Chapter 42
Industrial Applications of *Opuntia* spp. (Nopal, Fruit and Peel)

Tukayi Kudanga and Christiana Eleojo Aruwa

Abstract Research interest in the *Opuntia* species has been increased, especially in the past decade. Although it was previously thought to be a weed menace and underutilised, the *Opuntia* plant possesses several food and non-food applications. This chapter reviews the industrial applications of *Opuntia* spp. and the real prospects that could guide future research directions. In food applications, *Opuntia* can be used as feed/fodder, nutraceuticals, beverages, sweeteners, and food additives. Non-food applications have broadened to include the textile, fuel, bioplastic, wastewater treatment, pharmaceutical, medical, cosmeceutical, agrochemical, agroforestry, and pollution control industries. *Opuntia* aerial parts such as cladodes, fruits and peel by-products are rich in nutrients and phytochemicals, many of which are yet to be profiled and identified. It is therefore envisaged that biotechnological applications of the plant will continue to increase. Although the *Opuntia* plant has shown promise for several industries, many *Opuntia*-based products have not yet been commercialised. Factors contributing to this challenge are highlighted, and possible workable solutions suggested.

Keywords *Opuntia* spp. · Cladodes · Fruits · Peels · Non-food application · Commercialisation · Food applications

T. Kudanga (✉)
Department of Biotechnology and Food Science, Faculty of Applied Sciences, Durban University of Technology, Durban, South Africa
e-mail: tukayik@dut.ac.za

C. E. Aruwa
Department of Microbiology, School of Sciences, Federal University of Technology, Akure (FUTA), Ondo State, Nigeria
e-mail: cearuwa@futa.edu.ng

M. F. Ramadan et al. (eds.), *Opuntia spp.: Chemistry, Bioactivity and Industrial Applications*, https://doi.org/10.1007/978-3-030-78444-7_42

Abbreviations

Al	Aluminium
$Al_2(SO_4)_3$	Aluminium sulphate
ANADEC	National Association of Cactus Development
CactusNet	Cactus Network
CAM	Crassulacean Acid Metabolism
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
CODEX STAN	Codex Alimentarius Standard
COX	Cyclooxygenase
CSJ	Cactus and Succulent Journal
CSSG	Cactus and Succulent Specialist Group
FAO	Food and Agricultural Organisation
Fe	Iron
GMP	Good Manufacturing Practices
GRIN	Germplasm Resources Information Network
GSH	Glutathione
HACCP	Hazard Analysis and Critical Control Point
HCl	Hydrochloric acid
JECFA	Joint FAO/WHO Expert Committee on Food Additives
JPACD	Journal of the Professional Association for Cactus Development
LAB	Lactic Acid Bacteria
MAs	Macromolecular Antioxidants
MDA	Malondialdehyde
Mn	Manganese
QA	Quality Assurance
QC	Quality Control
R&D	Research and Development
SAERT	Sustainable Agriculture and Environmental Rehabilitation in Tigray
SOPs	Standard Operating Procedures
TSS	Total Soluble Solids
UVB	Ultraviolet B
WHO	World Health Organisation

1 Introduction

The cactus pear (*Opuntia*) plant dates back to the Aztecs in the Mesoamerican region (Pimienta, 1990). The Spanish people consider the *Opuntia* plant an all year round delicacy to be relished, while nomads considered proximity to the cactus pear plant a reason to take up settlements (Bravo-Hollis, 2002). The cactus pear fruit value was also equated to the value of silver and gold in the western Indies since a vast number of ethnomedicinal properties were alluded to members of the *Opuntia* species (Velásquez, 1998). The *Opuntia* plant is an integral part of the Mesoamerican history and contributes to the people's socio-economic life (Flores-Valdez, 2003). Either cultivated or wild, the *Opuntia* species grow across various agricultural conditions and climates where they serve as raw materials for various industries and as food. As a result, the plant has since spread from the Americas to regions and continents such as Asia (India), Africa (Angola, Tunisia, Nigeria, Algeria, Ethiopia, Egypt, South Africa, Eritrea, Morocco, Libya), Australia, Europe, the Caribbean and Mediterranean regions (FAO, 2013). Some of the wild *Opuntia* varieties include *Opuntia leucotricha*, *Opuntia robusta*, and *Opuntia hyptiacantha,* while the most cultivated *Opuntia* species are the *Opuntia streptacantha*, *Opuntia xoconostle*, *Opuntia amyclae*, *Opuntia megacantha*, and *Opuntia ficus-indica*. However, globally the *Opuntia ficus-indica* is the most widely cultivated (Uzun, 1996).

The *Opuntia* plant shows significant taxonomic complexity with significant variations in species and phenotypes across different environments, locations, and climates. It is classified within the Cactaceae family and reproduces either asexually or sexually (GRIN, 2005; Aruwa et al., 2018). The name 'nopal'refers to the entire cactus plant; the fruit is called 'tuna', the tender cladodes 'nopalitos', and the mature fleshy leaves or cladodes called 'penca', all of the Spanish nomenclature. Israelis call it 'sabras' meaning 'prickly on the outside but sweet on the inside'. It is mainly used as livestock forage in Brazil and was therefore named 'palma forrageira'. The plant's morphological and anatomical characteristics enhance its adaptability to various environments. This attribute makes the plant a valuable natural resource that cannot be overlooked in many ecological zones for its socioeconomic potential (FAO, 2013).

The cladodes are also scientifically referred to as stems, racquets, fleshy leaves, or paddles. Cladodes may or may not have spines. Cladodes function as thick cuticle bound leaves with a waxy covering (or glochids) that decrease water loss. The presence of numerous parenchyma enables its high water storage capacity. Mucilage, a hydrocolloid present in the paddle tissues, also has a tremendous capacity to bind water molecules (Nobel et al., 1992). Cladodes have stomata across the surface area, which prevent moisture loss and absorb carbon dioxide (CO_2) at night for photosynthetic roles. Its peculiar photosynthetic function is of the crassulacean acid metabolism (CAM), where stomata open at night to take in CO_2, which then gradually acidifies the paddles and stem (Díaz et al., 2017). Plants capable of CAM are also reported to resist high and low temperatures favourably (Nobel, 1998). Even in extreme droughts, cladodes are only slowly dehydrated and degraded. These characteristics increase the *Opuntia* plant's economic and agricultural viability across semi-arid and arid terrains, where little or no irrigation platform is required (Nobel, 1998; FAO, 2013).

Given the characteristics mentioned above, the economic potential of the *Opuntia* plant and cladodes is increasing. Table 42.1 summarises the food and non-food applications of various parts of the plant. These are further elaborated in respective sections. The chapter concludes with an overview of the factors affecting the commercialisation of *Opuntia*-based products.

Table 42.1 *Opuntia* plant parts and their food and non-food applications

S/N	*Opuntia* plant part	Product(s)	Industry application	Reference
Food application(s)				
1	Nopals and cladodes	Forage or feed	Agriculture	FAO (2001) and Fuentes (1991)
		Flour	Food (cooking, baking, maltodextrin, confectioneries)	FAO (2013)
		Jams, Sauces, Juices, Pickles	Food	FAO (2013)
		Hydrocolloids (mucilage)	Food (thickening agents)	Sáenz (2004)
		Mucilage or gum	Food (fruit leathers or edible films)	FAO (2013) and Sepúlveda et al. (2003)
		Cereals	Food (cereal and nopal flour mix; pelleted cereal products)	FAO (2013)
		Nopalitos in chilli sauce, Azteca, Nopal mixed with guava juice (export product)	Food	FAO (2013)
		'Agua de Nopal' also known as nopal water (cladode juice and sugar)	Food	FAO (2013)
2	Fruits	Beverages Syrup, Toffee (melcocha), and Cheese. Nectars, Gels, Juices, Jams, Liquors, Juice concentrates. Sweeteners, Vinegars, Wines and Brandies, Canned fruits, Frozen pulp, and other fruit products Functional foods (nutraceuticals)	Food	López et al. (1997), Corrales and Flores (2003), FAO (2013), Corrales and Flores (2003), Sáenz (2000) and Sloan (2000)
		Edible oils or fatty acids	Food and feed supplement	Ennouri et al. (2006) and Sawaya et al. (1983)
		Cocoa butter	Food (chocolate productions)	Jana (2012)
3	Peels	Thickeners, Prebiotic preparations	Food	Diaz-Vela et al. (2013)
		Sauces	Food	Sáenz (1999)

