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The therapeutic potential of *Opuntia ficus-indica* powder as a functional food for the management of type 2 diabetes mellitus: A comprehensive review

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Abstract

Type 2 diabetes mellitus (T2DM) is a rapidly escalating global health concern characterized by chronic hyperglycemia, insulin resistance, and progressive pancreatic β-cell dysfunction. Although pharmacological therapies remain the cornerstone of T2DM management, their long-term effectiveness is often constrained by adverse effects, economic burden, and suboptimal adherence, thereby stimulating growing interest in complementary nutritional strategies. *Opuntia ficus-indica* (OFI), commonly known as prickly pear cactus, has a long history of traditional use in glycemic control and has recently attracted scientific attention as a functional food with antidiabetic potential. This comprehensive review critically synthesizes current evidence on the therapeutic relevance of dehydrated OFI cladode powder in T2DM management. Particular emphasis is placed on its phytochemical composition, including soluble dietary fibers (mucilage and pectin), polyphenols, flavonoids, betalains, and essential micronutrients, as well as the influence of processing technologies on bioactive stability. The molecular mechanisms underlying its hypoglycemic effects—such as inhibition of carbohydrate-hydrolyzing enzymes, activation of AMP-activated protein kinase (AMPK), enhancement of insulin sensitivity, modulation of gut microbiota, and attenuation of oxidative stress—are systematically discussed. Evidence from preclinical models and human clinical studies is critically evaluated to assess efficacy, safety, and translational applicability in functional food development. Collectively, available data support OFI cladode powder as a promising, safe, and sustainable dietary adjunct for improving glycemic control in T2DM, while highlighting the need for standardized production and large-scale clinical trials.

Keywords: *Opuntia ficus-indica*, type 2 diabetes mellitus, functional foods, hypoglycemic activity, dietary fiber, polyphenols, gut microbiota

Introduction

1. Global burden of type 2 diabetes mellitus

Type 2 diabetes mellitus (T2DM) is a chronic, multifactorial metabolic disorder characterized by persistent hyperglycemia arising from insulin resistance, impaired insulin secretion, or both. The International Diabetes Federation (IDF) estimates that more than 537 million adults were living with diabetes worldwide in 2021, a figure projected to exceed 700 million by 2045 [1]. This unprecedented rise is primarily driven by population aging, urbanization, sedentary lifestyles, and increased consumption of energy-dense diets. Sustained hyperglycemia plays a central role in the pathogenesis of diabetic complications by promoting oxidative stress, chronic low-grade inflammation, endothelial dysfunction, and mitochondrial damage. These mechanisms ultimately lead to microvascular complications—such as retinopathy, nephropathy, and neuropathy- and macrovascular diseases, including coronary artery disease and stroke. Beyond its clinical consequences, T2DM imposes a substantial economic burden, accounting for a significant proportion of healthcare expenditures worldwide. Pharmacological interventions, including metformin, sulfonylureas, insulin, GLP-1 receptor agonists, and SGLT-2 inhibitors, are effective in glycemic control. However, their long-term use is frequently limited by gastrointestinal intolerance, hypoglycemia, weight gain, high costs, and declining adherence [2]. These challenges underscore the importance of adjunctive strategies that can support metabolic control while reducing reliance on medication.

2. Functional foods in diabetes management

Functional foods are increasingly recognized as integral components of dietary strategies for chronic disease prevention and management. Defined as foods that confer health benefits beyond basic nutrition, functional foods exert their effects through bioactive compounds that modulate metabolic, inflammatory, and oxidative pathways [3]. In the context of T2DM, dietary components capable of slowing carbohydrate absorption, improving insulin sensitivity, and attenuating oxidative stress are of particular interest. Plant-based functional foods are especially attractive due to their complex phytochemical matrices and favorable safety profiles. Among these, *Opuntia ficus-indica* has emerged as a promising candidate owing to its high soluble fiber content, antioxidant capacity, and longstanding use in traditional medicine.

