Exploration of Foods and Foodomics

Open Access Original Article

Rheological, pasting, and textural characteristics of wheat-sacha inchi (*Plukenetia volubilis*) composite flour and dough

Afifah Farhanah Abdullah[1], Macdalyna Esther Ronie[1], Ahmad Hazim Abdul Aziz[1], Yanty Noorzianna Abdul Manaf[1], Rovina Kobun[2], Mohd Sani Sarjadi[3], Nicky Rahmana Putra[4], Asep Awaludin Prihanto[5], Hasmadi Mamat[1]*

[1]Food Safety and Security Research Laboratory, Faculty of Food Science and Nutrition, Universiti Malaysia Sabah, Kota Kinabalu 88400, Sabah, Malaysia

[2]Faculty of Sustainable Agriculture, Universiti Malaysia Sabah, Sandakan 90509, Sabah, Malaysia

[3]Faculty of Science and Technology, Universiti Malaysia Sabah, Kota Kinabalu 88400, Sabah, Malaysia

[4]Faculty of Engineering Technology and Science, Higher College of Technology (HCT), Abu Dhabi P.O Box 25026, United Arab Emirates

[5]Department of Fishery Product Technology, Faculty of Fisheries and Marine Science, Brawijaya University, Malang 65145, Indonesia

***Correspondence:** Hasmadi Mamat, Food Safety and Security Research Laboratory, Faculty of Food Science and Nutrition, Universiti Malaysia Sabah, Kota Kinabalu 88400, Sabah, Malaysia. idamsah@ums.edu.my

Academic Editor: Dong-uk Ahn, Iowa State University, United States

Received: January 30, 2026 **Accepted:** July 7, 2026 **Published:** July 23, 2026

Cite this article: Abdullah AF, Ronie ME, Abdul Aziz AH, Manaf YNA, Kobun R, Sarjadi MS, et al. Rheological, pasting, and textural characteristics of wheat-sacha inchi (*Plukenetia volubilis*) composite flour and dough. Explor Foods Foodomics. 2026;4:1010178. https://doi.org/10.37349/eff.2026.1010178

Abstract

Aim: This study aimed to evaluate the functional role of sacha inchi (*Plukenetia volubilis*) flour in wheat-based composite dough systems and to determine optimal substitution levels that balance between improved proximate nutritional composition and acceptable processing and dough performance.

Methods: Six composite flour formulations (control—F5) were prepared by replacing wheat flour with sacha inchi flour at 5% intervals (0–25%). The flours and corresponding doughs were characterised for proximate composition, colour parameters, pasting properties and thermo-mechanical behaviour.

Results: Proximate analysis showed progressive increases in crude protein (8.60% to 14.20%), crude fat (1.20% to 16.0%), crude fibre (0.20% to 0.38%), and ash (0.41% to 0.83%), alongside reductions in moisture (14.00% to 9.40%) and carbohydrate content (56.00% to 35.40%) with increasing substitution, while colour analysis showed reduced lightness (93.20 to 87.90) and increased redness and yellowness. RVA analysis revealed significant decreases in peak viscosity (3,700 to 1,670 cP) and setback viscosity (1,600 to 1,000 cP). Mixolab measurements showed decreased water absorption, reduced protein stability (C2 decreased from 0.59 to 0.27 Nm), and modified starch gelatinisation behaviour, with C3 peaking at lower substitution levels. Texture profile analysis indicated increased dough hardness (1,070 g to 2,300 g) and decreased cohesiveness (0.78 to 0.23) and springiness (0.53 to 0.13) at higher substitution levels.

Conclusions: These findings demonstrate that sacha inchi flour functions as both a nutritional enhancer and a structural modifier in wheat-based systems. Substitution levels up to 15% are recommended to achieve an optimal balance between improved nutritional value and acceptable processing and dough performance, supporting its application in functional bakery formulations.

Keywords

sacha inchi flour, composite flour, dough rheology, pasting properties, functional bakery products

Introduction

The increasing demand for health-oriented, nutrient-dense, and sustainable bakery products has driven research into alternative and composite flour systems that enhance nutritional value while maintaining desirable processing and quality attributes. Conventional wheat flour, although widely used, has limitations in essential fatty acids and high-quality protein content and is unsuitable for individuals with gluten intolerance or coeliac disease, prompting exploration of novel plant-based composite flours [1]. Research has shown that substituting wheat with nutrient-rich flours can improve nutritional profiles, such as increased crude protein and fibre, but frequently alters dough behaviour and processing performance [2].

Rheological characterisation plays a pivotal role in food measurement and characterisation because it quantitatively describes how dough responds to stress and strain during mixing, fermentation, and baking, properties that are directly linked to product texture, stability, and quality [3]. Substituting wheat flour with alternative flours significantly alters viscoelasticity, water absorption, and structural development due to changes in protein content, starch dilution, fibre interactions, and lipid composition, which are detectable through instruments such as the Rapid Visco Analyser (RVA) and Mixolab [4–6]. For example, partial replacement of wheat with legume or pulse flours has been shown to increase protein and mineral content while reducing carbohydrate percentages, with clear effects on rheological curves that correlate with reduced gluten network strength [7]. Rheological metrics are therefore essential for optimising formulations that balance nutrition with acceptable dough handling and final product characteristics, yet many traditional studies focus on proximate and sensory outcomes without deep mechanistic insight into dough rheology.

Sacha inchi (*Plukenetia volubilis*), a seed from the Amazon region, is rich in high-quality protein and polyunsaturated fatty acids and has been investigated primarily for oil and by-product utilization, including press cake flours with improved emulsifying and foaming properties and enhanced rheological behaviour compared with some conventional seed proteins [8]. Proximate and techno-functional analyses suggest this species has strong potential as a functional ingredient, yet the effects of sacha inchi flour substitution on composite dough rheology particularly quantification of viscoelasticity, pasting, and thermo-mechanical responses remain poorly understood [9–11]. Recent studies highlight the importance of such data to guide formulation strategies that maintain dough performance, especially as hydrophilic and hydrophobic interactions change with increasing non-wheat components [12].

