36 mg and 178 mg/100g fresh weight, respectively (Table 2). In contrast, older cladodes from *Opuntia ficus-indica* did not contain malonic acid any more and were reduced in citric acid (31 mg/100 g fresh weight). Tartaric- and succinic acids were only found in traces [28, 29]. Interestingly, piscidic and phorbic acids (Fig. 1) were qualitatively detected but could not be quantified due to lack of standards. The relative increase in piscidic acid was fourfold with increasing age, whereas the phorbic acid contents was reduced by one half of the initial value [28, 29]. Phorbic and piscidic acids are rarely encountered in nature and restricted to plants exhibiting crassulacean acid metabolism (CAM) metabolism and succulence [30 – 32]. Only very recently, piscidic acid derivatives, such as 2-*E*-feruloyl-piscidic (cimicifugic acid E) and 2-*E*-isoferuloylpiscidic acids (cimicifugic acid F) from the rhizome of *Cimicifuga racemosa* (L.) Nutt. were reported [33].



Piscidic acid



Phorbic acid



Eucomic acid

Figure 1. Chemical structures of rare organic acids in cactus stems.

Table 2. Organic acid composition of *Opuntia* sp. cladodes at two different times of harvest[a)]

	Fresh weight (g/100 g)	
	6 a.m.	6 p.m.
Oxalic acid[b)]	35[c)]	35[c)]
Malic acid	985	95
Citric acid	178	31
Malonic acid	36	tr
Succinic acid	tr	tr
Tartaric acid	tr	tr
Phorbic acid	n.q.	n.q.
Piscidic acid	n.q.	n.q.
Eucomic acid	n.q.	n.q.

[a)] According to [27, 29, 34, 35]
[b)] Total oxalic acid including soluble and insoluble fractions
[c)] Dry weight basis mg/100 g; no date of harvest indicated
n.q. = not quantified
tr = traces

Eucomic acid (Fig. 1) and two new phenolic carbon esters assigned as *n*-butyleucomate and methyleucomate were identified in an ethanolic extract from *O. ficus-indica* [34]. Furthermore, malic acid ranging from 95 to 985 mg/100 g fresh weight constitutes part of the free acid pool [29, 35] being influenced by diurnal changes due to the CAM: the plant fixes carbon dioxide as malic acid and releases oxygen during the night to prevent water losses through transpiration. Malic acid is decarboxylated and the released carbon dioxide is converted into glucose *via* photosynthetic

action during the day when stomata are closed [36–39]. The main acid, however, is oxalic acid which either occurs dissolved (0.61 mg/g dry weight) or in crystalline form (34.5 mg/g dry weight) as whewellite ($Ca_2C_2O_4 \cdot H_2O$) or weddelite ($Ca_2C_2O_4 \cdot 2H_2O$) [21, 27, 40]. Moreover, oxalic acid has interesting inter-relationships with calcium and pectin metabolism [12, 16, 41].

3.1.4 Amino acids and amines

The crude protein content was reported to reach 11 g/100 g on a fresh or 0.5 g/100 g on a dry weight basis, respectively [42]. 77–112 mg/g dry weight depending on the month of harvest were found by others [19]. The same workers determined the amino acid pattern of *Opuntia ficus-indica* pads comprising 18 compounds. Another investigation on the composition of Tunisian *O. ficus-indica* var. *inermis* protein afforded 13.0% glutamic acid, 10.6% asparaginic acid, 8.3% leucine, 7.7% alanine, 7.0% valine, 6.5% proline, 5.9% lysine, 5.5% arginine, 5.2% isoleucine, 5.1% phenylalanine, 4.8% glycine, 4.3% threonine, 4.3% serine, 4.1% tyrosine, 2.3% histidine, 2.1% methionine, and 0.8% cysteine [43]. According to a more recent study considering both L- and D-enantiomers, 18 L-amino acids (Table 3) as well as the D-enantiomers of asparagine, asparaginic acid, glutamine, glutamic acid, and serine were detected [44]. Glutamine was by far the major amino acid followed by valine and serine (Table 3).

In contrast, glycine and arginine were found to be the predominant amino compounds in another investigation [45]. Older cladodes showed higher proline contents than younger stems [46] which goes along with the role of proline as an osmolyte [47–51]. In Italian *O. ficus-indica* cladodes, a similar role was proposed for the polyamines spermine and spermidine accumulating during periods of drought presumably maintaining the cellular anion/cation balance [52]. Putrescine correlated with malate accumulation during the onset of CAM metabolism, supposably serving as a buffer for cellular pH [52]. However, the relevance of putrescine reaching higher levels in irrigated compared to unwatered plants remained to be elucidated [53]. Finally, Egyptian researchers [54] identified the hallucinogenic alkaloid mescaline and the biogenic amines tyramine and *N*-methyltyramine *via* thin-layer chromatography in defatted cladode extracts of *Opuntia ficus-indica* [L.] Mill. *N*-Methyltyramine was also reported to be the main amine in whole plant extracts from *O. clavata* Engelm. [55]. Further, albeit rare findings report the presence of mescaline and 3,4-dimethoxyphenethylamine in trace amounts together with their potential precursors tyramine in *O. clavata* Engelm. [55], tyramine and 3-methoxytyramine in *O. spinosior* [Engelm.] Toumey [56], *O. imbricata* Haw. and *O. whipplei* Engelm. & Bigelov [57] as well as hordenine in *O. aurantiaca* Lindley, *O. clavata* Engelm., *O. maldonadensis* Arech., *O. versicolor* Engelm., and *O. vulgaris* Mill. [55, 57, 58]. Hordenine was also reported to occur in *O. hickenii* at 0.013 mg/kg fresh weight together with choline at 0.063 mg/kg fresh weight [59]. In summary, tyramine and its derivatives *N*-methyltyramine and 3-methoxytyramine turned out to be the most prominent compounds in *Opuntia* spp. [58]. Although these data require verification, it needs to be emphasized that amines and especially alkaloids are typical for globular cacti, mainly encountered in the tribus Cereeae within the subfamily Cactoideae [14, 60–63].

Table 3. Free L-amino acids in *Opuntia ficus-indica* cladodes[a)]

	Fresh weight basis (mg/100 g)
Alanine	0.6
Arginine	2.4
Asparagine	1.5
Asparaginic acid	2.1
Glutamic acid	2.6
Glutamine	17.3
Glycine	0.5
Histidine	2.0
Isoleucine	1.9
Leucine	1.3
Lysine	2.5
Methionine	1.4
Phenylalanine	1.7
Serine	3.2
Threonine	2.0
Tryosine	0.7
Tryptophane	0.5
Valine	3.7

[a)] Modified according to [44]

3.1.5 Lipids and terpenes

An investigation on the sterol fraction of the chlorophyll-containing cortex (chlorenchyma) demonstrated the presence of 5.0% and 4.4% cholesterol, 8.0% and 8.8% 24-ζ-methylcholesterol, as well as 87.0% and 86.7% sitosterol for *O. humifusa* and *O. comonduensis*, respectively [64]. In preliminary experiments, Muñoz de Chávez *et al.* [26] reported the presence of high contents of ω-3-fatty acids in the lipid fraction. Jianquin *et al.* [34] identified methyl-oleate (ω-9) and methyl-linoleate (ω-6) in *O. vulgaris* cladodes. In addition, the triterpenes α-amyrin, 3-β-acetyl-taraxerol, friedeline, and lupenone were found [34, 65].

