



Green valorization of *Opuntia ficus-indica* cladodes for low-glycemic reformulation of Vietnamese staple foods

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Abstract

The increasing prevalence of type 2 diabetes mellitus (T2DM) in Southeast Asia has intensified the need for culturally acceptable, nutritionally improved staple foods produced through sustainable and environmentally benign processes. This study explores the green valorization of *Opuntia ficus-indica* cladodes—an underutilized, drought-resilient biomass widely available in the South-Central Coast of Vietnam—as a functional ingredient for the reformulation of traditional rice- and wheat-based foods. Nopal cladode powder (NCP) was produced using a low-temperature, energy-efficient convective drying protocol and incorporated into Vietnamese thick noodles (*Banh canh*), rice paper (*Banh trang*), and wheat bread (*Banh mi*) at substitution levels ranging from 0 to 20% (w/w). The effects of NCP incorporation on proximate composition, color attributes, textural behavior, and *in vitro* starch digestibility were systematically evaluated. Results demonstrated a substantial increase in total dietary fiber (up to 14.8%) and mineral ash content, accompanied by significant modifications in water absorption and starch gelatinization behavior attributable to the hydrocolloid nature of nopal mucilage. *In vitro* digestion assays revealed a reduced starch hydrolysis rate, indicating a lower predicted glycemic index. A Life Cycle Thinking (LCA-lite) assessment further highlighted the environmental advantages of valorizing *Opuntia* cladodes, including low water demand, minimal agrochemical inputs, and the upcycling of agricultural residues. Overall, the study demonstrates that *Opuntia ficus-indica* cladodes represent a promising green chemistry solution for sustainable food reformulation and metabolic health promotion.

Keywords: Green chemistry, *Opuntia ficus-indica*, nopal mucilage, glycemic index, sustainable food systems, biomass valorization

Introduction

Green Chemistry and Sustainable Food Systems

Green chemistry provides a conceptual and practical framework for designing products and processes that reduce or eliminate hazardous substances while improving resource efficiency and sustainability [1]. Although originally developed within chemical manufacturing, green chemistry principles have increasingly been applied to food systems, where environmental sustainability, public health, and socio-economic resilience intersect [2, 8]. In this context, the valorization of renewable biomass into functional food ingredients represents a particularly attractive strategy, as it simultaneously addresses waste reduction, resource efficiency, and nutritional enhancement.

Glycemic Burden of Staple Foods in Vietnam

Dietary transitions in Southeast Asia have been accompanied by a marked increase in non-communicable diseases, particularly type 2 diabetes mellitus (T2DM). In Vietnam, refined rice and wheat-based foods remain central to daily diets and are characterized by high glycemic indices (GI), often exceeding 70 [3, 4]. Epidemiological evidence links frequent consumption of high-GI foods to postprandial hyperglycemia and elevated T2DM risk [4]. Importantly, public health interventions that require drastic dietary changes often face cultural resistance. Therefore, reformulating traditional staples to reduce glycemic impact while preserving sensory and culinary identity is considered a pragmatic and culturally sensitive approach.

Opuntia ficus-indica as a Climate-Resilient Functional Biomass

Opuntia ficus-indica, commonly known as nopal cactus, is a Crassulacean Acid Metabolism (CAM) plant renowned for its exceptional water-use efficiency and adaptability to arid and semi-arid environments [5]. Its cladodes are rich in soluble dietary fiber, pectin, mucilage polysaccharides, minerals (Ca, Mg, K), and antioxidant phytochemicals [6, 14]. Despite these attributes, cladodes are frequently discarded or underutilized in Vietnam, where *Opuntia* cultivation has expanded in drought-prone coastal regions. International studies have demonstrated that nopal powder can be successfully incorporated into bread, pasta, and biscuit formulations, improving dietary fiber content, modifying dough rheology, and reducing starch digestibility [7, 18–21]. However, limited research has explored its application in Southeast Asian rice-based food matrices, which differ fundamentally from gluten-based systems.

Objectives and Novelty

The present study aims to bridge this gap by investigating the functional incorporation of Vietnamese *Opuntia ficus-indica* cladode powder into traditional staple foods. Specifically, the objectives are to: (i) develop a green, low-temperature process for producing nopal cladode powder (NCP); (ii) evaluate its physicochemical and functional effects in rice- and wheat-based foods; (iii) assess its potential to reduce starch digestibility using *in vitro*

methods; and (iv) contextualize the findings within a Life Cycle Thinking (LCA-lite) framework aligned with green chemistry principles. The novelty of this work lies in its

integration of food chemistry, nutritional functionality, and sustainability assessment within a culturally relevant food system.