To address this research gap, this study examines the rheological characteristics of dough prepared using sacha inchi composite flour by evaluating how incremental substitution levels influence viscoelasticity, water absorption, pasting behaviour, and dough textural properties using standardised rheological methods. While previous studies have largely focused on end-product quality, nutritional composition, or individual functional attributes of sacha inchi-based systems, a comprehensive and integrated evaluation of its role within wheat-based composite dough matrices remains limited. Therefore, this study goes beyond conventional substitution approaches by systematically linking compositional changes with pasting (RVA), thermo-mechanical (Mixolab), and textural (TPA) properties to elucidate the structure–function relationships governing dough behaviour. This integrated approach provides new insight into the mechanistic role of sacha inchi flour and supports the development of nutritionally enhanced bakery products with predictable processing performance.

Materials and methods

Materials

Commercial wheat flour, instant dry yeast, sugar, salt, and vegetable oil were purchased from a local supplier in Kota Kinabalu, Malaysia. Sacha inchi (*Plukenetia volubilis* L.) seeds were obtained from a certified organic supplier in Sabah, Malaysia. All chemicals (Merck, Darmstadt, Germany) used for proximate analysis were of analytical grade.

Preparation of sacha inchi flour

Sacha inchi seeds were roasted in a hot air oven at 120°C for 30 min, cooled to room temperature, and milled using a high-speed blender. The ground material was sieved to obtain a fine, homogeneous flour, which was stored in airtight containers at ambient temperature until analysis. The roasting conditions were selected based on preliminary trials to optimise moisture reduction, flavour development, and milling performance, and are consistent with commonly reported processing approaches for oilseed-based flours.

Composite flour formulation and dough preparation

Composite flours were prepared by partially replacing wheat flour with sacha inchi flour at 0, 5, 10, 15, 20, and 25% (w/w), designated as Control, F1, F2, F3, F4, and F5, respectively (Table 1). The selected substitution range (0–25%) was based on previous studies and preliminary trials indicating that higher substitution levels (> 25%) may adversely affect dough structure and handling properties due to gluten dilution, while lower incremental levels (5%) enable systematic evaluation of functional and rheological changes. Dough was prepared using 100 g of composite flour, yeast (2 g), sugar (1 g), salt (1 g), vegetable oil (6 g), and water (65 g). A constant water addition (65 g) was applied across all formulations to enable direct comparison of the effects of sacha inchi flour substitution on dough rheological and textural properties. This approach isolates the impact of compositional differences (e.g., protein, lipid, and fibre content) on dough behaviour without introducing variability associated with formulation-specific water optimisation. While water absorption may vary among formulations, maintaining a fixed hydration level allows for a more controlled evaluation of structural and functional changes induced by sacha inchi incorporation. Ingredients were mixed for 8–10 min until a cohesive dough was obtained, followed by resting for 15–20 min at room temperature.

Table 1. Composite flour formulations containing different substitution levels of sacha inchi flour.

Formulation	Wheat flour (%)	Sacha inchi flour (%)
Control (F0)	100	0
F1	95	5
F2	90	10
F3	85	15
F4	80	20
F5	75	25

Proximate composition

Proximate composition (moisture, ash, crude protein, crude fat, and crude fibre) was determined according to standard AOAC methods [13]. Moisture (Method 925.10), ash (Method 923.03), crude protein (Kjeldahl; Method 979.09), crude fat (Soxhlet; Method 920.39), and crude fibre (Method 962.09) were analysed. All analyses were performed in triplicate and results were expressed as mean values. Carbohydrate content was calculated by difference.

Pasting properties

Pasting properties were determined using a Rapid Visco Analyzer (RVA, Newport Scientific) following the standard AACC method (AACC 61-02.01). Flour samples (4.0 g, moisture-corrected) were dispersed in

24 mL distilled water and subjected to a standard heating–cooling cycle (25–95–25°C) at a constant paddle speed of 160 rpm. Pasting temperature, peak viscosity, breakdown, final viscosity, and setback were recorded. Several pasting parameters were recorded, including peak viscosity, trough viscosity, breakdown viscosity, final viscosity, setback viscosity, peak time, and pasting temperature. Three repetition measurements were conducted to obtain the reported value.

Dough rheological properties

The thermo-mechanical behaviour of dough was evaluated using a Mixolab (Chopin Technologies) following the standard Chopin+ protocol. Approximately 45 g of composite flour was weighed and placed into the Mixolab mixing bowl, after which water was added gradually to achieve a target dough consistency of approximately 1.1 Nm torque, ensuring uniform hydration across formulations. The test was initiated at 30°C with mixing for about 8 min to assess dough development and stability, parameters closely associated with protein quality and gluten strength. The temperature was then progressively increased to 90°C to monitor starch gelatinisation and enzymatic activity, as reflected by changes in dough viscosity. Subsequently, the dough was cooled to approximately 50°C to evaluate starch retrogradation, which is closely related to texture development and shelf-life characteristics.

Texture profile analysis

Texture profile analysis (TPA) of dough samples was conducted using a texture analyzer (TA.XTplus, Stable Micro Systems, UK) equipped with a cylindrical probe (P/36R). Prior to testing, the instrument was calibrated for height and force using Exponent Connect software. Uniform dough samples (25 mm diameter × 20 mm height) were prepared and placed centrally on the analyzer platform. The test was performed using a pre-test speed of 2 mm/s, a test speed of 2–3 mm/s, and a post-test speed of 10 mm/s, with the samples compressed to approximately 60% strain. A moderate trigger force (75 mm) was applied upon probe contact with the dough surface, and a double-compression cycle with a 5 s interval between compressions was used to simulate mastication. Hardness, cohesiveness, springiness, and adhesiveness were calculated from the resulting force–time curves.