3.1.6 Vitamins, carotenoids, and chlorophylls

Total vitamin C (ascorbic and dehydroascorbic acid) in 100 g fresh weight amounted up to 22 mg, β-carotene to 11.3–53.5 µg, thiamine to 0.14 mg, riboflavin to 0.6 mg, and niacine to 0.46 mg, respectively [20, 22, 29, 66, 67] (Table 4). A recent investigation on the carotenoid profile

Table 4. Vitamin contents in *Opuntia* sp. cladodes[a)]

	per 100 g fresh weight
Total vitamin C	7–22 mg
Niacine	0.46 mg
Riboflavine	0.60 mg
Thiamine	0.14 mg
β-Carotene	11.3–53.5 µg

[a)] According to [20, 22, 35, 66]

of fresh cactus pear cladodes determined the presence of α-cryptoxanthin (20%), β-carotene (36%), and lutein (44%) amounting to 229 µg/g dry weight altogether with increasing amounts upon thermal treatment [68]. While lutein is typical for green vegetables [69 – 72], no information is yet available on folate in cactus usually accompanying chlorophyll in green vegetable tissues such as in spinach, lettuce or Swiss chard [73, 74]. Total chlorophyll of cladodes was reported to be 12.5 mg/100 g fresh weight, while chlorophyll a with 9.5 mg surmounted the chlorophyll *b* content with 3.0 mg [66].

3.1.7 Phenolic constituents

The total phenolic content in Mexican cactus pads accounted for 8 – 9 mg/100 g fresh weight [75]. Jaramillo-Flores *et al.* [68] differentiated between bound and free phenolics with the latter being in the same range as reported by [75]. In another investigation on a dried and milled total cladode extract, isorhamnetin 3-glucoside, isorhamnetin 3-galactoside, quercetin 3-rhamnoside, myricetin, vitexin, and orientin were detected [76] (Fig. 2). The cladode parenchyma *of O. basilaris* Engelm. & Bigelov, *O. leucotricha* de Candolle, *O. lindheimeri* Engelm., and *O. quimillo* K. Sch., contained quercetin, kaempferol, and isorhamnetin. For the first time, also methyl-3-quercetin was identified [77]. This dominance of flavonol derivatives has already been reported by [78] in a work on *O. robusta* Wendl. and *O. leucotricha*. In the spines and the cladode pericarp, quercetin, kaempferol, isorhamnetin, methyl-3-quercetin, and methyl-3-kaempferol, but also the 3-hydroxyflavanones taxifolin (dihydroquercetin) and aromadendrine (dihydrokaempferol) were found. Flavones and flavanones, however, could not be detected [79] (Fig. 2). Finally, Burret *et al.* [79] maintain that higher phenolic contents were present in the colorless spines compared to the chlorophyll containing tissue. This is plausible considering the complementary protective action of chlorophylls and flavonoids towards UV-radiation [82 – 84].

In most recent studies further structures were identified in an ethanolic extract from *O. dillenii* Haw. cladodes re-extracted with *n*-butanol in decreasing order [83, 84]: opuntioside, isorhamnetin 3-rutinoside, opuntiol, manghaslin (quercetin 3-[2G-rhamnosylrutinosid]), *p*-hydroxybenzoic acid, 1-heptanecanol, ferulic acid, 3,4-dihydroxybenzoic acid, vanillic acid, 3,3′-dimethylquercetin, malic acid, kaempferol-7-*O*-β-glucopyranoside, 3-*O*-methyl-quercetin 7-*O*-β-D-glucopyranoside, rutin (quercetin 3-rutinoside), ethyl 3,4-dihydroxybenzoic acid, 4-ethoxy-6-hydroxymethyl-α-pyrone, and kaempferol 7-*O*-β-D-glucopyranosyl (1→4)-β-D-glucopyranoside. The latter together with opuntioside and 4-ethoxy-6-hydroxymethyl-α-pyrone were reported for the first time, while opuntiol (= 2-hydroxymethyl-4-methoxy-α-pyrone) had been earlier detected in *Opuntia elatior* and *O. polyacantha* [85, 86] (Fig. 3).

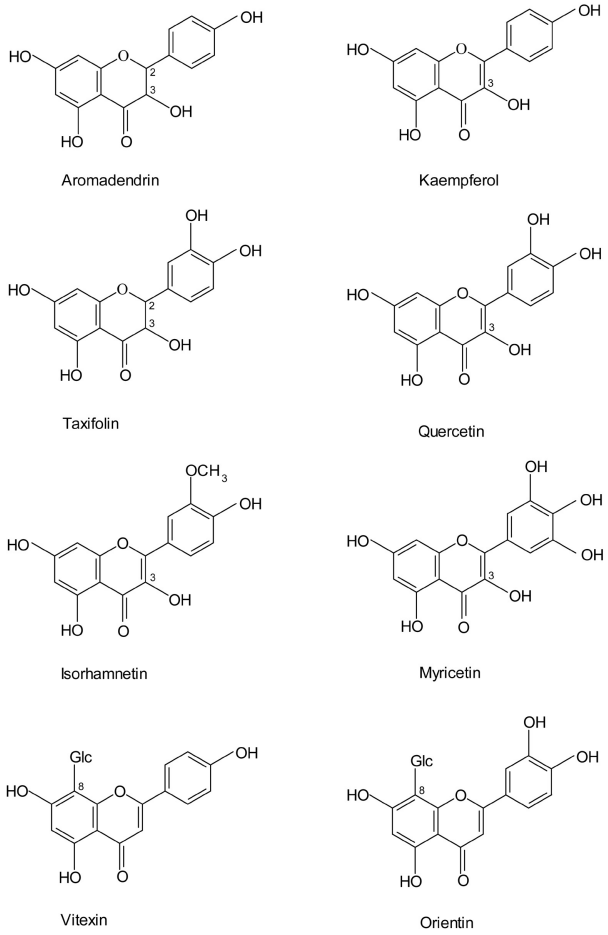


Figure 2. Chemical structures of some typical flavonoid aglycones from *Opuntia* cladodes.