(continued)

Table 42.1 (continued)

S/N	*Opuntia* plant part	Product(s)	Industry application	Reference
		Peel powder	Food (flour supplementation in bread baking, baked products improvers; substitutes for sugar, vitamin E, and fats)	Anwar and Sallam (2016) and Chougui et al. (2015)
Non-food application(s)				
1	Nopals and cladodes	Carbon sink	Ecosystem conservation (CO_2 removal or reduction)	Nobel and Bobich (2002)
		Carmine and grana	Paper, Ceramic, Textile, Cosmetic and Food	Aldama-Aguilera et al. (2005) and FAO/WHO (2000)
		Biogas and other fuels Carbon dioxide production Ethanol	Energy (cooking fuel, heating, electricity)	Aké Madera (2018), Ciriminna et al. (2019), Tegegne (2002), Varnero and García de Cortázar (1998), García de Cortázar and Varnero (1999) and Stintzing and Carle (2005)
		Capsules and tablets (for diabetes and obesity management) Gastric mucosal protectants Other potential pharmacological products	Pharmaceutical and medical	Frati-Munari et al. (1992), Trejo-González et al. (1996), FAO (2013), Aruwa et al. (2018), Díaz et al. (2017), Park et al. (2017) and Viegi et al. (2003)
		Shampoos, Gels, Creams, Lotions	Cosmetic	Corrales and Flores (2003)
		Natural additives	Cosmetic, Pharmaceutical, Food	FAO (2013)
		Binding agents Anti-corrosives	Construction (adherents, monument restoration, etc.)	Hammouch et al. (2004) and Torres-Acosta et al. (2005)
		Artisan crafts (baskets, bangles, earrings, artifacts)	Tourism	FAO (2013)
		Opuntia hydrocolloids or mucilage	Environment and water (water and wastewater treatment)	Miller et al. (2008) and Sáenz et al. (2004)
		Opuntia and its composted products	Agriculture (hedge, biofertiliser)	FAO (2013) and García (1994)
		Insect repellent	Ethnomedicinal	FAO (2013)
		Nopalitos and cattle manure vermicompost	Agriculture (vermiculture)	García (1994)

(continued)

Table 42.1 (continued)

S/N	*Opuntia* plant part	Product(s)	Industry application	Reference
		Drought protectant	Agriculture and conservation	FAO (2013)
		Gramophone needles	Music	Ramsay (1928)
		Biomaterials and bioplastics	Biomedicine and packaging materials production	López-Palacios et al. (2016)
2	Fruits	Pigments and colorants (natural additives)	Many industries	FAO (2013)
		Fruit fibres Other potential pharmacological products Nutrient supplements	Pharmaceutical (health and wellness)	FAO (2013), Hollingsworth (1996), Hahm et al. (2015), Serra et al. (2013), Chahdoura et al. (2015) and Ghazi et al. (2013)
		Fruit seed oils	Construction (anti-corrosion)	Hmamou et al. (2012)
		Dried or processed fruit by-products (seed)	Agriculture (food and feed supplement)	Sawaya et al. (1983)
		Cocoa butter	Pharmaceutical, Cosmetic and Toiletry production	Jana (2012)
3	Peels	Betanin (betalain), xanthophyll, and other pigments	Many industries (natural additives)	Abou-Elella and Ali (2014) and Cano et al. (2017)
		Biofertiliser	Agriculture	Quintanar-Orozco et al. (2018)
		Biogas and other fuels	Energy	Gebrekidan et al. (2014) and Quintanar-Orozco et al. (2018)
		Dried peel supplements, peel extracts and other potential pharmaceuticals	Pharmaceutical (pharmaceuticals for health and wellness)	Wiese et al. (2004), Abou-Elella and Ali (2014), Cerezal and Duarte (2005), Federici et al. (2009) and Milán-Noris et al. (2016)
		Bioprotein (additive)	Chemical and pharmaceutical	Gad et al. (2010)

2 Food Applications of the *Opuntia* Cladodes

Not many plant species are as versatile as the *Opuntia* with regard to processing into foods and food products. In particular, cladodes have been processed into many food products and have also been used as forage and feed.

2.1 Forage and Feed

The *Opuntia ficus-indica* cladodes are consumed as food and vegetables by humans and also serve as forage for livestock in locations like Mexico (Flores & Aguirre, 1979; Fuentes, 1991), Chile and the United States (Hanselka & Paschal, 1990), and Brazil (Domingues, 1963). Exploration for forage uses has also been reported in South Africa (Wessels, 1988) and North Africa (Monjauze & Le Houérou, 1965).

The use of *Opuntia* spp. as feed is closely linked to its ability to efficiently convert water to digestible energy and dry matter (Nobel, 1998). Another unique advantage of the plant is that in semi-arid and arid conditions, the *Opuntia* or CAM species play a superior role in the amount of dry matter converted per surface area than other broadleaves and grasses used as feed plants. The *Opuntia* plant and cladode are useful as forage for pigs and cattle but have to be mixed with other foods rich in proteins since *Opuntia* spp. are low in protein content (FAO, 2001). Since the cladodes have a high water holding capacity, they are a good feed source for cattle, especially during droughts (SAERT, 1994). Spiny and slow-growing *Opuntia* cladodes and cultivars do not need to be protected from herbivorous animals like the spineless cultivars. However, when using prickly varieties as feed, the spines have to be removed or burned off before utilisation as feed for livestock. About 100,000 ha and 900,000 ha of land have been dedicated to *Opuntia* cultivation for fruit production and forage, respectively, in countries worldwide (FAO, 2001). Thus, the use of *Opuntia* species as forage or feed still outweighs other applications.

2.2 Food Products

Examples of food products derived from *Opuntia* cladodes include jams, sauces, juices, and pickles (Table 42.1). Other products that require minimal processing are also possible. Cladodes may also be useful for processing into flour. At the age of 2 to 3 years, cladodes are partially lignified. In this form, they can be processed into flour for use in cooking and baking. The flour can also serve as food, a feed supplement, and an essential ingredient for the preparation of confectioneries (FAO, 2013).

The presence of mucilage and hydrocolloids in nopals makes them useful in producing thickeners (Sáenz, 2004). The mucilage or gum derived from the *Opuntia* have been shown to demonstrate specific properties. Such properties include the ability to maintain a system's viscosity while preventing system flocculation, to reduce surface tension and improve emulsion stabilisation (for dairy products and non-alcoholic beverages), and to stabilise foams (Garti, 1999). The use of mucilage in fruit leathers and edible film production, product texture development, syneresis inhibition, and crystallisation control has also been reported (FAO, 2013). However, fruit leathers have not been produced on an industrial scale (Sepúlveda et al., 2003).

New food product varieties that are *Opuntia* cladode-based have been produced in Mexico. They are a combination of tender cladodes and other ingredients and include cereal and nopal flour mixtures; pelleted cereal products from nopal powder, maltodextrin, wheat bran, and flour; tender nopalitos in hot chili (*Capsicum annuum*) sauce; Azteca, a nopalitos salad incorporating tuna fish; and a nopalitos puree or pâté with soybean and beef or chicken flavouring. A nopal juice product, which is combined with guava juice, is also commercially available for domestic markets and exportation. Another product is 'Agua de Nopal' meaning cladode water, and is composed of nopalitos juice and sugar. Pickled tender cladodes and crystallised and candied nopalitos products have also been produced (FAO, 2013).