Colour measurement

The colour of the sacha inchi composite flours was measured using a colorimeter (Neuhaus Neotec, Germany) based on the CIE $L^*a^*b^*$ colour system. According to HunterLab Associates Laboratory Inc., the L^* value indicates lightness (0 = black, 100 = white), a^* represents redness ($+a^*$) or greenness ($-a^*$), and b^* represents yellowness ($+b^*$) or blueness ($-b^*$). Prior to measurement, the colorimeter was calibrated using standard black glass and a white calibration tile. All measurements were performed in triplicate.

Statistical analysis

All experiments were conducted in triplicate, and results are expressed as mean ± standard deviation. Data were analysed using one-way analysis of variance (ANOVA), followed by Tukey's post hoc test to determine significant differences between means. Statistical significance was set at $p < 0.05$. All analyses were performed using SPSS software (version 30, IBM Corp., Armonk, NY, USA).

Results

The proximate composition, colour characteristics, pasting behaviour, rheological properties, and texture profile of sacha inchi composite flours and their corresponding doughs are presented in Tables 2, 3, 4, 5, 6. Moisture content decreased significantly ($p < 0.05$) from 14% in the control to 9.4% in F5, while ash content increased from 0.41% to 0.83% with increasing substitution level. Crude protein content rose progressively from 8.6% to 14.2%, and crude fat content increased markedly from 1.2% in the control to 16.0% in F5. Crude fibre content remained relatively unchanged from the control to F4 but increased significantly at F5 (0.38%). In contrast, carbohydrate content decreased significantly from 56.3% in the control to 35.4% in F5. Consistent with these compositional changes, colour analysis (Table 3) revealed a significant reduction in lightness (L^*) from 93.2 in the control to 87.9 in F5, accompanied by increases in

Table 2. Proximate composition of wheat-sacha inchi composite flours at different substitution levels.

Nutrient (%)	Control	F1	F2	F3	F4	F5
Moisture	14.00 ± 2.00[a]	11.90 ± 0.1[b]	11.70 ± 0.10[b]	10.40 ± 0.90[c]	10.30 ± 0.30[c]	9.40 ± 0.40[c]
Ash	0.41 ± 0.08[d]	0.53 ± 0.04[c]	0.56 ± 0.04[c]	0.63 ± 0.02[b]	0.74 ± 0.02[b]	0.83 ± 0.03[a]
Crude protein	8.60 ± 0.50[e]	10.3 ± 0.50[de]	11.80 ± 0.70[cd]	12.10 ± 0.80[bc]	13.00 ± 1.00[ab]	14.20 ± 0.60[a]
Crude fat	1.20 ± 0.20[f]	4.50 ± 0.20[e]	8.80 ± 0.20[d]	10.50 ± 0.40[c]	13.00 ± 0.60[b]	16.00 ± 0.80[a]
Crude fibre	0.20 ± 0.01[b]	0.21 ± 0.01[b]	0.22 ± 0.01[b]	0.24 ± 0.01[b]	0.27 ± 0.05[b]	0.38 ± 0.06[a]
Carbohydrate	56.00 ± 2.00[a]	52.20 ± 0.80[b]	45.70 ± 0.20[c]	44.00 ± 2.00[c]	39.00 ± 1.00[d]	35.40 ± 0.90[e]

Values are expressed as mean ± standard deviation (n = 3). Superscript letters indicate statistically significant differences among formulations within the same row, as determined by Tukey's test at $p < 0.05$.

Table 3. Colour parameters of sacha inchi composite flour dough.

Formulation	Lightness	Red–green	Yellow–blue
Control	93.20 ± 0.04[a]	−0.22 ± 0.06[e]	9.77 ± 0.07[d]
F1	92.40 ± 0.09[b]	−0.20 ± 0.01[e]	10.80 ± 0.20[c]
F2	91.16 ± 0.03[c]	0.05 ± 0.01[d]	11.64 ± 0.02[b]
F3	90.30 ± 0.06[d]	0.15 ± 0.03[c]	11.80 ± 0.10[b]
F4	89.10 ± 0.05[e]	0.24 ± 0.03[b]	13.00 ± 0.06[a]
F5	87.90 ± 0.10[f]	0.34 ± 0.02[a]	13.30 ± 0.20[a]

Values are expressed as mean ± standard deviation (n = 3). Superscript letters indicate statistically significant differences among formulations within the same column, as determined by Tukey's test at $p < 0.05$.

Table 4. Rapid visco analyzer (RVA) pasting properties of wheat-sacha inchi composite flour formulations at varying levels of sacha inchi substitution.

Formulation	Peak viscosity (cP)	Trough viscosity (cP)	Breakdown viscosity (cP)	Final viscosity (cP)	Setback viscosity (cP)	Peak time (min)	Pasting temperature (°C)
Control	3,700 ± 80[a]	1,910 ± 90[a]	1,790 ± 60[a]	3,470 ± 30[a]	1,600 ± 300[a]	5.50 ± 0.50[a]	67.80 ± 0.90[a]
F1	3,010 ± 90[b]	1,690 ± 20[b]	1,320 ± 70[ab]	3,040 ± 30[a]	1,350 ± 10[b]	5.80 ± 0.10[a]	67.70 ± 0.10[a]
F2	2,580 ± 50[c]	1,500 ± 50[c]	1,080 ± 30[bc]	2,750 ± 40[a]	1,250 ± 10[c]	5.80 ± 0.10[a]	68.50 ± 0.10[a]
F3	2,260 ± 30[d]	1,370 ± 70[cd]	890 ± 70[cd]	2,530 ± 80[a]	1,160 ± 40[d]	5.90 ± 0.10[a]	69.40 ± 0.90[a]
F4	1,940 ± 30[e]	820 ± 60[d]	760 ± 50[d]	2,320 ± 80[a]	1,140 ± 20[d]	5.90 ± 0.10[a]	81.80 ± 0.50[b]
F5	1,670 ± 30[f]	1,050 ± 10[d]	440 ± 30[d]	2,050 ± 20[a]	1,000 ± 10[e]	5.90 ± 0.00[a]	80.00 ± 10.00[b]

Values are expressed as mean ± standard deviation (n = 3). Means with different superscript letters within the same column are significantly different ($p < 0.05$).