3.2 High-molecular-weight compounds

Ben Thlija [87] report mean values in dry matter of five *Opuntia* sp. cladodes amounting to 11% cellulose, 8% hemicellulose, and 3.9% lignin, respectively, while 21.6%

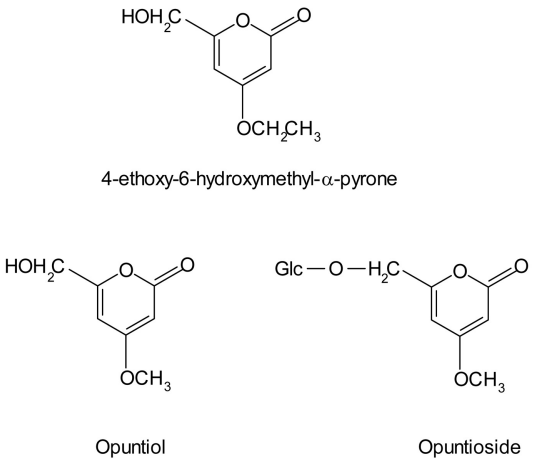


Figure 3. Structures of pyrone-derivatives from *Opuntia* stems (Glc = glucose).

cellulose and 3.6% lignin were found by [21] who did not differentiate between cellulose and hemicellulose. The starch content also addressed as glucan [24] from *O. ficus-indica* cladodes fluctuated with seasons and reached mean values of 85 – 171 mg/g dry weight [19]. The hydrocolloids comprised up to 36% of the cladode volume and due to their high swelling capacity, water storage reached 50% of their total weight. Sutton *et al.* [24] maintain that glucans act as carbon source for malic acid involved in CAM while mucilage was mainly involved in carbohydrate metabolism in *Opuntia bigelovii* Engelm. For 100 g fresh weight of *O. tomentosa* and *O. robusta* the hydrolysate from the carbohydrate fraction yielded 10.41 g total sugars, being subdivided into 8.49 g polysaccharides, 1.6 g disaccharides, and 0.32 g monosaccharides, respectively [26]. The total hexose concentration of 3.78 g divided up into 1.97 g polysaccharides, 1.55 g disaccharides, and 0.26 g monosaccharides. In addition, 5.12 g pentosans and only 0.1 g pentose monosaccharides were found in 100 g fresh material. Finally, another carbohydrate fraction (1.70 g) was isolated showing uronic acid units. Thus, it was concluded that mainly hexoses and pentoses are the building blocks of the cactus pad hydrocolloid.

According to Nobel *et al.* [88], the average sugar composition of the mucilage from *O. ficus indica* cladodes added up to 42% arabinose, 22% xylose, 21% galactose, 8% galacturonic acid, and 7% rhamnose, respectively. Precipitation was achieved by cation addition of calcium, lead, barium, silver, copper, iron, cobalt, or nickel [89], pointing to an anionic polyelectrolyte.

Majdoub *et al.* [90] investigated the polysaccharide fraction of the chlorophyll-containing stem parenchyma and also of the peeled cladode. Based on an identical yield of 85 mg/100 g fresh weight the chlorenchyma was composed of 53.7% rhamnose, and 46.3% galacturonic acid while the pulp showed one-fifth of the uronic acid concentrations (10.2%), lower rhamnose (46%), 15% arabinose, 9.1% xylose, 11.0% galactose, 4.1% mannose, 1.9% glucose, and 12.7% of a noncharacterized fraction. At pH 6.3, the polysaccharide fraction of the chlorenchyma exhibited a methoxylation degree of 88% and a molecular weight of 3.53×10^5 g/mol while the core tissue afforded 8.8% and 6.12×10^6 g/mol, respectively.

It is worth mentioning that a remarkable viscosity rise was monitored between pH 4 and 6, being lower for the chlorenchyma. At pH 2 – 4, a slight increase was detected while between pH 6 and 10, virtually no viscosity changes were monitored. When the pK_a value of 3.2 – 3.5 was reached, the molecule changed from a globular to a linear state. At an ionic strength of 0.025 M, the viscosity of the pulp extract doubled when compared to the pectin from the pericarp tissue [90, 91].

In addition to the distinct differences between pectic substances from core and cortex tissues, a further differentiation for the hydrocolloids from the core parenchyma was deemed necessary [92]. Most often disrespected in the literature, the authors distinguished mucilages and pectins. To prove the chemical differences of these two macromolecular fractions, an extraction protocol was proposed for separate workup. While the mucilages did not form a gel upon calcium addition, the pectins were sensitive to divalent cations. Additionally, the former exhibited emulsifying properties. By means of ultrafiltration, Majdoub *et al.* [91] were able to separate a high-molecular-weight (10%) and a low-molecular-weight fraction (90%) from an extract of peeled cactus pads. The latter consisted of 80% protein which was poorly water-soluble and similar to the 2S-albumin from *O. ficus-indica* seeds characterized earlier [93]. Although the high molecular fraction showed a slight sensitivity to calcium in solution, no viscosity increase was observed upon calcium addition because only weak intramolecular bonding was induced. Only when the mucilage concentration was increased to 10 g/100 g water, intermolecular bridging resulted in a gel-like network [91]. Since an unpurified extract performed visco-elastic properties, it was concluded that the protein fraction interacted with polysaccharides by intermolecular bonding.

In 1980 already, Karawya *et al.* [94] established a differentiation between mucilage and pectin, based on their specific neutral sugar and uronic acid contents. Interestingly, these authors found structural similarities with the polysaccharide fraction from swollen quince seeds, which is applied in cosmetic and pharmaceutical products [95, 96]. With respect to rheological characteristics, the *Opuntia* hydrocolloid behaved similarly to ocra (*Abelmoschus esculentus* [L.] Moench.) mucilages [97].

4 *Nopalea cochenillifera* (L.) Salm-Dyck

Only three studies were dedicated to the constituents of *Nopalea cochenillifera* (L.) Salm-Dyck., formerly known as *Opuntia cochenillifera* (L.) Mill. [98 – 100]. Malic and citric acids were found to be the major constituents while oxalic acid was only present in trace amounts [99]. Furthermore, fructose, glucose, sucrose, and maltose as well as traces of raffinose were detected [99, 100]. As expected for CAM plants, the sugar contents (calculated as glucose) depended on diurnal changes and ranged between 63.0 and 90.0 mg/100 g fresh weight [99]. The mean chemical composition was similar to other *Opuntia* spp. [20] (Table 1) and reported to be 91.8 g/100 g water, 18.2 g/100 g ash, 15.9 g/100 g mucilages, 10.1 g/100 g sucrose, 7.1 g/100 g proteins, 4.4 g/100 g fructose, and 2.5 g/100 g glucose on a fresh weight basis, respectively [100]. The amino acids in an alcoholic extract from fresh phylloclades comprised leucine, phenylalanine, valine, methionine, proline, alanine, glutamic acid, threonine, glycine, serine, lysine, cysteine, and γ-aminobutyric acid, respectively [98].

5 Production and uses of cactus stems

5.1 Production

Nowadays, *Opuntia* plants are grown in more than 30 countries on about 100 000 ha [3, 37] among others Mexiko, the Mediterranean (Egypt, Italy, Greece, Spain, Turkey), California, South America (Argentina, Brazil, Chile, Columbia, Peru), the Middle East (Israel, Jordan), North Africa (Algeria, Marocco, Tunisia), South Africa, and India [3, 101, 102]. For cladodes, a mean hectare yield of 30 – 80 t can be achieved annually [9, 22]. Mexico is the only country planting cladodes for commercial use on 10 000 ha with a total production of 600 000 tons per annum [67]. On the other hand, *Nopalea cochenillifera* is primarily cultivated in South California and Texas [9]. Their cladodes are softer, devoid of spines, containing less mucilages and being greener than those of *Opuntia* spp.

