Nutritional and Functional Benefits of Cactus Fruit (Opuntia spp.) Bioactives: Implications for Edible Coating Applications

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ABSTRACT *The cactus fruit (Opuntia spp.), commonly known as prickly pear, is a globally recognized source of valuable nutrients and bioactive compounds. This review consolidates recent scientific literature (2018–2024) to elucidate the comprehensive nutritional profile and functional properties of cactus fruit. It is particularly rich in dietary fiber, essential vitamins, minerals, and a diverse array of phytochemicals, including betalains, flavonoids, and phenolic acids. These bioactives confer significant health-promoting attributes, with documented benefits spanning cardiovascular health, modulation of glycemic response, digestive system regulation, potent antioxidant and anti-inflammatory activities, positive effects on dermal health, and robust immune system support. Beyond its direct consumption benefits, this review explores the promising potential of incorporating cactus fruit bioactives into edible coatings. Such applications aim to enhance the preservation of foods, extend their shelf-life, and simultaneously deliver added health benefits to consumers. The discussion delves into the underlying mechanistic insights supported by evidence from scientific literature, complemented by detailed tables presenting compositional data and bioactivity profiles.*

Keywords: Opuntia spp., edible coating, betalains, antioxidant, dietary fiber, functional food, bioactive compounds

1. *INTRODUCTION*

Cactus fruit, derived from various species of the Opuntia genus, has been a staple food source and traditional remedy across many arid and semi-arid regions of the world for centuries. Its unique organoleptic characteristics, coupled with a robust nutritional composition, have led to its increasing recognition and consumption globally. In recent years, scientific research has amplified its importance, highlighting its significant potential in the development of functional foods and its utility as a source of valuable bioactive components for novel applications, such as edible coatings.

The nutritional and therapeutic value of cactus fruit is attributed to its rich and diverse bioactive profile. Key constituents include a high content of dietary fiber, which plays a crucial role in digestive health and metabolic regulation.
Furthermore, it is an excellent source of vitamins, particularly Vitamin C, and essential minerals. Perhaps most significantly, cactus fruit is a notable source of potent phytochemicals, including betalains, a class of pigments responsible for the vibrant colors of many Opuntia fruits, as well as various flavonoids and phenolic acids. These compounds are well-established for their powerful antioxidant and anti-inflammatory properties, contributing to a wide range of health-promoting effects.

This review aims to provide a comprehensive overview of the current scientific understanding of cactus fruit. It will consolidate and analyze existingcompositional data, elucidate the molecular mechanisms underlying its health-related effects, and critically evaluate the evidence for its diverse physiological benefits. A key focus will be on connecting these intrinsic properties to emerging practical applications, particularly in the realm of edible coatings for food preservation, where its bioactives can offer both protective and nutritional advantages.

2. *Nutritional Profile*

The nutritional composition of cactus fruit (Opuntia spp.) is remarkably diverse, offering a spectrum of essential nutrients that contribute to its overall health benefits. Table 1 provides a detailed summary of the proximate composition and key micronutrient content, based on recent analytical studies, presented per 100 grams of fresh fruit pulp. These values are indicative and can vary depending on the specific Opuntia species, ripeness, growing conditions, and post-harvest handling.

Table 1. *Nutritional composition of cactus fruit (per 100 g fresh weight)*

Component	*Amount*
Energy(kcal)	*41-50[1,2,3]*
Carbohydrates(g)	*9.6-13[1,4]*
Protein (g)	*0.5–1.0[5,2]*
Total fiber (g)	*3.0-5.0[1,6]*
Vitamin C (mg)	*14–25[2,4]*
Calcium (mg)	*40–65[5,6]*
Magnesium (mg)	*80–110[4,3]*
Potassium (mg)	*200–260[2,6]*

Detailed Breakdown of Nutritional Components:

- Energy: Cactus fruit is a moderately caloric food, with energy content ranging from 41 to 50 kcal per 100 g of fresh weight. This makes it a suitable component in a balanced diet without contributing excessively to caloric intake.
- Carbohydrates: The primary macronutrient in cactus fruit is carbohydrates, contributing 9.6–13.0 g per 100 g. These carbohydrates are largely composed of natural sugars and, importantly, a significant amount of dietary fiber.
- Protein: The protein content of cactus fruit is relatively low, typically ranging from 0.5 to 1.0 g per 100 g. While not a primary source of protein, it contributes to the overall amino acid profile.
- Dietary Fiber: This is a standout nutritional component. Cactus fruit is exceptionally rich in dietary fiber, with amounts ranging from 3.0 to 5.0 g per 100 g. This fiber content is significant, comprising both soluble and insoluble fractions. The soluble fiber, including pectins and mucilages, contributes to its unique texture and offers substantial health benefits, such as blood glucose and cholesterol regulation.
- Vitamin C (Ascorbic Acid): Cactus fruit is a good source of Vitamin C, providing 14–25 mg per 100 g. Vitamin C is a powerful antioxidant, crucial for immune function, collagen synthesis, and wound healing.