Table 5. Mixolab parameters of dough prepared from wheat-sacha inchi composite flours at different substitution levels.

Formulation	C1 (Nm)	CS (Nm)	C2 (Nm)	C3 (Nm)	C4 (Nm)	C5 (Nm)	Stability (min)	Water absorption (%)
Control	1.12 ± 0.01[a]	1.10 ± 0.02[b]	0.59 ± 0.02[a]	1.87 ± 0.02[a]	1.70 ± 0.10[a]	3.37 ± 0.05[a]	10.50 ± 0.20[a]	57.00 ± 0.10[a]
F1	1.10 ± 0.03[a]	1.09 ± 0.03[b]	0.48 ± 0.02[b]	1.76 ± 0.04[b]	1.06 ± 0.02[b]	1.78 ± 0.07[b]	10.10 ± 0.10[a]	53.60 ± 0.10[b]
F2	1.13 ± 0.04[a]	1.15 ± 0.03[a]	0.43 ± 0.01[bc]	1.71 ± 0.01[c]	0.91 ± 0.02[c]	1.51 ± 0.01[c]	9.70 ± 0.20[a]	51.30 ± 0.10[c]
F3	1.14 ± 0.05[a]	1.13 ± 0.04[a]	0.39 ± 0.02[c]	1.66 ± 0.01[cd]	0.84 ± 0.01[d]	1.43 ± 0.01[d]	9.60 ± 0.10[a]	46.90 ± 0.10[d]
F4	1.08 ± 0.02[a]	1.06 ± 0.02[c]	0.31 ± 0.01[d]	1.60 ± 0.10[d]	0.72 ± 0.01[e]	1.24 ± 0.01[e]	9.50 ± 0.20[a]	45.50 ± 0.10[d]
F5	1.06 ± 0.01[a]	1.04 ± 0.02[c]	0.27 ± 0.03[d]	1.50 ± 0.10[e]	0.61 ± 0.03[f]	1.12 ± 0.03[f]	8.00 ± 1.00[b]	43.00 ± 2.00[e]

Values are expressed as mean ± standard deviation ($n = 3$). Means with different superscript letters within the same column are significantly different ($p < 0.05$).

Table 6. Texture profile analysis (TPA) parameters of dough prepared from wheat-sacha inchi composite flours at different substitution levels.

Formulation	Hardness (g)	Springiness	Cohesiveness	Stickiness (g·s)
Control	1,070 ± 80[b]	0.53 ± 0.03[a]	0.78 ± 0.01[a]	−57 ± 4[c]
F1	1,550 ± 60[ab]	0.42 ± 0.04[b]	0.60 ± 0.03[b]	−56 ± 5[bc]
F2	1,820 ± 40[ab]	0.36 ± 0.01[b]	0.44 ± 0.01[c]	−46 ± 6[abc]
F3	1,800 ± 100[ab]	0.25 ± 0.04[c]	0.37 ± 0.01[d]	−43 ± 8[ab]
F4	2,200 ± 100[a]	0.17 ± 0.02[cd]	0.27 ± 0.01[e]	−36 ± 2[a]
F5	2,300 ± 300[a]	0.13 ± 0.02[d]	0.23 ± 0.01[e]	−34 ± 3[a]

Values are expressed as mean ± standard deviation ($n = 3$). Means with different superscript letters within the same column are significantly different ($p < 0.05$).

redness (a^*) from −0.22 to 0.34 and yellowness (b^*) from 9.77 to 13.3 as the level of sacha inchi substitution increased. Although these compositional changes reflect the substitution of wheat flour with sacha inchi flour, they are scientifically relevant as they directly influence the functional behaviour of the dough system. In particular, increases in protein, lipid, and fibre contents, together with reduced carbohydrate (starch) levels, are expected to modify water distribution, gluten network formation, and starch gelatinisation, which underpin the rheological and textural properties discussed in subsequent sections.

The RVA pasting results are summarised in Table 4. RVA analysis showed a significant reduction in peak viscosity from 3,700 cP in the control to 1,670 cP in F5, accompanied by decreases in trough viscosity (1,910 to 820 cP), breakdown viscosity (1,790 to 440 cP), and setback viscosity (1,600 to 1,000 cP). Final viscosity did not differ significantly among formulations, and peak time remained constant across samples. Pasting temperature increased at higher substitution levels, reaching 81.8°C in F4.

To further elucidate the thermo-mechanical mechanisms underlying these pasting properties, Mixolab analysis was performed. Mixolab analysis (Table 5) showed no significant differences in initial dough consistency (C1) among formulations; however, protein weakening torque (C2) decreased significantly from 0.59 Nm in the control to 0.27 Nm in F5. Starch gelatinisation torque (C3) decreased from 1.87 Nm to 1.5 Nm, while C4 and C5 values also declined progressively. In parallel, dough stability decreased from 10.5 min to 8.1 min, and water absorption dropped significantly from 57.0% in the control to 43.3% in F5, reflecting the increasing influence of sacha inchi components on dough structure.

These thermo-mechanical changes were reflected in the macroscopic textural properties of the dough (Table 6). Dough hardness increased significantly from 1,070 g in the control to 2,300 g in F5, while springiness decreased from 0.53 to 0.13 and cohesiveness declined from 0.78 to 0.23. In parallel, stickiness values became less negative with increasing sacha inchi content, changing from −57 g·s in the control to −34 g·s in F5.

