AgriFood: Journal of Agricultural Products for Food

WILEY

RESEARCH PAPER OPEN ACCESS

Starch-Molded Snacks Enriched With Nance (*Byrsonima crassifolia* L.) Fruit Flour Functional Potential

Mariana Carolina Fregoso-Ultreras | Cinthia Jazmin Villegas-Ornelas | Victor Manuel Zamora-Gasga | Jorge Alberto Sánchez-Burgos | Sonia Guadalupe Sáyago-Ayerdi | Francisco Javier Blancas-Benitez

Tecnológico Nacional de México/Instituto Tecnológico de Tepic, Laboratorio Integral de Investigación en Alimentos, Tepic, Nayarit, México

Correspondence: Francisco Javier Blancas-Benitez (fblancas@tepic.tecnm.mx)

Received: 18 June 2025 | **Revised:** 11 November 2025 | **Accepted:** 4 June 2026

Keywords: bioaccessibility | dietary fiber | nance | phenolic compounds

ABSTRACT

This study aimed to develop starch-molded snacks enriched with nance (*Byrsonima crassifolia* L.) flour, a native tropical fruit rich in polyphenols, fiber, and bioactive compounds. Nance flour demonstrated significant functional properties, including high oil retention, swelling capacity, and glucose adsorption. Three snack formulations (12%, 25%, and 50% nance flour) were evaluated for their nutritional composition, phenolic content, antioxidant capacity (ABTS, DPPH, and FRAP), and in vitro bioaccessibility. Total phenolics and antioxidant capacity increased with flour substitution. HPLC-DAD-MS analysis identified key compounds, including gallic acid, quercetin, and gallotannins. In vitro digestion revealed that phenolic bioaccessibility ranged from 48% to 61%, with high intestinal absorption potential. Sensory analysis showed improved odor and flavor acceptability in all formulations. The findings support the incorporation of nance flour in functional snack products, contributing to sustainable food innovation and the valorization of underutilized native fruits.

1 | Introduction

Snacks have become a significant part of global eating habits, evolving into essential components of daily diets for children, adolescents, and adults. However, the lack of a unified definition for the term "*snack*" reflects the complexity of factors influencing its classification, including timing of consumption, energy content, type of food, and the cultural context of each country. In some nations, snacks are defined as foods or beverages consumed between main meals with a caloric value below 150 kcal. In contrast, in Mexico, snacks are also expected to be easy to prepare and suitable for children to consume independently (Potter et al. 2018).

A recent study by Ohio State University highlights that snacks contribute between 20% and 22% of total energy intake among U.S. adults, often lacking nutritional quality due to their predominant composition of carbohydrates and added sugars. This trend is not exclusive to the United States; in countries such as Mexico, snacks are similarly high in added sugars and saturated fats, often displacing fresh fruits and vegetables. Such consumption patterns contribute to growing public health concerns, including obesity and noncommunicable diseases (O'Kane et al. 2023).

In this context, nance (*Byrsonima crassifolia*), a native fruit of tropical America, emerges as a promising alternative for the development of healthier snacks. This small yellow fruit, known for its sweet and sour taste, is rich in bioactive compounds such as polyphenols, carotenoids, and dietary fiber. Among its most notable polyphenols are gallic acid and quercetin, whereas lutein and zeaxanthin are the predominant carotenoids (compounds known for supporting ocular health and exhibiting

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2026 The Author(s). *AgriFood: Journal of Agricultural Products for Food* published by John Wiley & Sons Australia, Ltd on behalf of International Association of Dietetic Nutrition and Safety.

antioxidant properties) (Sousa and de Souza Buarque 2020). Additionally, nance is an excellent source of vitamin C, with levels surpassing those found in fruits like apples and sapote, further reinforcing its immune-enhancing potential (Moo-Huchin et al. 2014).

From a nutritional standpoint, nance is distinguished by its high content of both soluble and insoluble dietary fiber, which supports digestive health and helps regulate appetite. Studies have reported soluble fiber content in nance reaching up to 11%, whereas insoluble fiber exceeds 30% on a dry weight basis (making it a valuable ally in the prevention of metabolic and cardiovascular diseases) (Agredano-De la Garza et al. 2021). Furthermore, its antioxidant capacity, evaluated through methods such as ABTS and DPPH, has been shown to surpass that of other tropical fruits, highlighting its potential to combat oxidative stress and prevent chronic illnesses (Moo-Huchin et al. 2014).

This article explores the need to transform consumption habits through the design of innovative and accessible food alternatives, with a focus on incorporating natural ingredients such as nance. This approach not only enhances the nutritional quality of snacks but also responds to the increasing demand for sustainability and a circular economy, promoting the comprehensive utilization of native and underutilized crops.

2 | Materials and Methods

2.1 | Preparation of Nance (*Byrsonima crassifolia*) Flour

The flour was obtained following the methodology described by Alves and Perrone (2015) with some modifications. Nance fruits (sweet, sour, and bittersweet) were purchased from local markets in Tepic, Nayarit, and selected based on their organoleptic characteristics and physiological maturity. Selected fruits had °Brix values ranging from 9 to 15, titratable acidity from 0.29% to 2.76%, and pulp pH between 3.07 and 4.40 (Medina-Torres et al. 2015; Moo-Huchin et al. 2014). The fruits were washed, disinfected, and manually pulped to separate the seeds. The resulting pulp was dehydrated for 15 h at 50°C in a forced-air convection oven (Cabela's TS160 D, Sidney, NE, USA). The dried pulp was then ground into a fine powder using a food processor (NutriBullet NBR-0804B, China) and sieved to obtain a particle size of $\leq$ 500 μm.

2.2 | Evaluation of Functional Properties of Nance Flour

After obtaining the nance flour, its functional properties were evaluated.

2.2.1 | *Water Retention Capacity (WRC)*

Water retention capacity was determined following the methodology described by Femenia et al. (1997). A 0.5 g portion of each sample was mixed with 5 mL of sodium phosphate buffer (0.028 g/mL) and stirred for 1 min, then incubated for 24 h. After incubation, the samples were centrifuged at 3500 rpm for 15 min. The supernatant was discarded, and the pellet weight (P_1) was recorded. WRC was calculated using the following formula:

$$\text{AAC} = (P_1 - P_2) / (P_2 - K), \quad (1)$$

where: $K = a(P_1 - P_2)$; $a = 28 \times 10^{-3}$ g salt/mL.

2.2.2 | *Oil Retention Capacity (ORC)*

The ORC of the flour was determined according to the method described by Kraithong et al. (2018), with slight modifications. One gram of sample was mixed with 10 mL of soybean oil. The mixture was left to stand for 24 h at room temperature and then centrifuged at 6000 rpm for 15 min. The supernatant was decanted, and the volume of retained oil was measured using a graduated cylinder.

ORC was expressed as grams of absorbed oil per gram of dry sample (g/g) and calculated using the following formula:

$$\text{ORC} = (\text{Weight of retained oil}) / (\text{Sample weight [g]}). \quad (2)$$

2.2.3 | *Swelling Capacity (SC)*

Swelling capacity was determined following the methodology described by Chandra et al. (2015). One gram of flour was weighed and transferred into 10 mL test tubes. The initial volume occupied by the sample (V_0) was recorded. Then, 10 mL of sodium phosphate buffer (0.028 g/mL) was added. The samples were shaken and incubated at room temperature for 24 h. After incubation, the final volume of the swollen sample (V_f) was measured.

Swelling capacity was calculated using the following formula:

$$\text{SC} = (V_f - V_0) / \text{Sample weight (g)}. \quad (3)$$

2.2.4 | *Glucose Adsorption Capacity (GAC)*

The glucose adsorption capacity was determined following the methodology proposed by Ou et al. (2001). Glucose quantification was carried out using the dinitrosalicylic acid (DNS) method, as described by Cummings and Englyst (1987).

2.3 | Formulation and Development of the Snack

A control formulation was prepared containing water, starch, pectin, and table sugar. The starch used was corn starch (Maizena, Unilever, Mexico), which was selected due to its widespread availability for food applications and its well-documented physicochemical behavior. According to the manufacturer and literature reports, corn starch contains approximately 25%–28% amylose and 72%–75% amylopectin, with a gelatinization temperature range of 62°C–72°C (K. Liu et al. 2019). These properties were considered suitable for snack development because the moderate amylose content favors gel formation and retrogradation, whereas the gelatinization profile supports adequate texture and stability after processing.

In addition, three formulations were developed in which table sugar was partially replaced with nance flour at levels of 50%, 25%, and 12%, based on the method established by Blancas-Benitez et al. (2015).

