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Opuntia cladodes (nopal): Emerging functional food and dietary supplement

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Abstract. Opuntia cacti are found in prolific abundance in arid regions of the world. The fleshy stems (paddles or nopals) have been a staple vegetable in many parts of Latin America (Central America and Mexico) since long. Even the Southwest US population have developed an interest in them. Now, they have been validated to be good sources of vital phytonutrients *viz*. dietary fibres, vitamins, minerals, mucilage, pectin. The succulent pads packed with nutrition are envisioned to be imbibed in foods for nutritional augmentation. Apart from additives, the mucilage-opulent cladodes have shown promise as encapsulating agents. Several biological roles of nopal *viz*. antioxidant, anti-inflammatory, anti-arthritic, anti-ulcerogenic, anticancer, and hypoglycaemic have been authenticated. This review embodies the recent findings, risks associated, current trends of investigations and untapped potentials of this xerophytic resource. Wide consumption and mass cultivation of nopal is expected to play the dual role of supplying nutrition and averting food insecurity.

Keywords: Nopal, functional food, antioxidant, anti-inflammation, antidiabetic

1. Introduction

Meeting the demand of nutritious food for the ever-expanding, world population is a huge challenge. Amidst this grim scenario, discovery of an inexpensive yet wholesome natural food source can be a great relief. In this regard, the xerophytes cacti hold immense promise. The cladodes of several cacti belonging to family Cactaceae have been evaluated to be safe and healthy, worthy of inclusion in food platter. So far, *Opuntia ficus-indica* or prickly pear cladodes (paddle or nopal) have gained fair popularity.

The spines on the paddles are removed and the fleshy pads are consumed fresh, cooked, dried or as juice (Fig. 1). The paddles are full of antioxidants, dietary fibres, vitamins (A, B complex and C) and minerals (Ca, Mg and Fe). Even, the erstwhile civilizations of Central America, the Aztec and Maya people devoured them. The paddles have been a staple of Mexican cuisine since pre-Hispanic era. They have recently gained popularity in the USA, especially in Latino (California, Arizona) and Tejano (Texas)-populated regions. Several species of *Opuntia* grow wild in deserts, high altitude volcanic regions of Mexico, and chaparrals of US Southwest (Fig. 2). *O. ficus-indica* is farmed in several thousands of hectares in the arid and semiarid regions of Mexico and the paddles are shipped in tons to other countries.

Since ancient times, nopal is being used in folk medicine to cure a variety of ailments. It's used as anti-infective, anti-diarrheal, diuretic and anti-rheumatic. The tea from the cladodes is used to ease colds, coughs, boils, abscesses, cystitis, indigestion, gastroeneteritis, diabetes, high blood cholesterol etc. A diverse range of nopal-based snacks and dietary supplements are now marketed in Mexican and USA markets. This review endeavours to furnish a distilled account of recent findings and prospects ahead, which is believed to drive consumer awareness for this healthy yet lesser-known vegetable.

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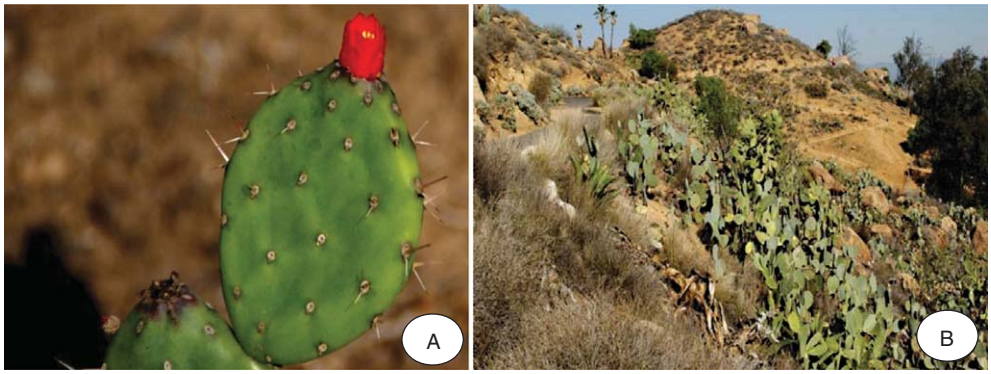

Fig. 1. (A) Opuntia cladode (B) Opuntia growing wild in slopes of South California.