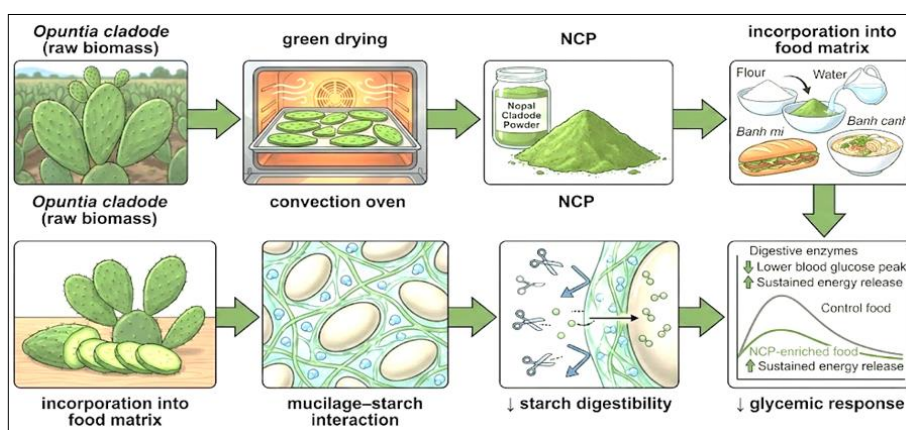


Fig 1: Conceptual framework of *Opuntia cladode* valorization for low-glycemic functional foods

Materials and Methods

1. Raw Materials

Fresh *Opuntia ficus-indica* cladodes (young to medium maturity, 20–30 cm length) were harvested from local farms in Bac Binh District, Binh Thuan Province, Vietnam. Commercial rice flour (*Oryza sativa*) and wheat flour (Type 11, 11% protein) were sourced from a certified supplier in Ho Chi Minh City.

2. Production of Nopal Cladode Powder (NCP)

Cladodes were washed, manually de-spined, and sliced into 2–3 mm strips. Blanching was conducted at 95 °C for 2 min to inactivate enzymes and reduce microbial load. Drying followed a stepwise convective protocol adapted from Vega-Gálvez *et al.* [10]: 60 °C for 2 h (initial moisture removal), 50 °C for 18 h (controlled dehydration), and 45 °C until constant weight (<5% moisture). Dried material was milled and sieved through a 200-mesh screen (74 µm).

3. Product Formulation

NCP replaced rice or wheat flour at 0, 5, 10, 15, and 20% (w/w). *Banh mi* was prepared using a straight-dough method, with water content adjusted (+2% per 5% NCP) based on farinograph data, and baked at 230 °C for 20 min. For *Banh canh* and *Banh trang*, rice flour and tapioca starch (8:2) were mixed with pre-hydrated NCP (40 °C). *Banh trang* was steam-coated for 45 s, while *Banh canh* was extruded into boiling water.

4. Analytical Methods

Proximate composition was determined using AOAC methods [12], with total dietary fiber measured enzymatically (AOAC 991.43). Color parameters (L^* , a^* , b^*) were measured using a Minolta CR-400 colorimeter. *In vitro* starch digestibility was assessed using the Englyst method, quantifying rapidly and slowly digestible starch fractions [13]. Statistical analysis employed one-way ANOVA with Duncan's multiple range test ($p < 0.05$).

Results and Discussion

1. Overview of Results in Relation to Green Chemistry Principles

Before detailing individual results, it is important to situate the findings within the broader framework of green

chemistry. The present study addresses several core principles, including the use of renewable feedstocks, design of safer materials, increased energy efficiency, and waste prevention [1]. The utilization of *Opuntia ficus-indica* cladodes—an agricultural by-product—demonstrates a shift from linear food production models toward circular and regenerative systems. The results discussed below are therefore interpreted not only in terms of food quality and nutrition, but also with respect to sustainability-driven design choices.

2. Nutritional Enhancement and Composition

NCP incorporation significantly increased dietary fiber and ash content across all products, reaching 14.8% total dietary fiber at 20% substitution. This level qualifies the products as high-fiber foods under Codex guidelines and aligns with reports on nopal-enriched bread and biscuits [18–20]. The increase in ash content reflects the mineral-rich composition of *Opuntia* cladodes, contributing to micronutrient enhancement.

3. Color and Sensory-Relevant Attributes

Increasing NCP levels reduced lightness (L^*) and shifted a^* values toward green hues due to chlorophyll pigments. While high substitution levels produced darker products, 10–15% NCP maintained acceptable visual quality. Similar trends have been observed in bakery products enriched with plant-based fibers [11, 18].

4. Matrix-Dependent Functional Effects

The functional impact of NCP differed between rice- and wheat-based systems. In rice-based matrices, mucilage competed with starch granules for water, limiting excessive swelling and yielding a cohesive yet pliable texture. In wheat-based *Banh mi*, mucilage interacted with gluten networks, increasing water absorption and influencing gas retention. These matrix-dependent effects are consistent with previous findings in wheat dough systems enriched with cactus mucilage [9, 20].

