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Impact of dehydration technologies on the stability of bioactive compounds in *Opuntia ficus-indica* powder: Implications for functional food development

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Abstract

Opuntia ficus-indica (OFI) cladodes have emerged as a promising plant-based ingredient for functional food and nutraceutical applications due to their high content of thermolabile bioactive compounds, including betalains, vitamin C, and high-molecular-weight mucilage. These constituents collectively contribute to antioxidant activity, modulation of postprandial glycemia, and gut health. However, the high moisture content and water activity of fresh cladodes necessitate dehydration to ensure microbial stability and industrial usability. Dehydration, while essential, imposes thermal, oxidative, and mechanical stresses that may compromise molecular integrity and functional performance. This work critically examines the impact of major dehydration technologies—lyophilization, spray drying, and convective hot-air drying—on the physicochemical stability of OFI bioactives and their functional implications, particularly in the context of Type 2 Diabetes Mellitus (T2DM). Special emphasis is placed on the preservation of the arabinogalactan–protein (AGP) mucilage complex, which governs rheological behavior and glucose diffusion retardation in the gastrointestinal tract. Accumulated evidence indicates that lyophilization provides superior retention of betalains (>90%), vitamin C, and mucilage viscosity by minimizing thermal and oxidative degradation and preserving porous microstructure. In contrast, convective hot-air drying promotes Maillard reactions, oxidative loss of antioxidants, and polysaccharide depolymerization, leading to diminished functional efficacy. Optimized spray drying, particularly when employing low-glycemic carriers such as inulin, represents a viable compromise between quality preservation and industrial feasibility. The review highlights the necessity of aligning dehydration technology and formulation strategies with targeted health claims to ensure the development of evidence-based functional foods.

Keywords: *Opuntia ficus-indica*, dehydration technologies, lyophilization, spray drying, arabinogalactan–protein, betalains, functional foods, type 2 diabetes mellitus

Introduction

The global demand for functional foods derived from plant sources has intensified in response to the rising prevalence of chronic metabolic disorders, particularly Type 2 Diabetes Mellitus (T2DM). Functional foods that provide health benefits beyond basic nutrition are increasingly sought as complementary strategies for disease prevention and management. Within this context, *Opuntia ficus-indica* (L.) Mill, commonly known as prickly pear cactus, has attracted considerable scientific and industrial interest. Native to arid and semi-arid regions, OFI is a drought-resistant plant characterized by minimal agricultural input requirements, making it a sustainable crop under climate stress conditions. Traditionally, OFI cladodes have been consumed as vegetables and used in folk medicine for the treatment of wounds, gastrointestinal disturbances, and metabolic disorders. Contemporary studies confirm that OFI cladodes are rich in soluble dietary fiber, mucilage, phenolic compounds, betalains, vitamins, and minerals, which collectively contribute to antioxidant activity and glycemic regulation [1, 3]. Despite these advantages, the utilization of fresh OFI cladodes is constrained by their extremely high moisture content (typically >90%) and water activity (a_w > 0.95), rendering them highly susceptible to microbial spoilage and enzymatic degradation. Dehydration is therefore indispensable to extend shelf life, reduce transportation costs, and enable incorporation into stable food formulations. However, dehydration processes may significantly alter the chemical structure and functional properties of OFI bioactive compounds. Previous research has largely focused on compositional analysis or isolated processing parameters such as yield, color retention, or moisture reduction. Less attention has been paid to the mechanistic relationship between dehydration-induced molecular changes and physiological functionality, particularly glycemic modulation. This review aims to integrate current knowledge on OFI bioactive chemistry, dehydration technologies, and functional outcomes, with an emphasis on developing functional foods suitable for individuals with T2DM.