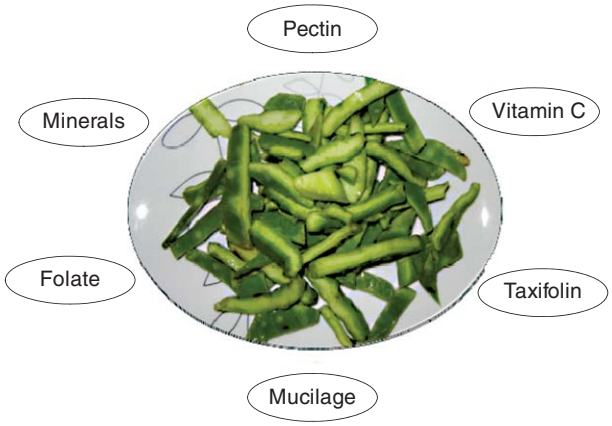

Fig. 2. Biological roles of Opuntia cladodes.

2. Nutritional importance of nopal

Persuasive instances exist to authenticate the food and nutritional supplement potentials of nopal. The recent validated findings have been discussed below.

3. Food and additives

Nopal tastes tart and is slimy in consistency. It's consumed in myriad forms *viz*. raw, grilled or cooked. It's relished as tortilla, frittata, fajita, fry, salsa, burrito, salad, soup, stew, jerky juice, smoothie, yoghurt or tamale. Even top restaurants offer nopal-based delicacies. The possibility of fortifying wheat flour with *O. boldinghii* Britton cladode flour for bread making was evaluated. The substitution at 5–10% demonstrated the best baking behaviour and sensory appeal, with regards to colour, odour, flavour; texture development [1].

Apart from the organoleptic properties, nopal deserves to be incorporated in regular diet for its dietary fibres, prebiotic potential, vitamins and antimicrobial compounds. The fibre contents of Opuntia cladodes were assessed for possible development of functional foods [2]. Also, the effect on the expression of GPR43 (a short chain fatty acids receptor involved in signal transduction mechanisms) was evaluated. This receptor binds with butyrate to generate different physiological effects in colonocytes. O*puntia* diet at 5% concentration had a direct influence on the quantitative expression of GPR43 [3]. The prebiotic effect of *O. ficus-indica* cladode mucilage and pectic-derived

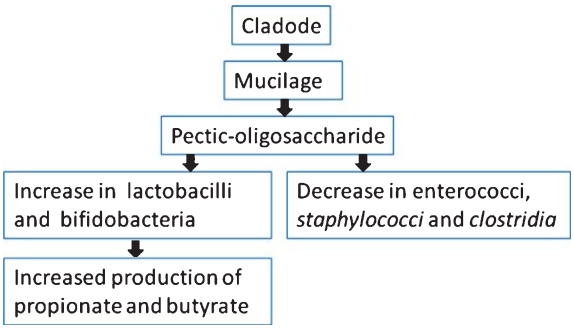

Fig. 3. Opuntia cladode as a prebiotic.

oligosaccharides on the cultures and metabolic activity of microbes from the human colon was investigated. The mucilage-derived oligosaccharide treatment enhanced the lactobacilli growth up to 23.8%, while pectic-derived oligosaccharides increased the bifidobacteria population by 25%. Addition of these oligosaccharides led to a slight decrease in pathogens as *Enterococci*, *Staphylococci* and *Clostridia*. Increased levels of the short-chain fatty acids (SCFA) were attained in the beneficial bacteria cultures by both types of oligosaccharides treatments. Propionate and butyrate production increased to at least 50%. The findings indicate that nopal could be tapped as a prebiotic source [4]. The prebiotic mechanism of nopal-derived oligosaccharides has been illustrated in Fig. 3.

