Food Hydrocolloids 170 (2026) 111730

Contents lists available at ScienceDirect

Food Hydrocolloids

journal homepage: www.elsevier.com/locate/foodhyd

Pulp and peel breadfruit flours as techno-functional ingredients. Rheological and staling behavior of their gels

Caleb S. Calix-Rivera [a,b,c], Grazielle Náthia-Neves [d], Marina Villanueva [a,b], Felicidad Ronda [a,b,*]

[a] Department of Agriculture and Forestry Engineering, Food Technology, College of Agricultural and Forestry Engineering, University of Valladolid, 34004 Palencia, Spain
[b] Bioeconomy Research Institute - BioEcoUVa, PROCEREALtech Group, University of Valladolid, 47005 Valladolid, Spain
[c] Department of Agroindustrial Engineering, Regional University Center of the Pacific Littoral, National Autonomous University of Honduras (UNAH), 51101 Choluteca, Honduras
[d] Research Group for Bioactives – Analysis and Application, Technical University of Denmark, National Food Institute, Kgs. Lyngby DK-2800, Denmark

ARTICLE INFO

Keywords:
Breadfruit flours
Techno-functional properties
Pasting characteristics
Gel rheology
Retrogradation kinetics

ABSTRACT

Breadfruit represents an exceptional nutritional source. However, its potential as a techno-functional food ingredient remains largely unexplored. In this context, this study aimed to produce and characterize flours derived from breadfruit (BF) pulp and peel in terms of their physical, techno-functional, pasting and rheological properties. Banana flour was used as a reference for comparison purpose. BF flours formed heat-stable gels at a 4 % concentration, double the threshold required for banana flour, with higher water absorption capacity (+68 %), swelling power (+75 %), and five-fold lower solubility than banana flour. BF-pulp flour demonstrated 10 % higher emulsifying activity and 60 % higher emulsion stability. Additionally, it showed a higher pasting temperature, increased final viscosity (+24 %), and substantially lower breakdown viscosity (−75 %) compared to banana. All gels exhibited pseudoplastic flow behavior, with BF-pulp presenting the highest consistency index and thixotropy. Dynamic oscillatory tests revealed superior viscoelastic properties in BF-gels, with storage and loss moduli exceeding those of banana gel at equivalent concentrations. Retrogradation kinetics showed faster amylopectin recrystallization in BF gels, in particular those from BF-pulp flour, compared to banana gel, suggesting an earlier achievement of structural stability during storage. In contrast, banana gels exhibited a higher leveling-off retrogradation enthalpy, reflecting a firmer and more stable texture over long-term storage. These findings position BF-pulp flour as a high-performance hydrocolloid, offering enhanced gel strength and emulsion stability, suitable for gluten-free sauces or bakery fillings. Meanwhile, the lower viscosity and unique shear rheology of BF-peel flour may benefit low-viscosity applications. The distinct viscometric and staling profiles exhibited by BF-samples enable the design of novel foods with a wide range of textures.

1. Introduction

Breadfruit (*Artocarpus altilis* (Parkinson) Fosberg) is a tropical fruit native to Malaysia, belonging to the Moraceae family, which has expanded across tropical and subtropical regions worldwide (de Souza Oliveira et al., 2022). It has been a staple food and traditional crop in the Pacific for over 3000 years and is currently being cultivated to improve food security in tropical regions (Turi et al., 2015). The limited commercialization of this fruit can be attributed to the restricted knowledge of crop management and characterization of its derived products. A major limitation of breadfruit (BF) is its high perishability, as it tends to deteriorate within 5 days after harvesting (Harsanto et al., 2022). One method for extending its shelf life is by transforming it into flour or starch (Adebowale et al., 2005). While starch offers a neutral taste and high purity for specific industrial applications, flour retains the full nutritional profile of the fruit, including dietary fiber, essential amino acids, minerals, and bioactive compounds, which are often lost during starch extraction (Puncha-Arnon & Uttapap, 2013). Therefore, flour is considered a more suitable option for the development of functional foods (Bi et al., 2017; Mehta et al., 2023).

BF has attracted substantial research interest as a sustainable alternative to traditional crops like corn, wheat, and tropical staples (banana,

* Corresponding author. Av. Madrid, s/n, 34004, Palencia, Spain.
E-mail address: mfronda@uva.es (F. Ronda).

https://doi.org/10.1016/j.foodhyd.2025.111730
Received 1 May 2025; Received in revised form 3 July 2025; Accepted 5 July 2025
Available online 7 July 2025

cassava, yams) due to its functional properties and high nutritional value (de Souza Oliveira et al., 2022). Unlike wheat, BF is naturally gluten-free, addressing a growing demand for celiac-friendly ingredients (Mehta et al., 2023). Moreover, its high dietary fiber content (exceeding that of refined wheat and corn flours) makes it a promising ingredient for fortified foods (Turi et al., 2015). Compared to banana, cassava and yams, BF flour exhibits higher fiber, superior protein quality (rich in lysine and leucine, which are often limiting in plant-based diets) and a lower glycemic index, making it especially suitable for diabetic-friendly formulations (Huang et al., 2019; Turi et al., 2015). In addition, BF demonstrates enhanced functional properties, including superior water- and oil-holding capacities compared to banana and wheat flours (Huang et al., 2019), which may contribute to improved textural and sensory characteristics in food applications. These nutritional and functional advantages, along with its richness in minerals and bioactive compounds (Calix-Rivera et al., 2025), support the use of BF flour as a valuable ingredient or substitute for traditional flours in the development of healthy-oriented food products.