Snack preparation followed the procedure described by Blancas-Benitez et al. (2015). Water, starch, and pectin were mixed and homogenized for 10 min at 6000 rpm using a high-speed homogenizer (Ultra-Turrax T25). The mixture was then heated to 120°C for 5 min, after which sugar and nance flour were added and stirred again at 6000 rpm for an additional 5 min. The resulting mixture was poured into preformed molds placed in trays filled with dry starch (approximately 7% moisture content). The product was dehydrated in a food dehydrator (Cabela's TS160 D, Sidney, NE, USA) at 55°C for 8 h. The dried pieces were treated with mineral oil to remove excess starch, ground and sieved to a particle size of 0.5 mm, and stored at −20°C until analysis.

2.4 | Chemical-Proximal Analysis of Nance Flour and Snacks

The guava flour samples were subjected to proximate analysis using methods of the AOAC (Helrich 1990): moisture (Method 925.10), protein (Method 920.87) and crude fat (Method 920.39). Dietary fiber content was calculated using the AOAC method (Method 991.42) modified by (Manas et al. 1994). Total carbohydrates were calculated by difference.

2.5 | Quantification of Total Phenolic Compounds in Nance Flour and Snack Formulations

Aqueous-organic extraction (methanol–water 50:50 v/v and acetone–water 70:30 v/v) was performed on nance flour and snacks following the methodology proposed by Pérez-Jiménez et al. (2009). The supernatant obtained from the extraction was used to determine the total soluble phenols (TSP) content using the Folin–Ciocalteu reagent (F9252, Sigma-Aldrich, St. Louis, MO, USA), following the method described by Montreau (1972). Absorbance was measured at 750 nm using a 96-well microplate reader (Bio-Tek Synergy HT, USA) with Gen5 software (Alvarez-Parrilla et al. 2011). A standard curve of gallic acid was prepared, and the results were expressed as milligrams of gallic acid equivalents per gram of dry weight (mg GAE/g DW).

The residue obtained from the aqueous-organic extraction was used to determine the hydrolyzable polyphenols (HP) content, following the methodology proposed by Hartzfeld et al. (2002). For both TSP and HP assays, gallic acid was used as the standard, and results were reported as mg GAE/g DW.

Finally, the remaining residue was used to quantify condensed tannins (CT), according to the method described by Reed et al. (1982). The CT content was determined using a calibration curve prepared with carob pod extract (0.0–200 mg/L; $R^2 = 0.9997$), and results were expressed as milligrams of carob tannin equivalents per gram of dry weight (mg CTE/g DW). Total phenols (TP) content was calculated as the sum of TSP, HP, and CT, and expressed in mg/g DW.

2.6 | Evaluation of Antioxidant Capacity in Nance Flour and Snacks

Antioxidant capacity was evaluated with three assays. The ABTS assay was conducted as described by Re et al. (1999). A solution of ABTS (7 mM) was prepared by dissolving it in potassium persulfate (2.42 mM) and maintaining it in the dark for 14 h. The ABTS solution was then diluted with phosphate buffer (0.1 M, pH = 7.4) until it reached an absorbance of 0.80 ± 0.02, measured at 734 nm using a microplate reader. A 20 μL aliquot of each aqueous-organic extract was mixed with 255 μL of the diluted ABTS solution. The AOX was determined by interpolating the absorbance values against a Trolox standard curve (37.5–600 μM/mL, $R^2 = 0.9984$). The results were expressed as μmol Trolox equivalents per gram (mMol TE/g). The radical scavenging activity was assessed by the reduction in the DPPH radical (2,2-diphenyl-1-picrylhydrazyl) at 517 nm using a microplate reader, following the method of Prior et al. (2005) with modifications by Alvarez-Parrilla et al. (2011). A 20 μL aliquot of the aqueous-organic extracts was mixed with 200 μL of a 190 μM methanolic DPPH solution for 10 min. The results were expressed as μmol Trolox equivalents per gram (mMol TE/g) using a calibration curve (37.5–600 μM/mL, $R^2 = 0.9985$). The ferric-reducing antioxidant power (FRAP) assay was performed according to the method of Benzie and Strain (1996), with modifications by Alvarez-Parrilla et al. (2010). The FRAP solution was prepared by mixing sodium acetate buffer (0.3 M, pH 3.6), TPTZ-HCl (10 mM in 40 mM HCl), and ferric chloride hexahydrate (20 mM) in a 10:1:1 (*v*/*v*/*v*) ratio, and then heated to 37°C before use. An aliquot of 24 μL of the extracts was mixed with 180 μL of the FRAP solution, and the absorbance was measured at 595 nm after 30 min using a microplate reader (Biotek, Synergy HT). The results were expressed as μmol Trolox equivalents per mL g (mMol TE/g) using a calibration curve (0.0081–0.13 mM/mL, $R^2 = 0.9938$).

2.7 | Identification of Phenolic Compounds by HPLC-DAD-MS

The supernatants obtained from nance flour and snack extractions were subjected to phenolic compound identification using high-performance liquid chromatography (HPLC). The analysis was conducted on a 1260 series system (Agilent Technologies, Santa Clara, CA, USA) equipped with a UV–vis diode array detector (DAD; Agilent G4212-60008) and coupled to a 6120 Single Quadrupole LC/MS (Agilent Technologies) with an electrospray ionization (ESI) interface operating in negative ion mode (drying gas: N_2, 13.0 L/min; nebulizer pressure: 40 psi; drying temperature: 350°C; capillary voltage: 3500 V) (Blancas-Benitez et al. 2018).

Aliquots of 10 μL were injected into a Poroshell 120 EC-C18 column (4.6 mm × 150 mm, 2.7 μm particle size; Agilent Technologies) at a flow rate of 0.4 mL/min. A multistep gradient was applied using solvent A (water acidified with 0.1% acetic acid, Sigma-Aldrich) and solvent B (acetonitrile acidified with 0.1%, Sigma-Aldrich) under the following program: 0 min, 5% B; 10 min, 23% B; 15 min, 50% B; 20 min, 50% B; 23 min, 100% B; 25 min, 100% B; 27 min, 5% B; 30 min, 5% B.

Detection was performed in the 280–320 nm range. Mass spectrometry analysis was carried out under the aforementioned ESI conditions. Data acquisition and processing were performed using OpenLab CDS ChemStation Edition software (Agilent Technologies, Santa Clara, CA, USA). Phenolic compound characterization was based on retention time (RT) in the DAD and mass spectrometric signal (single MS scan in the

100–1000 m/z range), and was directly compared with the RTs of analytical standards.

2.8 | Sensory Analysis of the Snack

The snacks were subjected to a sensory evaluation to determine their acceptability. The tasting panel consisted of 30 untrained participants (15 males and 15 females), aged 21–45 years, with no reported food allergies related to the snack ingredients. All participants were informed about the sensory evaluation procedures and provided written consent prior to participation.

Snacks were coded using randomized 3-digit numbers and presented under double-blind conditions to minimize bias. Evaluations were conducted in a controlled environment (quiet room, uniform lighting, and consistent serving temperature). Participants rated their preferences for each snack formulation using a 5-point hedonic scale, ranging from 1 = "strongly dislike" to 5 = "strongly like," assessing odor, taste, and texture (Ramirez-Maganda et al. 2015). This approach ensures reproducibility, transparency, and reliability of the sensory evaluation results.

2.9 | Bioaccessibility Evaluation of Phenolic Compounds

The snack was subjected to an in vitro gastrointestinal digestion process following the standardized INFOGEST protocol, developed by an international consortium for the simulation of food digestion in the gastrointestinal tract (Brodkorb et al. 2019). However, it should be noted that the INFOGEST model applied does not include intestinal α-amylase and α-glucosidase, which may result in an overestimation of phenolic bioaccessibility. This limitation has been acknowledged.