Discussion

Incorporation of sacha inchi flour produced clear formulation-dependent changes across compositional, pasting, rheological, textural, and colour attributes, reflecting the distinct physicochemical nature of sacha inchi relative to refined wheat flour. Moisture content decreased significantly with increasing substitution level, with the control exhibiting the highest value and formulation F5 the lowest. The systematic nature of this reduction indicates that moisture loss was directly associated with sacha inchi incorporation rather than random variability. This behaviour reflects the lower water affinity of lipid-rich sacha inchi flour, which promotes redistribution of water from free to bound states within the dough matrix. Such changes are functionally important, as they influence dough consistency, mixing behaviour, and shelf-life stability. This behaviour is consistent with reports that sacha inchi flours typically contain less than 10% moisture due to their high lipid content and low intrinsic water affinity [14]. Reduced moisture is advantageous for flour stability and shelf life, while also influencing water redistribution during dough mixing, favouring bound over free water and contributing to increased dough consistency and resistance to mechanical stress [15]. While these trends are consistent with compositional changes, the extent of functional modification observed at higher substitution levels highlights a clear trade-off between nutritional enhancement and technological performance, particularly in relation to gluten network integrity and dough elasticity.

Ash content increased progressively with increasing substitution, reflecting the higher mineral concentration of sacha inchi seeds compared with refined wheat flour [16]. This increase suggests enhanced mineral content in the composite flour, as ash represents the total inorganic residue. From a nutritional perspective, this may contribute to improved intake of essential minerals; however, the specific mineral composition was not determined in this study and warrants further investigation. Elevated ash levels contribute to changes in ionic strength and buffering capacity, which can influence protein interactions and dough stability during mixing and fermentation. Similarly, crude protein content increased significantly with higher levels of sacha inchi flour, consistent with the high storage-protein content of this oilseed [9]. Unlike gluten proteins, sacha inchi proteins tend to form compact aggregates that enhance dough firmness but restrict extensibility at higher inclusion levels, a pattern reported previously for oilseed-wheat composite systems such as flaxseed and press-cake-enriched doughs [17]. Moderate substitution levels have been shown to enhance protein content without severe impairment of dough handling, as plant proteins contribute to water binding and gas cell stabilisation rather than replacing gluten functionality. Collectively, the increase in protein, lipid, and fibre contents contributes to a structural transition in the dough system, where gluten continuity is progressively disrupted and replaced by a more heterogeneous matrix governed by protein–lipid–fibre interactions. From a consumer perspective, darker colour and increased yellowness or redness may influence product acceptability, depending on the type of bakery product and consumer expectations. While such changes may be acceptable or even desirable in wholegrain or functional products, they could be less favourable in products where a lighter appearance is preferred. Therefore, colour modification should be considered in formulation design alongside nutritional and functional properties.

Crude fat content increased markedly with increasing substitution, reflecting the naturally high oil content of sacha inchi seeds. Replacement of low-lipid wheat flour with sacha inchi flour therefore resulted in substantial lipid enrichment of the composite system. Increased lipid levels influence dough rheology by modifying protein interactions and surface properties, often reducing stickiness and altering mixing torque. Studies on sacha inchi protein-enriched breads have shown that lipid–protein complexes can preserve dough handling and structural integrity, even when gluten content is diluted [18]. Crude fibre content also increased progressively, with a significant rise observed at the highest substitution level, confirming effective incorporation of fibre-rich seed components. Dietary fibre increases water-binding capacity through hydroxyl-rich polysaccharide structures, physically interferes with gluten continuity, and increases dough tenacity while reducing extensibility, trends widely reported in fibre-enriched composite flours [19, 20]. In contrast, carbohydrate content decreased steadily from the control to F5, reflecting starch dilution as protein, lipid, fibre, and mineral fractions became more dominant. This compositional shift has direct implications for thermal and rheological behaviour, as starch is the primary contributor to gelatinisation viscosity and retrogradation [21].

Colour analysis showed a progressive decrease in lightness (*L**) and increases in redness (*a**) and yellowness (*b**) with increasing substitution level, indicating darker and more yellow–reddish flour. This trend reflects replacement of bright wheat endosperm with protein-, lipid-, and mineral-rich sacha inchi flour, which absorbs and scatters light more effectively [16]. Increased *a** values suggest enhanced browning potential associated with higher protein content and Maillard reaction precursors, while increased *b** values reflect the intrinsic yellowish pigments and lipid fractions of sacha inchi kernels [22]. Similar colour shifts have been reported for oilseed- and multigrain-enriched dough systems and are generally acceptable at moderate substitution levels. These compositional and colour changes are further discussed in relation to their impact on rheological and functional properties in the following section.

RVA analysis demonstrated that increasing sacha inchi substitution significantly altered pasting behaviour. Peak viscosity decreased sharply from the control to F5, indicating restricted starch swelling and a reduced capacity to develop high viscosity during heating. The reduction in peak, breakdown, and setback viscosities can be attributed to starch dilution and competitive interactions for water. Replacement of wheat flour with sacha inchi flour reduces the relative starch content, limiting granule swelling and viscosity development. In addition, proteins, lipids, and dietary fibre compete for available water and promote amylose–lipid complex formation, further restricting starch gelatinisation and swelling. These interactions collectively contribute to the observed decrease in viscosity parameters. This reduction is consistent with starch dilution and competition for water from proteins and lipids, as well as amylose–lipid complex formation that limits granule expansion [9, 23]. In addition, the formation of amylose–lipid complexes further restricts starch granule swelling and limits viscosity development, indicating that the observed pasting behaviour arises from both compositional dilution and physicochemical interactions within the system. Trough and breakdown viscosities also decreased in the present study, indicating reduced susceptibility to shear- and heat-induced disintegration as substitution increased. Similar reductions in pasting viscosities have been reported in composite flour systems, where incorporation of non-wheat ingredients lowered peak, trough, and breakdown values due to modification of starch behaviour by proteins and lipids (e.g., lower pasting viscosities in composite systems relative to wheat flour alone) [24]. Despite lower maximum viscosity, reduced breakdown values can also be associated with structural modifications around starch granules that enhance resistance to mechanical stress, a feature noted in RVA applications for assessing functional quality in heating–cooling cycles [25].