Although some studies have focused on the nutritional properties of BF and its use in traditional products, such as bread (Ragone, 2018), significant gaps remain in understanding its technological application, particularly concerning the concentration-dependent rheological behavior of gels, shelf-life stability, and the evolution of their properties over time, which are key factors for industrial applications. Previous research has characterized BF starch morphology and molecular structure (Nwokocha & Williams, 2011), thermal behavior (Wang et al., 2011), and nutritional profile (Calix-Rivera et al., 2025); however, limited attention has been paid to the gelling and retrogradation properties of BF flours. Several interrelated factors contribute to this knowledge gap: (1) a continued scientific focus on conventional staple crops (wheat, corn, rice); (2) predominant consumption patterns that favor fresh fruit or minimally processed forms, thereby limiting investigations into the technological applications of BF flour (Appiah et al., 2016); (3) challenges in standardizing BF flour properties due to the existence of over 120 cultivars and variations in processing methods (Mehta et al., 2023); and (4) limited industrial adoption, despite promising results in pilot studies (Turi et al., 2015). This has restricted its potential use in innovative food formulations (Huang et al., 2019). These gaps highlight the need for comprehensive studies examining the techno-functional behavior of BF flours, particularly their gelling and retrogradation performance, in order to support their incorporation into innovative food formulations and contribute to the valorization of this underutilized crop.

An integrated approach using both the pulp and peel of BF to produce flours offers significant benefits in terms of sustainability, nutritional enhancement, and technological functionality. Firstly, the peel, which constitutes 5–16 % of the fruit's mass (Jones et al., 2011), is a rich source of dietary fiber, ash, and fat (Turi et al., 2015). Secondly, its polyphenol content is four times higher than that of the pulp (Calix-Rivera et al., 2025), contributing to antioxidant properties that may potentially extend product shelf life. By valorizing the peel, typically discarded as waste, this approach aligns with circular economy principles, reducing environmental impact while creating value-added ingredients (Bertolini et al., 2010).

Thus, this study aimed to characterize the techno-functional (hydration and emulsifying), pasting and gelling properties of flours derived from the pulp and peel of BF, and evaluate the rheological and staling behavior of the gels made with these flours. Furthermore, it compares these properties with those of banana flour, a well-established reference among starchy tropical fruits. The findings of this study will provide valuable insights for the development of new food products and expand our understanding of this underutilized crop, which holds significant strategic potential for the food industry and global sustainability.

2. Materials and methods

2.1. Materials

Breadfruit fruits, from Otea (White heart) variety, were collected from local growers in *El Progreso*, northern Honduras (15°30′1.2″N 87°43′43.7″W). A total of 22 fruits were collected in June 2022 for this study. All fruits, which constituted a single batch, were visually inspected to confirm their physiological maturity stage. Commercial banana (*Musa* sp.) flour, used as reference in this study, was obtained from Products Goya Nativo S.L (Ecuador). BF pulp and peel flours were obtained using the procedure described in Calix-Rivera et al. (2025). The resulting flours were stored in sealed plastic bags at 4 °C for further assays. The proximal composition, previously determined by Calix-Rivera et al. (2025) and expressed as percentage (g/100 g dry basis, db), was as follows: for BF pulp flour 9.6 % humidity, 3.35 % protein, 1.7 % fat, 16.6 % dietary fiber, 3.65 % ash, and 61 % starch; for BF peel flour, 8.8 % humidity, 3.64 % protein, 3.0 % fat, 20.9 % dietary fiber, 5.78 % ash, and 50 % starch; and for banana flour, 12.7 % humidity, 2.09 % protein, 0.8 % fat, 8.0 % dietary fiber, 2.66 % ash, and 79 % starch. The amylose content of the samples was 10.9, 12.2, and 17.7 g/100 g starch for BF pulp, BF peel, and banana flours, respectively (see Supplementary Table S1).

2.2. Particle size, bulk and true density and color

The particle size distribution of the samples was determined using a Mastersizer 3000 laser diffraction particle size analyzer (Malvern, UK), as described by Calix-Rivera et al. (2023). The median diameter (D_{50}) and dispersion ($(D_{90}-D_{10})/D_{50}$) were calculated, and each sample was analyzed in triplicate. The bulk density (BD) and true density (TD) of flours were determined in duplicate according to methods described by Abebe et al. (2015). Flour color was assessed using a PCE-CSM5 colorimeter (PCE Instruments, Meschede, Germany) equipped with CQCS software. The color parameters L* (luminosity), C* (Chroma) and h (hue: h = 0 for red; h = 90 for yellow; h = 180 for green; h = 270 for blue) were measured using the CIE L*C*h coordinates with a D65 standard illuminant and a 10° standard observer. At least five measurements were performed for each sample.