Snack samples were treated according to the INFOGEST protocol. In the oral phase, salivary amylase (10 mg/mL; Sigma-Aldrich, A1031) and simulated salivary fluid were used. During the gastric phase, pepsin (30 mg/mL; Sigma-Aldrich, P7000) and lipase (100 mg/mL; Sigma-Aldrich, L-3126) were added. In the intestinal phase, digestion was carried out with pancreatin (134 mg/mL; Sigma-Aldrich, P-1750) and bile salts (200 mg/mL; Sigma-Aldrich, B-8631) phenolic compounds (PC) that were obtained at this stage of digestion were considered the compounds present in the intestinal fraction (IntF). The phenolic compounds identified in this fraction are considered potentially absorbable in the small intestine, as they are released from the food matrix following the application of triple enzymatic hydrolysis. These compounds were identified using HPLC-DAD-MS. After enzymatic hydrolysis, the samples were centrifuged (15 min, 25°C, 2616 g) to separate the supernatants and divide the fractions into soluble indigestible fraction (SIF) and insoluble indigestible fraction (IIF). The supernatant was dialyzed (D9652, 12-14 KDa, Sigma Aldrich) for 3 h in a manner to simulate passive absorption. After the dialysis process, the membrane content was analyzed by HPLC-DAD-MS. The phenolic compounds associated with the SIF were identified. The residue obtained during centrifugation was considered as the nonextractable fraction containing the phenolic compounds associated with IIF, after performing an aqueous-organic extraction with acidic methanol–water (50:50 v/v; pH 2) and acetone–water (70:30, v/v) (Pérez-Jiménez et al. 2008). Both SIF- and IIF-associated phenolic compounds, corresponded to compounds that will not be bioaccessible in the small intestine. However, it should be noted that the INFOGEST model applied does not include intestinal α-amylase and α-glucosidase, which may result in an overestimation of phenolic bioaccessibility. This limitation has been acknowledged.

The percentage bioaccessibility (BA%) in vitro of phenolic compounds was determined by the Equation (4), according to the total PC quantified by HPLC-DAD-MS. Phenolic compound bioaccessibility was calculated using a modified mass balance approach, intended to estimate the potentially absorbable fraction while correcting for analytical overestimation inherent to the standard method. The following formula was employed:

$$\% \text{ BA} = [(\text{PCs_IntF} - \text{PCs_SIF}) / (\text{PCs_IntF} + \text{PC_IIF})] \times 100, \quad (4)$$

where PCs_IntF represents the mass of phenolic compounds released in the intestinal fraction; PCs_SIF are the compounds associated with the soluble indigestible fraction; and PCs_IIF are the compounds associated with the insoluble indigestible fraction. This adjusted formula allows for the quantification of the net mass of compounds that are entirely released from the food matrix and are available for small intestine absorption.

The percentage bioaccessibility of phenolic compounds was calculated, and inter-group statistical differences (between formulations) were analyzed using a one-way ANOVA followed by Fisher's least significant difference (LSD) test with a significance level of $p < 0.05$. The complete ANOVA results for total bioaccessibility are presented in (Table S1).

Additionally, the in vitro intestinal absorption percentage of phenolic compounds was calculated using the equation described by Pais et al. (2024):

$$\text{IA } (\%) = 100 - (\text{SIF} / \text{IF} \times 100), \quad (5)$$

2.10 | Statistical Analysis

Data were expressed as mean ± standard deviation ($n = 3$). A unifactorial design was employed, using analysis of variance (ANOVA) and Fisher's LSD test at a 95% confidence level ($\alpha = 0.05$). For acceptability evaluation, a nonparametric Friedman test was applied at a 95% confidence level ($\alpha = 0.05$), using the Statistica software version 12 (StatSoft, USA).

3 | Results and Discussion

3.1 | Functional Properties of Nance Flour

Nance flour exhibited notable functional properties relevant to food formulation. Its water holding capacity was 2.46 ± 0.05 g/g, indicating a strong ability to retain moisture, which can contribute to improved texture. This value was higher than that reported by Alam et al. (2024) for papaya seed flour, which was 1.80 g/g. The oil adsorption capacity was 1.61 ± 0.27 g/g, which was higher than the value reported by Alam et al. (2024) for papaya seed flour (0.96 g/g), reflecting the potential of nance flour to retain lipids and enhance both flavor and mouthfeel in

food products. Additionally, the flour demonstrated a high glucose adsorption capacity of 7.94 ± 0.02 mmol/g, suggesting potential in moderating postprandial glucose levels (Meng et al. 2021). Lastly, the swelling capacity (SC) of nance flour was 5.99 ± 0.19 mL/g, supporting its potential use in formulations where volume expansion and satiety are desirable. This value was notably higher than that reported by Li et al. (2022) for millet flour (1.39 ± 0.04 mL/g). Millet flour has recently gained attention as a gluten-free alternative to conventional flours and is considered suitable for individuals with celiac disease (Munshi and Dashora 2024).

These functional properties are closely related to the presence of hydrophilic molecules such as dietary fiber and proteins. Fiber, due to its reticulated structure, can entrap both water and oil molecules, retaining them through capillary action and molecular interactions facilitated by its functional groups. Similarly, proteins containing polar amino acids exhibit affinity for water molecules, whereas their capacity to retain oil depends on the surface availability of nonpolar amino acid residues (Li et al. 2022).

3.2 | Proximate Composition of Nance Flour and Derived Snack Products

The results of the proximate composition analysis are presented in Table 1. The moisture content of the nance flour was 7.59 ± 0.19 g/100 g, which falls within the optimal range for preserving the physicochemical properties and stability of dry food products. Importantly, higher moisture levels are associated with increased microbial growth (Fueyo-González et al. 2024). In the case of the snacks, moisture content ranged from 10.54% ± 0.57% to 16.12% ± 0.86%. These values are considered favorable, as lower moisture content contributes to product stability by limiting microbial proliferation, thereby extending shelf life (Acuff et al. 2023).

Nance flour exhibited a high protein content (15.21 ± 1.3 g/100 g), surpassing that of many fruits, vegetable, and even cereal flours, including pumpkin (6.99–10.66 g/100 g), sorghum–mango (9.55 g/100 g), and wheat flour (12.07 ± 0.3 g/100 g) (Bekele and Emire 2023). This elevated protein level enhances its value as a functional ingredient and offers a promising alternative for plant-based or vegan formulations (Saari et al. 2021). The protein content of the snacks increased proportionally with the level of sugar substitution by nance flour, reaching 10.62% ± 0.18% in the formulation with 50% substitution. Statistically significant differences were observed between this formulation and those containing 12% and 25% nance flour. The elevated protein content qualifies these snacks as a good source of plant-based protein, exceeding the levels typically found in many commercial snack products, such as cereal bars (Aleksejeva et al. 2017).

Unlike most fruits, nance flour exhibited a high lipid content (9.2% ± 0.13%). This value is slightly higher than that reported by de Barros Vinhal et al. (2022) who found 7.3% ± 0.30% in nance fruit. Furthermore, Pires et al. (2019) characterized the lipid profile of nance, reporting that 63% of its fatty acids are unsaturated (41% monounsaturated and 22% polyunsaturated). The presence of these fatty acids is considered beneficial to health. Previous studies have highlighted mechanisms by which omega-3 polyunsaturated fatty acids help lower triglyceride levels and exert anti-inflammatory effects (Q. K. Liu 2021). Similar to protein content, in the snacks the lipid content increased proportionally with the level of nance flour substitution, with statistically significant differences observed among all formulations. The highest lipid content (1.54% ± 0.08%) was found in the snack containing 50% nance flour. As previously reported, the fatty acids in nance fruit are predominantly unsaturated, which may contribute to various health benefits when included in the diet.

Nance flour exhibited a high total dietary fiber content (44.22% ± 1.38%), including 6.1% ± 0.38% soluble dietary fiber (SDF) and 13.88% ± 0.25% insoluble dietary fiber (IDF), exceeding values reported for common fruit by-products such as Red Delicious apple pomace (35 g/100 g) Zlatanović et al. (2019). Dietary fiber, composed of nondigestible carbohydrates, plays a critical role in gastrointestinal health by modulating digestion, reducing blood lipid and glucose absorption, and promoting gut microbiota activity. These effects are linked to functional groups (hydroxyl, aldehyde, and carboxylic) that interact with macronutrients, and to the physical properties of SDF and IDF, which enhance viscosity, entrap nutrients, and generate short-chain fatty acids (SCFAs) through colonic fermentation (Huo et al. 2024).