Final viscosity did not differ significantly among formulations, indicating that sufficient reassociation occurred during cooling to support structural development, consistent with observations in other composite systems where final viscosity remains stable despite changes in peak viscosity [26]. Setback viscosity decreased significantly with increasing substitution, indicating reduced retrogradation tendency and potential for slower firming during storage. This aligns with studies showing that composite flours often exhibit lower setback values due to interference with starch re-alignment during cooling cycles [27]. Peak time remained unchanged across formulations, suggesting similar gelatinisation kinetics, whereas pasting temperature increased at higher substitution levels, reflecting restricted water penetration into starch granules due to surrounding protein–lipid matrices—a behaviour previously observed in pasting profiles of modified or enriched flour systems [28]. Furthermore, the observed reductions in peak and setback viscosities are consistent with amylose–lipid complex formation and starch dilution, phenomena commonly reported in oilseed–wheat composite systems and indicative of restricted granule swelling rather than simple loss of starch content [29].

Mixolab analysis further confirmed that sacha inchi incorporation modified dough thermo-mechanical behaviour by affecting both protein and starch functionality. Initial dough consistency (C1) remained relatively stable, indicating that early dough formation was not severely compromised. However, protein weakening torque (C2) decreased progressively with increasing substitution, reflecting gluten dilution and interference from non-gluten sacha inchi proteins that lack viscoelastic network-forming capacity [30]. From a technological perspective, the reduction in C2 reflects weakening of the gluten network, resulting in reduced dough stability during mixing. Lower C3 values at higher substitution levels indicate reduced starch gelatinisation capacity, while the decline in C4 and C5 suggests decreased thermal stability and retrogradation tendency. These changes imply that higher substitution levels may reduce dough strength but could contribute to slower staling in final baked products. This confirms that sacha inchi flour not only dilutes gluten content but actively interferes with network formation, resulting in reduced viscoelastic stability and altered dough resistance under thermal and mechanical stress. Starch gelatinisation torque (C3) increased at intermediate substitution levels, suggesting enhanced starch swelling following protein denaturation, while higher substitution levels showed reduced C3 values consistent with starch dilution. Parameters C4 and C5 declined progressively, indicating reduced starch stability during heating and diminished retrogradation during cooling. Dough stability decreased steadily with increasing substitution, reflecting reduced tolerance to mechanical stress due to cumulative effects of lipid coating, fibre interference, and gluten dilution [8, 30]. Water absorption also declined significantly, consistent with reduced starch availability and increased lipid content. Although a fixed water addition was applied during dough preparation, the decrease in water absorption observed in Mixolab analysis reflects the intrinsic hydration capacity of the composite flours under standardised testing conditions rather than the actual formulation water used. This indicates that sacha inchi flour has lower water-binding capacity compared with wheat flour, likely due to its higher lipid content and reduced starch fraction.

TPA showed that increasing sacha inchi substitution shifted the dough system from a soft, elastic, gluten-dominated matrix to a firmer, less cohesive structure. Dough hardness increased markedly, while springiness and cohesiveness declined progressively, indicating reduced elastic recovery and structural integrity under repeated deformation. In practical terms, increased hardness and reduced cohesiveness indicate a firmer dough that may improve shape retention during processing but reduce gas retention during fermentation, potentially leading to denser baked products. Reduced stickiness is advantageous for dough handling and machinability, facilitating industrial processing. These trends reflect disruption of gluten continuity by non-gluten proteins, lipid-rich domains, and fibre particles [31]. From a functional perspective, this indicates a shift toward a firmer but less elastic dough system, which may enhance shape retention during processing but limit extensibility and gas retention at higher substitution levels. Stickiness values became less negative with increasing sacha inchi flour substitution, indicating reduced dough adhesion. Lower dough stickiness is generally associated with improved dough handling convenience during processing because highly sticky dough can hinder processing operations and adhere to processing equipment [32]. The concurrent increase in hardness and reduction in cohesiveness suggests water immobilisation within a rigid internal network rather than accumulation at the surface. Although firmness increased, reduced chewiness and resilience indicate that the dough breaks down more readily after initial fracture, producing a denser but less elastic structure.

The integration of RVA, Mixolab, and texture profile analyses provides a unified and mechanistic understanding of how sacha inchi flour modifies wheat-based dough systems. Rather than acting solely as a nutritional supplement, sacha inchi functions as an active structural modifier, influencing starch gelatinisation, protein network development, and water distribution simultaneously. The consistent trends observed across these techniques demonstrate a coordinated transition from a starch-dominated system to one governed by protein–lipid–fibre interactions. This multi-scale behaviour highlights the importance of considering compositional and functional interactions together when designing composite flour systems with predictable processing performance. This integrated interpretation highlights that the functional limitations observed at higher substitution levels arise from cumulative and interacting effects across starch, protein, and structural domains rather than isolated changes in individual components.

A key limitation of this study is that gluten content was not directly quantified, despite the observed changes in dough rheology suggesting progressive gluten dilution. Therefore, conclusions regarding reduced-gluten functionality are inferred from compositional substitution rather than direct analytical measurement. Future work should include quantitative gluten analysis (e.g., gluten content or gluten index) to validate these findings. From an application perspective, substitution levels up to 15% represent a practical threshold at which improvements in nutritional composition are achieved without substantial loss of dough functionality. Beyond this level, the pronounced reduction in cohesiveness, springiness, and dough stability, together with increased hardness, indicates diminished processing tolerance and likely negative impacts on product volume and texture. Therefore, higher substitution levels may require formulation adjustments (e.g., hydrocolloids or gluten supplementation) to restore functional performance. In addition, the darker colour and potential nutty or beany flavour associated with sacha inchi flour may influence consumer acceptance. These factors highlight the importance of formulation optimisation and the need for future sensory evaluation to ensure product acceptability.