Molecular Architecture and Glycemic Interaction Mechanisms

1. Arabinogalactan–Protein (AGP) Mucilage Complex

The mucilage extracted from OFI cladodes is a complex, high-molecular-weight polysaccharide–protein conjugate, commonly classified as an arabinogalactan–protein (AGP) complex with an average molecular weight on the order of 10^6 Da [2,4]. Structurally, the backbone consists predominantly of α-(1→4)-linked D-galacturonic acid residues, interspersed with α-(1→2)-linked L-rhamnose units typical of rhamnogalacturonan-I regions. Side chains composed mainly of β-D-galactose and α-L-arabinose extend from the rhamnose residues, creating a highly hydrated and flexible “hairy” structure. Protein moieties within the AGP complex act as cross-linking nodes, contributing to the formation of a three-dimensional network upon hydration. This hierarchical architecture underpins the exceptional water-holding capacity, viscosity, and viscoelastic behavior of OFI mucilage.

2. Viscosity, Diffusion, and Glucose Entrapment

At physiological pH, deprotonation of carboxyl groups along the galacturonic acid backbone generates electrostatic repulsion, promoting molecular expansion and network formation. Upon hydration in the gastrointestinal tract, this network increases luminal viscosity, thereby reducing the diffusion coefficient of glucose molecules according to the Stokes–Einstein relationship. This physical barrier effect delays glucose absorption across the intestinal epithelium, attenuating postprandial glycemic responses [13].

3. Processing Sensitivity of AGP Structure

The functional performance of OFI mucilage is highly sensitive to processing conditions. Thermal exposure may induce β-elimination reactions within galacturonic acid-rich regions, while mechanical shear—particularly during spray drying atomization—can reduce molecular weight distribution. These alterations compromise hydration capacity, viscosity, and gel-forming ability, ultimately diminishing glycemic modulation efficacy [4, 6].

4. Interactions with Gastrointestinal Physiology

Beyond glucose diffusion retardation, OFI mucilage may influence gastric emptying and satiety due to its high water-holding capacity. Additionally, partial fermentation of neutral sugar side chains by colonic microbiota produces short-chain fatty acids (SCFAs), such as acetate and propionate, which have been associated with improved insulin sensitivity and lipid metabolism [17, 18]. Processing-induced depolymerization may alter fermentation patterns and reduce these secondary metabolic benefits.

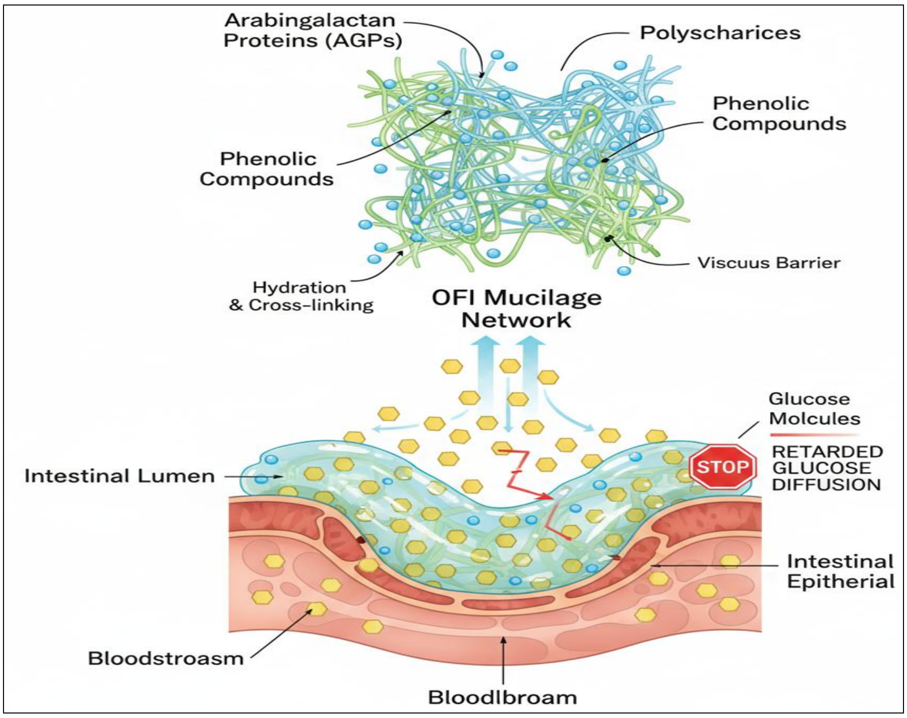

Fig 1: Schematic illustration of OFI mucilage (AGP complex) network formation and its role in retarding glucose diffusion in the gastrointestinal tract [6, 18]