- Minerals: The fruit is also a valuable source of several essential minerals.
    - Calcium: With 40–65 mg per 100 g, it contributes to bone health and various physiological processes.
    - Magnesium: Ranging from 80–110 mg per 100 g, magnesium is vital for numerous enzymatic reactions, muscle and nerve function, and blood glucose control.
    - Potassium: The fruit contains a notable amount of potassium, between 200–260 mg per 100 g, which is essential for maintaining fluid balance, nerve signals, and blood pressure regulation.

The references cited [1-6] represent recent studies that have meticulously analyzed and reported these nutritional values, providing a solid foundation for understanding the intrinsic nutritional power of Opuntia fruits.

3. Bioactive Mechanisms

Beyond its fundamental nutritional profile, cactus fruit is lauded for its rich array of bioactive compounds, which confer specific physiological benefits through various intricate mechanisms. Table 2 synthesizes key bioactive compounds found in Opuntia species and outlines their principal mechanisms of action, linking them to documented health benefits and citing relevant scientific literature.

Table 2. *Bioactive compounds and mechanisms of action*

Bioactive compound	Mechanism of action	Health benefit
Betalains	Reactive oxygen species (ROS) scavenging, modulation of inflammatory pathways (e.g., NF-κB downregulation), chelation of metal ions.	Anti-inflammatory, antioxidant[7,8]
Flavonoids	Inhibition of digestive enzymes (e.g., α-glucosidase), enhancement of endothelial function via nitric oxide production, antioxidant activity.	Glycemic control, heart health[9,10]
Phenolic acids	Inhibition of lipid peroxidation modulation of inflammatory cytokines, direct antioxidant effects, potential enzyme inhibition	Reduced CVD risk[11,12]
Mucilage & pectins modulation	Binding and sequestration of bile acids, delayed gastric emptying, promotion of beneficial gut microbiota, viscosity enhancement. Crucial cofactor for collagen	Cholesterol lowering, satiety, digestive modulation[13,14]
Vitamin C	synthesis, potent ROS scavenger, enhancement of immune cell function and proliferation.	Skin health, immunity[15]

Detailed Explanation of Bioactive Mechanisms:

- Betalains: This unique class of water-soluble pigments, responsible for the characteristic red, purple, and yellow colors of many cactus fruits, exhibits potent antioxidant and anti-inflammatory activities.
    - ROS Scavenging: Betalains are highly effective at neutralizing reactive oxygen species (ROS), thereby protecting cellular components like DNA, proteins, and lipids from oxidative damage. This is a primary mechanism for their antioxidant effects.
    - NF-κB Downregulation: Nuclear factor-kappa B (NF-κB) is a key transcription factor that regulates inflammatory responses. Betalains have been shown to inhibit the activation and nuclear translocation of NF-κB, thereby suppressing the production of pro-inflammatory

mediators such as cytokines (e.g., TNF-α, IL-6). This mechanism underpins their anti-inflammatory properties.
- ◦ Metal Ion Chelation: Some betalains can chelate metal ions like iron and copper, which can otherwise catalyze the formation of free radicals, thus contributing indirectly to antioxidant defense.

• Flavonoids: A broad class of polyphenolic compounds, flavonoids are well-known for their diverse health-promoting effects.

- ◦ α-Glucosidase Inhibition: Many flavonoids can inhibit the activity of α-glucosidase, an enzyme in the small intestine responsible forbreaking down complex carbohydrates into glucose. By inhibiting this enzyme, they slow down glucose absorption into the bloodstream, leading to a more gradual and lower postprandial rise in blood glucose levels. This is crucial for glycemic control and managing type 2 diabetes.
- ◦ Endothelial Function Enhancement: Flavonoids can improve cardiovascular health by enhancing endothelial function. They promote the production and bioavailability of nitric oxide (NO), a potent vasodilator that helps relax blood vessels, improve blood flow, and reduce blood pressure.
- ◦ Antioxidant Activity: Similar to betalains, flavonoids are potent antioxidants, scavenging free radicals and protecting against oxidative stress.

• Phenolic Acids: These are another significant group of polyphenols found in cactus fruit.

- ◦ Lipid Peroxidation Inhibition: Phenolic acids are adept at preventing lipid peroxidation, a damaging process where free radicals attack polyunsaturated fatty acids in cell membranes. This action is critical in preventing cellular damage and contributing to cardiovascular health.
- ◦ Anti-inflammatory Modulation: They can modulate inflammatory pathways by inhibiting the production of pro-inflammatory mediators and influencing signaling cascades involved in inflammation.
- ◦ Direct Antioxidant Effects: Their chemical structure allows them to donate hydrogen atoms to free radicals, stabilizing them and terminating chain reactions.

• Mucilage & Pectins: The high mucilaginous and pectin content of cactus fruit, particularly in the peel and seeds, contributes significantly to its functional properties, especially related to digestion and metabolic health.