5. Mechanistic Insights into Starch Digestibility Reduction

The reduction in starch hydrolysis rate can be attributed to multiple mechanisms: increased matrix viscosity, formation of a physical barrier around starch granules, and thickening

of the unstirred water layer that limits enzyme diffusion [15]. Comparable hypoglycemic mechanisms have been reported in nopal-enriched bread and biscuits [7, 18, 19]. The present results confirm that these effects extend to rice-based foods, broadening the applicability of *Opuntia* mucilage as a functional hydrocolloid.

The incorporation of *Opuntia ficus-indica* cladode powder (NCP) significantly altered starch digestibility behavior in both rice- and wheat-based products, as evidenced by *in vitro* hydrolysis assays. To rationalize these observations, a mechanistic interpretation based on starch–hydrocolloid interactions is proposed (Figure 2).

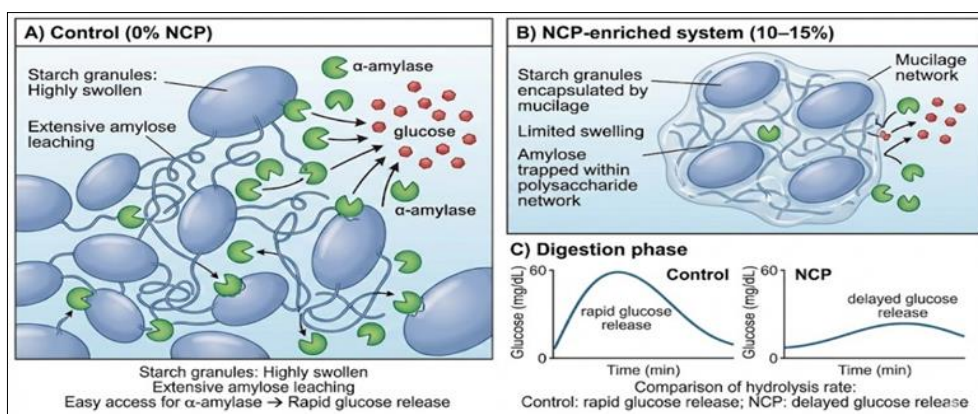


Fig 2: Mechanism of starch digestibility reduction by NCP mucilage

Figure 2. Proposed mechanism of starch digestibility reduction in rice- and wheat-based foods enriched with *Opuntia ficus-indica* cladode powder (NCP). The hydrated nopal mucilage forms a viscous hydrocolloid network that (i) competes with starch granules for water during gelatinization, (ii) limits starch swelling and amylose leaching, and (iii) creates a physical barrier that sterically hinders α -amylase access to glycosidic bonds, thereby slowing enzymatic hydrolysis and glucose release. [21-23]

As illustrated in Figure 2, the reduction in starch digestibility observed in NCP-enriched products can be attributed to a combination of physicochemical mechanisms associated with nopal mucilage. Upon hydration, the soluble polysaccharides form a highly viscous matrix that competes with starch granules for available water during thermal processing. This competition restricts starch granule swelling and limits amylose leaching, resulting in a less accessible substrate for enzymatic attack. Furthermore, the mucilage network acts as a physical diffusion barrier, sterically hindering the access of α -amylase to starch surfaces and slowing glucose release during digestion. Similar mechanisms have been reported for other viscous dietary fibers, although the effect observed here is achieved using a minimally processed, regionally sourced biomass.

6. Life Cycle Thinking (LCA-lite)

From an LCA-lite perspective, *Opuntia ficus-indica* cultivation offers substantial environmental advantages, including low water demand, minimal fertilizer and pesticide use, and high biomass productivity on marginal and arid lands [5, 17]. The valorization of cladodes—often treated as agricultural residues—contributes to waste reduction and supports circular bioeconomy models. Although drying requires energy input, the use of low-temperature convective drying represents a relatively mild processing step, particularly when integrated with renewable or decentralized energy sources. Overall, the proposed valorization pathway aligns with several principles of green chemistry, including the use of renewable feedstocks, waste prevention, and design for energy efficiency [1, 2, 8, 16].

In this study, a Life Cycle Thinking (LCA-lite) approach was adopted to qualitatively identify key environmental hotspots associated with *Opuntia* cladode valorization. Rather than conducting a full ISO-compliant life cycle assessment, the analysis focused on major stages such as biomass cultivation, low-temperature drying, local processing, distribution, and end-of-life considerations. This streamlined framework (Figure 3) enables sustainability-oriented decision-making under limited data availability and is particularly relevant for emerging bio-based food systems in developing regions.