3 Non-Food Applications of *Opuntia* Nopals/Cladodes

The industrial potential of the *Opuntia* plant extends beyond food applications. Some of the non-food applications of *Opuntia* are discussed in this section.

3.1 Carbon Sink

Given the rise in fossil fuel usage, deforestation, and the subsequent increased levels of atmospheric CO_2, the earth's ecosystem faces a major challenge. Through its paddles, the *Opuntia* plant could serve as an absorbent for the removal of excess carbon dioxide in regions that may be suitable for the establishment of the plant, which sometimes are unfavourable for other plant species. In this scenario, the plant acts as a carbon sink (Nobel & Bobich, 2002).

3.2 Grana/Carmine Production

Some *Opuntia* species, such as the *Opuntia cochenillifera* and *Opuntia ficus-indica*, are specifically chosen for rearing female cochineal insects (*Dactylopius coccus*) for grana and carmine (an industrial colourant) production. To date, of several *Opuntia* species, only a few have been explored for grana or cochineal production on a large scale (Uzun, 1996). Grana or carmine produced from cochineal insects are natural colorants used in the paper, ceramic, textile, cosmetic, and food industries. Laboratory dyes are also prepared from cochineal products. Carmine, in its various marketed forms (carmine, carminic acid or carminic solutions), has been added by the Joint FAO/WHO Expert Committee on Food Additives (JECFA) to the authorised food additives list of the Food and Agricultural Organisation (FAO) (FAO/WHO, 2000). Peru leads the international exportation market for dried cochineal products. Globally, the export value for carmine or grana stands at \$60 to \$112 per kilogram of dried carmine. With increased awareness about this natural colorant, global demand is expected to increase (Aldama-Aguilera et al., 2005). Natural pigments serve as excellent and favourable alternatives to synthetic colourants.

3.3 Fuel and Bioenergy Generation

When cladodes become completely hardened or lignified, they may be burned as fuel. Cladodes, thus, play a role in the energy sector. As cladodes age, the fiber content increases to about 16.1% in the lignified stems (Flores et al., 1995), and crude fiber content as high as 17.5% in lignified cladodes has been recorded (Flores-Valdez, 1999). Tegegne (2002) reported higher ash content in lignified cladodes compared to younger paddles. This property makes the use of lignified cladodes as fuels possible.

The digestion of nopals with factory waste results in the production of biogas for cooking and other uses. Nopal and manure mixtures at various ratios and under different conditions produce a variety of biogases when fermented. Carbon dioxide is the major gas generated at a pH < 5.5 such that the gas's energy content and combustibility is reduced. Biogas with a 60% methane content was also generated at a pH ≥ 6. Biogas composition from fermentation is closely linked to the raw materials' pH (Varnero & García de Cortázar, 1998).

More recent reports have shown that compared to jatropha, corn, palm, and sugar cane plant biomasses, the nopal biomass shows great economic feasibility in its ability to generate biogas. The *Opuntia* nopal utilises less biomass to generate more biogas (Kleiner, 2018; Ciriminna et al., 2019). In Chile, a small scale biogas plant started operations and highlighted some identifiable technical considerations linked to biogas production from the *Opuntia* nopal. Some of these include the rapid degradation of nopals compared to manure, and fermentation takes place within an acidic range of 6.5 to 6.8 and at room temperature. It can be produced using a bioreactor with an epoxy resin internal coating (economically viable and does not require stainless steel). The fermentation wastewater was also rich in nitrogen and was useful in plantation irrigation. The fermentation residue or solid fibre could also be directly used as a fertiliser or included in compost (Kleiner, 2018). A company in Mexico, NopaliMex, has also successfully used *Opuntia* cladode-derived biogas in running its tortilla production processes. The gas met the company's electricity and heating and fuel needs (Aké Madera, 2018).

Ethanol production follows a more complex procedure and usually requires specific yeast cultures for maximum ethanol generation (García de Cortázar & Varnero, 1999). Bioethanol generation has been recorded through cladode fermentation following prior treatment with acid (hydrochloric acid), and enzyme (cellulase) hydrolysis. These pre-treatments served for the release of saccharides required for *Saccharomyces* sp. fermentation. A yield of 9 L was derived from a 100 kg cladode biomass. Again, an average of 3000 L from irrigated and 300 L from non-irrigated lands could be produced from a plant density of 635 to 5000 per hectare (Retamal et al., 1987; Stintzing & Carle, 2005).

3.4 Pharmaceutical and Medical Applications

Cladode fibre has been made into capsules or tablets for diabetes and obesity control. Capsules made from *Opuntia streptacantha* (Frati-Munari et al., 1992) and *Opuntia fulginosa* (Trejo-González et al., 1996) showed the most effective hypoglycaemic action compared to *O. ficus-indica*. Mucilage extracts have also been used to make gastric mucosal protectants. Other potential pharmacological effects reported for cladode extracts include antioxidant, antibacterial (Lee et al., 2002a; Aruwa et al., 2019a, b), antiviral (Ahamd et al., 1996), anti-inflammatory (Galati et al., 2002), analgesic (Park et al., 1998), and antiulcerogenic (Lee et al., 2002b; Galati et al., 2002) effects. Other researchers reported anti-atherogenic (Budinsky et al., 2001) and anti-spermatogenic (Gupta et al., 2002) properties.

New possibilities abound for the identification of pharmaceutical products based on nopalito extracts and compounds. An array of biomedical applications are possible, including use in chronic disease (cancer, obesity and diabetes, cardiovascular and atherosclerosis diseases) therapy (Osuna-Martínez et al., 2014; Díaz et al., 2017). Nopalito powder has been used to increase fibre intake and in blood sugar and weight management. Rehydrated powder gels are used in wound healing due to the cooling effect. Soluble nopal fibre extracts improved peristaltic movement in the colon, which impacted stool bulking and passage, while insoluble cladode fibres are reported to bind toxins (Stintzing & Carle, 2005). *Opuntia* species like *O. streptacantha* and *O. fuliginosa* have been implicated in liver injury, fatigue, gastritis, and dyspnoea therapies in ethnomedicinal applications (Hitchcock et al., 1997; Shapiro & Gong, 2002a, 2002b). In Italy, *O. ficus-indica* ethnoveterinary use has been reported (Viegi et al., 2003). Cladodes have also been used in arteriosclerosis and acidosis treatment (Warschkow & Warschkow, 1994; Hegwood, 1990). The liver protective activity has also been recorded for cladode extracts (Hfaiedh et al., 2008). Antioxidant and antidiabetic extract activities were linked to the presence of lignans, polysaccharides, phenolic acids, and flavonoids (Fig. 42.1). Various substitution patterns in medicinal plants are possible to yield different classes of flavonoids, such as flavones and flavanols (Rocchetti et al., 2018). α-Pyrones and the new opuntioside and opuntiol moieties with analgesic activity have also been identified in O. *dillenii* cladode extracts (Siddiqui et al., 2016). Protection against ultraviolet B (UVB) skin damage is also a potential use for *O. humifisa* pad extracts (Park et al., 2017).