2.3. Least gelation concentration

The least gelation concentration (LGC) was determined following the method described by Deriu et al. (2022), with slight modifications. Flour dispersion at concentrations of 0.5, 1, 2, 4, 6, 8, 10, 12, and 14 g dry flour/100 mL water were prepared in glass test tubes. The tubes were heated in a water bath at 90 °C for 1 h, rapidly cooled under running water, and stored at 4 °C for 2 h. The LGC was established as the lowest concentration at which the sample did not slip when the tube was inverted. Gels appearance was evaluated by sensory assessment (visual and textural), classifying samples as liquid or viscous if no gelation occurred, and as soft gel, firm gel, or very firm gel if gelation was observed.

2.4. Functional properties

Water absorption capacity (WAC), water absorption index (WAI), water solubility index (WSI), and swelling power (SP) of the flours were determined using the methods described by Calix-Rivera et al. (2023). Emulsifying activity (EA) and emulsification stability (ES) were evaluated following the procedure described by Abebe et al. (2015).

2.5. Pasting properties by rapid visco analyzer (RVA)

The pasting properties were determined using the Rapid Visco Analyzer (RVA) model RVA 4500 (PerkinElmer, Australia), following

AACC method 76–21.02 Standard 1 (AACC, 2010). A 3.5 g flour sample (14 % moisture basis) was mixed with 25 ± 0.1 mL of distilled water in an aluminum canister. ThermoCline for Windows TCW3 software (PerkinElmer, Australia) was used to calculate pasting temperature (PT), peak viscosity (PV), trough viscosity (TV), breakdown viscosity (BV = PV-TV), final viscosity (FV) and setback viscosity (SV = FV-TV). Each sample was analyzed in duplicate.

2.6. Rheology behavior of gels

The rheological properties of the gels were analyzed by steady shear and dynamic oscillatory tests (strain and frequency sweeps). Both analyses were carried out using a Kinexus Pro + rheometer (Malvern Instruments Ltd, UK) equipped with serrated parallel plate geometry (40 mm) and a working gap of 1 mm. Gels obtained from RVA were promptly transferred to the rheometer plate, which was maintained at 25 °C using a KNX2002 C25P Peltier plate for temperature control. The excess of sample was carefully removed, and the exposed parts were covered with a thin layer of vaseline oil (Darmstadt, Germany) to prevent moisture loss during the analysis. Samples were allowed to rest for 5 min prior to measurement to ensure temperature equilibration and stress relaxation.

2.6.1. Steady shear analysis

Flow tests were performed on gels made from 8 g flour dry matter/100 g dispersion. The measurements were carried out over a shear rate range of 0.1–200 s^{-1}. To establish the degree of thixotropy, shear rate cycles (up-down) were conducted, maintaining the maximum shear rate of 200 s^{-1} for 2 min between the up and down phases. The thixotropy degree of the gels was determined from the area of the hysteresis loop. The experimental data from both the ascending and descending shear rate curves were fitted to Ostwald de Waele model (Equation (1)):

$$\sigma = K \cdot \gamma^n \tag{1}$$

where σ is the shear stress (Pa), γ is the shear rate (s^{-1}), K is the consistency index (Pa·s^n), and *n* is the flow behavior index. All gel samples were measured in duplicate.

2.6.2. Dynamic oscillatory tests

Oscillatory tests were performed on gels prepared at five concentrations. The amounts of flour (based on 14 % moisture basis) of 1.5, 2.0, 2.5, 3.0, and 3.5 g were mixed with 25 g of distilled water in the RVA canister to prepare the gels. The resulting gel concentrations, expressed as g of dry flour/100 g of dispersion, were 4.9, 6.4, 7.8, 9.2, and 10.6, respectively. Strain sweeps were performed from 0.1 to 1000 % at a frequency of 1 Hz. These tests enable the determination of the maximum stress within the linear viscoelastic region (LVR), or the stress at which the gel structure broke down (τ_{max}), as well as the stress at the crossover point ($G' = G''$). Frequency sweeps were performed from 10 to 1 Hz at constant strain of 1 % (within the LVR). The frequency sweep data were fitted to the power law model as described by Abebe and Ronda (2014):

$$G'(\omega) = G'_1 \cdot \omega^a \tag{2}$$

$$G''(\omega) = G''_1 \cdot \omega^b \tag{3}$$

$$\tan\delta(\omega) = \frac{G''(\omega)}{G'(\omega)} = \left(\frac{G''}{G'}\right)_1 \cdot \omega^c = (\tan\delta)_1 \cdot \omega^c \tag{4}$$

The coefficients G'_1, G''_1 and $(\tan\delta)_1$ represent the storage modulus, the loss modulus, and the loss tangent at a frequency of 1 Hz. The exponents *a*, *b* and *c*, quantify the degree of dependence of these moduli and the loss tangent on the oscillation frequency, ω expressed in Hz. The fittings were performed across the entire frequency range studied (1–10 Hz), where a linear double logarithm curve was systematically obtained.