The folate content of nopal was assessed by a microbiological assay, using *Lactobacillus casei* (ATCC 7469) in enzymatically-treated extracts, to release the bound vitamin. Trienzyme treatment (alpha-amylase-protease-conjugase) and ELISA protocol determined the folate content at nanogram level [5].

Natural antimicrobial compounds are often sought after to hold back the spoilage microorganisms. The efficacy of methanolic extracts of *O. ficus-indica* against *Vibrio cholera* was determined. Four fluorogenic techniques were recruited to assess the effect of the extract on membrane integrity of the pathogen. The extract disrupted the cell membranes and raised permeability, leading to decreased cytoplasmic pH and dwindled cellular ATP concentration [6].

4. Edible film and encapsulating agent

Nopal mucilage has demonstrated promise as edible film encapsulating agent for pharmaceutical applications. It was extracted and characterized by its composition and molecular weight distribution. The ability to form edible films under different pH conditions and in presence or absence of calcium was determined. It was observed that mucilage films without addition of calcium have the best water vapour barrier properties and tensile strength [7]. The microcapsules of gallic acid were generated, using nopal mucilage, which demonstrated pseudoplastic behaviour. The results indicated that mucilage could be used as wall material for microencapsulation of gallic acid by the spray-drying process [8]. A cheap and effective natural excipient was developed from the mucilages of *O. ficus-indica* and *O. stricta*. These mucilages showed promise as substitutes of sodium carboxymethylcellulose (NaCMC) for suspending function in paracetamol formulations [9].

5. Oxidative stress and toxicity mitigation

Nopal has shown ability to improve oxidative status and alleviate stress. The biological effects of consuming tortillas or bars supplemented with nopal dietary fibre was evaluated. The addition of nopal increased the fibre and polyphenols content in both foods. The trolox equivalent antioxidant capacity, polyphenols and vitamin C content increased in volunteer's plasma after intake. Also, lower levels of glucose, total cholesterol, low-density lipoprotein and triglycerides were observed in plasma after the supplementation [10]. Non-alcoholic fatty liver disease (NAFLD) is associated with multiple factors such as obesity, insulin resistance, and oxidative stress. The effect of nopal

consumption on the development of hepatic steatosis and hepatic oxidative stress was assessed, emphasizing on the regulation of genes involved in hepatic lipid metabolism. Obese rats fed with a diet containing 4% nopal for 7 week had 50% lower hepatic triacylglycerol than the control group. Also, reduction in hepatomegaly (abnormal enlargement of liver) and biomarkers of hepatocyte injury such as alanine aminotransferase (ALAT) and aspartate aminotransferases (ASAT) were observed. Hepatic reactive oxygen species and lipid peroxidation biomarkers were significantly lower in rats fed nopal compared to the control rats. Furthermore, rats fed the nopal diet had a lower postprandial serum insulin concentration and a greater liver phosphorylated protein kinase B (pAKT):AKT ratio in the postprandial state [11].