As a CAM plant, *Opuntia* spp. are characterized by a high water use efficiency of 4 – 10 mmol CO_2 per mol H_2O compared to C_3- and C_4-plants with 1.0 – 1.5 mmol and 2 – 3 mmol CO_2 per mol H_2O, respectively. Through succulence, the ability to store considerable quantities of water, the plant may survive despite harsh environmental conditions [103]. Furthermore, *Opuntia* exhibits the highest production rate of overground-growing plants [88, 104]. Interestingly, the biomass production was even found to increase upon otherwise deleterious rise of atmospheric CO_2 concentrations [105 – 107], thus counteracting the greenhouse effect.

According to Flores-Valdez [108], high season is from April to August when cladodes attain a market price of 0.1 USD per kg while during off-season from November till February the price may increase tenfold. Cactus vegetable is harvested when reaching a weight of 90 – 100 g and a length of 15 – 20 cm [5, 109]. In contrast, the quality of cladodes derived from *Nopalea cochenillifera* (clone 1308) was optimal when reaching 40 g and 11 – 13 cm length [100]. Qualitatively, high-value cactus stems are thin, with a strong green color as well as a high turgescence and freshness. They usually derive from *O. robusta*, *O. streptacantha*, *O. leucotricha*, *O. hyptiacantha*, and *O. chavena*. Plantations exist in Mexico for *O. rastera*, *O. robusta*, *O. engelmannii*, *O. megacantha*, and *O. phaecantha*, *while O. ficus-indica* var. *inermis* and *O. lindheimeri* are usually encountered in Texas [9].

Since very recently, *O. atropes* Rose is getting popular in Mexico due to its pleasant smell and texture [8]. *O. leucotricha* ("duraznillo") and *O. robusta* ("tapon") yield high-quality cladodes, since the pericarp can be easily removed, will neither fall apart during boiling nor release mucilages [8, 22]. Because of the high water content and low pH, the cladodes are prone to rapid microbiological decay limiting fresh marketing. Hence, postharvest technologies are required for upholding its quality [5, 22, 75].

5.2 Postharvest technology

If cladodes are harvested before reaching a length of 10 cm, the tissue is still CAM-inactive and virtually devoid of spines. Bigger cactus stems need to be harvested according to the respective acidity required ranging from 0.94% in the morning to 0.47% in the afternoon [5, 110]. According to a very recent study on CAM active cladodes, the acid content was not only dependent on the time of harvest during the day but also on the respective *Opuntia* spp. variant (0.28 – 0.76%), and the postharvest conditions applied [111]. With age, the acid content rose till the harvest date, but was levelled through storage at elevated temperatures [20]. In contrast, cool storage maintained the acidity or even amplified it. The sugar content and pH were decreased while protein increased [22]. Cactus stems (*Opuntia* sp.) may be stored at 20°C for one week. After the 6th day, a weight loss of 10% was registered [109] also being obvious by turgor loss. However, after 7 days of storage at 20°C, ascorbic acid contents dropped by 20 – 40% [67]. It has been shown that cladodes need to be carefully harvested to minimize mechanical injuries on the tissue and thus reduce losses through respiration and infection by *Penicillium* sp., *Aspergillus* sp., and *Alternaria* sp., respectively [22, 66, 112].

When cladodes were stored in open boxes at 5°C and 85 – 90% rel. humidity or 10°C and 80 – 90% rel. humidity, tissue injuries were manifest after 15 d or 21 d, respectively. Storage periods of 4 weeks at 5°C or 2 weeks at 10°C were

achieved when polypropylene foil (25 μm) was used [67, 75]. Chilling injury symptoms, *i. e.*, physiological disorders induced by low temperatures, were registered after three weeks at 5°C. The weight loss could be reduced from 28 to 2% when cladodes were stored at 5°C during 30 days in modified atmosphere at partial pressures of up to 8.6 kPa O_2 and up to 6.9 kPa CO_2, respectively [66]. Moreover, rapid enzymatic browning and mucilage drip at the cutted ends were thus minimized. Identical effects were achieved by dipping the cladodes into chlorinated water (100 ppm, 4°C, 15 min) or ascorbic acid solution (100 ppm). Other authors proposed a blanching step (85°C/15 s or 80°C/120 s) and subsequent treatment with bisulfite, citric or ascorbic acid solutions [75, 109]. Additionally, modified atmosphere ($\leq$8.6 kPa O_2, $\leq$6.9 kPa CO_2) reduced microbial growth (moulds, yeasts) considerably, albeit not totally suppressed it. Compared to unpacked samples, only the mesophilic counts were increased all of them being devoid of pathogenic species [66, 112]. A passive (8 kPa O_2, 7 kPa CO_2) or semi-active modified atmosphere with 20 kPa CO_2 afforded the best results [112]. The textural properties generally suffering from storage, could be conserved by modified atmosphere which was ascribed to decreased cellulase, hemicellulase, and pectinase activities. In addition, the green color was kept through reduction of chlorophyllase action [66, 112].

Being more susceptible to cold storage, *Nopalea cochenillifera* cladodes only lost 7% weight during 12 days at 20°C [100]. Packaging in polyvinylchloride (10 μm) was advantageous up to three weeks when the temperature was kept between 12–20°C. Polyethylene (30 μm) was less appropriate. Alternatively, after 7 days at 20°C or 14 days at 12°C, an acceptable acid content was obtained, when the cladodes were treated with dim light prior to marketing because malic acid catabolism was thus induced. High relative humidities of 85–89% proved to be disadvantageous [100].

5.3 Vegetable

The young cladodes deriving from the *Platyopuntia* species *O. ficus-indica* Mill., *O. streptacantha* Lem., *O. amyclaea* Ten., *O. robusta* Wendl., *O. ficus indica* var. *inermis* De candolle, and *Nopalea cochenillifera* (L.) Salm-Dyck are called nopalitos [9]. Because of diurnal acidity changes, the cladodes should be harvested after 2 h of sunshine to be best for use as vegetable [9, 26]. Then, the chlorenchyma together with spines and glochids are removed. The peeled cladodes are sliced or cut into small cubes blanched or cooked and further processed into sour vegetables or nopalito sauce. Further products derived from cladodes are jam, chutney or pickles, candied nopales, *etc.* [10, 113]. While cladodes have been traditionally used as a meat substitute during fasting periods, they are nowadays served with meals similar to green beans [114]. Based on the determination of ten amino acids a biological valence of 72.6% compared to total egg protein was found [28, 42]. Lysine, methionine, and tryptophane concentrations were higher than in most cereals [26].

5.4 Further uses as food, pharmaceutical, and cosmetic products

Further studies were dedicated to the technological use of cladodes. According to Medina-Torres *et al.* [115] a cactus polysaccharide solution of 10 g/100 g water and a xanthan solution of 2 g/100 g water showed comparable rheological behavior. The viscosity of the former could be increased by either increasing the pH or lowering the ionic strength. A 5% solution at 35°C exhibited stronger tendencies to gel formation which was ascribed to a conformational change of the polysaccharide. Irrespective of hydrocolloid concentration, no temperature dependency was found [115]. In a subsequent study, interactions with ι- and κ-carrageenan solutions (2 g/100 g) were monitored [116]. While upon addition of ι-carrageenan a decrease in viscosity was registered, the gel strength was slightly improved when 60/40 or 80/20 w/w blends from the cactus hydrocolloid and κ-carrageenan were tested.