2.7. Retrogradation analysis by differential scanning calorimetry (DSC)

The retrogradation kinetics of the studied samples were analyzed using a Differential Scanning Calorimeter (DSC3, STARe-System, Mettler-Toledo, Switzerland). Approximately 6 mg of each sample were weighted into 40 μL aluminum pans, and deionized water was added to achieve a 30:70 (flour:water, w/w) ratio. Samples were scanned from 0 to 110 °C at a heating rate of 5 °C/min, using an empty sealed pan as the reference. After the first scan, the gelatinized samples were stored at 4 ± 2°C for 3, 6, 24, 168, 336, 504 and 672 h to study the amylopectin retrogradation kinetics. The stored samples were then rescanned under the same conditions as the first scan. Each sample was analyzed at least in duplicate. The enthalpy was expressed in J/g of flour dry matter. The evolution of the melting enthalpy of recrystallized amylopectin with storage time was fitted to Avrami model (Equation (5)) as described by Ronda and Roos (2011):

$$\frac{H_\infty - H_t}{H_\infty - H_o} = \exp\left(-kt^n\right) \tag{5}$$

where H_∞ is the levelling-off value of melting enthalpy, related to the maximum extent of starch crystallization at infinite time, H_t is the melting enthalpy at time t, and H_o is the melting enthalpy at initial time, k is the rate constant, and n is the Avrami exponent. The constants k and n were used to calculate the value of half-life, $t_{1/2}$ for crystallization. Half-life was taken as the time required to achieve 50 % of the levelling-off extent of crystallinity (Equation (6)):

$$t_{1/2} = \left(-\frac{\ln 0.5}{k}\right)^{\frac{1}{n}} \tag{6}$$

2.8. Statistical analysis

Statistical analysis and nonlinear (Avrami model) regression were performed using Statgraphics Centurion XIX software (Statgraphics Technologies, Inc. Virginia, U.S.A.). Experimental data were analyzed using one-way analysis of variance (ANOVA), and the means were compared at $p < 0.05$ using Fisher's least significant difference (LSD) test.

3. Results and discussion

3.1. Particle size distribution, density and color of the flours

The results of the particle size distribution, density and color of the studied flours are shown in Table 1. Granulation and particle size uniformity have a significant impact on the processing of flours. The BF flours displayed a bimodal particle size distribution, with the first peak appearing at ~10 μm and the second one ranging from 80 to 100 μm, with the flour from the pulp being more symmetrical (see Supplementary Fig. 1). Similar bimodal distributions for BF flour were reported by Huang et al. (2019), who attributed this to the distinct separation of particle size between starch granules and other constituents presents in these flours. The smallest particle size peak coincided with the starch granule size of BF flour, which according to Wang et al. (2011), ranged from 4 to 16 μm. Likewise, the second peak observed in BF flours could be associated with larger structures like fibers, which constitute a significant proportion of their proximal composition (Calix-Rivera et al., 2025). In contrast, the banana flour showed a trimodal distribution (Supplementary Fig. 1), with the largest peak corresponding to a size of ~29 μm, which also coincides with the size reported for the starch granules of the banana flour, ranging from 6 to 70 μm (Yang et al., 2022). This suggests that starch granules were the predominant particles in the flours. Regarding particle size dispersion, BF pulp exhibited the lowest $(D_{90}-D_{10})/D_{50}$ values, which may be linked to a higher uniformity of particles, consistent with previous reports (Calix-Rivera et al.,

Table 1
Particle size distribution, density and color parameters for breadfruit pulp, breadfruit peel and banana flours.

	Parameter	Breadfruit pulp	Breadfruit peel	Banana
Particle size distribution	D_{50} (μm)	33.7 ± 0.9 c	22.3 ± 0.3 a	31.4 ± 0.4 b
	$(D_{90}-D_{10})/D_{50}$	4.6 ± 0.1 a	8.8 ± 0.5 c	5.9 ± 0.3 b
Density	Bulk density (g/cm^3)	0.691 ± 0.005 b	0.672 ± 0.001 a	0.793 ± 0.003 c
	True density (g/cm^3)	1.467 ± 0.005 ab	1.474 ± 0.006 b	1.459 ± 0.001 a
Color parameters	L*	87.3 ± 0.3 c	81.6 ± 0.2 a	84.1 ± 0.2 b
	C*	14.8 ± 0.2 b	18.6 ± 0.1 c	12.4 ± 0.2 a
	h	73.3 ± 0.5 c	71.8 ± 0.1 b	66.5 ± 0.2 a

D50: mean diameter; (D90-D10)/D50: size dispersion. L*: luminosity; C*: chroma; h: hue angle. Data are the mean ± standard deviation. Similar letters in the same row indicate no statistically significant differences ($p > 0.05$) between means.

2025). The disparity in granulation and uniformity of particle size among the studied flours may influence their physicochemical properties, such as techno-functional, thermal and pasting behaviors. For instance, larger particle sizes and/or greater carbohydrate content, particularly non-starch hydrophilic like fibers, could enhance water-holding capacity (Huang et al., 2019). Similarly, higher particle size uniformity could lead to a narrower gelatinization temperature range (Calix-Rivera et al., 2025). Additionally, flours with smaller particle sizes tend to exhibit higher SP because they are more likely to hydrate, consequently making them more susceptible to gelatinization (Calix-Rivera et al., 2023).