The fusarial mycotoxins zearalenone is often associated with detrimental food poisoning, leading to reproductive disorders. The safety and efficacy of *O. ficus* cladodes in prevention of the deleterious effects of the toxin was evaluated in mice models. The combined treatment of zearalenone with the lowest tested dose of cactus extracts (25 mg/kg) showed a total reduction of the toxin-induced oxidative damage for all tested markers [12]. The potency of cactus cladode extract in counteracting the Aflatoxin B1-induced alterations in oxidative stress markers was investigated. Healthy BALB/c (20–25 g) male mice were pre-treated by intraperitonial administration of *O. ficus-indica* (50 mg/Kg) for 2 weeks. The extract increased the expression of pro-apoptotic proteins p53 and bax while decreasing the expression of bcl2. The treatment, before or after exposure to the toxin, led to a major slump in the induced oxidative damage markers and bolstered antioxidant defence, eventually curbing hepatic damage [13]. The protective effects of regular ingestion of juice of *O. ficus indica* cladode juice against nickel chloride ($NiCl_2$) toxicity were evaluated in rat models. The test animals were given 25% of the juice for one month followed by daily injection of $NiCl_2$ for 10 days. Significant increases in lactate dehydrogenase (LDH), ASAT, ALAT activities and as well as raised cholesterol, triglycerides and glucose levels were observed in the blood of control group. These adverse changes were not detected in the nopal-administered group which indicates the protective effect of the cactus [14]. The role of *O. ficus indica* cladode extract against liver damage induced in mice by an organophosphorous insecticide, the chlorpyrifos was investigated. Both chlorpyrifos and cactus extract were administrated orally via gavages. The combined treatment resulted in the normalization of ALAT, ASAT, PAL, LDH, cholesterol and albumin levels in the serum [15]. It was reported that following ingestion of nopal-based tortillas, overall oxidative status of healthy human volunteers improved [16]. *O. humifusa* cladodes were investigated for their antioxidant content. The ethyl acetate fraction from an 80% ethanol extract showed high total phenolic and flavonoid contents. compared to other fractions. The flavanol taxifolin was identified to be the most abundant phenolic compound [17]. *O. ficus-indica* cladode extract when injected intraperitoneally alone or with methotrexate drug for 10 days to rats, could check the side effects caused by the drug. The extract restored the decreased hematocrit, hemoglobin, white blood cells and increased the serum biochemical enzyme activities [18].

6. Joint pain relief

Osteoarthritis is known to be a debilitating disease for which natural remedies are constantly sought-after. The anti-inflammatory effect of lyophilised extracts obtained from *O. ficus indica* (L.) cladode was determined and compared with that of hyaluronic acid. The key molecules (nitric oxide (NO), glycosaminoglycans (GAGs), prostaglandins (PGE2) and reactive oxygen species (ROS)) released from the pro-inflammatory cytokine interleukin-1β (IL-1β)-stimulated human chondrocyte cultures were measured. Further, the antioxidant effect of these extracts was evaluated by DPPH test. The chondro-protective effect of the extracts by suppression of harmful effects of IL-1β was revealed. Also, its superiority over hyaluronic acid in ameliorating the arthritic pain came forth [19]. The effect of calcium intake from a vegetable source on bone mineral density and calciuria in menopausal and non-menopausal women with low bone mass was evaluated. The two-year study revealed that the consumption of nopal improved bone mineral density in the total hip and lumbar spine regions, maintaining constant and normal calciuria levels [20].

7. Wound healing

Plant polysaccharides have oft-been validated to possess wound healing properties. In this regard, the potential of two lyophilized polysaccharide extracts obtained from *O. ficus-indica* (L.) cladodes was evaluated in rat injury

models. When topically applied for 6 days, the polysaccharides exerted a repairing effect on the cutaneous lesions. Re-epithelization and remodelling by influencing the cell-matrix interactions and modulating laminin deposition was derived to be the therapeutic mechanism. It was observed that polysaccharides with molecular weight ranging from 10^4–10^6 Da and hygroscopic, rheological and viscoelastic attributes are better suited for wound-nursing [21].

8. Cancer prevention

Selenium is an essential micro-nutrient with crucial role in redox reactions and ability to curb oxidative stress in cells. Several studies have reported the anti-metastatic capacity of dietary selenium supplementation [22]. A series of spectroscopic and enzymatic digestion tests were conducted to detect selenium in the cladodes of opuntia. It was concluded that opuntia is a secondary selenium-accumulating plant whose cladode contain mostly free seleno-cystathionine and SeMet. When consumed, the organic forms in the cladode are expected to improve health by augmenting selenium intake and thus, help in prevention of multiple human cancers [23]. *O. ficus-indica* extract was investigated for its efficacy against benzo(a)pyrene-induced liver injury and related mechanisms in Balb/C mice. The genotoxin triggers DNA damage as manifested in chromosomal aberrations of bone marrow cells. Also, it promotes the expression of bcl2, lowering that of bax. The cactus extract administered prior to or following the toxin exposure, negated the detrimental effects. Modulation of the expression of p53 was elucidated to be the protective mechanism against the mutagenesis risk [24].