The identified pharmacological effects of *Opuntia* extracts and compounds are closely linked to an array of action mechanisms. Pharmacological activities such as cardio-protection and antioxidant activities attributed to flavonoid compound groups have to do with redox-active metal chelation and lipid peroxidation inhibition mechanisms. These mechanisms involve the transfer of electrons (Tsao, 2010). Other modes of action include oxidase inhibition and antioxidant enzyme activation (Cos et al., 1998). In the case of reducing inflammation, mechanisms such as nitric oxide synthase and cyclooxygenase-2 (COX-2) enzyme induction, as well as other

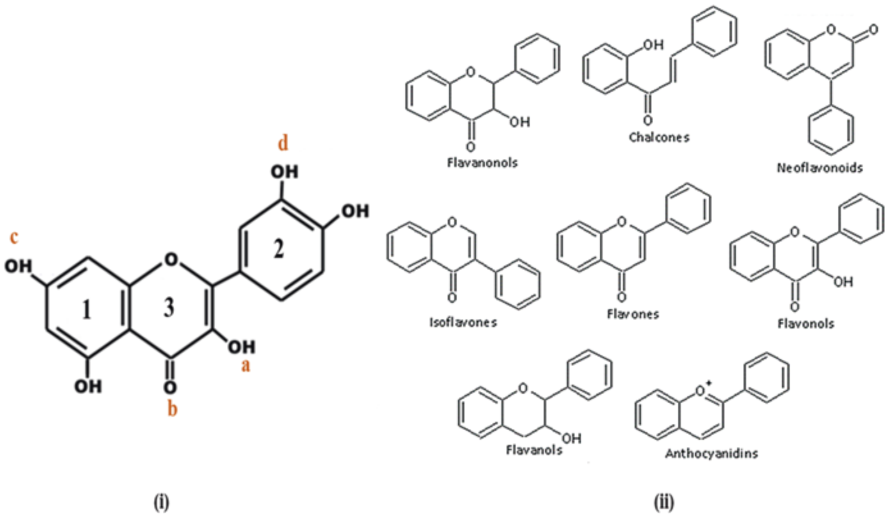

Fig. 42.1 (**i**) Structure of *Opuntia* flavonoids showing possible substitution points (a–d) and 3 major rings (1–3); (**ii**) A diagrammatic representation of some flavonoid classes (anthocyanidins, isoflavones, flavones, flavonols). (Adapted from Heim et al., 2002 with permission from Elsevier)

inflammatory enzyme and pathway inhibition, have been reported for bioactive plant compounds (Togna et al., 2014). Bioactive plant compounds also cause cancerous cell death by upregulating some pro-apoptotic proteins' expression to bring about their anticancer action. Cancerous cells may also experience a reduction in membrane depolarisation potential and condensation of chromatin shrinkage in response to biologically active compounds (Lin et al., 2014).

3.5 Cosmetics

Very few cosmeceutical companies are aware of the utilisation of nopalitos in making shampoos, gels, creams, and lotions. This application is underexplored, possibly because the properties of the *Opuntia* for this use are not widely known, thus limiting demand for them. Again, cosmetics do not necessarily require considerable amounts of plant material during production (Corrales & Flores, 2003). Nopalito powder added to make-up and skincare products reduces melanin and cytokine production and protects against free radical generation. A 14% reduction in pigmentation (melanin production), a 31% decrease in facial wrinkles, decreased UV-induced oxidation, and upregulation of skin defence systems was demonstrated in a recent clinical trial using nopalito powder (Naolys, 2018).

3.6 Natural Additives

Given the growing global awareness of the attendant risks associated with synthetic additives, demand for natural products and additives is rising as regional laws are withdrawing many synthetics. This is so because anything natural is generally regarded as secure and safe, even though this may not always be the case. Additives are in high demand for cosmetics, pharmaceutics, and foods and are therefore well used in these industries. Examples include carminic acid and gum additives derived from cladodes (FAO, 2013).

3.7 Construction

Nopal mucilage is useful in the production of binding agents for use in the construction industry. Mucilage is also being explored on steel for its anti-corrosive features (Hammouch et al., 2004). Anticorrosive properties were reported for a mixture of mucilage with a concrete mix poured around steel strengthening rods (Torres-Acosta et al., 2005). When added to lime, nopal mucilage serves as an adherent for paints (Ramsey, 1999). The organic adhesive produced from the mixture of nopal juice and lime is used to protect and restore historical monuments. Flexible ratio mixtures of nopal mucilage and lime result in dried pastes with varying mechanical properties tailored to different applications (Cárdenas et al., 1997). In a study undertaken in 2004, *Opuntia* mucilage added to cement mixtures improved the cement products (Torres-Acosta et al., 2004). Mucilage has also uses as a stucco water barrier and brick and adobe plaster.

3.8 Tourism

Mature lignified cladodes have been useful for making artisan crafts such as baskets, bangles, artifacts, and earrings, and find applications in the tourism sector (FAO, 2013).

3.9 Water Clarification and Wastewater Treatment

Cladodes have been used for water clarification (Table 42.1). *Opuntia stricta* var. *dillenii* and *O. ficus-indica* mucilage have been shown to effectively clarify medium to highly turbid drinking water samples compared to the conventional aluminium sulphate [$Al_2(SO_4)_3$] agent. No disagreeable odour was recorded following the water treatment. The effective reported concentration was 0.8 mL mucilage per litre of water. Also, iron (Fe), aluminium (Al), and manganese (Mn) heavy metals were removed, while faecal coliforms and the water chemical oxygen demand (COD) decreased (López, 2000).

In another study, *Opuntia* cladode mucilage coagulative properties were high in water within the basic pH range (pH 8–10) and up to 98% removal of water turbidity. Dose increased as the initial water turbidity increased under experimental conditions (Miller et al., 2008). Another natural coagulant, *Moringa oleifera*, showed similar coagulative action. The mechanism of action for the coagulative capability of *Opuntia* cladodes varies and remains a subject of research. Nonetheless, a study has pointed to the mechanism being linked to adsorption and bridging or sweep flocculation action. In this mechanism, particles make contact, bind together, and form a polymer material which constitutes the floc. The optimised use of natural coagulants in water treatment provides a cheap and practical option in developing areas (Miller et al., 2008). Wastewater clarification has also been reported for *Opuntia* hydrocolloids by some authors (Domínguez López, 1995; Muñoz de Chávez et al., 1995; Vigueras & Portillo, 2001; Anderson, 2001; Sáenz et al., 2004).

3.10 Agricultural Uses

The improvement of drainage, organic matter, infiltration, or seeping of water into soils has been reported as an application for nopals (Gardiner et al., 1999). The *Opuntia* is useful as a hedge plant. *Opuntia*-based biogas production plants have delivered steady nutrient-rich wastewater for irrigation and fertilisation of food crops grown close to the gas generation plant (FAO, 2013). A biofertilizer made from nopalitos and animal manure was reported to improve plant biomass by providing soil nutrients (García, 1994), and enhanced sprouting and root development in *Opuntia* plants (García de Cortázar & Nobel, 1992). Compared to fresh farm manure, biofertilizers, including *Opuntia*, showed better stability for biogas production and easier to handle. Biofertilisers also improve the biological, chemical, and physical characteristics of the soil.

3.11 Insect Repellent

The *Opuntia* has been traditionally used as an insect repellent, but no publication exists that explicitly demonstrates the technique, use, and scope. According to the FAO (2013), a patented product is available for sale in Honduras.

3.12 *Nopal Residues in Vermiculture and Biofertilizer Production*

Vermiculture refers to earthworm cultivation on biodegradable organic materials, which have undergone semi-composting. The resultant material is a worm cast or vermicompost, added to soil as a biofertilizer. One such biofertilizers are made from nopalitos with cattle manure and improved agricultural production systems' sustainability and efficiency, especially in arid areas (García, 1994).

3.13 *Drought Survival*

Recurrent drought is a major problem in arid regions, and *Opuntia* cultivation provides a workable solution to farmers in these areas. The nutritive and succulent nature of the crop enables livestock growers to carry on despite harsh and extended drought periods.

3.14 *Other Non-Food* **Opuntia** *Cladode Applications*

As far back as the late 1920s, cladode spines had been patented for use as gramophone needles (Ramsay, 1928). Fuel combustion had also later been enhanced with the addition of *Opuntia* cladode extract (Scifoni, 1985). *Opuntia* stem hydrocolloids (pectin and mucilage) may also be applied to produce new biomaterials and bioplastics for biomedicine and packaging materials production (López-Palacios et al., 2016; Medina-Torres et al., 2000).