As a powder, partly sold in capsules, cladodes are used to regulate weight, blood sugar, or proliferate the general fibre intake. After hydration, the resulting gel exerts a cooling effect, will ease the skin and thus contribute to accelerated wound healing similar to *Aloe vera* preparations. Mulas [117] and Saénz [113] report cladode flour to be composed of 52–53% carbohydrates, 20–22% ash, 15–16% proteins, 9.75% water, 9.5% fibers, and 0.25% lipids, respectively. It was claimed that the insoluble fibres bind toxins, while the soluble fraction increased stool bulking through which the peristaltics were improved and the passage time through the colon reduced; hence the use as a substitute for *Psyllii semen* (*Plantago psyllium* L.). Although the amount applied in cosmetics is less important, the range of potential products is large. Juice from cladodes may be found in shampooing, conditioners, lotions, soaps, and sun protectors [10, 113] and was also claimed to improve hair growth [118]. Cladode powder was also proposed as ingredient of drinks based on milk, whey, and water with up to 10% nopalito [10, 113]. Furthermore, the farinaceous nopalito may be applied up to 20% as a thickening agent in vegetable soups, dessert gels, an ingredient for breakfast cereals and also as a wheat flour substitute. For the latter, the freeness is crucial for determination of the water binding behavior. Finally, the cactus hydrocolloids are used as fat replacers and adsorbers for unpleasant smells [10, 113, 114, 119].

Companies processing cladodes into various foods are exclusively found in Mexico. Consequently, the greatest

product variety is found in Mexico and the USA. The small percentage of exported products mainly constitute of vegetable preserves [10, 113].

5.5 Cochineal production

Cochineal is produced by drying and milling adult female *Dactylopius coccus* Costa, parasitic insects that host on cactus pear pads. To obtain 1 kg of cochineal, 140 000 insects are required that may contain up to 50% pigment of their total weight. The hectar yield usually adds up to 100 – 200 kg. Cochineal is a pigment blend mainly consisting of carminic acid (hydroxyanthraquinone derivative), but also kermesic and flavokermesic acids (Fig. 4). In addition, four compounds hitherto unidentified contribute considerably to cochineal color [120 – 122]. The predominant component carminic acid (E 120; C.I. natural red 3) is used for all kinds of food with pH values usually above pH 3.5. Aluminum-calcium salts of 50 – 65% carminic acid on aluminium hydroxide are applied for cosmetic and textiles. Further information on processing, chemistry, use, cochineal cultivation and qualities can be taken from reviews by [10, 122 – 125].

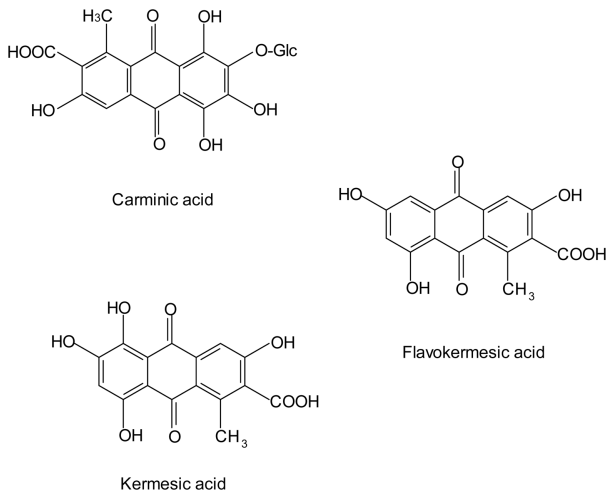


Figure 4. Chemical structures of the typical constituents of cochineal (Glc = glucose).

In 1988, the worldwide cochineal production was 400 t [126], 300 t in 1997, 90% of which was from Peru, then the Canary Islands, and finally Mexico [9, 101]. Since 1990, Argentina, Bolivia, Chile, and South Africa have been enhancing their presence on the international cochineal market [10] and today Peru, the Canary Islands, and Chile are the main producers, followed by Mexico, Bolivia, South Africa, and Argentina [121]. During the 90es, market prizes of 60 – 100 USD rendered cochineal business profitable [26, 101]. Recently, cochineal is increasingly replaced by cheaper synthetic alternatives or by other natural pigments of plant origin [9] possibly amplified by the increasing demand for kosher and halal foods [127] but also the spreading allergy issue [128]. Moreover, the market prize is highly fluctuating, depending on seasonal demands, origin and quality. As a result, cochineal production is suffering a serious decline and producers are therefore looking for alternative uses for their plantations. Besides fruit production [12] cactus stem processing represents an economically viable alternative.

5.6 Use as forage

Especially in periods of severe drought, the cladodes serve as supplementary fodder for cows, sheep, and goats in Brazil, Chile, California, Marocco, Mexico, South Africa, Texas, and Tunisia. They cover a considerable amount of the animals' water requirements, although mineral and protein supplements are recommended [101, 129]. Tunisia dedicates 500 000 ha to the cultivation of cactus as cattle feed, succeeded by Brazil and Mexico [130]. Wild *Opuntia* plants primarily used as cattle feed are *O. cantabrigensis*, *O. lindheimeri*, *O. leucotricha*, *O. streptacantha*, *O. rastera*, *O. microdasys*, *O. pilifera*, *O. maxima*, and *O. robusta*. Before feeding, the cladodes need to be burnt with propane to remove the spines [131]. Because of its laxative effect ascribed to the high oxalic acid content, a combination with straw is recommended. On the other hand, low phenolic and tannin contents of cactus stems facilitate digestion and improve meat production [130, 132]. Finally, taste and color improvement of milk was stated after feeding cactus pads [131]. An update on the use of cactus as forage can be taken from [133].

5.7 Fuel production

In the search for alternative combustibles, cladodes were subjected to fermentation. Reasonable yields were only achieved after acid (1 N HCl, 100°C, 30 min) and enzymatic hydrolyses (cellulase, 47°C, 4 h, pH 4.5) of cladodes releasing di- and monosaccharides for subsequent fermentation by *Saccharomyces* sp. [23]. The resulting yields were 9 L from 100 kg cladodes and therefore not competitive with fermented fruits. Whereas a conversion rate of 5 – 10 mL/100 mL fermentation broth was calculated to be economically feasible, only 1.77 was attained for the cladodes being far below the limit. On the basis of a plant density of 635 – 5000 per hectare, a mean of 300 L and 3000 L ethanol could be produced on nonirrigated and irrigated lands, respectively [23].

5.8 Further uses in the nonfood sector

Cladode spines were patented as gramophone needles in 1928 [134]. When cladode extract was added to fuel the

combustion process could be improved [135]. The cladode mucilage was also proposed as a protecting agent against corrosion [136, 137]. In the countries of origin, the cladodes are added to building material to improve stability and compressibility [138]. Further uses such as clarification of waste water with cactus hydrocolloids are compiled elsewhere [5, 7, 8, 14, 26, 139].