9. Diabetes management

Diabetes mellitus is a metabolic syndrome characterized by abnormally high blood glucose level. Nopal is the most commonly used herbal hypoglycaemic among people of Mexican descent. A systematic review of 58 controlled clinical trials was conducted on individuals with diabetes or impaired glucose tolerance. Nopal showed positive preliminary results, warranting further research [25]. Also, a survey on perception of Hispanics regarding diabetes was conducted. Many of them responded that nopal consumption can attenuate the risk of the metabolic disorder [26]. The hypoglycaemic effects of polysaccharides, prepared from O. monacantha cladodes were determined. It decreased the water consumption, increased food intake and improved the control in blood glucose and serum lipid levels of streptozotocin-induced diabetic rats. The mechanism of hypoglycemic action was assumed to be similar with anti-diabetic drug, dimethylbiguanide [27]. The influence of ethnicity as a predictor of the use of complementary and alternative medicine (CAM) among diabetes patients was evaluated. A questionnaire was administered to 806 participants, to which Hispanics reported using nopal as CAM [28]. It was determined whether *O. humifusa* stem regulates blood glucose levels and hypolipidemic responses in streptozotocin-induced diabetic rats. After 7 weeks of treatment, the fasting blood glucose and triglyceride levels of the opuntia groups were significantly lower when compared to control group. Decrease in serum total cholesterol, low-density lipoprotein cholesterol, ALAT and ASAT was reported. On the other hand, increase in serum high-density lipoprotein cholesterol and relative beta cell volume of pancreas was observed [29]. The effects of *O. ficus-indica* complex on blood glucose metabolism were investigated in db/db mice for a period of 4 weeks. Histopathological analysis showed that the morphology of pancreatic islets was improved in the Opuntia-treated db/db mice. Histochemical and immunological tests confirmed the enhanced insulin production from the pancreatic islets and increase in the number of β-cells [30]. The effects of an *O. ficus-indica* cladode aqueous extract and a proprietary stem/fruit skin-blend (stem/fruit skin ratio 75/25) on blood glucose and plasma insulin was investigated in normal rats. Oral administration of the extract in a dose range of 6–176 mg/kg exerted maximum effect on blood glucose and insulin. The proprietary blend significantly increased the basal plasma insulin level indicating a direct action and superior effect than the extract on the pancreatic beta cells [31]. The effects of a dietary pattern (a blend of soy protein, nopal, chia seed and oat) on the cardiovascular disease and diabetes were evaluated. In this randomized trial, the dietary pattern group had decreased serum total glycerol and C-reactive protein. Also, the participants in this group had a greater decrease in body weight [32]. The anti-hyperglycemic effects of two extracts of *O. streptacantha* cladodes were investigated. The filtered extracts contained (4-hydroxy)-phenyl acetic acid derivate which when administered to STZ-diabetic rats before oral glucose tolerance test, improved the

glycaemic control by blocking the hepatic glucose output, especially in the fasting state [33]. Korean Food and Drug Administration (KFDA) also approves *O. streptacantha* as an effective antidiabetic herbal ingredient [34].

10. Effect of processing, maturity and cultivars

The effects of air-drying flow rates on the amount and antioxidant capacity of *O. ficus indica* cladode extracts were evaluated. Nopal drying at 45°C and air flow rate of 3 m/sec showed higher values of phenols, flavonoids and flavonols. The air flow rate affected the amount of polyphenols and radical scavenging, but did not modify the chain-breaking activity and the low-density lipoprotein inhibition activity [35]. The effect of convective drying on bioactive components and rheology of nopal was assessed. The best conditions for bioactive compound preservation were the drying temperature of 45°C and air flow rate of 3 m/s which resulted in 40.97 g phenols, 23.41 g flavonoids, 0.543 g β-carotene and 0.2815 g ascorbic acid/kg. Non-Newtonian shear-thinning behaviour was ascertained for samples dried at this temperature [36]. The enzymatic hydrolysis of cactus cladode homogenate with a blend of Rapidase and Viscozyme (1:3, v/v) increased the quercetin and isorhamnetin contents, contributing to increase radical scavenging activity [37]. The cladode with peels and without were powdered and compared for their dietary fiber content. The powder with peels contained higher soluble fiber content which was assumed to be due to the mucilage content of epidermis [38].