4 *Opuntia* Fruit Applications

The *Opuntia* fruits show variable skin thickness, low acidity, vary in colour and are pulpy and juicy with good sugar content. Once harvested, *Opuntia* fruits do not ripen; that is, they are non-climacteric. Thus, fruit harvest indices should be based on each type of fruit in a specific harvesting area. It has been reported that the best harvest time for *Opuntia* fruits could be determined based on indices such as fruit size and fill, fruit firmness, flower receptacle depth, fall of the glochids, change in fruit peel colour, and content of total soluble solids (TSS) (Inglese, 1999; Cantwell, 1999).

Opuntia species can be differentiated by the characteristics of the fruits they produce. *O. streptacantha* fruits are juicy and sweet but purple. *Opuntia ficus-indica* fruits are sweet and colour varieties range from red to purple to orange and yellow.

The *Opuntia xoconostle* fruits are more acidic, pink, or purplish-green on the insides and smaller compared to the *O. ficus-indica* fruits (Scheinvar, 1999). In terms of purposeful cultivation, Mexico has the largest expanse of land under *Opuntia* fruit production. Other countries with dedicated areas for *Opuntia* fruit production include Italy, Chile, Peru, Spain, South Africa, North African countries (Egypt, Tunisia, Morocco, and Algeria), Venezuela, Argentina, Bolivia, Jordan, Israel, and the United States (Barbera, 1999). In these countries where awareness of the *Opuntia* plant's potential benefits exists, the fruits are used as raw materials in the food, cosmeceutical, and pharmaceutical industries. The fruit chemical composition, ripening stage, pulp yield, and property of the desired industrial end product must be considered before choosing the processing conditions and techniques to derive high quality and safe products. The *Opuntia* plant growth location and prevailing climate have been reported to impact the plant parts' mineral and phytochemical profile, causing variations in fruit content (FAO, 2013). Several *Opuntia* fruit applications are outlined and discussed in the following paragraphs.

4.1 Food, Beverages, and Other Food Products

Vegetables and fruits are industrially processed into beverages and a wide array of products in order to achieve;

1. Employment generation,
2. Improve shelf life and quality before reaching the target market,
3. Product price stabilisation, especially in the case of excess market supply,
4. Product availability all year round, and
5. Value-added finished products with better marketing potential.

On the offside, the *Opuntia* fruits' large scale use and marketability are considerably reduced because the fruits spoil rapidly and are fragile. Their use is mainly directed towards producing various fermented beverages and foodstuffs (López et al., 1997). *Opuntia* fruits have also been processed and preserved into syrups, which can last for long periods without spoilage. When the fruit pulp is boiled, a toffee product named 'melcocha' is produced, and on further processing results in an *Opuntia* fruit-based cheese (Table 42.1). When sun-dried, the fruits have also yielded cactus pear raisins or dried fruits (Corrales & Flores, 2003). Other food products prepared from *Opuntia* fruit processing include nectars, gels, juices, jams, liquors, and juice concentrates (FAO, 2013). Sweeteners, vinegars, wines, canned fruits, frozen pulp, and fruit products are also possible (Sáenz, 2000; Corrales & Flores, 2003).

Colonche made from *Opuntia streptacantha* juice is a low-alcohol fermentation product produced in Mexico. Its production involves the use of *Saccharomyces* sp. as a starter culture. Aguardiente (brandy) and wine (Table 42.1) are *Opuntia*-based products made by *O. streptacantha* and *O. robusta* (Corrales & Flores, 2003). However, the fermentation and production processes can still be modified to produce different beverages and liquor brands. This is also the case with vinegar production.

The *Opuntia* nopal and fruits are rich in functional compounds which form the basis of most new food formulations and functional foods. Examples of some functional components are fibre, hydrocolloids, carotenoid, and betalain pigments, potassium and calcium minerals, ascorbic acid (vitamin C) (Sáenz, 2004; Díaz et al., 2017), and an array of phytochemical antioxidant molecules (Aruwa et al., 2019b) including macromolecular antioxidants (MAs) (Aruwa et al., 2019a; Serra et al., 2013). Functional components contribute to a healthy diet and are also integral to designing new food formulations and functional food. Functional food formulations that incorporate one or more functional ingredients are targeted towards providing physiological benefits such as disease therapy or prevention, improvement of mental and physical well-being, and health enhancement (Sloan, 2000).

4.2 Pigment Production

Betalains (Fig. 42.2a-c) are biologically active phenolic compounds and pigments found in *Opuntia* fruits. Betalains consist of two major compound classes; betacyanin (i.e., betanin Fig. 42.2b), and betaxanthin (i.e., indicaxanthin Fig. 42.2c). Betalain pigment derivation and extraction from purple and red *Opuntia* fruits are possible. Other colour varieties remain unexplored, even though the orange *Opuntia* fruit has relatively good levels of carotenoids. These pigments have applications in the food industry as colourants and additives (FAO, 2013).

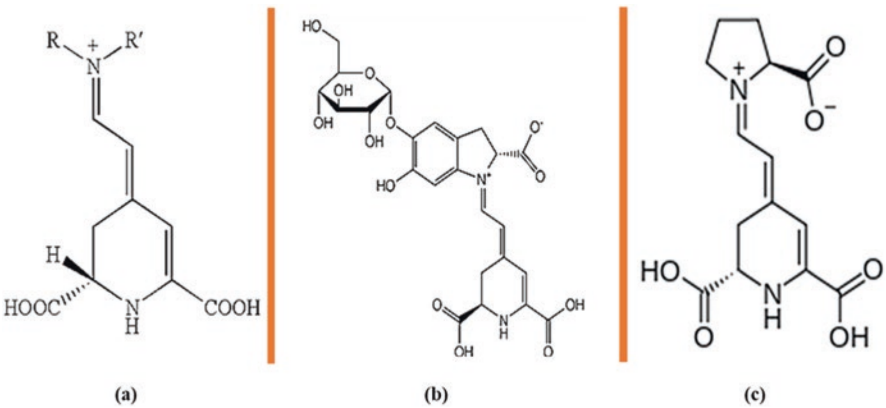

Fig. 42.2 (**a**) The structure of betalain pigments (**b**) structure of betanin, a common betacyanin compound with antioxidative potential, and (**c**) structure of a betaxanthin compound, indicaxanthin. (Adapted from Khan & Giridhar, 2015 with permission from Elsevier)

4.3 Pharmaceutical Uses

Due to phenolic acids, betalains, flavonoids, and other phenolic antioxidants in *Opuntia* fruits, some pharmacological properties have been linked to *Opuntia* fruit extracts. Some of these include hepatoprotective, cardioprotective, antidiabetic, neuroprotective, anti-inflammatory activities (Serra et al., 2013), and antioxidative activity (Albano et al., 2015; Alimi et al., 2013). Anticancer properties have also been recorded (cervical cancer at an effective concentration of 100μg/mL extract) linked to fruit extract content of dihydrokaempferol, *trans* taxifolin, and flavonoids (Hahm et al., 2015). Hepatic, colonic, and prostate cancer cells have also been inhibited by *Opuntia robusta*, *O. violaceae*, and *O. rastrera* fruit extract (Chavez-Santoscoy et al., 2009). *Opuntia ficus-indica* varieties cultivated on drainage sediments showed increased selenium levels and chemotherapeutic activities (Bañuelos et al., 2012). A new (1→4)-α-d-glucan polysaccharide compound was identified in *O. ficus-indica* fruit fractions (Ishurd et al., 2010). Both known and new compounds identified and derived from *Opuntia* fruits could be harnessed to provide health benefits. Of the many components of the *Opuntia*, fruit fibres are the most studied, and their link to health and wellness are well understood, such as the prevention of obesity, diabetes, and control of cholesterol (Hollingsworth, 1996; FAO, 2013).

4.4 Fruit By-Product Applications

Production efficiency is significantly increased when agricultural industries optimise raw materials received into the production area. This is where *Opuntia* by-products like *Opuntia* fruit seeds and peels come in. The processing of by-products into commercial value products reduces waste, boosts company income, and reduces enterprise costs (FAO, 2013).