The BD and TD of the studied flours are depicted in Table 1. BD is crucial for predicting packaging requirements and impacts handling, storage, transportation, and processing costs (Abebe et al., 2015). The BD values of BF flours, 0.691 g/cm^3 for BF pulp and 0.672 g/cm^3 for BF peel, were notably lower than that of banana flour (0.793 g/cm^3), which is consistent with the range reported by Huang et al. (2019) for BF flour (0.52–0.70 g/cm^3). The lower BD values observed in BF samples compared to banana flour may partly be attributed to the higher fiber content in BF, which creates a porous, irregular microstructure that reduces packing efficiency. In contrast, banana flour's starch-dominated composition allows for more efficient packing due to the compact nature of starch granules (Adebo & Kesa, 2023). Additionally, the moisture content of flours acts as an adhesive and plasticizer for starch chains, facilitating particle aggregation and denser packing. Therefore, the lower moisture content in BF flours may limit aggregation and contribute to their lower BD values. (Adebo & Kesa, 2023).

Additionally, variations in the particle size and shape can significantly influence the BD values in samples. Larger particle sizes typically indicate the presence of agglomerated particles, which increase air spaces and reduce mass per unit volume, resulting in lower BD values (Salazar et al., 2021). Smaller particles with more regular shapes, such as spherical and oval, possess higher compaction capacities. This reduces porosity and leads to an increase in BD (Odeku & Itiola, 2007). BF flour from peel had a significantly higher TD (1.474 g/cm^3) than banana flour (1.459 g/cm^3), but no significant difference was observed between the two BF flours. This could be due to the fact that TD is mainly influenced by the chemical composition of the flour, which showed minimal variation between the two BF samples (Abebe et al., 2015).

Significant differences ($p < 0.05$) in the color of the flours were observed based on the type of fruit and the specific part of the fruit. The L* of the flours varied in the following order: BF peel (81.6) < banana (84.1) < BF pulp (87.3). BF peel exhibited the darkest flour that could be due to the higher polyphenols content (Calix-Rivera et al., 2025). The C* of BF flours (14.8 and 18.6 for the pulp and the peel, respectively) was significantly ($p < 0.05$) higher than that of banana flour (12.4), indicating more vivid and intense colors. The C* value of BF samples was also higher than that of conventional flours, such as wheat and rice (twice as high) (Abebe et al., 2015). In terms of h, BF flours showed significant differences depending on the part of the fruit (73.3 in the pulp vs. 71.8 in the peel), denoting a more yellowish color in the flour obtained from the pulp, although both flours showed higher h values than banana flour (66.5), which exhibited a more reddish color. However, both BF flours showed lower hue values compared to wheat (86.5) and rice (91) flours (Abebe et al., 2015). The differences in color observed in the BF samples compared to banana, wheat and rice flours could be attributed to the increased levels of free sugars and phenolic compounds (Calix-Rivera et al., 2025). During the drying process (60 °C) employed in flour production, brown-colored pigments may be formed through the heat-induced oxidation of polyphenols (Kumar et al., 2020). This can be an advantage in the production of gluten-free products, normally criticized for their pale colors associated with the common ingredients used in gluten-free formulations, mainly white starches and rice flour.

3.2. *Gelation characteristics of flours*

The results obtained from the LGC assay are presented in Table 2. BF pulp and peel flours required a concentration of 4 g flour/100 mL of water to form a gel, while banana flour needed only 2 g/100 mL. The differences in flour composition between banana and BF critically influence their gelation behavior. Banana flour, with its higher amylose content (see section 2.1), promotes efficient gel network formation at lower concentrations due to amylose's capacity for rapid molecular reassociation. During cooling, linear amylose chains align cooperatively, forming double helices stabilized by hydrogen bonds, which aggregate into junction zones via intermolecular cross-linking, creating a rigid gel network (Olawoye et al., 2022). In contrast, BF flours' lower amylose content reduces the density of cross-linking sites, delaying gelation and necessitating a higher flour concentration to achieve gelation. Additionally, the higher fiber and protein content in BF samples not only dilutes the starch, the primary gelling component, but also competes with it for water impeding amylose–amylose interactions (Kaushal et al., 2012). This dual effect requires a higher flour concentration for gel formation, resulting in a higher LGC value. These findings align with those of Adebowale et al. (2005), who reported an LGC of 6 % (w/v) for BF starch, slightly higher than the values observed in this study. The

Table 2
Least gelation concentration of flours.

Concentration (% w/v)	Samples					
	Breadfruit pulp		Breadfruit peel		Banana	
0.5	(−)	Liquid	(−)	Liquid	(−)	Viscous
1	(−)	Viscous	(−)	Viscous	(−)	Viscous
2	(−)	Viscous	(−)	Viscous	(+)	Soft gel
4	(+)	Soft gel	(+)	Soft gel	(+)	Soft gel
6	(+)	Soft gel	(+)	Soft gel	(+)	Soft gel
8	(+)	Soft gel	(+)	Soft gel	(+)	Soft gel
10	(+)	Firm gel	(+)	Firm gel	(+)	Soft gel
12	(+)	Very firm gel	(+)	Very firm gel	(+)	Soft gel
14	(+)	Very firm gel	(+)	Very firm gel	(+)	Firm gel
LGC (%)	4		4		2	

(−) No gelation; (+) gelation; (−: liquid or viscous), (+: Soft gel, Firm gel, Very firm gel). LGC: least gelation concentration.

lower the LGC the better is the gelling ability and the swelling capacity of the flour (Kaushal et al., 2012).