6 Pharmacological profile

Traditionally, cactus pads contribute considerably to the human diet in Mexico and still serve as therapeutic agents. In folk medicine, especially *O. fuliginosa* and *O. streptacantha* have been used for the treatment of gastritis, fatigue, dyspnoe, and liver injury following alcohol abuse [140–142]. Traditionally, heated poltices were applied to treat rheumatic disorders, erythemas and chronic skin infections, but also to improve digestion and enhance the general "detoxification processes" [26]. Recently, positive effects of cladodes on hyperglycemy, acidosis, and artheriosclerosis were reported [118, 143]. Finally, a review on folk veterinary medicine compiles *Opuntia ficus-indica* as a plant species for ethnoveterinary use in Italy [144].

6.1 Antioxidant capacity

The total phenols in an ethanolic cladode extract from lyophilized South Korean *O. ficus-indica* var. *saboten* were held responsible for the radical scavenging activity towards superoxide and hydroxyl anions. In addition, a cell growth-regulating activity was noted [145]. When the antioxidant activity of cladode extracts were monitored, conclusive results were not obtained. The DPPH-assay proved that the 4′-hydroxy-substituted flavonoids, such as kaempferol, exhibited lower potency than their corresponding 3′,4′-dihydroxy-derivatives (quercetin) (Fig. 5). Moreover, hydroxyl substitution at positions 3′ and 7 proved to be essential for antioxidant activity. In the superoxide anion assay, the 4′-hydroxy compounds were superior being additionally increased by 3-methoxyl-substitution [83]. In a parallel investigation, the presence of quercetin, (+)-dihydroquercetin and quercetin-3-methyl ether in fruits and cladodes from *Opuntia ficus-indica* var. *saboten* was reported which proved to be efficient radical scavengers towards the neuronal cell damage caused by H_2O_2 and xanthin/xanthinoxidase [146]. In the latter case, the methanolic cladode fraction was re-extracted with ethyl acetate, dichloromethane, or *n*-butanol. Only the ethyl acetate fraction showed a higher activity than the methanol fraction. Again, quercetin 3-methylether was more effective than quercetin or (+)-dihydroquercetin underlining the importance of the double bond at position 2 and 3 and methylation at 3 (Fig. 5). A medical application of

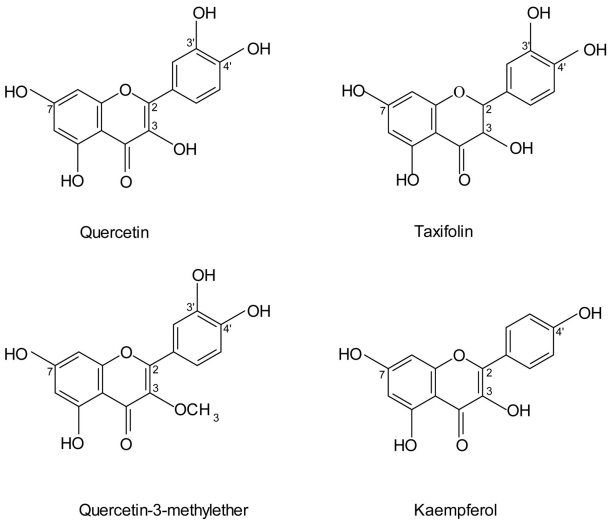


Figure 5. Chemical structures of the most bioactive phenolics from cactus stem tissue.

these compounds has been patented recently [147]. According to [68] the processing temperature also affected the antioxidant potency of cladodes which was mainly ascribed to an increased extraction of the carotenoids α-cryptoxanthin, β-carotene, and lutein, respectively, while the phenolic contents was decreased.

6.2 Anti-inflammatory and analgesic effects

6.2.1 Analgesic action

An ethanolic extract of the cladodes (300–600 mg/kg body weight) from *O. ficus-indica* var. *saboten* showed a similar analgesic effect as acetylsalicylic acid (200 mg/kg body weight) [148] without toxic effects in mice (LD_{50} > 2 g/kg body weight) even at high dosages.

6.2.2 Anti-inflammatory properties

Reduction of acute inflammation by ethanolic *O. ficus indica* stem extracts was ascribed to a lower leucocyte migration. In contrast to nonsteroidal inflammation inhibitors, no adverse effects were noted. Therefore, cladode extracts were proposed for inflammation treatment [148]. In further experiments with a methanolic extract from *O. ficus-indica* cladodes, the fractions obtained after re-extraction with hexane and ethyl acetate were most efficient to accelerate the healing process [65]. A follow-up study identified β-sitosterol to be the active principle [149]. Galati *et al.* [150] tested a wound-healing topical preparation containing 15% cladode extract. A fast regeneration of the tissue was ascribed to inflammation inhibition, stimulation of the fibroblast migration with accelerated collagen formation and faster angio-

genesis. Again, a low-molecular-weight compound was held responsible for the observed effect.

6.2.3 Antiulcerogenic effect

Furthermore, Lee *et al.* [151, 152] postulated an antiulcerogenic effect of the cladode or fruit powder from *O. ficus-indica* var. *saboten* Makino. Stomach lesions triggered by hydrochloric acid/ethanol or hydrochloric acid/acetylsalicylic acid were reduced, but no anti-inflammatory effect could be proven. The secretion rate of both gastric juice as well as the pH value remained constant. Galati *et al.* [153, 154] confirmed these results. However, the protective effect was ascribed to the cladodes' hydrocolloid acting as a buffer, spreading out on the gastric mucosa and increasing mucus production by enhancing the number of secretory cells.

6.3 Hypoglycemic and antidiabetic effect

Human studies in the 80es demonstrated glucose and insulin levels in healthy fasting subjects were stable when eating cladodes. The positive contribution to overall health in diabetes mellitus type II (non-insulin-dependent diabetes) patients was assumed to be due to a reduced postprandial sugar absorption. Following a glucose challenge test, the increase in insulin and glucose were retarded. Also, the glucose and insulin plasma levels were reduced. After 10 days of cladode ingestion prior to meals, a signifiant reduction of the serum glucose level was noticed [26, 155]. Since these effects did not depend on glucagon, cortisone, and human growth hormone levels, which are closely interrelated with glucose metabolism, a gastric enterohormone was held responsible for the hypoglycemic effect [26]. In an earlier report, the unidentified anti-diabetic factor was assumed to be of steroidal nature, presumably a saponin [4].

The efficiency of cladode preparations was underlined by [156] who investigated the hypoglycemic potential of *O. ficus-indica* cladodes on non-insulin-dependent diabetics. Both fried and and raw despined cladodes showed a therapeutic effect that could not be ascribed to the functional properties of the hydrocolloids. Moreover, the potency of the extract did not depend on temperature but on the comminution degree, whereby a finer grading was favorable [156]. Although the responsible principle could not be elucidated by [156 – 158], the hypoglycemic effect stayed away when the pancreatic tissue was removed from the animals prior to *O. streptacantha* ingestion [158]. The application of an ethanol extract from ground *O. megacantha* cladodes (20 mg/100g body weight over the period of 5 weeks) resulted in a weight decrease in diabetic animals, that could not be observed in healthy individuals. In both groups, the plasma glucose levels were decreased by about 20% [159]. However, the mechanism of these pharmacological effects could not be clarified.