- ◦ Bile Acid Sequestration: Soluble fibers like pectins can bind to bile acids in the digestive tract. This binding promotes the excretion of bile acids, which in turn stimulates the liver to produce more bile acids from cholesterol, thereby lowering circulating cholesterol levels.
- ◦ Delayed Gastric Emptying: The viscous nature of mucilage and pectins can slow down the rate at which stomach contents empty into the small intestine. This contributes to a feeling of satiety and helps regulate the absorption of nutrients, including glucose.
- ◦ Gut Microbiota Promotion: These fibers act as prebiotics, serving as a food source for beneficial bacteria in the gut, promoting a healthier gut microbiome.

• Vitamin C: As a well-known essential nutrient, Vitamin C plays multifaceted roles.

◦ Collagen Synthesis: It is an indispensable cofactor for the enzymes involved in the synthesis of collagen, a key structural protein in skin, cartilage, and blood vessels, thus supporting skin health and wound healing.
◦ Immune Cell Activation: Vitamin C supports various immune functions, including the proliferation and function of immune cells, and acts as a potent antioxidant within these cells.

The cited references [7-15] support these proposed mechanisms, highlighting the intricate biochemical interactions of cactus fruit bioactives with biological systems.

4. Discussion

Recent scientific investigations continue to underscore the remarkable versatility of cactus fruit constituents, not only in their capacity to promote human health but also in their significant potential for application in extending the shelf-life of perishable foods, particularly when incorporated into edible coating matrices. The integration of natural, functional ingredients into edible coatings represents burgeoning trend in food science, driven by consumer demand for minimally processed foods with enhanced health profiles and extended usability.

The antioxidant properties of cactus fruit bioactives, particularly betalains and various polyphenols, are of paramount importance in this context. When applied as part of an edible coating, these compounds can act as potent scavengers of reactive oxygen species (ROS) and other free radicals. This capability is instrumental in mitigating oxidative spoilage in fresh produce, which is a major cause of quality deterioration, discoloration, and nutrient loss. By intercepting these damaging agents, cactus fruit extracts can help maintain the visual appeal, texture, flavor, and nutritional integrity of fruits and vegetables. Furthermore, these embedded antioxidants can elicit beneficial physiological responses in consumers, activating endogenous antioxidant defense systems and contributing to overall health protection against cellular damage.

The substantial dietary fiber content of cactus fruit, comprising both soluble and insoluble fractions, offers a dual advantage. Firstly, it plays a critical role in improving cholesterol metabolism and regulating glycemic responses, directly aligning with current nutritional guidelines advocating for the prevention and management of cardiovascular diseases and type 2 diabetes. The ability of fiber to bind bile acids and modulate glucose absorption makes it a key functional component for these metabolic health benefits. Secondly, when incorporated into foods via edible coatings, this fiber contributes to the overall dietary intake, subtly enhancing the nutritional value of the coated product without altering its primary sensory attributes significantly.

Beyond their antioxidant and fiber-related benefits, the synergistic interplay between the micronutrients (such as Vitamin C, calcium, magnesium, and potassium) and the phytonutrients present in cactus fruit further broadens its potential applications. This combined action can support robust immune function, a critical aspect of overall well-being, and contribute to skin integrity through its role in collagen synthesis and protection against oxidative stress. These attributes open avenues for cactus fruit bioactives not only in functional foods but also in functional cosmetic applications, where topical or internal use could yield benefits for skin health and protection.The exploration of cactus fruit bioactives in edible coatings is a promising frontier. These natural compounds offer a sustainable and health-conscious alternative to synthetic preservatives and antioxidants, addressing growing

consumer concerns about food additives. The challenge and opportunity lie in optimizing extraction and encapsulation techniques to ensure the stability and bioavailability of these bioactives within the coating matrix, maximizing their efficacy both in food preservation and in delivering physiological benefits to the consumer.

5. Conclusion

Cactus fruit (Opuntia spp.) stands out as a valuable natural resource, offering a multifaceted profile of nutritional and functional benefits. Its rich composition, characterized by a high content of dietary fiber, essential vitamins, minerals, and potent bioactive compounds such as betalains, flavonoids, and phenolic acids, positions it as a significant ingredient for enhancing both human health and food preservation strategies.

The integration of cactus fruit bioactives into edible coatings represents a particularly innovative and promising application. This approach effectively meets the escalating consumer demand for natural, minimally processed food products that not only offer extended shelf-life but also contribute positively to health and well-being. By harnessing the antioxidant, anti-inflammatory, and metabolic regulatory properties of these natural compounds, edible coatings derived from cactus fruit can serve as an effective barrier against oxidative and microbial spoilage while simultaneously delivering direct physiological benefits to consumers, such as improved cardiovascular health and better glycemic control.

In summary, cactus fruit bioactives are a versatile resource that bridges the gap between functional foods and advanced food preservation technologies. Their utilization in edible coatings offers a sustainable and health-conscious pathway to meet modern food industry challenges and consumer expectations. Continued research into extraction, stabilization, and application methods will further unlock the full potential of this remarkable fruit.

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