TABLE 1 | Proximate composition of nance flour and snacks formulated with nance flour.[a]

Parameter (g/100g)	Flour	CTRL	SN:12	SN:25	SN:50
Moisture	7.56 ± 0.19^{a}	12.42 ± 0.57^{c}	11.32 ± 0.34^{bc}	10.54 ± 0.28^{b}	16.12 ± 0.86^{d}
Protein	15.21 ± 1.3^{d}	4.34 ± 0.48^{a}	5.66 ± 0.87^{ab}	6.31 ± 0.88^{b}	10.62 ± 0.18^{c}
Lipids	9.2 ± 0.13^{e}	0.06 ± 0.039^{a}	0.39 ± 0.01^{b}	0.73 ± 0.005^{c}	1.54 ± 0.08^{d}
Ash	3.8 ± 0.13^{d}	0.39 ± 0.22^{a}	0.50 ± 0.001^{a}	0.88 ± 0.001^{b}	1.42 ± 0.07^{c}
Total dietary fiber[b]	44.22 ± 1.38^{e}	9.94^{a}	13.03^{b}	17.71^{c}	22.64^{d}
Soluble fiber	6.1 ± 0.38^{c}	3.52 ± 0.12^{a}	4.04 ± 0.66^{ab}	4.14 ± 0.50^{ab}	4.47 ± 0.24^{b}
Insoluble fiber	38.13 ± 2.96^{d}	6.42 ± 0.45^{a}	9.03 ± 0.09^{ab}	13.23 ± 0.07^{b}	18.16 ± 0.12^{c}
Carbohydrates	26.38	85.27	79.14	73.09	62.5

Abbreviations: CTRL, control formulation; dw, dry weight; SN:12, snack with 12% nance flour; SN:25, snack with 25% nance flour; SN:50, snack with 50% nance flour.
[a]Values represent the mean ± standard deviation ($n = 3$). Different letters in each column express significant statistical differences ($p < 0.05$). Dietary fiber values are reported as grams glucose equivalent (g GE).
[b]Total dietary fiber calculated as the sum of SDF + IDF.

As anticipated, total dietary fiber content in the snacks increased with the level of nance flour substitution, reaching 22.64% in the 50% formulation. Significant differences were observed among all formulations, including the control.

According to NOM-086-SSA1-1994 (Secretaría de Salud 1994), a product is considered fiber-enriched if it contains $\geq$ 2.5 g of fiber per serving. Based on a 30 g serving size and the WHO's daily recommendation of 25 g, the 12%, 25%, and 50% substitution formulations provide 15.6%, 21.2%, and 27.2% of the recommended intake, respectively. These values confirm the nutritional relevance of incorporating nance flour into functional snack formulations.

3.3 | Total Phenolic Content and Antioxidant Capacity of Nance Flour and Its Snack Formulations

The phenolic compound content of nance flour is shown in Table 2, with a total phenolic content (TPC) of 87.71 mg GAE/g, calculated as the sum of total soluble phenolics (TSP), hydrolyzable phenolics (HP), and condensed tannins (CT). This value is notably higher than those reported for other plant-based flours, such as grape pomace flour, which contains 41.11 $\pm$ 3.01 mg GAE/g (Urquiaga et al. 2015), and approximately seven times higher than that reported for kiwi peel flour (7.12 mg GAE/g) (Soquetta et al. 2016). These results highlight nance flour as a promising source of phenolic compounds with potential functional applications.

da Silva et al. (2016) reported a total soluble phenolics content of 28.27 mg GAE/g in nance flour, which is comparable to the value obtained in this study. However, to date, no previous reports are available regarding the hydrolyzable phenolics and condensed tannins content in nance flour or fresh nance fruit. Interestingly, the CT content in the present study was higher than the TSP content. Total phenolic content compounds are soluble in aqueous-organic solvents, such as methanol, acetone, and water, making them easily extractable from the food matrix through relatively simple procedures. These compounds are typically digested and absorbed in the small intestine (Saura-Calixto 2011). In contrast, CT compounds are classified as nonextractable using conventional solvents. These high-molecular-weight compounds (mainly composed of flavan-3-ols such as catechin, epicatechin, gallocatechin, and epigallocatechin) are often bound to proteins or dietary fiber carbohydrates. Due to their resistance to enzymatic digestion in the stomach and small intestine, they remain intact until reaching the colon, where they may undergo microbial fermentation, leading to the production of short-chain fatty acids (SCFAs) (Saura-Calixto 2011).

Hydrolyzable phenolics are complex compounds primarily composed of gallic or ellagic acid linked to carbohydrates, and are classified as gallotannins or ellagitannins, respectively. Typically bound to dietary fiber or proteins, their extraction requires harsh hydrolytic conditions. As a result, they often bypass digestion in the upper gastrointestinal tract and are metabolized in the colon, where microbial transformations can release bioactive compounds such as gallic acid and pyrogallol through nonenzymatic degradation and decarboxylation (de la Rosa et al. 2019).

The phenolic content of the snack formulations is presented in Table 2. The formulation with 50% nance flour substitution exhibited the highest total phenolic content (32.59 $\pm$ 1.27 mg GAE/g), with CT being the predominant fraction over total soluble phenolics (TSP; 5.87 $\pm$ 0.48 mg GAE/g) and hydrolyzable phenolics (HP; 9.22 $\pm$ 0.85 mg GAE/g). All values increased significantly with higher nance flour levels ($p < 0.05$).

Although the control formulation showed detectable phenolic content, this may be attributed to the nonspecific nature of the Folin–Ciocalteu assay, which can be influenced by reducing substances such as sugars (Lawag et al. 2023). Nonetheless, all formulations containing nance flour exhibited significantly higher phenolic levels compared to the control.

Phenolic compounds play a key role in neutralizing reactive oxygen species (ROS) and free radicals, justifying their inclusion in daily diets. The antioxidant capacity of nance flour extract was evaluated using ABTS, DPPH, and FRAP assays, each targeting different reaction mechanisms. The results surpassed those reported for fresh nance in previous studies, likely due to differences in extraction solvents and moisture content, which affect phenolic concentration and bioactivity. Although fresh

TABLE 2 | Total phenolic content and antioxidant capacity of nance flour and its snack formulations.

Determination	Flour	CTRL	SN:12	SN:25	SN:50
Total soluble phenols (mg/g)	29.70 $\pm$ 1.58^{e}	1.21 $\pm$ 0.02^{a}	2.58 $\pm$ 0.04^{b}	3.67 $\pm$ 0.19^{c}	5.87 $\pm$ 0.48^{d}
Hydrolyzable polyphenols (mg/g)	22.83 $\pm$ 0.04^{e}	1.48 $\pm$ 0.05^{a}	4.88 $\pm$ 0.41^{b}	6.88 $\pm$ 1.19^{c}	9.22 $\pm$ 0.85^{d}
Condensed tannins (mg/g)	35.18 $\pm$ 1.29^{d}	ND	5.53 $\pm$ 1.12^{a}	13.55 $\pm$ 0.81^{b}	32.59 $\pm$ 1.27^{c}
Total phenols (mg/g)	87.71	2.69	12.99	24.1	47.68
Antioxidant capacity					
FRAP (mmol/g)	34.87 $\pm$ 8.98^{e}	0.082 $\pm$ 0.33^{a}	6.33 $\pm$ 1.17^{b}	12.98 $\pm$ 0.38^{c}	27.12 $\pm$ 2.75^{d}
ABTS (mmol/g)	154.13 $\pm$ 0.69^{e}	1.24 $\pm$ 0.82^{a}	12.84 $\pm$ 0.98^{b}	20.11 $\pm$ 1.59^{c}	35.38 $\pm$ 2.25^{d}
DPPH (mmol/g)	184.83 $\pm$ 1.03^{d}	1.47 $\pm$ 1.65^{a}	12.59 $\pm$ 0.21^{b}	21.32 $\pm$ 3.16^{c}	27.36 $\pm$ 1.89^{c}

Note: Values represent the mean $\pm$ standard deviation ($n = 3$). Different letters in each column express significant statistical differences ($p < 0.05$). The values for total soluble phenols (TSP) and hydrolyzable polyphenols (HP) are expressed in mg gallic acid equivalents (GAE) per gram of dry weight (DW). CT are reported in mg CTE/g DW, TP are the sum of TSP, HP and CT, reported in mg/g DW.
Abbreviations: CTRL, control formulation; SN:12, snack with 12% nance flour; SN:25, snack with 25% nance flour; SN:50, snack with 50% nance flour.

nance extracts yielded lower antioxidant values (Moo-Huchin et al. 2014), dehydrated samples showed similar levels to nance flour (de Barros Vinhal et al. 2022). The use of complementary assays is essential, as they reflect different antioxidant mechanisms, namely hydrogen atom transfer (HAT) and single electron transfer (SET), providing a broader understanding of antioxidant behavior (Rumpf et al. 2023).

The antioxidant capacity of the snack formulations increased significantly with higher levels of nance flour, following the same trend as phenolic compound content ($p < 0.05$). As shown in Table 2, the 50% substitution formulation exhibited the highest antioxidant activity across all assays (FRAP, ABTS, and DPPH), with ABTS and DPPH yielding comparable results, whereas FRAP showed the lowest values. Minor antioxidant activity detected in the control sample may be attributed to ingredients such as pectin and sugar, which possess limited antioxidant potential due to their functional groups. However, this activity was significantly lower than that observed in the nance-enriched formulations.