3. *Opuntia ficus-indica*: ethnomedicine to evidence-based nutrition

Opuntia ficus-indica (L.) Mill, commonly known as prickly pear cactus or nopal, is native to Mexico and widely cultivated in arid and semi-arid regions worldwide. Its cladodes (young pads) have been traditionally consumed as vegetables and medicinal foods, particularly for the management of diabetes, hyperlipidemia, and gastrointestinal disorders [4]. Advances in food processing technologies have facilitated the development of dehydrated OFI cladode powder, offering extended shelf life, standardized dosing, and greater versatility in functional food applications. This review aims to critically synthesize current evidence on the phytochemical composition, mechanistic pathways, and clinical relevance of OFI cladode powder as a functional food for the management of T2DM.

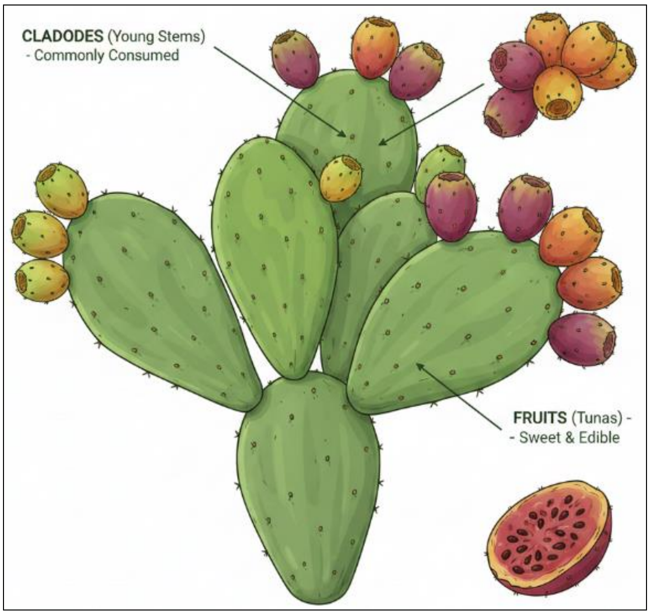

Fig 1: Botanical structure of *Opuntia ficus-indica* and commonly consumed plant parts (cladodes and fruits) [2, 4]

Phytochemical Composition and Nutritional Profile

1. Dietary fiber: mucilage and pectin

OFI cladode powder is exceptionally rich in dietary fiber, with total fiber content often exceeding 40 - 50% of dry weight [5]. A substantial proportion of this fiber is soluble, primarily in the form of mucilage and pectin. Mucilage is a heteropolysaccharide hydrocolloid composed mainly of arabinose, galactose, rhamnose, and xylose. Its high water-binding capacity enables the formation of viscous gels in the gastrointestinal tract. Pectin, another soluble fiber, interacts with glucose and bile acids, forming a physical matrix that delays nutrient diffusion. These physicochemical properties increase intestinal viscosity, slow gastric emptying, and reduce the rate of glucose absorption across the intestinal epithelium, thereby attenuating postprandial glycemic excursions [6].

2. Polyphenols and flavonoids

OFI cladode powder contains a diverse array of phenolic compounds with strong antioxidant activity. The most abundant flavonoids are glycosylated derivatives of isorhamnetin, quercetin, and kaempferol, with isorhamnetin-3-O-glucoside and isorhamnetin-3-O-rutinoside considered key bioactive markers [7]. Beyond their antioxidant properties, these compounds modulate intracellular signaling pathways involved in glucose uptake, insulin sensitivity, and inflammation. Isorhamnetin derivatives have been shown to interact with carbohydrate-hydrolyzing enzymes and metabolic kinases, supporting their role in glycemic regulation.

3. Betalains

OFI is one of the few plant sources of betalains, nitrogen-containing pigments classified as betacyanins and betaxanthins. Although more abundant in fruits, cladodes contain physiologically relevant levels. Betalains exhibit potent antioxidant and anti-inflammatory activities, which are particularly relevant in mitigating diabetes-associated oxidative stress and meta-inflammation [8].

4. Essential micronutrients

OFI cladode powder provides essential minerals that support glucose homeostasis, including magnesium, zinc, chromium, and calcium. Magnesium, in particular, acts as a cofactor for insulin receptor tyrosine kinase activity and is frequently deficient in individuals with T2DM.