3.3. Hydration and emulsifying properties of samples

The functional properties of the studied flours are summarized in Table 3. The composition of carbohydrates, mainly hydrophilic, as well as the presence of polar amino acid residues of proteins, which have an affinity for water molecules, are factors that contribute to variations in WAC values among the different flours (Kumar et al., 2020). The WAC values varied significantly ($p < 0.05$) among the samples. BF peel flour had a significantly higher WAC value (2.24 g/g) than pulp (2.06 g/g), although both were nearly twice as high as banana flour (1.22 g/g). The high WAC values found in BF flours were previously reported (Huang et al., 2019) and were also higher than those observed in other flours, such as rice (1.73 g/g) (Kaushal et al., 2012), wheat (0.70 g/g) (Abebe et al., 2015), millet (1.96 g/g) (Kumar et al., 2020) and tef (0.95 g/g) (Náthia-Neves et al., 2023). These results suggest that BF flours have a high amount of non-starch hydrophilic constituents, such as fiber, which could significantly contribute to their WAC (Adebo & Kesa, 2023; Kaushal et al., 2012). The WAI and SP values of BF flour (11.2 and 11.3, respectively) were 75 % and 60 % higher than those of banana flour. The higher swelling capacity of BF flours can be partially attributed to their lower amylose content (10.9 % and 12.2 %, in the BF pulp and peel, respectively, versus 17.7 % in banana flour). Starches with lower amylose content tend to be less rigid and less reinforced, resulting in a greater swelling of the starch when heated (Yang et al., 2022). Additionally, the varying dietary fiber content in the samples may influence swelling values. According to Lai et al. (2011), the high content of dietary fiber, both soluble and insoluble, can modify amylopectin structure and interact with starch, forming more stable structures that enhance swelling capacity. Furthermore, Calix-Rivera et al. (2025) observed that BF starch granules were characterized by smaller size and rougher surfaces compared to those found in banana, favoring water infiltration into the granules for hydration and subsequent swelling (Yang et al., 2022). The WSI values found were significantly ($p < 0.05$) different among the samples studied. This parameter is related to the amount of soluble solids present in sample, mostly low molecular weight material and water-soluble polysaccharides (Irakli et al., 2020). It was much lower (−71 %) in the flour from BF pulp (1.1 g/100 g) and peel (1.5 g/100 g) than in banana flour. This could indicate greater degradation and dextrinization of starch molecules in banana compared to BF flours. The WSI of BF flours was also lower than that reported for other flours such as wheat (4.4 g/100 g) (Abebe et al., 2015), rice (2.6 g/100 g) (Kaushal et al., 2012) and tef (5.1 g/100 g) flours (Calix-Rivera et al., 2023). These differences in solubility may also be ascribed to the low amylose content in BF samples (Huang et al., 2019). According to Bento et al. (2022), flours with low WSI values, such as BF flours, are well-suited for pasta and baked products development. Another important property of flours for food applications is their ability to form stable emulsions that resist mechanical stress. Therefore, EA and ES of flours were evaluated. The formation of emulsions is mainly due to the reduction in the interfacial tension of oil droplets in aqueous systems and the electrostatic repulsion among them (Bento et al., 2022), which results from the diffusion of surface-active constituents, at the oil–water interfaces (Irakli et al., 2020). Flour from BF pulp had the highest EA (50.0 %), significantly higher (+11 %) than that from banana. However, the EA of the flour from BF peel was the lowest (7.3 %). The highest ES value was also found for BF pulp flour, which was 34 % higher than for BF peel flour and 147 % higher than for banana flour. This indicates that the emulsion made with BF pulp flour is the most stable and resistant to time and heat. The substantial presence of carbohydrates, such as starch and fiber, in BF pulp flour may improve EA and ES by creating bulky barriers between oil droplets, thereby reducing the coalescence rate. Similarly, these polysaccharides can increase the viscosity of the system, contributing to the stabilization of the emulsion (Kaushal et al., 2012).

Interestingly, despite its low EA, BF peel flour exhibited a relatively high ES, doubling that of banana flour. This dissociation between emulsion formation and stability in BF peel sample may be attributed to two phenomena: (1) its high content of insoluble dietary fiber (IDF), which can increase the viscosity of the continuous phase, creating a physical network that hinders droplet coalescence; and (2) the presence starch microparticles (~5 μm) (Calix-Rivera et al., 2025), which may acted as Pickering stabilizers by irreversibly adsorbing to oil-water interfaces. These microparticles participate in stabilizing the multi-phase structure by providing a physical barrier to emulsion droplet coalescence (Dickinson, 2012). The variations in emulsion characteristics between BF pulp and peel flours may be attributed to their different ratios of insoluble dietary fiber/soluble dietary fiber (SDF). SDF, containing pectin and certain hemicelluloses, is predominantly found in the pulp, and IDF, consisting of cellulose and hemicellulose, is mainly present in the peel (Huang et al., 2020). Soluble components may play leading roles in the formation of emulsions, while the insoluble constituents

Table 3
Functional, pasting and flow properties of flours studied.