It is worth to be noted that cladodes from *O. streptacantha* exerted hypoglycemic activity irrespective of the harvest time [160]. However, interspecific variations of the plant material and different application modes (oral, intravenous) have to be considered [161, 162]. In feeding trials with pigs, diabetic individuals exhibited reduced blood glucose levels 1 h after ingestion of an extract from *O. lindheimeri* Engelm. When 250 mg extract per kg body weight were applied, a 24% glucose decline was registered while at a 500 mg dose, even a reduction by 42% was noted [163]. Since diabetic pigs develop the same secondary injuries as humans such as microvascular eye and kidney damage as well as proliferating nonresponsiveness to insulin, this model should be preferred to tests on dogs, rabbits, rats, or mice. While neither the active component nor the underlying mechanism could be elucidated, it was suspected that a protein-like compound similar to insulin was responsible for the effects observed [163]. Based on a two-month study with regular consumption of *O. fuliginosa* Griffiths extract, a daily intake of 1 mg per kg body weight was recommended [164]. A decoct from dried *O. streptacantha* Lem. phylloclades showed an anti-hyperglycemic effect that was proposed as alternative to oral antidiabetics [165], thereby preventing insulin resistance. The hypoglycemic effect of *Opuntia* fruits that was also observed after cladode ingestion seemed to be related to improved sensibility of the pancreatic cells with a concomitant improved glucose usage [166]. These effects deserve special attention since the populations of developed countries are increasingly suffering from obesity and diabetes symptoms urgently requiring effective countermeasures [167 – 171].

6.4 Anti-hyperlipidemic and cholesterol-lowering effect

6.4.1 Anti-hyperlipidemic properties

The anti-hyperlipidemic effect after cladode ingestion was investigated only in recent studies [166, 172 – 177]. In general, a prolonged period of satiety was registered after cladode consumption. In a series of studies with Guinea pigs, Fernández *et al.* [173 – 175] demonstrated that the reduction of blood lipids triggered by isolated pectin from *Opuntia* was due to the enhanced binding of bile acid. It was concluded that through reduced bile absorption in the colon the enterohepatic circle was disrupted [173, 174]. In a follow-up study, the same authors presented evidence that the low-density lipoprotein (LDL)-catabolism was considered to be more important than the modulation and *de novo* synthesis in the liver [175]. The same pectic-like substances were held responsible for a decreased lipid absorption, lower blood lipid levels, and finally weight reduction [141].

6.4.2 Cholesterol-lowering properties

In a recent study it was shown that a daily consumption of 250 g of prickly pear pulp reduced the risk of thrombosis in

patients suffering from hyperlipidemia and diabetes [177]. The authors did not disclose whether the observed effects were due to fruit or cladode ingestion. In addition, the botanical origin of the plant material was not provided, however, *O. robusta* had been used by this group in earlier studies [166, 172, 176]. Wolfram *et al.* [166] reported a reduction of total cholesterol, LDL, apolipoprotein levels, triglycerides, fibrinogen, blood glucose, insulin and urate, while body weight, high-density lipoprotein (HDL)-cholesterol, apolipoprotein A-1 and lipoprotein A levels were found to remain unchanged. The anti-hyperlipidemic effects were ascribed to the pulp pectin, which both reduced lipid absorption and increased fecal sterol excretion, thus disrupting the enterohepatic circle. Since the level of 3-hydroxy-3-methyl-glutaryl-coenzyme A, the key enzyme of cholesterol biosynthesis, did not exhibit any activity changes, the reduced LDL levels and modified LDL composition were ascribed to an enhanced hepatic apo-B/E-receptor [176]. These results were proven by the same authors when an enhanced activity of the apo-B/E-receptor in the human liver was found, resulting in an enhanced LDL degradation [176]. The exact mechanisms, however, still need to be elucidated.

6.5 Anti-atherogenic effect

Decreasing isoprostane levels in urine, serum and plasma as an indicator for oxidative stress and generally improved blood parameters levels were held responsible for the anti-atherogenic effect of broiled *O. robusta* pulp [172]. Unfortunately, it was not clearly indicated whether the pulp was derived from the fruit or rather the cladode.

6.6 Diuretic effect and impact on uric acid metabolism

An ethanolic extract from *O. megacantha* was reported to decrease blood glucose but also affect kidney function in rats [178]. While sodium excretion was enhanced, potassium levels in urine decreased. In contrast, sodium, calcium, and magnesium levels in the plasma dropped, but phosphate, creatinine, and urea concentrations increased [178]. Both observations were related to the hormonal regulatory mechanisms of the kidney [159, 178]. In rats, uric acid excretion was enhanced and lower uric acid levels were detected in the serum after administration of an *O. megacantha* extract. Whether the latter effects can be ascribed to increased renal excretion or rather to an inhibition of uric acid synthesizing enzymes, such as xanthine oxidase, is still open. Anyhow, its potential for gout treatment was claimed to be promising [179]. In this context, oxalic acid needs to be taken into consideration since calcium availability was found to be decreased due to sequestration by oxalic acid and high oxalic acid contents resulted in an enhanced urinary calcium oxalate excretion [27].

After *Opuntia* extract ingestion, the water intake rose and the urine volume was increased [179]. Galati *et al.* [180] investigated the diuretic effect of a 15% extract from flowers, fruits, and peeled cladodes from *O. ficus-indica*, respectively. The latter showed the highest diuretic effect while urea levels in blood and urine remained unchanged. The diuretic effect was chiefly ascribed to the high potassium content of *Opuntia* cladodes amounting to 548 mg/kg. Nephrotoxic effects of the *Opuntia* extract could not unambiguously be clarified [178].

6.7 Further pharmacological effects

6.7.1 Antispermatogenic properties

A methanolic extract from *O. dillenii* Haw. defatted with chloroform and petroleum ether exerted antispermatogenic effects in animal tests on rats. According to [76], the flavone derivatives vitexin and myricetin (Fig. 2) were found to be the active principles. When 250 mg extract per kg body weight was applied, the weight of testis, epididymis, seminal vesicle, and ventral prostate were reasonably, that of Sertoli cells, Leydig cells, and gametes considerably reduced. The motility of the sperms was also diminished [76]. Unfortunately, data about the solvent used for extraction are missing.

6.7.2 Antiviral properties

A cladode extract from *O. streptacantha* Lem. was reported to exhibit antiviral properties towards DNA viruses, such as herpes, and RNA viruses, such as influenza type A and human immunodeficiency virus (HIV)-1. The active principle was located in the outer noncuticular tissue and ascribed to a protein with unknown mechanisms of action [181]. Both the replication of DNA and RNA viruses was inhibited while the extract from the parenchyma acted both preventively and post-infectionary. In security tests on mice, horses (27 g/day over the period of 2 – 4 weeks) and finally humans (6 g/day for 1 month or 3 g/d over 6 months), all dosages were well tolerated [181].