3.4 | Identification of Phenolic Compounds in Nance Flour and Snacks

Table 3 presents the characterization of phenolic compounds in the nance flour extract, identifying four major classes: hydroxybenzoic acids (predominantly gallic acid), hydroxycinnamic acids (mainly sinapic acid), flavonoids (such as quercetin and its derivatives), and gallotannins. These compounds are known for their biological activities. Gallic acid exhibits strong antioxidant, neuroprotective, anticancer, and antibacterial properties, the latter linked to its interactions with proteins, bacterial membranes, and iron chelation (Obafemi et al. 2023). Quercetin has also been widely studied for its role in preventing cardiovascular disease, diabetes, and colon cancer, largely due to its potent antioxidant capacity (Trakooncharoenvit et al. 2020). Table 3 shows the phenolic compounds identified in each snack formulation. All four families detected in the flour (hydroxybenzoic acids, hydroxycinnamic acids, flavonoids, and gallotannins) were also found in the formulations. However, compound concentrations were higher in the flour and progressively decreased with lower levels of nance flour substitution. At 12% substitution, several compounds, such as specific quercetin derivatives, coumaric acid glucose, and caffeoylquinic acid, were no longer detectable. Similarly, gallotannins were absent in the 25% formulation, likely because their concentrations fell below the detection threshold as the proportion of nance flour decreased.

3.5 | Sensory Analysis of Snacks Enriched With Nance Flour

The results of the sensory analysis for odor, flavor, and texture attributes are presented in Table 4. Statistically significant differences ($p < 0.05$) were observed between the control and the formulations containing nance flour for both odor and flavor, with the substituted formulations receiving higher acceptability

TABLE 3 | Phenolic compounds identified in nance flour and nance-enriched snack formulations.

No.	Phenolic compounds (μg/g)	Flour	CTRL	SN:12	SN:25	SN:50
Hydroxybenzoic acids						
1	Gallic acid	114.60 ± 5.06^{c}	n.d	24.78 ± 2.91^{a}	28.9 ± 6.35^{a}	79.65 ± 9.30^{b}
2	Digallic acid	86.7 ± 4.39^{c}	n.d	73.53 ± 4.44^{ab}	63.24 ± 12.18^{a}	77.11 ± 7.39^{ab}
Hydroxycinnamic acids						
3	Caffeic acid	6.63 ± 0.040	n.d	n.d	n.d	
4	Sinapic acid	56.02 ± 2.10^{c}	n.d	31.51 ± 9.05^{a}	38.23 ± 3.96^{ab}	49.74 ± 8.33^{bc}
5	p-coumaroylquinic acid	36.44 ± 3.52^{c}	n.d	9.76 ± 1.19^{a}	10.84 ± 0.91^{a}	9.46 ± 1.90^{b}
6	Coumaric acid glucose	22.1 ± 1.44^{b}	n.d	n.d	7.9 ± 1.83^{a}	8.17 ± 1.28^{a}
7	Caffeoylquinic acid	17.9 ± 0.84^{b}	n.d	n.d	7.9 ± 0.63^{a}	6.43 ± 1.89^{a}
Flavonoids						
8	Quercetin	43.39 ± 2.63^{c}	n.d	18.58 ± 0.67^{a}	20.57 ± 0.78^{ab}	21.95 ± 0.60^{b}
9	Quercetin derivative	29.3 ± 0.19^{b}	n.d	27.06 ± 1.06^{a}	27.36 ± 0.41^{ab}	28.31 ± 1.96^{ab}
10	Quercetin derivative	28.71 ± 2.09^{a}	n.d	n.d	27.06 ± 1.06^{a}	28.36 ± 1.38^{a}
11	Quercetin derivative	37.08 ± 0.57^{b}	n.d	n.d	n.d	33.47 ± 0.89^{a}
12	Quercetin derivative	38.98 ± 0.05^{b}	n.d	n.d	n.d	35.1 ± 1.08^{a}
Gallotannins						
13	1-O-galloyl-β-D-glucose (isomer)	105.52 ± 8.38^{b}	n.d	n.d	n.d	45.04 ± 0.71^{a}
14	1-O-galloyl-β-D-glucose (isomer)	80.53 ± 3.60^{b}	n.d	n.d	n.d	33.35 ± 2.62^{a}
15	p-coumaroyl aldarate	14.18 ± 0.35^{b}	n.d	n.d	n.d	8.77 ± 0.25^{a}
16	p-coumaroyl aldarate	13.22 ± 0.32^{b}	n.d	n.d		9.49 ± 0.39^{a}
Total		709.2		185.22	232	474.4

Note: Different letters in each column express significant statistical differences ($p < 0.05$).
Abbreviations: CTRL, Control formulation; n.d., not detected; SN:12, snack with 12% nance flour; SN:25, snack with 25% nance flour; SN:50, snack with 50% nance flour.

scores. However, no significant differences ($p > 0.05$) were found among the formulations with varying levels of nance flour. Regarding texture, no statistically significant differences were observed among any of the formulations.

Overall, the inclusion of nance flour improved the snacks' perceived flavor and odor. This enhancement may be attributed to the volatile compounds naturally present in nance fruit, which influence sensory characteristics. Uekane et al. (2017) identified 65 volatile compounds in nance fruit using gas chromatography, including ethyl butyrate, ethyl hexanoate, 1-octen-3-ol, and 2-phenylethanol. These compounds are recognized as key odorants of nance extract, contributing aroma notes reminiscent of cheese, pineapple, and cherry (Uekane et al. 2017).

TABLE 4 | Hedonic sensory evaluation of snacks enriched with nance flour.

Sample	Mean acceptability level		
	Odor	Flavor	Texture
CTRL	2.65 ± 0.93^{b}	3.05 ± 1.11^{b}	3.28 ± 1.17^{ab}
SN:12	3.22 ± 1.11^{a}	3.82 ± 1.09^{a}	3.57 ± 1.24^{b}
SN:25	3.45 ± 1.03^{a}	3.60 ± 1.06^{a}	3.08 ± 1.19^{a}
SN:50	3.2 ± 1.3^{a}	3.62 ± 1.33^{a}	3.34 ± 1.18^{ab}

Note: Results are expressed as the mean ± standard deviation. Different letters in each column express significant statistical differences ($p < 0.05$).
Abbreviations: CTRL, control formulation; SN:12, snack with 12% nance flour; SN:25, snack with 25% nance flour; SN:50, snack with 50% nance flour.

3.6 | Bioaccessibility of Phenolic Compounds in Snacks

Following in vitro gastrointestinal digestion of the snacks, phenolic compounds were quantified in the intestinal phase (IP), soluble indigestible fraction (SIF), and insoluble indigestible fraction (IIF) to estimate bioaccessibility (BA) and intestinal absorption (IA).

Phenolic bioaccessibility across all formulations ranged from 48.49% (SN:50) to 61.27% (SN:12). The highest BA% was observed in the SN:12 formulation (61.27%), possibly due to reduced dietary fiber and protein content, which may have facilitated the release of phenolic compounds. Conversely, the SN:50 formulation, with the highest fiber content, showed the lowest BA% (48.49%). The observed difference in BA% between formulations was statistically significant ($p < 0.05$). The full ANOVA results for the inter-group comparison of bioaccessibility are detailed in Table S1.

The corresponding in vitro intestinal absorption (IA) potential remained consistently high across all formulations, ranging from 84.3% (SN:12) to 89.12% (SN:50). This suggests that the majority of the released compounds became available for absorption in the small intestine, whereas the remainder may reach the colon, where they could exert additional biological effects (Rodrigues et al. 2022).