Before processing fruit juice into various products, fruits are deseeded, and the seed is set aside or discarded. However, the fruit seed by-products may be useful in deriving specific products such as edible oils. The seeds contain oils that are edible and rich in linoleic and other unsaturated fatty acids. Oil yields can reach up to 17%, which favourably compares with known oilseeds for possible commercial exploitation (El Kossori et al., 1998). The optimal use of plant by-products contributes to their valorisation and waste materials management. The seeds may also be used as components in animal feed (Sawaya et al., 1983). Sulphur, amino acids, and minerals are richly present in *Opuntia* seeds (Sawaya et al., 1983). Other potential *Opuntia* seed chemicals for use in various industries include vitamins from *O. macrorhisa*, organic acids, and sugars (Chahdoura et al., 2015), sterols from *O. ficus-indica O. dillenii* (Ghazi et al., 2013), and an array of phenolic compounds groups (flavonoids and tannins) (Chougui et al., 2013). *Opuntia* seed oils have demonstrated anti-corrosion capability (Hmamou et al., 2012), and the reduction of animal feed conversion efficiency when used as a feed supplement (Ennouri et al., 2006).

4.5 *Other* Opuntia *Fruit Products*

An equivalent of cocoa butter (Table 42.1) was produced from the growth of *Cryptococcus curvatus* on *Opuntia* fruit juice. Cocoa butter is useful in producing chocolate, toiletries, pharmaceuticals, and ointments (Jana, 2012).

5 *Opuntia* Peel Applications

The amount of *Opuntia* peel by-product derived from *Opuntia* fruits varies depending on the plant's cultivation location and growth stage. The thick *Opuntia* peel is rich in mucilage, high in fibre, and protects the fruit against excess water loss (Sepúlveda & Sáenz, 1990). Some *Opuntia* peel and peel powder applications are discussed below.

5.1 *Food Products*

Peels from *O. xoconostle* have been used in sauces made in the United States and Mexico (Sáenz, 1999). A considerable amount of hydrocolloid mucilage is extractable from *Opuntia* peels for utilisation as a thickening agent. The high fibre content of peels makes them suitable raw materials for prebiotic preparations and antioxidants. They may also be subjected to fermentation using cultures such as bifidobacterial and lactic acid bacteria (LAB) to generate new compounds for expanded applications (Diaz-Vela et al., 2013). Peel powders rich in antioxidants used to supplement wheat flour enhanced the nutritional properties of baked bread, while decreasing staling and increasing bread shelf life. Peels and peel powders are also used as water and oil retention capacity improvers and substitutes for sugar and fat to stabilize oxidative processes in food (Anwar & Sallam, 2016). *Opuntia* peel fractions have been added to margarines and showed improved oxidation resistance compared to vitamin E-supplemented margarines. The extract did not negatively impact the margarine's microbiological and physicochemical properties (Aruwa et al., 2018; Chougui et al., 2015).

5.2 *Betalains and Other Pigment Production*

As is the case with the *Opuntia* fruits, the purple and red *Opuntia* cultivars are useful in deriving natural betalain pigments (Table 42.1 and Fig. 42.2a–c). Betalain (betanin) (Abou-Elella & Ali, 2014) and other pigments like hydrocarbon carotenes, xantophylls, and chlorophyll (Cano et al., 2017) have been identified in *Opuntia* peels. The production of betalains and other pigments from *Opuntia* peels needs to be optimised for commercialisation.

5.3 Pharmaceutical and Medical Uses

Dried peels from *Opuntia ficus-indica* serve as dietary supplements and functional food (Fig. 42.3) in places like the United States. This use is linked to its ability to reduce the hangover effect associated with excess alcohol consumption (Wiese et al., 2004). Thus, new potential applications continue to emerge from research on the *Opuntia* species, even in the medical industry. Carbohydrates, fatty acids, antioxidants, vitamins (Cerezal & Duarte, 2005), and lipids (Ramadan & Mörsel, 2003) are derived from *Opuntia* peels. They could be channelled toward producing pharmaceuticals that provide specific health benefits such as antimicrobial, antioxidant, and anticancer benefits (Fig. 42.3). Peel extracts used to supplement animal diets influenced the reduction in cholesterol levels *in vivo* (Milán-Noris et al., 2016). Peel

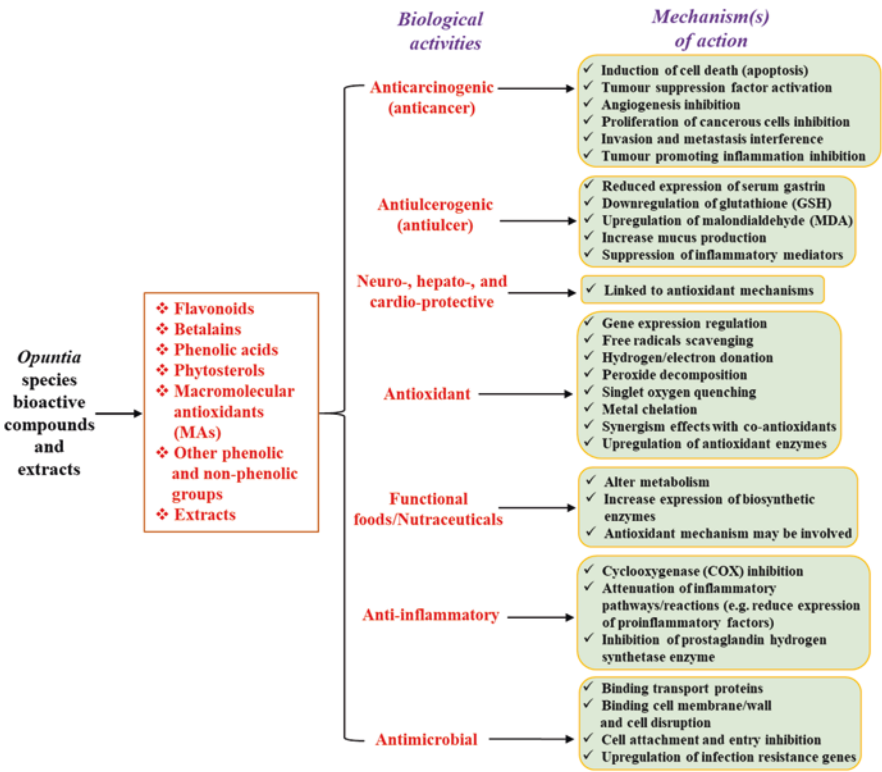

Fig. 42.3 An overview of *Opuntia* compounds and extracts, biological activities, and action mechanisms

extracts have also been used against hypertension (Federici et al., 2009), and cancer (Abou-Elella & Ali, 2014).

Plant sterols (Fig. 42.3) such as those derived from *Opuntia* species, decrease lipid absorption (Aruwa et al., 2018; Bartnikowska, 2009). Phytosterols may raise antioxidative enzymes' levels, thus bringing about cell death (Soodabeh et al., 2014). Within living organisms, *Opuntia* peel extracts have shown hypocholesterolemic action linked to extract's ability to block bile acid transportation and cholesterol absorption and inhibit liver HMG-CoA enzyme activity (Milán-Noris et al., 2016). *O. ficus-indica* peel extracts have also demonstrated the ability to increase the amount of calcium in cancer cell lines (Jurkat T-cell), and cause the cancerous cell membrane to be hyperpolarised (Aires et al., 2004).

Generally, the extent to which biologically active plant compounds are branched, their composition, structure, absence, or presence of sugar molecules, and their physicochemical attributes go a long way to determine such compound's pharmacological activity profile (Koubaa et al., 2015). Most bioactive phytochemicals are aromatic. Flavonoids and other phenol classes are hydroxylated aromatics (Ciocan & Bara, 2007). The number of hydroxyl groups present in the structure of a compound impact its activity range. A high number of hydroxyl groups favours antimicrobial activity in a compound. Antimicrobial action occurs through the compound's ability to destroy the membrane integrity of microbial cells and cultures (Ciocan & Bara, 2007). For example, quinone molecules bind to extracellular proteins and penetrate the cell membrane to cause a killing or static effect. Phenolic coumarin compounds act *via* a similar mechanism. Polymeric phenols with multiple numbers of hydroxyl groups generally show enhanced antimicrobial action. Examples include tannins, which may be in the condensed or hydrolysable form. Polymeric tannins inactivate microbial enzymes and adhesins, bind cell walls, and transport proteins, thus inhibiting protease activity and preventing microbial growth (Ciocan & Bara, 2007).