6.7.3 Monoamino-oxidase inhibition

Besides catecholmethyltransferases, the monoamino-oxidases (MAOs) are usually involved in the catabolism of catecholamines, thus regulating the overall amine pool [182]. In cladodes and fruits from the Korean *O. ficus-indica* var. *saboten* Makino, methyl esters derived from organic acids were identified as MAO inhibitors [183]. The aqueous extracts showed least inhibitory activity, followed by the *n*-butanol fraction and the hexane extract whereas the ethyl acetate fraction exerted the highest inhibitory action. The

active agents were identified as 1-methyl malate, 1-monomethyl citrate, 1,3-dimethylcitrate, and 1,2,3-trimethylcitrate. The purified components showed MAO-A inhibitory action with increasing number of methyl substituents, whilst the MAO-B inhibitory action was superior for 1-methylmalate compared to the mono- and dimethylcitrates. However, 1,2,3-trimethylcitrate exerted the strongest inhibition on both MAOs. When citrate was compared with its corresponding methyl derivatives, the methoxy moiety proved to be the effective moiety [183]. However, the authors did not disclose the extraction procedure applied. Since prolonged storage, especially under acidic conditions, may result in free carboxylic group derivatization, the formation of these derivatives during sample workup needs to be ruled out prior to further pharmacological testing.

7 Summary and perspectives

7.1 Chemistry

Since the composition of plant materials greatly depends on the edaphic factors, age, and respective species, quality may change greatly. On the other hand, targeting towards specific properties selectively applying this knowledge is possible: while the acid and sugar is subject to diurnal changes, protein, and fiber content depend on the age, fertilization, and storage practices applied. In view of the literature data presented, there is much to be done to fully assess the potential of *Opuntia* cladodes. Little is known about the amino acid and amine composition to evaluate both the nutritional, pharmacological, and toxicological potential of cladodes.

The analyses of malic and citric acids but also vitamin C may be helpful for nutritional and sensorial evaluation of the respective *Opuntia* sp. studied. Free and bound oxalic acids, but also rare compounds such as phorbic and piscidic acids could be valuable markers for specific species and their respective physiological stage. It would be of particular interest to examine whether the methyl derivatives of malic and citric acids are genuine compounds of the cladodes with the respective pharmacological properties or rather extraction artifacts. In addition, the presence and quantity of alkaloids in *Opuntia* spp. should be checked. In the light of recent reviews, promoting the knowledge of phenolic constituents in the everyday diet as well as their impact on human health (*e.g.*, [184 – 186]), in-depth studies on the phenolic constituents deserve special attention.

7.2 Potential applications

7.2.1 Food

With the exception of Mexico, fresh cladodes and products derived therefrom are still rare on the European, Asian, and US market and can only be encountered more often in California. While the potential of cladode vegetable does not appear too attractive, processed cactus stems implemented into refined products for the food, pharmaceutical, and cosmetic sector may present a more rewarding avenue for future markets.

The potential of the meanwhile well-characterized mucilages and pectins from the cladodes is not at all exploited. Cactus cladodes could find broad acceptance either as gelling or thickening agent but also as emulsifier in nonalcoholic beverages or dairy products. The interaction between the amphiphilic protein fraction (mucilage) and the polyanion (pectin) was claimed to be of utmost importance for the emulsifying properties [90, 115, 116] while others claim the sole hydrocolloid fraction to be sufficient [190, 191]. Incompatibility (segregation), co-solubility, and complexation (association) behaviors of protein-polysaccharide blends have been discussed recently [192, 193]. In this respect, it needs to be investigated how variations of the pectin:mucilage ratio will affect the technological properties. Precipitation, fertilization practices, cultivation temperatures, and species-dependent differences need to be considered [22, 194]. Transferring the physiological properties of hydrocolloids in plants [195] to their functional properties in food would be worthwhile for profitable technological use. The ratio of rhamnose and uronic acids is of major interest, since the former will affect hydrophobicity while the latter is governing hydrophilicity of the macromolecule [196]. Since hydrocolloid compositions depend on the respective extraction procedure, the latter needs to be carefully designed [92, 197, 198]. Furthermore, the compatibility of the cactus constituents with the respective target food should be checked.

Pintado *et al.* [199] isolated a protein fraction from unripe cactus fruits with coagulant and caseinolytic activities. Hence, its use as a substitute for chymosin, as a plant-derived rennet was suggested. In extracts from frozen cladodes, however, only marginal proteolytic activities were found [200] which could be due to protein-pectin interactions [201]. Future studies in this area seem to be of interest. With the increasing demand for kosher [127] and genetically modified organisms (GMO)-free foods, *Opuntia* could be a novel source of proteolytic activities besides cleaver (*Galium verum* L.), various thistles, such as artichoke (*Cynara* sp.) [202, 203], fig [204 – 206], kiwi [207, 208], papaya [209], and pineapple [210], respectively.

7.2.2 Pharmaceutical and cosmetic applications

Not only the biofunctional properties but also the assumed role of cladode polysaccharides in the medicinal sector are interesting such as cholesterol reduction and its preventive action in diabetes and adipositas therapies [5, 26, 211, 212].

Since the hydrocolloid fraction is also rich in proteins, further research should be conducted whether the alleged positive effects are due to the pectic substances or rather to the protein fraction. Furthermore, it should be investigated whether these proteins are acting as heat-shock and antifreeze proteins [213–220] in the cactus tissue [221, 222]. Whether the same proteins acting as repair molecules in plants could be used for pharmaceutical purposes merits further consideration. Special attention should also be given to the oligosaccharide fraction that has not been characterized so far. Immunomodulatory properties have been postulated for glucans from roots of *Periandra mediterranea* (Vell.) Taub. [223] and glucomannans from *Aloe* sp. [224]. According to a very recent publication [225], small oligosaccharides with a polymerization degree of 6 and above with a tendency to form helical structures are potent immune modulators.

For topical applications, *Opuntia* hydrocolloids could be applied in wound creams (cooling cream) similar to *Aloe vera* (L.) Burm. [224, 226, 227]. Analogously, cosmetic products would profit from cladode preparations. Since luteolin is known to reduce cholesterol considerably by indirect inhibition of 3-HMG-CoA reductase, the key enzyme for cholesterol biosynthesis [228], the action of flavonoids on cholesterol metabolism would be attractive to be pursued. Furthermore, both a dose-dependent and a structure-related bioactivity was demonstrated for flavonoids either stimulating or attenuating cholesterol formation [229]. Finally, sterol ingestion has been inversely correlated with cholesterol absorption and compensatory stimulation of cholesterol synthesis [230].

Many more compound-activity relations may be discovered in the future. This assumption is substantiated by the multiple uses of *Aloe* sp. [224] which bioactivities cannot only be ascribed to its hydrocolloids such as acemannan but rather to the great diversity of low-molecular-weight constituents of the plant [231].

8 Conclusions

In summary, the constituents of *Opuntia* cladodes are only partly known and often not quantitatively determined. Investigations were mostly performed 20 years ago and need to be validated with up-to-date methods. Furthermore, data stem from all kinds of different *Opuntia* spp. and it is open to question whether the botanical classification has properly been assessed in each case. Beside a sound systematic classification, the background of cladode physiology needs to be considered. Based on additional data, a reliable nutritional evaluation can be performed. The technofunctional properties of the respective extracts can be efficiently exploited for manifold food, cosmetic and medicinal applications. Analogies to the multiple uses of *Aloe* sp. are obvious. Whether isolated substances or rather a concerted action of several components in the complex plant matrix are responsible for the big variety of biological activities remains unknown, let alone the underlying mechanisms of the traditional curative treatments being still little understood.

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9 References

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