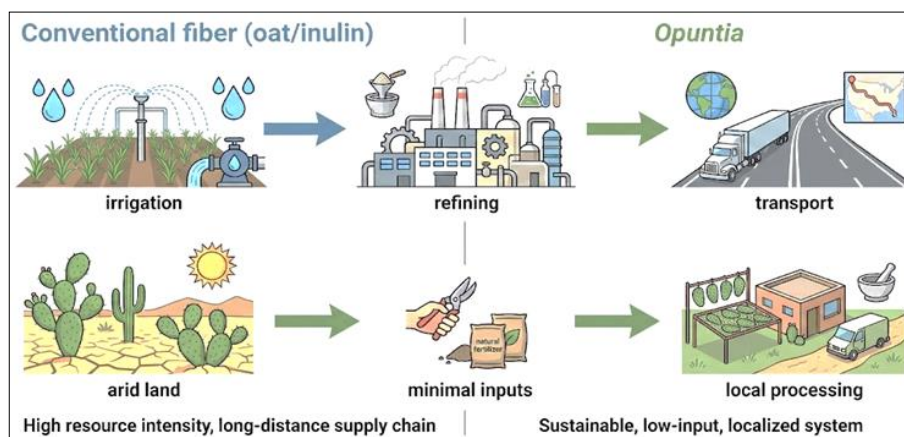


Fig 3: LCA-lite conceptual diagram

Figure 3. Conceptual Life Cycle Thinking (LCA-lite) framework comparing conventional plant-based dietary fibers (e.g., oat β -glucan, inulin) with *Opuntia ficus-indica* cladode valorization. The schematic highlights key environmental hotspots related to water use, processing intensity, transportation distance, and system localization. The LCA-lite approach supports early-stage sustainability evaluation without requiring full quantitative life cycle inventory data.

Broader Implications for Green Food Design and Regional Sustainability

1. Cultural Compatibility and Consumer Acceptance

One of the critical challenges in functional food development is achieving health benefits without disrupting cultural food practices. Unlike Western dietary interventions that often rely on novel or imported products, the present approach focuses on reformulating foods that are already embedded in Vietnamese daily life. *Banh canh*, *Banh trang*, and *Banh mi* are consumed across socio-economic groups, making them ideal vehicles for nutritional intervention. The moderate substitution levels identified in this study (10–15% NCP) preserve recognizable sensory attributes while delivering meaningful functional benefits. This culturally compatible strategy enhances the likelihood of long-term adoption and public health impact, a factor increasingly emphasized in sustainable nutrition research.

2. Socio-Economic and Agricultural Impacts

From a regional development perspective, valorizing *Opuntia* cladodes may provide supplementary income streams for farmers in drought-prone coastal areas of Vietnam. Because cladodes regenerate rapidly and harvesting does not require replanting, their utilization does not compromise fruit production or plant longevity^[5, 17]. Small-scale drying and milling operations could be implemented at the community level, reducing transportation emissions and supporting local circular economies. Such decentralized processing models align with green chemistry's emphasis on inherently safer and locally adapted technologies.

3. Comparison with Other Plant-Based Fiber Ingredients

Plant-derived fibers such as oat β -glucan, psyllium, and inulin have been widely studied for glycemic modulation^[15]. However, many of these ingredients rely on intensive agricultural inputs or complex extraction processes. In contrast, *Opuntia* cladode powder requires minimal processing and retains its native polysaccharide structure, reducing the need for chemical modification. This positions NCP as a competitive alternative within the growing portfolio of sustainable hydrocolloids, particularly for regions facing water scarcity and climate stress.

4. Limitations and Future Research Directions

Despite the promising results, several limitations must be acknowledged. The hypoglycemic potential was assessed using *in vitro* digestion models, which cannot fully replicate physiological responses in humans. Sensory evaluation was conducted at a pilot scale and should be expanded to include larger and more diverse consumer panels. Future studies should incorporate *in vivo* glycemic index testing, explore fermentation-assisted processing to further enhance functionality, and conduct full life cycle assessment (LCA) to quantitatively compare environmental impacts with

conventional fiber ingredients. These directions will strengthen the evidence base for scaling up *Opuntia*-based functional foods. This study is limited by the use of *in vitro* starch digestibility assays rather than *in vivo* glycemic response measurements. Sensory evaluation was conducted at a pilot scale and should be expanded to include diverse consumer panels. Future research should focus on clinical validation of glycemic response, optimization of drying energy efficiency, and full life cycle assessment to quantify environmental impacts more precisely.

Conclusions

The green valorization of *Opuntia ficus-indica* cladodes provides a viable and sustainable strategy for reformulating traditional Vietnamese staple foods into fiber-rich, low-glycemic products. By enhancing nutritional quality, modulating starch digestibility, and utilizing a climate-resilient biomass, this approach aligns strongly with green chemistry principles and sustainable food system goals. The findings support the broader adoption of *Opuntia* cladodes as a multifunctional ingredient for health-oriented and environmentally responsible food innovation.

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