Stability of Low-Molecular-Weight Bioactive Compounds

1. Betalains: Chemistry and Degradation

Betalains are water-soluble nitrogenous pigments exclusive to the Caryophyllales order, comprising red-violet betacyanins and yellow-orange betaxanthins. In OFI cladodes, betanin and indicaxanthin are the predominant forms. These pigments are potent antioxidants but exhibit limited stability under thermal, oxidative, and photolytic conditions. Thermal degradation primarily involves hydrolysis of the central aldimine (C=N) bond, yielding betalamic acid and cyclo-DOPA derivatives. This reaction follows first-order kinetics, with degradation rates approximately doubling for every 10 °C increase in temperature (Q_{10} rule) [1, 7]. Exposure to oxygen and light further accelerates oxidative degradation.

2. Vitamin C Degradation

Vitamin C (L-ascorbic acid) acts as a primary electron donor and is highly sensitive to oxidation during thermal processing. While its initial oxidation product, dehydroascorbic acid, retains vitamin activity, subsequent hydrolysis produces biologically inactive compounds. Prolonged convective drying often results in 60–80% loss of vitamin C content [8].

3. Protective Role of the Mucilage Matrix

The mucilage matrix can partially protect embedded bioactives through hydrogen bonding and physical entrapment, limiting oxygen diffusion. However, once processing temperatures exceed the glass transition temperature of the polysaccharide matrix, structural collapse occurs, negating this protective effect [3].

4. Synergistic Degradation Effects

Degradation of one class of bioactives may accelerate deterioration of others. Vitamin C can participate in non-enzymatic browning reactions under thermal conditions, while betalain degradation products may interact with amino groups, exacerbating Maillard reactions. These synergistic pathways highlight the need for integrated quality assessment during dehydration [20, 21].

Impact of Dehydration Technologies on the Stability and Functional Properties of *Opuntia ficus-indica* Powder

1. Overview of Dehydration Technologies Applied to *Opuntia ficus-indica*

Fresh *Opuntia ficus-indica* (OFI) cladodes possess a moisture content exceeding 85–90% and a water activity typically above 0.95, conditions that favor rapid microbial proliferation and enzymatic degradation shortly after harvest. Dehydration is therefore indispensable to ensure microbiological stability, prolong shelf life, and enable the transformation of OFI into stable functional ingredients suitable for food and nutraceutical applications. Nevertheless, dehydration represents a critical processing step that profoundly influences the chemical stability, molecular architecture, and physiological functionality of OFI bioactive compounds. OFI cladodes are particularly rich in thermolabile and oxidation-sensitive constituents, including betalain pigments, ascorbic acid, and high-molecular-weight mucilage composed mainly of arabinogalactan–protein (AGP) complexes [1, 3]. The functional efficacy of OFI, especially its hypoglycemic and antioxidant properties, is strongly dependent on the preservation of both the chemical integrity and supramolecular organization of these components. Alterations in mucilage molecular weight, chain conformation, or hydration capacity can markedly impair viscosity development and glucose diffusion retardation in the gastrointestinal tract [2, 4]. Among the dehydration technologies investigated for OFI processing, lyophilization (freeze drying), spray drying, and convective hot-air drying are the most extensively studied and industrially relevant methods [1, 4, 10]. These technologies differ substantially in terms of thermal exposure, mechanical stress, oxygen availability, and drying kinetics, resulting in distinct physicochemical transformations within the OFI matrix. The following sections provide a detailed comparative analysis of these dehydration techniques, emphasizing mechanistic links between processing conditions and the resulting functional quality of OFI powders.