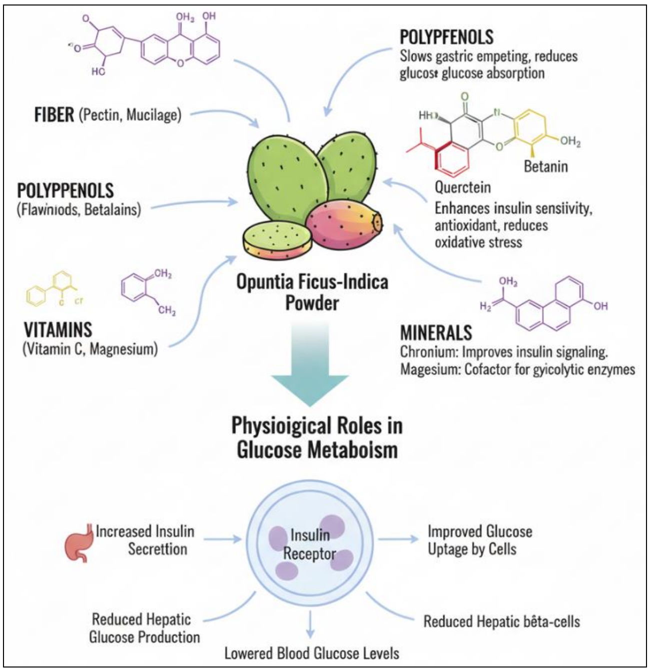

Fig 2: Major bioactive components of *Opuntia ficus-indica* powder and their physiological roles in glucose metabolism [6, 8]

Impact of Processing Technologies on Bioactive Stability

Given the exceptionally high moisture content of fresh *Opuntia ficus-indica* cladodes (typically 88–95%), dehydration is indispensable for preservation, safe storage, and subsequent incorporation into functional food products [5, 7]. However, processing conditions strongly influence the stability, extractability, and biological functionality of OFI bioactive compounds, including soluble dietary fibers, phenolic compounds, flavonoids, betalains, and antioxidant constituents that are implicated in glycemic regulation [5, 8].

1. Freeze-drying (lyophilization)

Freeze-drying is widely recognized as the most effective technique for preserving thermolabile bioactive compounds in OFI cladodes. By removing water through sublimation under low temperature and reduced pressure, freeze-drying minimizes oxidative degradation, enzymatic activity, and structural collapse of plant tissues. Ramirez-Moreno *et al.* [9] reported that freeze-dried OFI cladode powders retained more than 90% of total phenolics and antioxidant capacity compared with fresh material. Additionally, betalains and ascorbic acid, which are highly sensitive to heat, exhibited significantly higher retention than in conventionally dried samples. From a functional standpoint, freeze-drying preserves the native polymeric structure of OFI mucilage, maintaining its high water-holding capacity and viscosity upon rehydration. This characteristic is particularly relevant for glycemic control, as increased gastrointestinal viscosity has been associated with delayed gastric emptying and reduced postprandial glucose absorption [8, 11]. Despite these advantages, freeze-drying is associated with high operational costs, long processing times, and substantial energy demand, limiting its feasibility for large-scale industrial applications.

2. Spray-drying

Spray-drying is frequently employed for the industrial production of OFI powders and extracts due to its scalability, continuous operation, and cost efficiency. Medina-Torres *et al*. [10] demonstrated that spray-drying OFI mucilage produces fine powders with good solubility and flowability, characteristics desirable for food and nutraceutical formulations. Nevertheless, the elevated inlet temperatures commonly used in spray-drying (120–180 °C) can induce partial degradation of heat-sensitive compounds such as flavonoids and betalains if process parameters are not adequately optimized. To mitigate thermal and oxidative losses, encapsulating agents such as maltodextrin or gum arabic are often incorporated, forming a protective matrix around bioactive compounds and improving powder stability [10]. When appropriately optimized, spray-drying can retain approximately 70–80% of total phenolics and antioxidant activity while producing standardized ingredients suitable for functional food applications. However, compared with whole cladode flours, spray-dried powders may exhibit reduced apparent viscosity, potentially attenuating their ability to physically retard intestinal glucose diffusion [8].