5.4 Other Peel Products

Citric acid was economically produced through solid-state fermentation of *Opuntia* peels using *Aspergillus niger* (Jana, 2012) and could serve various industries. Hydrocolloids from *Opuntia* peels may also find added value in their use in making new thickening and film producing agents and emulsifiers in cosmetics, foods, and pharmaceuticals. Biomaterials production (Table 42.1) for biomedicine and packing materials are also possible (Peña-Valdivia et al., 2012; Rodríguez-González et al., 2014). *Opuntia* peels as plant by-products have also been channelled for biogas (Gebrekidan et al., 2014), and biofertiliser (Quintanar-Orozco et al., 2018) production. Production of products such as bioprotein from *Opuntia* peels have also been reported and have application in the chemical and pharmaceutical industries as additives (Gad et al., 2010). Future research and development (R&D) studies on *Opuntia* peel potentials would not only provide greater insights and knowledge but broaden knowledge on their application(s) for many industries.

6 Factors Affecting the Commercialisation of *Opuntia*-Based Products

Some of the factors that impact and influence the successful or unsuccessful commercialisation of *Opuntia*-based products are highlighted and discussed in this section.

6.1 Opuntia *Fruit Softness and pH*

These characteristics (Fig. 42.4) make *Opuntia* fruit processing a peculiarly arduous task. The softness of the fruits, when ripe, make them prone to rapid spoilage. Rapid spoilage then leads to agricultural losses and reduced economic and financial gains to farmers. This could be circumvented by using specialised storage facilities and

Fig. 42.4 Factors affecting the commercialisation of *Opuntia*-based products

fresh fruits or processing fruits into various forms that would aid their preservation before consumption, use, or sale. Fruits may also be harvested some days before they become fully mature. Maturity is dependent on the harvester's need and intended use for the fruits. Again, *Opuntia* fruits are within the acidic pH range of 5.3 to 7.1, low acid group with a pH > 4.5. However, a pH of ≤3.5 has been reported for *Opuntia xoconostle* fruits (Mayorga et al., 1990). Heat treatment of the fruits is, therefore, necessary to achieve microbial growth control. This treatment is usually done at a temperature minimum of 115.5 °C and is important since the pH range value of the fruits and their high TSS creates a favourable environment for the growth of spoilage microorganisms.

6.2 **Opuntia** ***Nopal and Fruit Seasonality and Perishability***

Opuntia fruits are perishable and seasonal. The high water content of nopalitos makes them perishable, but nopals are not seasonal. Therefore, effective preservation is necessary to avoid all forms of spoilage linked to physical, biological, nutritional, chemical, or enzymatic changes. Preservation also ensures their availability as raw materials for various industrial processes for most of the year. Preservation techniques need to be carefully selected to prevent tremendous losses. Biochemical (alcoholic or lactic fermentation), chemical (preservatives, sugar addition, acidification, and salting), and physical (dehydration, canning, refrigeration, pasteurisation, freezing, electric pulsing, high pressure, and irradiation) preservation methods are some of the effective techniques being used. One or more preservation methods can be combined to achieve the best possible result. Further studies are still required to determine the best preservation and processing method(s) to be used since these differ for *Opuntia* species and depend on several other factors.

6.3 Pulp Viscosity

The presence of hydrocolloids such as mucilage and pectin make *Opuntia* fruit pulp highly viscous. These hydrocolloids are important components of the *Opuntia* dietary fibres. Pup viscosity can, however, be harnessed and developed into food thickeners upon extraction of the hydrocolloids from the pulp (Sáenz et al., 2004). These hydrocolloids may favourably compete with existing thickening agents such as guar, locust bean gum, and other gum types (Goycoolea et al., 2000; Medina-Torres et al., 2003).

6.4 Processing Pitfalls and Harvesting Peculiarities

Fruit aroma has been reported to change during processing. A sweet aroma turns to one which smells like grass or hay during heat processing to produce certain products. This factor is a challenge that future studies could aim to solve. However, change in the aroma is mainly dependent on the processing need for the desired product. Another recorded pitfall is the darkening of cladodes and nopals due to phenolics, which make preservation difficult (Rodríguez-Félix, 2002). Also, during harvesting, the nopals' acidity needs to be considered because young cladodes' acidity levels vary during the day due to CAM. Preservation of the stems can be facilitated using their acidity, and the acidity can also improve consumer acceptability of the end product. Processing and storage technologies after harvesting could also be improved to reduce losses.

6.5 Farm Management and Pest Control

A good example under this challenge is with cochineal breeding for grana or carmine production. It is advised that agricultural space for cochineal production be done separately from other nopal and fruit planting areas. Such demarcation and defining of boundary lines are practiced in the Canary Islands and Chile, where cochineal is commercially produced (FAO, 2013). This avoids problems with pests on the nopal and fruit farms. Prevention and control of insect pest attacks on *Opuntia* plantations is an integral crop management activity.

6.6 Restriction to Use as a Weed and Low Awareness Level

Many countries and regions to which *Opuntia* plants have spread still view the plant as a weed and nuisance which takes up useful land space. As a result, they are cut and burned off. This is, however, linked to a lack of knowledge (Fig. 42.4) on the potential applications of the plant. While some regions where the *Opuntia* is indigenous have explored the plant's benefits over time, many countries still lack awareness of the *Opuntia* species capacity for subsistent and commercial gains to individuals, groups, and nations. Awareness may be broadened using all possible and available media such as the television, radio, and social media platforms. Such platforms could be dedicated to educating the public, companies, potential investors, governments, and industries on the potential socio-economic and financial gains from the *Opuntia* plant's growth and use.

6.7 Lack of Enabling Policies

National and international policies to aid the acquisition or use of land for large scale agricultural cultivation of the *Opuntia* plant remain a major challenge in many countries. This is more prominent in low and middle-income developing countries. Bureaucratic bottlenecks within the agricultural sector bars discourage herders and farmers who could want to venture into *Opuntia* cultivation. To tackle this, governmental agencies need to be sensitised regularly on the potential profits and economic gains derived from the cultivation of *Opuntia* species for food and specific industrial applications. Associations such as the Cactus Network (CactusNet), National Association of Cactus Development (ANADEC), and Cactus and Succulent Specialist Group (CSSG) need to expand and open new branches worldwide, especially in developing regions where there are no such associations. These may be able to favourably impact policies that could aid in facilitating the cultivation of *Opuntia* species. Regular papers, bulletins or publications from cactus associations and scientific researchers in cactus pear-focused journals [Journal of the Professional Association for Cactus Development (JPACD) and Cactus and Succulent Journal (CSJ)] on emerging and trending topics on the *Opuntia* plant and their applications can be integral to keeping governments informed, updated, and also impact policies.

6.8 Research Needs

While research on the *Opuntia* species is on the rise, many related species and variants still require in-depth research to expand our knowledge on potential new applications and benefits. *Opuntia* applications may be broadened beyond what is already known. New knowledge and research data continue to emerge on the plant, especially from different geographical locations, as the phytochemical profile of similar *Opuntia* species show major variations. The exploration and exploitation of the array of known and new compounds derivable from *Opuntia* species remain largely understudied. Future agricultural, scientific, and multidisciplinary research could contribute immensely to bridging the research and knowledge gap around the *Opuntia* species.