Building on these findings, this study demonstrates that sacha inchi (*Plukenetia volubilis*) flour is a promising functional ingredient for wheat-based composite flour systems, providing substantial enhancement of protein, lipid, and fibre contents while systematically modifying dough pasting, rheological, and textural properties. Incorporation of sacha inchi flour reduced starch pasting viscosity and retrogradation tendency, reflecting restricted starch swelling and altered water distribution arising from interactions among proteins, fibres, and lipids. Rheological and textural analyses further showed progressive weakening of the gluten network with increasing substitution, accompanied by increased dough firmness and reduced cohesiveness at higher inclusion levels. These results highlight the dual role of sacha inchi flour as both a nutritional fortifier and a structural modifier of dough systems. Importantly, low-to-moderate substitution levels, particularly up to 15%, achieved an optimal balance between nutritional enhancement and acceptable dough handling and functional performance. At higher substitution levels, increased stiffness and reduced structural cohesion became more pronounced, emphasising the need for controlled formulation strategies.

Overall, the findings indicate that successful application of sacha inchi flour in wheat-based or gluten-diluted bakery systems depends on optimised inclusion levels, hydration, and processing conditions to maintain desirable rheological behaviour and product quality. Future research should focus on evaluating the sensory attributes and consumer acceptance of products developed using sacha inchi composite flour, as well as assessing storage stability and shelf-life in relation to its elevated lipid content. In addition, pilot-scale and industrial trials are recommended to validate processing performance and support large-scale application of this composite flour system.

Abbreviations

RVA: Rapid Visco Analyser

TPA: texture profile analysis

Declarations

Author contributions

AFA: Writing—original draft, Formal analysis, Data curation. MER: Visualization, Software. AHAA: Methodology, Conceptualization. YNAM: Resources. RK: Writing—review & editing. MSS: Validation, Conceptualization. NRP: Visualization, Validation, Formal analysis. AAP: Resources. HM: Writing—review & editing, Supervision, Project administration, Funding acquisition. All authors read and approved the submitted version.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent to publication

Not applicable.

Availability of data and materials

The datasets supporting the findings of this study are available from the corresponding author upon reasonable request.

Funding

This research was funded by the Universiti Malaysia Sabah Research Grant (Grant No. GUG0633-2/2023 and DN22104). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Publisher's note

Open Exploration maintains a neutral stance on jurisdictional claims in published institutional affiliations and maps. All opinions expressed in this article are the personal views of the author(s) and do not represent the stance of the editorial team or the publisher.

References

1. Olamiti G, Ramashia SE. Impact of Composite Flour on Nutritional, Bioactive and Sensory Characteristics of Pastry Foods: A Review. Curr Res Nutr Food Sci J. 2024;12:1018–34. [DOI]
2. Hafeez F, Sultan MT, Raza H, Khalid MU, Ikram A, Arshad MT, et al. Integration of Multi-Cereals Into Wheat Flour: Nutritional Composition, Dough Rheology, and Sensory Profile of Composite Breads. Food Sci Nutr. 2025;13:e71267. [DOI] [PubMed] [PMC]
3. Lomonaco A, Galgano F, Condelli N, Paganoni C, Carmela Mecca L, Di Cairano M. Influence of processing on the technological and sensory quality of bread: an overview. Ital J Food Sci. 2025;37: 53–79. [DOI]
4. Bojňanská T, Musilová J, Vollmannová A. Effects of Adding Legume Flours on the Rheological and Breadmaking Properties of Dough. Foods. 2021;10:1087. [DOI] [PubMed] [PMC]
5. Feng YY, Zhu Y, Wang Z, Li X. Effects of whole quinoa flour addition on the pasting property, dough rheology, and steam bread textural property of wheat flour. Int Food Res J. 2023;30:1212–20. [DOI]
6. Garcia-Amezquita LE, Tejada-Ortigoza V, Ramírez-Aguirre MD, Cantu-Cantu A, Pérez-Carrillo E, Welti-Chanes J. Substitution of Wheat Flour by Extrudate Orange Peel Dietary Fiber Concentrate in Biscuits: Changes in Mixolab Thermomechanical Behavior, Flour Technofunctionality, and Water Sorption Isotherm Properties. Int J Food Sci. 2025;2025:1657293. [DOI] [PubMed] [PMC]
7. Neagu Dragomir C, Dossa S, Jianu C, Cocan I, Radulov I, Berbecea A, et al. Composite Flours Based on Black Lentil Seeds and Sprouts with Nutritional, Phytochemical and Rheological Impact on Bakery/ Pastry Products. Foods. 2025;14:319. [DOI] [PubMed] [PMC]
8. Njoroge JW, Phonphimai P, Khatmorn P, Ketnawa S, Tonkla P, Vong V, et al. Valorization of Sacha Inchi press cake: Technological advances, market, and regulatory considerations for sustainable food applications. Food Chem Adv. 2025;9:101151. [DOI]