3. Convective hot-air drying

Convective hot-air drying remains the most commonly used dehydration technique due to its simplicity, low capital investment, and wide availability. However, drying temperature and airflow conditions critically affect bioactive retention. High drying temperatures (>60 °C) have been associated with significant reductions in total phenolic content, antioxidant capacity, and betalain stability, along with undesirable color changes and non-enzymatic browning reactions [5, 7].

In contrast, low-temperature hot-air drying (40–50 °C) under controlled conditions has been shown to preserve a substantial proportion of bioactive compounds while maintaining acceptable functional properties. Interestingly, moderate thermal processing may enhance the release of certain bound phenolic compounds by disrupting cell wall structures, thereby increasing their extractability, although this effect is often counterbalanced by overall oxidative losses [13]. Compared with freeze-dried powders, hot-air-dried OFI products generally exhibit lower solubility and rehydration capacity but remain suitable for incorporation into bakery products and solid food matrices [19].

4. Implications for antidiabetic efficacy and product development

The selection of processing technology has direct implications for the antidiabetic potential of OFI-based products. For applications targeting postprandial glycemic control, preservation of soluble fiber viscosity and mucilage integrity is critical, favoring freeze-dried or minimally processed powders [8, 16]. Conversely, for formulations emphasizing antioxidant and insulin-sensitizing effects mediated by flavonoids and phenolic compounds, spray-dried extracts standardized to specific markers may provide a practical and scalable alternative [11, 12]. Consequently, aligning processing strategies with intended physiological outcomes is essential for maximizing the functional efficacy and clinical relevance of OFI-derived ingredients.

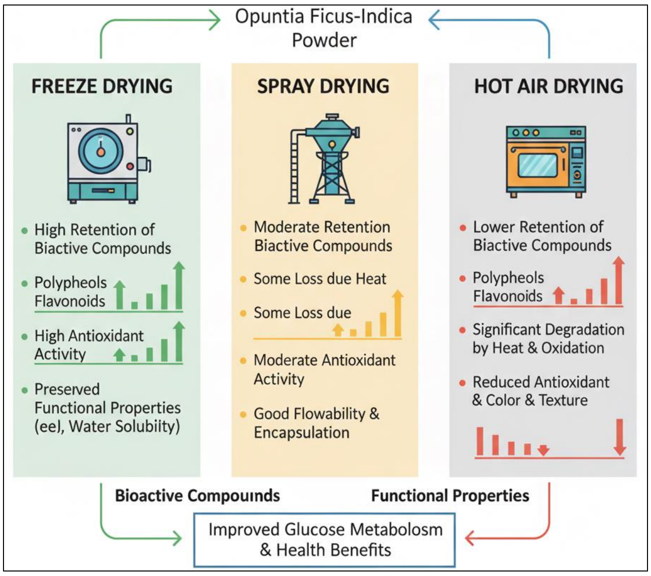

Fig 3: Effect of different drying techniques on the retention of bioactive compounds and functional properties of *Opuntia ficus-indica* powder [11, 16]

Mechanisms of Action in Glucose Homeostasis

The hypoglycemic effects of OFI powder arise from complementary intraluminal and systemic mechanisms. OFI extracts inhibit α-amylase and α-glucosidase activities, slowing carbohydrate digestion and reducing postprandial glucose spikes [11]. Flavonoids such as isorhamnetin activate AMPK, enhancing glucose uptake in skeletal muscle and suppressing hepatic gluconeogenesis [12]. Antioxidant compounds mitigate glucotoxicity and protect pancreatic β-cells by reducing oxidative stress and upregulating endogenous antioxidant enzymes [13]. Additionally, OFI fibers modulate gut microbiota composition, promoting short-chain fatty acid production and incretin secretion, thereby improving insulin sensitivity and satiety [15].

