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Development of Functional Foods Enriched with Microencapsulated Habanero Pepper Leaf Extract and Their Bioaccessibility Assessment

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Abstract

The increase in habanero pepper (Capsicum chinense Jacq.) production in Yucatán, Mexico generates large volumes of agro-industrial by-products, particularly leaves, which represent an underutilized food resource. This study focuses on the valorization of habanero pepper leaves (HPL) for the design of a novel functional food ingredient, aligned with circular economy and sustainable material development principles, transforming plant residues into value-added materials for food applications. A polyphenol-rich extract was obtained using natural deep eutectic solvents (NADES) combined with ultrasound-assisted extraction. Extraction process was optimized considering molar ratio and water content as critical variables to maximize recovery efficiency of phenolic compounds. The optimized NADES (glucose:choline chloride, 0.8:1 mol/mol, 68% added water) yielded a total polyphenol content of 271.46 mg GAE/100 g dry weight (DW), with a maximum antioxidant inhibition of 89.79% (DPPH assay). Key individual polyphenols were identified, including diosmin + hesperidin (148.9 mg/100 g DW), quercetin + luteolin (49.38 mg/100 g DW), and vanillin (19.15 mg/100 g DW), confirming the high functional potential of the extract and its suitability as a source of bioactive compounds. Extracts showed no cytotoxic effects (L-929 fibroblasts) and no acute oral toxicity in vivo, supporting its safety and applicability as a functional food material. To enhance stability, handling, and applicability in food systems, the optimized extract was microencapsulated by spray drying using a polysaccharide-based carrier system. Microencapsulation conditions were optimized to balance polyphenol retention and antioxidant activity. Optimal drying conditions (inlet temperature 89.4 °C, 7.8% guar gum) produced microencapsulates with 8.55 mg GAE/100 g powder, while conditions maximizing antioxidant capacity (104.1 °C, 8.06% guar gum) achieved 19.19% DPPH inhibition. Before incorporating the microcapsules into a food matrix, bioaccessibility was validated using a standardized in vitro digestion model, which revealed a substantial increase in polyphenol bioaccessibility during the intestinal phase, reaching up to 283.28%, thereby demonstrating the protective role of encapsulation against gastrointestinal degradation. The microcapsules were then successfully incorporated into two different food matrices, an isotonic beverage and a cookie, highlighting the microcapsules versatility. In the enriched isotonic beverage, total polyphenol content reached 6.98 ± 0.03 mg GAE/100 ml under fasting conditions, representing a 39% increase compared to the control beverage, while individual polyphenols such as rutin (1.24 ± 0.05 mg/100 ml) and quercetin + luteolin (1.10 ± 0.10 mg/100 ml) remained stable or increased throughout gastrointestinal digestion. In the enriched cookie, total polyphenol content reached 273.64 ± 12.21 mg

GAE/100 g after intestinal digestion, with bioaccessibility values exceeding 1600% for quercetin + luteolin and 860% for catechin. Overall, this work demonstrates that habanero pepper leaves can be transformed into a high-value functional food material through NADES-based green extraction and microencapsulation strategies, contributing to the development of innovative materials from food resources and sustainable food systems.

Keywords: Habanero pepper leaf, NADES, polyphenols, Functional food, In vitro Digestion

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