Figure 1c presents the phenolic compounds identified in the different fractions obtained from the in vitro gastrointestinal

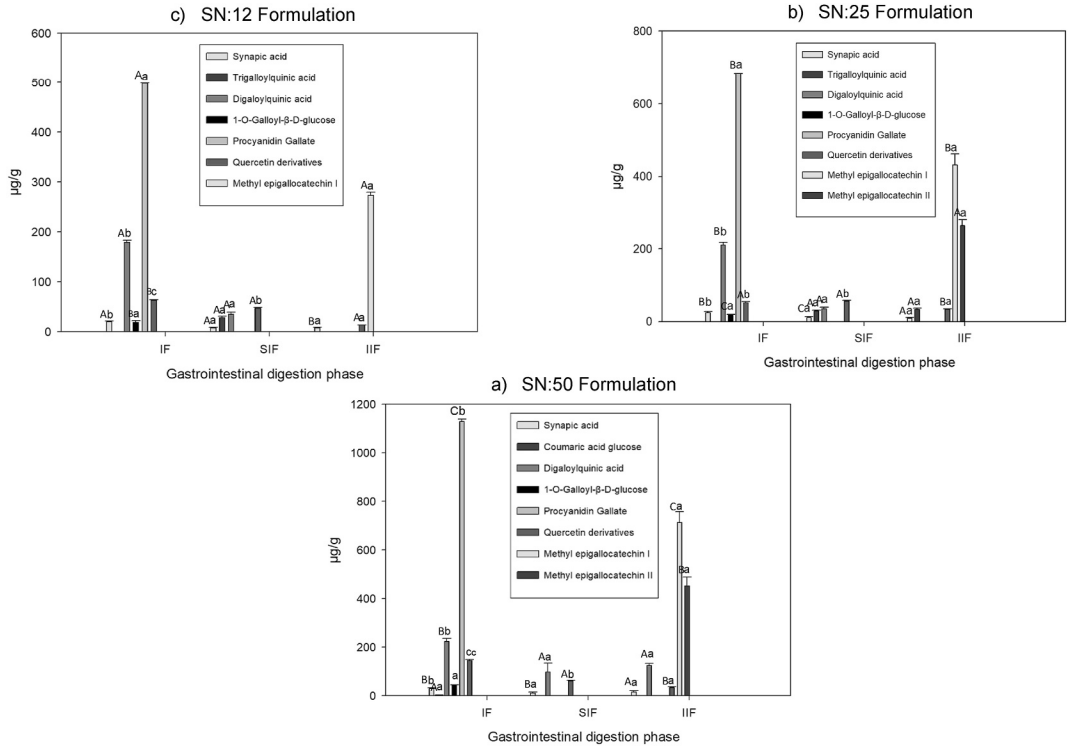


FIGURE 1 | Identified phenolic compounds in snack formulations post-in vitro gastrointestinal digestion. (a) Phenolic compound profile of snacks with 12% substitution. (b) Phenolic compound profile of snacks with 25% substitution. (c) Phenolic compound profile of snacks with 50% substitution. Different capital letters denote statistical differences across formulations, while different lowercase letters denote statistical differences among the gastrointestinal digestion stages of a single formulation ($p < 0.05$). IF, intestinal fraction; IIF, insoluble indigestible fraction; SIF, soluble indigestible fraction.

digestion (GD) of the SN:50 snack (Snack with 50% nance flour). In the intestinal fraction (IF), the predominant compounds were digalloylquinic acid (223.95 ± 11.70 μg/g) and procyanidin gallate (1128.31 μg/g), the latter being exclusively detected in this phase. Although quercetin itself was not identified, the presence of its derivatives suggests potential structural modifications occurring during digestion.

In the SN:25 snack, phenolic bioaccessibility was 49.30%, and in vitro intestinal absorption (IA) was 86.66%, indicating that most released compounds could potentially be absorbed. As in the SN:50 snack, digalloylquinic acid and procyanidin gallate were the predominant compounds in the IF, whereas trigalloylquinic acid appeared in both the soluble and insoluble indigestible fractions (SIF and IIF), likely due to incomplete release. Methyl epigallocatechins were found exclusively in the IIF, suggesting they originated from condensed tannins.

In the SN:12 formulation, bioaccessibility was higher (61.27%), possibly due to reduced dietary fiber and protein content, which may have facilitated the release of phenolic compounds. Despite this, the IA remained comparable (84.3%). As in the other formulations, digalloylquinic acid and procyanidin gallate predominated in the IF, with methyl epigallocatechins again detected in the IIF.

The modulation of phenolic release is mechanistically governed by the interaction between dietary fiber and these bioactive compounds. The high content of insoluble dietary fiber provided by the nance flour (specifically the IIF fraction that increased with substitution) can physically encapsulate phenolic compounds, reducing their immediate release during the early stages of digestion (Villegas-Ornelas et al. 2025). Although direct data on the bioaccessibility percentage (BA%) for nance are not available, our findings are comparable to related studies on tropical fruit by-products. For example, Villegas-Ornelas et al. (2025), in evaluating bread enriched with guava by-product flour, reported that the combined effect of heat treatment (baking) and enzymatic hydrolysis during in vitro gastrointestinal digestion cleaves bonds in phenolic compounds bound to dietary fiber. This process releases phenolic acids and catechins, making these bioactive compounds potentially absorbable in the small intestine. Conversely, those nonbioaccessible compounds that remain strongly bound can reach the large intestine, where they undergo biotransformation by the colonic microbiota. Our measured BA%$ for the SN:12 formulation (61.27%) showed a slightly lower bioaccessibility than that reported for fresh guavas with and without seeds (64.79% and 67.69%, respectively), but significantly exceeded the 37%–47% range reported by Durán-Castañeda et al. (2023) for two other guava species.

Our results are consistent with previous findings in guava and other tropical fruits, confirming the role of dietary fiber in modulating phenolic release and stability. The interaction between soluble/insoluble fiber and phenolics likely facilitates gradual release during digestion, enhancing intestinal availability.

4 | Conclusions

This work successfully establishes the first reported incorporation of *nance* (*Byrsonima crassifolia* L.) flour as a functional ingredient within a starch-molded snack matrix. Nance incorporation countered the functional limitations of conventional starch-based snacks, which typically exhibit low fiber and bioactivity.

The 50% substitution snack achieved a high dietary fiber content (22.64 g/100g) and notable phenolic content, resulting in a significantly enhanced antioxidant capacity. In vitro digestion confirmed the functional relevance, showing a phenolic compound bioaccessibility (BA) of 48%–61% and a high intestinal absorption (IA) potential of 84%–89%.

These results, supported by high sensory acceptability in odor and flavor, position this work as a valuable contribution to sustainable food innovation and the functional valorization of native tropical fruits.

Author Contributions

Mariana Carolina Fregoso-Ultreras: investigation, writing – original draft. **Cinthia Jazmin Villegas-Ornelas:** writing – review and editing, validation. **Victor Manuel Zamora-Gasga:** writing – review and editing, supervision. **Jorge Alberto Sánchez-Burgos:** writing – review and editing, validation. **Sonia Guadalupe Sáyago-Ayerdi:** writing – review and editing, validation. **Francisco Javier Blancas-Benitez:** conceptualization, funding acquisition, writing – review and editing, project administration, supervision.

Acknowledgments

This work was supported by National Council for the Humanities, Sciences and Technologies (CONAHCYT). Scholarship number: 844365. Blancas-Benitez, Francisco Javier, gratefully acknowledges the Laboratorio Nacional CONAHCYT de Apoyo a la Evaluación de Productos Bióticos (LaNAEPBi), located in Tepic, Nayarit, Mexico, for providing access to its facilities and analytical resources that supported the completion of this study.

Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Acuff, J. C., J. S. Dickson, J. M. Farber, et al. 2023. "Practice and Progress: Updates on Outbreaks, Advances in Research, and Processing Technologies for Low-Moisture Food Safety." *Journal of Food Protection* 26, no. 1: 100018. https://doi.org/10.1016/j.jfp.2022.11.010.

Agredano-De la Garza, C. S., R. Balois-Morales, G. Berumen-Varela, et al. 2021. "Physicochemical Characterization and Dietary Fiber of 15 Nance (*Byrsonima crassifolia* L.) Fruits Selections From Nayarit." *Scientia Horticulturae* 289: 110460. https://doi.org/10.1016/j.scienta.2021.110460.

Alam, M., M. M. Hasan, M. K. Debnath, et al. 2024. "Characterization and Evaluation of Flour's Physico-Chemical, Functional, and

Nutritional Quality Attributes From Edible and Non-Edible Parts of Papaya." *Journal of Agriculture and Food Research* 15: 100961. https://doi.org/10.1016/j.jafr.2023.100961.

Aleksejeva, S., I. Siksna, and S. Rinkule. 2017. "Composition of Cereal Bars." *Journal of Health Science* 5, no. 3: 139–145. https://doi.org/10.17265/2328-7136/2017.03.004.

Alvarez-Parrilla, E., L. A. De La Rosa, R. Amarowicz, and F. Shahidi. 2011. "Antioxidant Activity of Fresh and Processed Jalapeño and Serrano Peppers." *Journal of Agricultural and Food Chemistry* 59, no. 1: 163–173. https://doi.org/10.1021/jf103434u.

Alvarez-Parrilla, E., L. A. De La Rosa, P. Legarreta, L. Saenz, J. Rodrigo-García, and G. A. Gonzlez-Aguilar. 2010. "Daily Consumption of Apple, Pear and Orange Juice Differently Affects Plasma Lipids and Antioxidant Capacity of Smoking and Non-Smoking Adults." *International Journal of Food Sciences & Nutrition* 61, no. 4: 369–380. https://doi.org/10.3109/09637480903514041.