2. Detailed Comparative Analysis of Dehydration Technologies

Lyophilization (Freeze Drying)

Lyophilization removes water through ice sublimation under reduced pressure at low temperatures, thereby minimizing thermal and oxidative stress. This technology has consistently demonstrated superior preservation of OFI bioactive compounds, with reported retention levels exceeding 90% for betalains and 85–95% for vitamin C [1, 4]. The formation of a highly porous, honeycomb-like microstructure during freeze drying enables rapid and complete rehydration, allowing mucilage polymers to re-expand and recover viscosities comparable to those of fresh cladode extracts. The preservation of mucilage molecular weight and chain conformation is particularly critical, as it underpins the formation of viscous networks responsible for glucose entrapment and delayed intestinal absorption. Consequently, freeze-dried OFI powders exhibit the highest glucose diffusion retardation capacity and antioxidant activity among the evaluated dehydration methods [2, 3]. Despite these advantages, lyophilization remains economically constrained due to high energy consumption, long processing times, and limited throughput, restricting its application mainly to high-value nutraceutical and pharmaceutical products.

Spray Drying

Spray drying is a continuous dehydration process in which liquid OFI extracts are atomized into fine droplets and dried rapidly in a stream of hot air, typically at inlet temperatures of 120 – 180°C. Although such temperatures are high, the extremely short residence time (on the order of seconds) significantly limits thermal degradation. Optimized spray drying conditions can retain approximately 75 – 85% of betalains and 60 – 80% of vitamin C in OFI powders [4, 10]. However, spray drying imposes substantial mechanical shear during atomization and requires feed solutions with relatively low viscosity, which conflicts with the naturally high viscosity of OFI mucilage solutions. Shear-induced depolymerization of AGP complexes can reduce rehydrated viscosity and weaken viscoelastic behavior, thereby partially compromising glycemic modulation capacity [6]. To mitigate these limitations, the incorporation of appropriate carrier agents is indispensable, as discussed in Section

Convective Hot-Air Drying

Convective hot-air drying involves prolonged exposure of OFI tissues to heated air, typically at 50–70°C for 12–48 h. While this method is economically attractive and technologically simple, it consistently results in the most severe degradation of OFI bioactive compounds. Extended drying times promote oxidative reactions, Maillard browning, and extensive loss of vitamin C, often exceeding 50% of the initial content [1, 7]. Thermal hydrolysis and β-elimination reactions within galacturonic acid-rich regions of the mucilage lead to significant molecular weight reduction, loss of hydration capacity, and drastic decreases in rehydrated viscosity [12]. A comparative summary of the major physicochemical and functional impacts of lyophilization, spray drying, and convective hot-air drying on OFI powder is presented in Table 1. The table highlights the trade-offs between bioactive retention, microstructural preservation, and industrial feasibility among the evaluated dehydration technologies, thereby supporting the mechanistic discussion in this section [1, 4, 10, 12].

Table 1. Comparative effects of dehydration technologies on physicochemical and functional quality attributes of *Opuntia ficus-indica* cladode powder [1, 4, 7, 10, 12]

Quality attribute	**Lyophilization (Freeze drying)**	**Spray drying**	**Convective hot-air drying**
Drying principle	Ice sublimation under vacuum at low temperature	Rapid evaporation of atomized droplets in hot air	Moisture removal by prolonged exposure to heated air
Typical conditions	−40 to −10 °C; high vacuum	Inlet 120–180 °C; outlet 60–90 °C	50–70 °C; 12–48 h
Thermal stress	Very low	Moderate (short exposure)	High (long exposure)
Mechanical stress	Negligible	High (atomization shear)	Low
Microstructure	Porous, honeycomb-like	Spherical or shriveled particles	Dense, collapsed, case-hardened
Rehydration behavior	Rapid and complete	Rapid, carrier-dependent	Slow and incomplete
Betalain retention (%)	90–98%	75–85%	40–60%
Vitamin C retention (%)	85–95%	60–80%	< 50%
Mucilage molecular integrity	Preserved	Partially degraded	Extensively degraded
Rehydrated viscosity	Comparable to fresh	Slightly reduced	Drastically reduced
Glucose diffusion retardation	High	Moderate	Low
Production cost	Very high	Medium	Low
Industrial scalability	Limited	Excellent	Excellent
Recommended applications	Nutraceuticals, pharmaceuticals	Functional foods and beverages	Low-value ingredients