	Parameter	Breadfruit pulp	Breadfruit peel	Banana
Functional properties	WAC (g/g)	2.06 ± 0.04 b	2.24 ± 0.01 c	1.22 ± 0.01 a
	WAI (g/g)	11.2 ± 0.1 b	11.2 ± 0.1 b	6.4 ± 0.1 a
	WSI (g/100 g)	1.1 ± 0.1 a	1.5 ± 0.2 b	5.2 ± 0.2 c
	SP (g/g)	11.34 ± 0.06 b	11.32 ± 0.09 b	6.70 ± 0.01 a
	EA (%)	50.0 ± 0.6 c	7.3 ± 0.2 a	44.9 ± 0.4 b
	ES (%)	9.4 ± 0.9 c	7.0 ± 0.2 b	3.8 ± 0.2 a
Pasting properties	PT (°C)	82.9 ± 0.1 b	83.3 ± 0.1 b	80.8 ± 0.1 a
	PV (cP)	4370 ± 5 b	2384 ± 6 a	5624 ± 32 c
	TV (cP)	3852 ± 36 b	2088 ± 18 a	3580 ± 23 c
	BV (cP)	518 ± 41 b	296 ± 11 a	2044 ± 55 c
	FV (cP)	6643 ± 66 c	3627 ± 24 a	5341 ± 38 b
	SV (cP)	2791 ± 102 c	1539 ± 6 a	1761 ± 61 b
Steady shear analysis		Upward curve		
	K (Pa·s^n)	56.9 ± 0.2 c	37.9 ± 0.8 a	52.9 ± 1.6 b
	n	0.286 ± 0.001 b	0.241 ± 0.002 a	0.359 ± 0.001 c
	R^2	0.997 ± 0.001 a	0.997 ± 0.001 a	0.996 ± 0.001 a
		Downward curve		
	K (Pa·s^n)	23.7 ± 1.4 b	10.7 ± 0.5 a	33.5 ± 0.9 c
	n	0.423 ± 0.001 a	0.455 ± 0.001 c	0.429 ± 0.002 b
	R^2	0.996 ± 0.001 b	0.995 ± 0.001 a	0.999 ± 0.001 c
	Hysteresis loop area (Pa·s^{-1})	7365 ± 454 c	5612 ± 33 a	6471 ± 78 b

WAC: water absorption capacity; WAI: water absorption index; WSI: water solubility index; SP: swelling power. EA: Emulsifying activity; ES: Emulsifying stability. WAC, WAI, WSI, SP are referred to dry matter. PT: pasting temperature; PV: peak viscosity; TV: trough viscosity; BV: breakdown viscosity; FV: final viscosity and SV: setback viscosity. K: consistency index (Pa·s^n), *n*: flow behavior index (dimensionless), R^2: determination coefficient. Data are the mean ± standard deviation. Different letters in the same row indicate statistically significant differences ($p < 0.05$) between means.

contribute to emulsion stability. This could explain why BF pulp shows higher emulsifying activity (EA) and emulsion stability (ES) compared to BF peel, although the difference in ES is less pronounced. These results suggest that BF pulp flour could be useful as a natural emulsifier in formulated foods, while BF peel flour shows potential as a natural stabilizer in emulsion-based products.

3.4. Pasting properties

Pasting parameters of BF pulp, BF peel, and banana flours are summarized in Table 3, and their pasting profiles are shown in Fig. 1. Pasting properties play a crucial role in determining the functionality of flours as food thickener and binder (Kumar et al., 2020). The pasting curves of BF samples were similar to those reported in previous studies (Huang et al., 2019). The PT values of both BF flours were similar (82.9–83.3 °C) and significantly ($p > 0.05$) higher than that of banana flour (80.8 °C), suggesting that the starch in BF flours is more resistant to swelling and rupture (Kaushal et al., 2012). These findings are in agreement with the higher gelatinization temperatures observed for BF in DSC assays (Calix-Rivera et al., 2025), which have been attributed to their lower amylose content and smaller starch granule size. Additionally, the higher fat content in BF flours may contribute to the delayed swelling of starch granules by forming complexes with amylose (Náthia-Neves et al., 2024). The presence of non-starch polysaccharides in the BF samples could also enhance the thermal stability of the flours by limiting water accessibility to the amorphous regions of the starch granules (Bertolini et al., 2010; Niu et al., 2018). In contrast, Bakare et al. (2012) reported lower PT values (~64 °C) for BF flours, which may reflect differences in proximate composition, processing conditions, or cultivar. The peak, trough, breakdown, final, and setback viscosities of BF peel flour were significantly lower ($p < 0.05$) than those of the pulp flour, despite the two showing similar pasting profiles in shape. This behavior is likely due to the higher fiber and lower starch contents of the peel flour (Bertolini et al., 2010). As shown in Fig. 1, both BF samples showed lower PV compared to banana flour. This can be explained by the smaller starch granule size of BF, which limits the swelling capacity and, consequently, the volume occupied during pasting. Additionally, differences in amylopectin molecular weight ($AP\text{-}M_W$) and root-mean-square-radii (r_{rms}) could also play a role. Calix-Rivera et al. (2025), observed that BF starches have lower $AP\text{-}M_W$ and r_{rms} values compared to banana, which are associated with reduced paste viscosity (Abebe & Ronda, 2014). BV of BF pulp and peel flours were significantly lower (4 and 7 times, respectively) than that of banana flour, indicating