Alves, G., and D. Perrone. 2015. "Breads Enriched With Guava Flour as a Tool for Studying the Incorporation of Phenolic Compounds in Bread Melanoidins." *Food Chemistry* 185: 65–74. https://doi.org/10.1016/j.foodchem.2015.03.110.

Bekele, D. W., and S. A. Emire. 2023. "Effects of Pre-Drying Treatment and Particle Sizes on Physicochemical and Structural Properties of Pumpkin Flour." *Heliyon* 9, no. 11: e21609. https://doi.org/10.1016/j.heliyon.2023.e21609.

Benzie, I. F. F., and J. J. Strain. 1996. "The Ferric Reducing Ability of Plasma (FRAP) as a Measure of 'Antioxidant Power': The FRAP Assay." *Analytical Biochemistry* 239, no. 1: 70–76. https://doi.org/10.1006/abio.1996.0292.

Blancas-Benitez, F. J., R. de Jesús Avena-Bustillos, E. Montalvo-González, S. G. Sáyago-Ayerdi, and T. H. McHugh. 2015. "Addition of Dried 'Ataulfo' Mango (Mangifera indica L) by-Products as a Source of Dietary Fiber and Polyphenols in Starch Molded Mango Snacks." *Journal of Food Science and Technology* 52, no. 11: 7393–7400. https://doi.org/10.1007/s13197-015-1855-7.

Blancas-Benitez, F. J., J. Pérez-Jiménez, E. Montalvo-González, G. A. González-Aguilar, and S. G. Sáyago-Ayerdi. 2018. "In Vitro Evaluation of the Kinetics of the Release of Phenolic Compounds From Guava (*Psidium guajava* L.) Fruit." *Journal of Functional Foods* 43: 139–145. https://doi.org/10.1016/j.jff.2018.02.011.

Brodkorb, A., L. Egger, M. Alminger, et al. 2019. "INFOGEST Static in Vitro Simulation of Gastrointestinal Food Digestion." *Nature Protocols* 14, no. 4: 991–1014. https://doi.org/10.1038/s41596-018-0119-1.

Chandra, S., S. Singh, and D. Kumari. 2015. "Evaluation of Functional Properties of Composite Flours and Sensorial Attributes of Composite Flour Biscuits." *Journal of Food Science and Technology* 52, no. 6: 3681–3688. https://doi.org/10.1007/s13197-014-1427-2.

Cummings, J. H., and H. N. Englyst. 1987. "Fermentation in the Human Large Intestine and the Available Substrates." *American journal of clinical nutrition* 45, no. 5: 1243–1255. https://doi.org/10.1093/ajcn/45.5.1243.

da Silva, P. M. C., L. C. Neves, V. J. Bastos, C. G. B. Lima, K. G. M. de Araújo, and S. R. Roberto. 2016. "Harvesting Period of Murici (*Byrsonima crassifolia* Kunth) Fruit in Relation to Physical and Chemical Parameters Evaluated During Fruit Development." *Scientia Horticulturae* 200: 66–72. https://doi.org/10.1016/j.scienta.2015.12.041.

de Barros Vinhal, G. L. R. R., M. A. Ribeiro Sanches, M. T. Barcia, D. Rodrigues, and P. B. Pertuzatti. 2022. "Murici (*Byrsonima verbascifolia*): A High Bioactive Potential Fruit for Application in Cereal Bars." *Lebensmittel-Wissenschaft & Technologie* 160: 113279. https://doi.org/10.1016/j.lwt.2022.113279.

de la Rosa, L. A., J. O. Moreno-Escamilla, J. Rodrigo-García, and E. Alvarez-Parrilla. 2019. "Phenolic Compounds." In *Postharvest Physiology and Biochemistry of Fruits and Vegetables*, 253–271. Woodhead Publishing.

Durán-Castañeda, A. C., A. P. Cardenas-Castro, J. Pérez-Jiménez, et al. 2023. "Bioaccessibility of Phenolic Compounds in *Psidium guajava* L. Varieties and *P. friedrichsthalianum* Nied. After Gastrointestinal Digestion." *Food Chemistry* 400: 134046. https://doi.org/10.1016/J.FOODCHEM.2022.134046.

Femenia, A., A. C. Lefebvre, J. Y. Thebaudin, J. A. Robertson, and C. M. Bourgeois. 1997. "Physical and Sensory Properties of Model Foods Supplemented With Cauliflower Fiber." *Journal of Food Science* 62, no. 4: 635–639. https://doi.org/10.1111/j.1365-2621.1997.tb15426.x.

Fueyo-González, F., A. Cenit, R. Villodres, et al. 2024. "Flour Moisture Detection With an Europium-Based Luminescent Probe." *Sensors and Actuators B: Chemical* 401: 134924. https://doi.org/10.1016/j.snb.2023.134924.

Hartzfeld, P. W., R. Forkner, M. D. Hunter, and A. E. Hagerman. 2002. "Determination of Hydrolyzable Tannins (Gallotannins and Ellagitannins) After Reaction With Potassium Iodate." *Journal of Agricultural and Food Chemistry* 50, no. 7: 1785–1790. https://doi.org/10.1021/jf011155.

Helrich, K. C., ed. 1990. *Official Methods of Analysis of the AOAC*, Vol. 2 (No. Ed. 15), xvii+–1298.

Huo, Y., Y. Niu, S. Feng, L. Zhang, J. Xu, and Q. Hu. 2024. "Effect of Three Modification Methods on Physical and Functional Properties of Flaxseed Cake Dietary Fiber." *Lebensmittel-Wissenschaft & Technologie* 198: 116076. https://doi.org/10.1016/J.LWT.2024.116076.

Kraithong, S., S. Lee, and S. Rawdkuen. 2018. "Physicochemical and Functional Properties of Thai Organic Rice Flour." *Journal of Cereal Science* 79: 259–266. https://doi.org/10.1016/j.jcs.2017.10.015.

Lawag, I. L., E. S. Nolden, A. A. Schaper, L. Y. Lim, and C. Locher. 2023. "A Modified Folin-Ciocalteu Assay for the Determination of Total Phenolics Content in Honey." *Applied Sciences* 13, no. 4: 2135. https://doi.org/10.3390/app13042135.

Li, M., L. Chang, J. Ren, et al. 2022. "Nutritional, Physical, Functional Properties and Antioxidant Potential of Different Colors Proso Millet Husks and Brans." *Lebensmittel-Wissenschaft & Technologie* 171: 114092. https://doi.org/10.1016/j.lwt.2022.114092.

Liu, K., B. Zhang, L. Chen, X. Li, and B. Zheng. 2019. "Hierarchical Structure and Physicochemical Properties of Highland Barley Starch Following Heat Moisture Treatment." *Food Chemistry* 271: 102–108. https://doi.org/10.1016/j.foodchem.2018.07.193.

Liu, Q. K. 2021. "Triglyceride-Lowering and Anti-Inflammatory Mechanisms of Omega-3 Polyunsaturated Fatty Acids for Atherosclerotic Cardiovascular Risk Reduction." *Journal of Clinical Lipidology* 15, no. 4: 556–568. https://doi.org/10.1016/j.jacl.2021.05.007.

Mañas, E., L. Bravo, and F. Saura-Calixto. 1994. "Sources of Error in Dietary Fibre Analysis." *Food Chemistry* 50, no. 4: 331–342. https://doi.org/10.1016/0308-8146(94)90201-1.

Medina-Torres, R., P. Juárez-López, S. Salazar-García, et al. 2015. "Evaluación de calidad en frutos de 41 genotipos de nanche (*Byrsonima crassifolia* L. HBK) de Nayarit, México." *Revista Mexicana de Ciencias Agrícolas* 6, no. 2: 253–264. https://doi.org/10.29312/remexca.v6i2.686.

Meng, X., C. Wu, H. Liu, Q. Tang, and X. Nie. 2021. "Dietary Fibers Fractionated From Gardenia (Gardenia jasminoides Ellis) Husk: Structure and in Vitro Hypoglycemic Effect." *Journal of the Science of Food and Agriculture* 101, no. 9: 3723–3731. https://doi.org/10.1002/jsfa.11003.

Montreau, F. R. 1972. "Sur le dosage des composés phénoliques totaux dans les vins par la méthode Folin-Ciocalteu." *OENO one* 6, no. 4: 397–404. https://doi.org/10.20870/oeno-one.1972.6.4.2071.

Moo-Huchin, V. M., I. Estrada-Mota, R. Estrada-León, et al. 2014. "Determination of Some Physicochemical Characteristics, Bioactive

Compounds and Antioxidant Activity of Tropical Fruits From Yucatan, Mexico." *Food Chemistry* 152: 508–515. https://doi.org/10.1016/j.foodchem.2013.12.013.