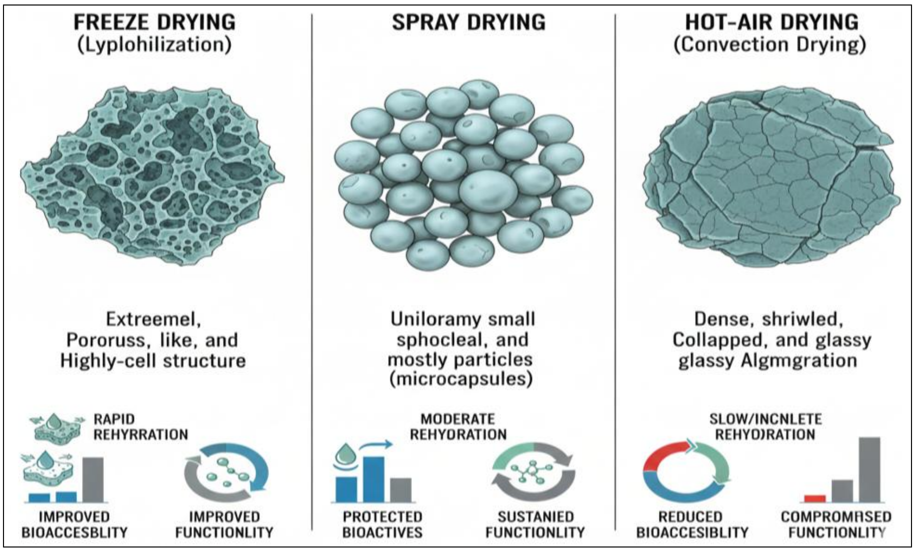

Fig 2: *Opuntia ficus-indica* powders produced by different dehydration technologies and their implications for rehydration and functionality [7, 14]

3. Role of Carrier Agents in Spray Drying of OFI

The application of spray drying to OFI extracts necessitates the use of carrier agents to improve drying efficiency, reduce stickiness, and protect sensitive bioactive compounds. Carrier materials increase the glass transition temperature of the drying matrix, enhance powder flowability, and provide a protective barrier against thermal and oxidative degradation [10, 11]. Maltodextrin is widely employed in spray drying due to its low cost and favorable technological properties; however, its high glycemic index (GI 85–105) fundamentally contradicts the intended hypoglycemic functionality of OFI-based products [11]. The incorporation of maltodextrin may therefore diminish or negate the metabolic benefits associated with OFI mucilage. Gum arabic offers superior film-forming and emulsifying properties and has been shown to enhance betalain stability, but its high cost and supply variability limit its industrial attractiveness [5]. Inulin has emerged as a particularly suitable carrier for OFI spray drying, owing to it's near-zero glycemic index, prebiotic properties, and compatibility with functional food formulations. Inulin-based systems effectively protect betalains and vitamin C while simultaneously enhancing the dietary fiber content of the final product [11, 16]. Binary carrier systems combining inulin with gum arabic or modified starches provide an optimal balance between technological performance and metabolic suitability. For diabetes-oriented OFI products, the exclusion of maltodextrin and preferential use of inulin-containing carriers should be regarded as a critical formulation criterion rather than an optional modification.

4. Industrial Feasibility and Application-Oriented Selection of Dehydration Methods

The selection of an appropriate dehydration technology for OFI must reconcile quality preservation with economic and industrial considerations. Lyophilization remains the benchmark for preserving molecular integrity, antioxidant capacity, and rheological functionality, making it ideally suited for high-value nutraceutical and pharmaceutical applications. However, its high production costs and limited scalability constrain its use in mass-market products. Spray drying, when combined with low-glycemic carrier systems such as inulin-based matrices, represents the most viable option for large-scale production of OFI functional ingredients. This approach offers a favorable compromise between bioactive retention, functional performance, and production cost, enabling incorporation into beverages, dietary supplements, and functional foods targeting metabolic health [10, 12]. In contrast, convective hot-air drying, despite its economic advantages, fails to meet the quality requirements for functional OFI powders and should be avoided in applications where glycemic modulation and antioxidant efficacy are primary objectives. From a quality control perspective, conventional parameters such as moisture content and color are insufficient to guarantee functional performance. Instead, intrinsic viscosity, mucilage molecular weight distribution, and betalain content should be established as critical quality attributes (CQAs) for commercial OFI powders [2, 6]. Future research should focus on hybrid dehydration technologies, including vacuum spray drying and microwave–vacuum drying, which may bridge the gap between the superior quality of freeze drying and the economic advantages of spray drying [12, 24].