9. Narváez Cadena RA, Salas Zambrano AP, Bravo Gómez JE, Muñoz Pabon KS, Roa-Acosta DF. Characterization of sacha inchi (Plukenetia volubilis) and taro (Colocasia esculenta) flours with potential application in the preparation of both gluten-free and high protein foods. F1000Research. 2025;12:378. [DOI] [PubMed] [PMC]
10. Narváez Cadena RA, Roa Acosta DF, Bravo Gómez JE. Effects of thermo-mechanical and chemical processes on the nutritional and functional quality of Sacha inchi (Plukenetia volubilis) flour. Front Sustain Food Syst. 2025;9:1591362. [DOI]
11. Alejandro Ruiz FE, Jácome JFO, Pinargote MGC, Mora JR, Landázuri AC, Duchicela PV, et al. Influence of partial or total substitution of wheat flour and sunflower oil with Sacha inchi (Plukenetia volubilis L.) flour and oil on the quality and nutritional properties of cookies. PLOS One. 2026;21:e0340190. [DOI] [PubMed] [PMC]
12. Darko HSO, Ismaiel L, Fanesi B, Pacetti D, Lucci P. Current Trends in Food Processing By-Products as Sources of High Value-Added Compounds in Food Fortification. Foods. 2024;13:2658. [DOI] [PubMed] [PMC]
13. AOAC. Official Methods of Analysis. Gaithersburg: AOAC International; 2000.
14. Mich M, Phaltevy Ung R, Chab S, Net M, Kong S, Tan R, et al. Alkaline Extraction of Protein from Sacha Inchi Oil Press-cake: Effect of pH, Temperature, and Extraction Time. J Food Sci Nutr Res. 2024;7: 74–9. [DOI]
15. Atudorei D, Atudorei O, Codină GG. Dough Rheological Properties, Microstructure and Bread Quality of Wheat-Germinated Bean Composite Flour. Foods. 2021;10:1542. [DOI] [PubMed] [PMC]
16. Alejandro Ruiz FE, Ortega Jácome JF, Mora JR, Landázuri AC, Vásconez Duchicela P, Vásconez Espinoza J, et al. Comprehensive characterization and valorization potential of Amazonian Sacha inchi (Plukenetia volubilis L.) seeds, oil, and oilcake by-products for sustainable food applications. Front Nutr. 2025;12:1597300. [DOI] [PubMed] [PMC]
17. Codină GG, Istrate AM, Gontariu I, Mironeasa S. Rheological Properties of Wheat–Flaxseed Composite Flours Assessed by Mixolab and Their Relation to Quality Features. Foods. 2019;8:333. [DOI] [PubMed] [PMC]
18. Mironeasa S, Codină GG. Dough Rheological Behavior and Microstructure Characterization of Composite Dough with Wheat and Tomato Seed Flours. Foods. 2019;8:626. [DOI] [PubMed] [PMC]
19. Verbeke C, Debonne E, Versele S, Van Bockstaele F, Eeckhout M. Technological Evaluation of Fiber Effects in Wheat-Based Dough and Bread. Foods. 2024;13:2582. [DOI] [PubMed] [PMC]
20. Abidin NSA, Mohd Fikri SNF, Zamri NS. Nutritional Composition and Functional Properties of Sacha Inchi Spent Flour. Int J Biomass Util Sustain Energy (IJBUSE). 2025;3:20–9. [DOI]
21. Katyal M, Kaur A, Singh N. Evaluation of pasting and dough rheological properties of composite flours made from flour varied in gluten strength. J Food Sci Technol. 2019;56:2700–11. [DOI] [PubMed] [PMC]
22. Martínez E, Ramos-Escudero F. Valorization of flours from cocoa, sinami and sacha inchi by-products for the reformulation of Peruvian traditional flatbread ('Pan Chapla'). Int J Gastron Food Sci. 2024;36: 100930. [DOI]
23. Wu Y, Xiao S, Jia Z, Zhao K, Hou L, Ding W, et al. Effects of modified starches on the dough rheological properties of wheat flour and frozen storage stability of frozen raw noodles. Food Chem: X. 2025;27: 102392. [DOI] [PubMed] [PMC]
24. Ocheme OB, Adedeji OE, Chinma CE, Yakubu CM, Ajibo UH. Proximate composition, functional, and pasting properties of wheat and groundnut protein concentrate flour blends. Food Sci Nutr. 2018;6: 1173–8. [DOI] [PubMed] [PMC]
25. Nastasi JR, Alagappan S, Cozzolino D. The Combination of Machine Learning Tools with the Rapid Visco Analyser (RVA) to Enhance the Analysis of Starchy Food Ingredients and Products. Appl Sci. 2025;15:3376. [DOI]

26. Balet S, Guelpa A, Fox G, Manley M. Rapid Visco Analyser (RVA) as a Tool for Measuring Starch-Related Physiochemical Properties in Cereals: a Review. Food Anal Methods. 2019;12:2344–60. [DOI]
27. Tang J, Xie C, Chang W, Quan Z, Ding X. Characteristics of Highland Barley-Wheat Composite Flour and Its Effect on the Properties of Coating Batter and Deep-Fried Meat. Foods. 2023;12:3923. [DOI] [PubMed] [PMC]
28. Li C. Recent progress in understanding starch gelatinization - An important property determining food quality. Carbohydr Polym. 2022;293:119735. [DOI] [PubMed]
29. Saleh M, Amr A, Mehyar G, Ondier G. Predicting farinograph parameters by rapid visco analyser pasting profile using partial least square regression. Qual Assur Saf Crops Foods. 2016;8:41–9. [DOI]
30. Cordero-Clavijo LM, Espinosa-Ramírez J, Antunes-Ricado M, Chuck-Hernandez C, Serna-Saldívar SO, Lazo-Vélez MA. Sacha Inchi (*Plukenetia volubilis*) Protein-Enriched Bread: Protein Quality, Breadmaking Properties, Textural Profile, and Bioactivity. J Food Sci. 2025;90:e70743. [DOI] [PubMed]
31. Bakare AH, Osundahunsi OF, Olusanya JO. Rheological, baking, and sensory properties of composite bread dough with breadfruit (*Artocarpus communis* Forst) and wheat flours. Food Sci Nutr. 2015;4: 573–87. [DOI] [PubMed] [PMC]
32. Agrahar-Murugkar D, Gulati P, Kotwaliwale N, Gupta C. Evaluation of nutritional, textural and particle size characteristics of dough and biscuits made from composite flours containing sprouted and malted ingredients. J Food Sci Technol. 2014;52:5129–37. [DOI] [PubMed] [PMC]