Munshi, M., and K. Dashora. 2024. "Comparative Study of Physico-Chemical Composition, Functional, Morphological and Pasting Properties of Major and Minor Millet Flours as a Gluten Free Alternative to Wheat Flour." *Measurement* 16. https://doi.org/10.1016/j.meafoo.2024.100202.

Obafemi, T. O., B. E. Ekundayo, O. B. Adewale, et al. 2023. "Gallic Acid and Neurodegenerative Diseases." *Phytomedicine Plus* 3, no. 4: 100492. https://doi.org/10.1016/j.phyplu.2023.100492.

O'Kane, N., S. Watson, L. Kehoe, et al. 2023. "The Patterns and Position of Snacking in Children in Aged 2–12 Years: A Scoping Review." *Appetite* 188: 106974. https://doi.org/10.1016/j.appet.2023.106974.

Ou, S., K. C. Kwok, Y. Li, and L. Fu. 2001. "In Vitro Study of Possible Role of Dietary Fiber in Lowering Postprandial Serum Glucose." *Journal of Agricultural and Food Chemistry* 49, no. 2: 1026–1029. https://doi.org/10.1021/jf000574n.

Pais, A. C. S., E. R. Coscueta, M. M. Pintado, A. J. D. Silvestre, and S. A. O. Santos. 2024. "Exploring the Bioaccessibility and Intestinal Absorption of Major Classes of Pure Phenolic Compounds Using in Vitro Simulated Gastrointestinal Digestion." *Heliyon* 10, no. 7: e28894. https://doi.org/10.1016/j.heliyon.2024.e28894.

Pérez-Jiménez, J., S. Arranz, and F. Saura-Calixto. 2009. "Proanthocyanidin Content in Foods is Largely Underestimated in the Literature Data: An Approach to Quantification of the Missing Proanthocyanidins." *Food Research International* 42, no. 10: 1381–1388. https://doi.org/10.1016/j.foodres.2009.07.002.

Pérez-Jiménez, J., S. Arranz, M. Tabernero, et al. 2008. "Updated Methodology to Determine Antioxidant Capacity in Plant Foods, Oils and Beverages: Extraction, Measurement and Expression of Results." *Food Research International* 41, no. 3: 274–285. https://doi.org/10.1016/j.foodres.2007.12.004.

Pires, F. C. S., A. P. D. S. Silva, M. D. L. A. R. Salazar, et al. 2019. "Determination of Process Parameters and Bioactive Properties of the Murici Pulp (*Byrsonima crassifolia*) Extracts Obtained by Supercritical Extraction." *Journal of Supercritical Fluids* 146: 128–135. https://doi.org/10.1016/j.supflu.2019.01.014.

Potter, M., A. Vlassopoulos, and U. Lehmann. 2018. "Snacking Recommendations Worldwide: A Scoping Review." *Advances in Nutrition* 9, no. 2: 86–98. https://doi.org/10.1093/advances/nmx003.

Prior, R. L., X. Wu, and K. Schaich. 2005. "Standardized Methods for the Determination of Antioxidant Capacity and Phenolics." *Journal of Agricultural and Food Chemistry* 53, no. 10: 4290–4302. https://doi.org/10.1021/jf0502698.

Ramirez-Maganda, J., F. J. Blancas-Benitez, V. M. Zamora-Gasga, et al. 2015. "Nutritional Properties and Phenolic Content of a Bakery Product Substituted With a Mango (Mangifera Indica) 'Ataulfo' Processing by-product." *Food Research International* 73: 117–123. https://doi.org/10.1016/j.foodres.2015.03.004.

Re, R., N. Pellegrini, A. Proteggente, A. Pannala, M. Yang, and C. Rice-Evans. 1999. "Antioxidant Activity Applying an Improved ABTS Radical Cation Decolorization Assay." *Free Radical Biology and Medicine* 26, no. 9–10: 1231–1237. https://doi.org/10.1016/S0891-5849(98)00315-3.

Reed, J. D., R. T. E. McDowell, P. J. van Soest, and P. R. J. Horvath. 1982. "Condensed Tannins: A Factor Limiting the Use of Cassava Forage." *Journal of the Science of Food and Agriculture* 33, no. 3: 213–220. https://doi.org/10.1002/jsfa.2740330302.

Rodrigues, D. B., M. C. Marques, A. Hacke, P. S. Loubet Filho, C. B. B. Cazarin, and L. R. B. Mariutti. 2022. "Trust Your Gut: Bioavailability and Bioaccessibility of Dietary Compounds." *Current Research in Food Science* 5: 228–233. https://doi.org/10.1016/j.crfs.2022.01.002.

Rumpf, J., R. Burger, and M. Schulze. 2023. "Statistical Evaluation of DPPH, ABTS, FRAP, and Folin-Ciocalteu Assays to Assess the Antioxidant Capacity of Lignins." *International Journal of Biological Macromolecules* 233: 123470. https://doi.org/10.1016/j.ijbiomac.2023.123470.

Saari, U. A., C. Herstatt, R. Tiwari, O. Dedehayir, and S. J. Mäkinen. 2021. "The Vegan Trend and the Microfoundations of Institutional Change: A Commentary on Food Producers' Sustainable Innovation Journeys in Europe." *Trends in Food Science and Technology* 107: 161–167. https://doi.org/10.1016/j.tifs.2020.10.003.

Saura-Calixto, F. 2011. "Dietary Fiber as a Carrier of Dietary Antioxidants: An Essential Physiological Function." *Journal of Agricultural and Food Chemistry* 59, no. 1: 43–49. https://doi.org/10.1021/jf1036596.

Secretaría de Salud. 1994. *Bienes y Servicios. Alimentos y Bebidas no Alcohólicas con Modificaciones en su composición. Especificaciones Nutrimentales (NOM-086-SSA1-1994)*. Diario Oficial de la Federación.

Soquetta, M. B., F. S. Stefanello, K. da Mota Huerta, S. S. Monteiro, C. S. da Rosa, and N. N. Terra. 2016. "Characterization of Physiochemical and Microbiological Properties, and Bioactive Compounds, of Flour Made From the Skin and Bagasse of Kiwi Fruit (*Actinidia deliciosa*)." *Food Chemistry* 199: 471–478. https://doi.org/10.1016/j.foodchem.2015.12.022.

Sousa, M. S. B., and D. de Souza Buarque. 2020. "Murici (*Byrsonima crassifolia* (L.) Kunth): Antioxidant Effects and Application to Aging." *Aging: Oxidative Stress and Dietary Antioxidants*: 259–265. https://doi.org/10.1016/B978-0-12-818698-5.00025-0.

Trakooncharoenvit, A., S. Tanaka, E. Mizuta, T. Hira, and H. Hara. 2020. "Water-Soluble Dietary Fibers Enhance Bioavailability of Quercetin and a Fiber Derived From Soybean Is Most Effective After Long-Term Feeding in Rats." *European Journal of Nutrition* 59, no. 4: 1389–1398. https://doi.org/10.1007/s00394-019-01992-9.

Uekane, T. M., L. Nicolotti, A. Griglione, et al. 2017. "Studies on the Volatile Fraction Composition of Three Native Amazonian-Brazilian Fruits: Murici (*Byrsonima crassifolia* L., Malpighiaceae), Bacuri (*Platonia insignis* M., Clusiaceae), and Sapodilla (*Manilkara sapota* L., Sapotaceae)." *Food Chemistry* 219: 13–22. https://doi.org/10.1016/j.foodchem.2016.09.098.

Urquiaga, I., S. D'Acuña, D. Pérez, et al. 2015. "Wine Grape Pomace Flour Improves Blood Pressure, Fasting Glucose and Protein Damage in Humans: A Randomized Controlled Trial." *Biological Research* 48: 1–10. https://doi.org/10.1186/s40659-015-0040-9.

Villegas-Ornelas, C. J., S. G. Sáyago-Ayerdi, V. M. Zamara-Gasga, and F. J. Blancas-Benítez. 2025. "The Impact of Composite Flours in the in Vitro Gastrointestinal Digestion on Phenolic Compounds in Bakery Products." *Food Research International* 221: 117574. https://doi.org/10.1016/j.foodres.2025.117574.

Zlatanović, S., A. Kalušević, D. Micić, et al. 2019. "Functionality and Storability of Cookies Fortified at the Industrial Scale With up to 75% of Apple Pomace Flour Produced by Dehydration." *Foods* 8, no. 11: 561. https://doi.org/10.3390/foods8110561.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Table S1: Analysis of variance (ANOVA) and inter-group comparison for phenolic compound bioaccessibility (BA%) across nance flour snack formulations.