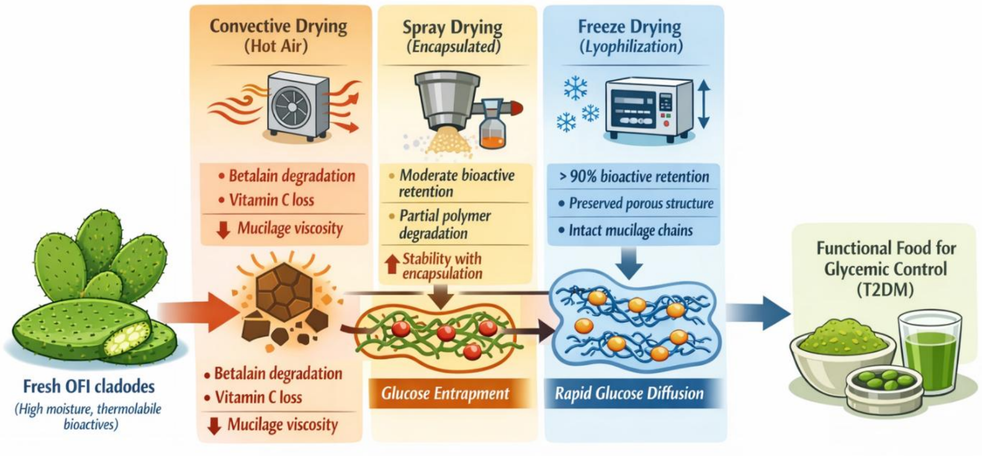

Fig 3: Effect of dehydration technologies on bioactive stability in *Opuntia* ficus indica [20, 24]

Functional Implications for Type 2 Diabetes Management

1. Rheological Integrity and Glycemic Control

In vitro digestion models demonstrate that lyophilized OFI powders exhibit significantly higher glucose diffusion retardation indices than hot-air-dried powders. This effect correlates directly with preserved mucilage viscosity and molecular weight distribution, underscoring the importance of structural integrity for glycemic modulation [2, 13].

2. Antioxidant Preservation and Oxidative Stress

T2DM is characterized by chronic oxidative stress, contributing to β-cell dysfunction and vascular complications. Preservation of betalains and vitamin C enhances the antioxidant capacity of OFI powders, offering potential cytoprotective benefits against glucotoxicity [3, 7].

3. Formulation and Translational Challenges

Incorporation of OFI powders into food products exposes them to secondary thermal and mechanical stresses. Encapsulation strategies, protective packaging, and controlled storage conditions are therefore essential to maintain functional efficacy throughout shelf life [23, 24].

Conclusion

The functional performance of *Opuntia ficus-indica* powders is intrinsically linked to dehydration technology and formulation strategy. Lyophilization remains the gold standard for preserving bioactive integrity but is economically restrictive. Optimized spray drying, particularly with low-glycemic carriers such as inulin, represents the most realistic pathway for large-scale functional food production targeting T2DM. Conventional hot-air drying, despite its low cost, results in substantial functional degradation and should be avoided when metabolic health claims are pursued. Future research should prioritize hybrid drying technologies, establish intrinsic viscosity and molecular weight distribution as critical quality attributes, and validate *in vitro* findings through *in vivo* and clinical studies. Such efforts will facilitate the translation of OFI’s biochemical potential into evidence-based functional foods capable of addressing the growing global burden of metabolic disorders.

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