6.9 Quality and Safety Concerns

Quality and safety (Figs. 42.4 and 42.5) are measured mainly by adherence to set acceptable standards for various product categories irrespective of the industry they serve. Since most *Opuntia* products are largely distributed in regions aware of the plant's potential, attaining international quality standards may be an arduous task. Nonetheless, current national and international food quality standards that apply to

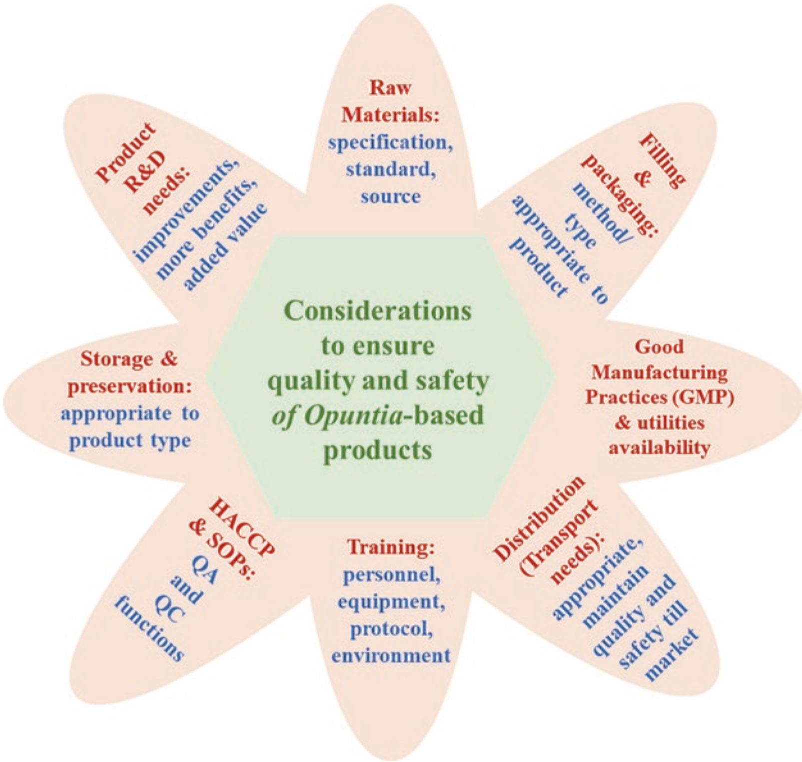

Fig. 42.5 Quality and safety parameters to be considered in *Opuntia*-based product manufacturing. *HACCP* Hazard Analysis and Critical Control Point, *SOPs* Standard Operating Procedures, *QA* Quality Assurance, *QC* Quality Control, *R&D* Research and Development

respective food categories can be used while *Opuntia* product awareness gradually reaches international acclaim and pending the development of quality standards, especially for new product formulations.

Setting standards facilitates collaboration along the value chain. The use of standard operating procedures (SOPs) (Fig. 42.5) within production industries goes a long way to improve consumer protection. A Codex Alimentarius standard exists for prepared, packed, and marketed cladodes, that is, the CODEX STAN 185–1993. No international standard exists for brined and pickled nopal products which are processed industrially (FAO, 2013). Brands, seals, and certification of products that eventually reach the target market are dependent on compliance checks. All stakeholders and local, national, and international inspectorates and regulatory agencies have a crucial role in ensuring and maintaining compliance with set standards (FAO, 2003).

Hygienic practices go a long way to ensure and assure product safety. The role played by good manufacturing practices (GMP) (Fig. 42.5), and implementation of hazard analysis and critical control point (HACCP) principles cannot be overemphasised in achieving food safety and quality. Maintenance of quality and safety from farm to fork is likewise an imperative, as they impact the quality of the finished products. This is where good quality control and assurance activities play essential functions.

6.10 Marketability

Potential investors must develop experience with market exploitation and identification. Substantial market research (Fig. 42.4) before the start-up of *Opuntia*-based processing or production firm on any scale, whether small, medium, or large, is essential. In some instances, insufficient market capacity may exist. Product brands and earned seal or certification, safety, quality, labeling, and presentation tremendously impact on *Opuntia* products' price and marketability (Fellows, 1997). Given the increased consumer awareness, some, if not all consumer groups, tend to appreciate the inclusion of a product's raw material origin on the product labels, provided they are truthful. These qualities set products apart, especially from similar ones in the market, even those made from other fruits and vegetables. Novelty backed by consumer acceptance could also boost *Opuntia*-based products' marketability. Trial-runs on a small production scale with small product samples could give a pointer to the potential prospect. Product differentiation based on functional and nutritional (improved fibre, antioxidant and mineral content), and physical (aroma, taste, texture, appearance) product characteristics could also be key to the successful sale and acceptance of a product (Fig. 42.4). Unique marketing campaigns, such as those highlighting high-value products and novel products' functionalities, could suffice to improve *Opuntia*-based products' marketability.

6.11 Filling, Packaging, and Storage Peculiarities

Producers of *Opuntia*-based products must take time to familiarise themselves with their product(s) of choice before processing and production. Finished product filling, packaging, and storage before, during, and after production has to be carefully thought out and selected to suit the end product characteristics; otherwise, the entire production process can experience immense wastage if care is not taken (FAO, 2013).

6.12 Economies of Scale

These have to do with weighing business capital for successful operations, as well as infrastructure needs and location, equipment, transportation, target market proximity, utilities, and services (water, electricity, energy), and raw material, and labour availability considerations, among others. Training and cleaning routines should also be factored in. A business plan should be drawn, backed by a feasibility study that addresses these economic aspects. This is integral to reducing the risk of business failure and deciding if a venture is worth starting or investing in.

6.13 Land and Credit Access

Access to land and credit facilities is a limitation in the agro-industrial utilisation of *Opuntia* species. Terms and conditions attached to accessing credit and loan facilities and letting and purchasing arable land for cultivation or production processes vary from region to region. The terms could be continuously evaluated to make land and credits more accessible to subsistent, medium, and large scale investors and growers to boost *Opuntia* species' cultivation for food and non-food applications (FAO, 2013).

6.14 Limited Extension Services and Technical Know-How

Farmer, investors, and stakeholders need to garner efforts to create extension services (Fig. 42.4). Increasing and improving extension services could help bridge the gap of ignorance and increase technical knowledge concerning *Opuntia* cultivation and applications after harvesting. These are integral to getting interested persons, organisations and industries to fully grasp, understand, manage, control and exploit the many opportunities open to them through *Opuntia* cultivation and application. Cactus pear associations may also provide technical assistance where and when required. Training on modern techniques used in other countries may also boost the technical capacity of newcomers and experts.

6.15 The Presence of Spines on Some Opuntia *Varieties*

Spiny *Opuntia* species need regular supervision and pose a major problem. The spines are useful when the plant is used as a hedge or living fence. Innovation is still required to define, design, and evaluate techniques that may be useful for integrating the spiny variants.

In summary of this chapter, the *Opuntia* plant's industrial applications need to be integrated across several industries. Integration is possible when demand and supply and the efficient utilisation of raw materials can be managed and optimised for greater profits and net returns to stakeholders and investors. In regions tackling food security issues, the populace's empowerment through encouraging *Opuntia* species cultivation and *Opuntia*-based products manufacturing can help reduce food insecurity. This is possible since the *Opuntia* plant can grow where others cannot. *Opuntia* species have multiple advantages, which are evident in their many uses in the agro- and other industries compared to other plant species. Also, many non-food applications are itemised here, which are of special value and interest to many industries. These non-food uses require exploitation on an industrial scale. Good manufacturing practices and hygiene must not be overlooked in industrially valuable products from the *Opuntia* plant. A lot still needs to be done concerning setting acceptable standards and thresholds across relevant industries to ensure uniformity in *Opuntia* products that eventually reach the market. The *Opuntia* plant is a perennial which could be exploited as a naturalised resource, even in the wild. Such exploitation should be expanded to include new species and cultivars. The introduction of new management practices, methods, and institutional capacity within the *Opuntia* value chain would bolster the industrialisation and use of the *Opuntia* plant globally.

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