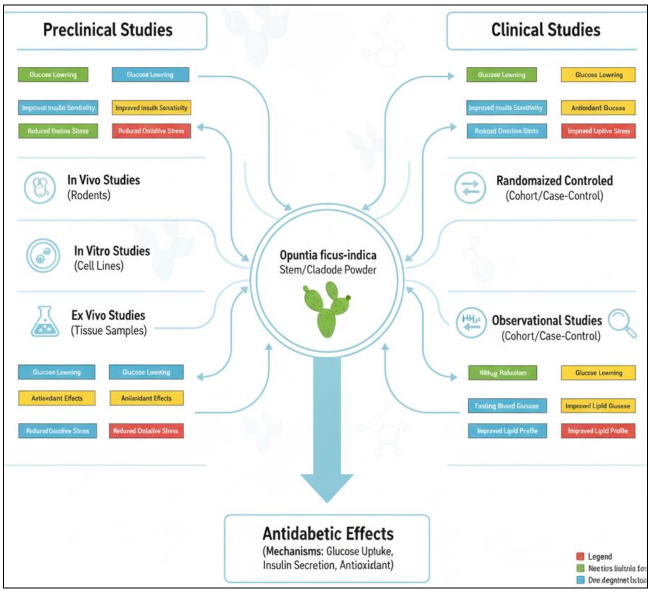

Fig 4: Evidence map of preclinical and clinical studies evaluating the antidiabetic effects of *Opuntia ficus-indica*

Preclinical Evidence

Animal studies consistently demonstrate that dietary supplementation with OFI cladode powder reduces fasting blood glucose, improves lipid profiles, and preserves pancreatic architecture in streptozotocin-induced diabetic and insulin-resistant models [14].

Clinical Evidence

Human studies indicate that acute consumption of OFI significantly lowers postprandial glucose and insulin responses [16]. Longer-term supplementation trials have reported reductions in HbA1c and improvements in metabolic parameters, although outcomes vary depending on product standardization and dosage [17].

Safety and Drug–Nutrient Interactions

OFI powder has been successfully incorporated into bakery products, cereals, dairy matrices, and beverages, enhancing dietary fiber content and lowering glycemic index while presenting manageable sensory challenges [19].

Challenges and Future Perspectives

OFI is generally recognized as safe. Reported adverse effects are mild and primarily gastrointestinal. Oxalate content and potential interactions with orally administered drugs warrant appropriate processing and consumption timing [18, 20].

Fig 5: Factors influencing the efficacy and standardization of *Opuntia ficus-indica* cladode powder as a functional food ingredient [15, 20]

Conclusion

Collectively, available evidence supports *Opuntia ficus-indica* cladode powder as a multifunctional and promising functional food for the management of type 2 diabetes mellitus. Its hypoglycemic effects arise from synergistic mechanisms, including the physical retardation of glucose absorption by soluble dietary fibers, enhancement of insulin sensitivity through flavonoid-mediated AMPK activation, antioxidant protection of pancreatic β-cells, and prebiotic modulation of gut microbiota. These complementary pathways position OFI powder as a valuable dietary adjunct rather than a substitute for conventional pharmacotherapy. Despite encouraging preclinical and clinical findings, several challenges remain. Considerable variability exists among commercial “nopal powders” due to differences in cultivar, cladode maturity, harvesting season, and processing technology, leading to inconsistent fiber composition and bioactive content. Furthermore, most clinical studies to date have involved small sample sizes, short intervention periods, and heterogeneous product formulations, limiting the generalizability of outcomes. The lack of standardized biomarkers and dose–response data further complicates clinical translation. Future research should prioritize the standardization of OFI cladode powder based on defined physicochemical and phytochemical markers, such as soluble fiber viscosity and isorhamnetin glycoside content. Large-scale, well-designed randomized controlled trials are required to establish optimal dosage, long-term safety, and interactions with antidiabetic medications. From a broader perspective, the cultivation of *Opuntia ficus-indica*, a drought-tolerant CAM plant, aligns with global sustainability goals and offers a climate-resilient strategy for developing functional foods that support metabolic health. Collectively, these efforts will be critical for integrating OFI-based products into evidence-based nutritional guidelines for diabetes management.

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