The physicochemical and nutrimental contents *O. ficus indica* (Redonda variety) fresh nopal and its powder produced at different stages of maturity were compared. The ash content increased from 18.41 to 23.24%, calcium content increased from 1.52 to 3.72%, while phosphorous dropped off from 0.43 to 0.27%, respectively. Calcium oxalate decreased from 7.95 to 3.47 mg/g and the Ca/P ratio varied from 3.6–11. The soluble fibre decreased from 25.22 to 14.91%, while the insoluble fibre increased from 29.87 to 41.65% [39]. It was found that the older cladodes contained more calcium [40]. Nopal powders from three different maturity stages were subjected to various methods of drying. Among the freeze-dried, forced-air oven and tunnel method, freeze-dried proved to be the most efficient in retention of higher contents of protein, soluble fibre, fat and colour. The soluble fibres decreased with the age of nopal, while insoluble fibers and ash content increased [41]. The nutritive value of 16 cultivars and clones of spineless cladodes were evaluated and wide variation in dry matter, Ca, K and oxalates were reported [42].

11. Anticipated risks

It was reviewed that the copious mucilage, spines and pathogen sensitivity are the hurdles in the path of popularity of nopal as a vegetable. Eliminating these undesirable characteristics might boost its approval [43]. Nopal is prone to contamination with salmonella from water and soil, causing risks to the consumer health. So, proper disinfection should be taken care of. Many phytochemicals have pharmacokinetic or pharmacodynamic interactions with drugs. The undesirable herbal interactions between opuntia and anti-diabetic agents (glipizide and metformin), resulting in abnormal hypoglycaemia were reviewed. The underlying mechanism might be the resultant of the additive glucose lowering effect of the cactus and the drugs. It mandates that the patients with type 2 diabetes mellitus should be routinely counselled about the use of herbal products to minimize the risk of adverse drug reactions [44].

12. Current standing and future trends

The formulation of cladode-based balanced diet for ruminants is on the verge of commercialization [45]. This might be possible for human consumption as well, given due interest. Improvement of visual appeal, handling ease and nutritional characteristics of nopal is sure to gain more consumers. Vast swathes of arid, barren lands can be reclaimed by planting these xerophytic vegetables. The cactus industry in Mexico alone is worth $150 million and employs 10,000 workers. Also, it is being grown as cash crop in Central America and Israel. Nopal horticulture ought to be promoted with proper incentives to farmers. Annual Nopal fair (Feria de Nopales) is organized in Mexico and several places in US southwest to motivate people to consume nopal. Microbial fermentation is being regarded as a

strategy for valorisation of nopal. It is touted to be a plant-origin substitute of chitosan. In recent times, chitosan has gained credence as low calorie, food additive with ability to bring satiety [46]. Nopal possessing similar properties might also be useful in tackling weight issues and obesity.

13. Conclusion

To wrap up the topic, nopal has a pool of dietary fibers, phenolic compounds, minerals and vitamins. Further, the physical properties as water retention, oil holding and swelling capacities, non-Newtonian flow behaviour make it desirable for food processing. It is emerging not only as a gourmet, but also a wholesome diet. Additionally, it has incredible potential to be developed as effective dietary supplements and alternative medicines at affordable cost. Its antioxidant abundance could be tapped to detoxify body and minimize the risk of chronic ailments. More clinical trials should be undertaken to dig out its hitherto unknown health benefits. Wider cultivation and consumption must be given a thrust. This review is believed to stimulate research in nopal and contribute to bioprospecting.

Conflict of interest

There is no conflict of interest in submission of this manuscript.

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