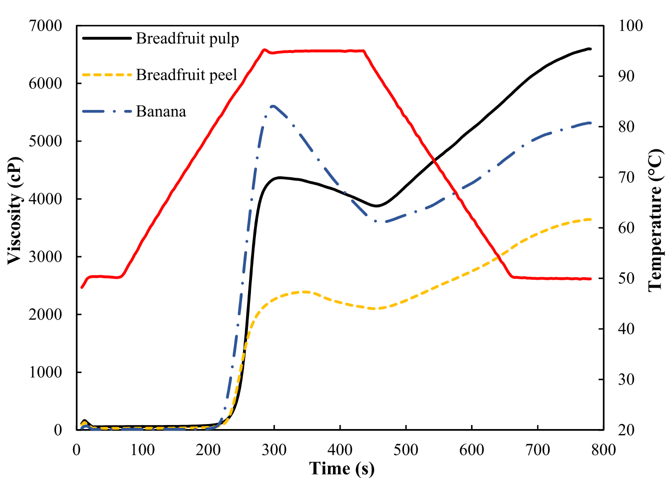

Fig. 1. Pasting profiles of breadfruit pulp, breadfruit peel and banana flours. The red line represents the temperature (right ordinate-axis). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

that after initial swelling, BF starch granules are structurally stronger and more resistant to shear-induced disintegration, providing enhanced hot paste stability (Wang et al., 2011). Such characteristics are desirable in food products subjected to intense heating and stirring, such as soups and sauces (Abebe et al., 2015). SV of BF pulp flour was significantly higher ($p < 0.05$) than those of both the peel (+81 %) and banana (+58 %) flours, indicating a greater tendency of amylose from BF pulp flour to reassociate after gelatinization. This contributes to stronger gel formation, making the pulp flour suitable for applications in gel-based foods (Yang et al., 2022). In contrast, the lower SV observed in BF peel flour suggests reduced retrogradation capacity, which may be advantageous for food systems where viscosity loss and phase separation are concerns (Kaushal et al., 2012).

Although the viscosity parameters of BF flours during heating were generally lower than those of banana flour ($p < 0.05$), this trend reversed after cooling, with the BF pulp sample exhibiting higher FV and SV values. This behavior is likely due to the stronger reassociation ability of BF amylose, which leads to faster retrogradation compared to banana starches, as previously reported by B. Li et al. (2022). On the other hand, the BF peel flour consistently exhibited lower values than both pulp and banana, indicating limited thickening ability. Nevertheless, both BF flours showed pasting properties superior to many conventional cereals and tubers flours. For example, wheat, tef and taro exhibit notably lower PV values (1676, 2060 and 1946 cP, respectively) (Abebe et al., 2015; Kaushal et al., 2012). The differences in pasting properties can be attributed to a combination of factors, including the presence of non-starch components (e.g., fibers and proteins), starch granule size, amylose-to-amylopectin ratio, and starch resistance to swelling (Huang et al., 2019). Dietary fiber can compete with starch for water, while proteins may limit water access to starch by embedding granules within a protein matrix, thus restricting gelatinization (Yang et al., 2022). Additionally, the lower amylose content and smaller granule size in BF flours may contribute to their higher PT values, these features require more energy to disrupt starch crystallinity (Calix-Rivera et al., 2025). Overall, the pasting characteristics of BF flours suggest they are promising ingredients for developing food products with tailored textural properties, particularly those requiring stability under heat or strong gel formation.

3.5. Rheological properties of gels

3.5.1. Flow behavior

The flow curves of the gels prepared from the studied flours are shown in Fig. 2a. The Ostwald-de Waele model was applied to describe the flow behavior of the samples, and the fitting parameters for both the upward and downward flow curves are summarized in Table 3. The high coefficients of determination ($R^2 > 0.9950$) indicate an excellent fit of the experimental data to the model. In all samples, the flow behavior index, *n*, was below 1, denoting a pseudoplastic non-Newtonian (shear-thinning) behavior, characterized by a decrease in apparent viscosity with increasing shear rates (Fig. 2b). The strongest pseudoplastic behavior was observed in the gel prepared from BF peel flour, which had an *n*-index 15 % lower than that of the pulp gel. Conversely, *n*-values of gels made from banana flour were 25 % and 49 % higher than those of the BF pulp and peel, respectively. The higher pseudoplasticity of the gels made from BF flours in comparison with those of banana flour means shear rate favors molecules disentanglement leading to uncrosslinked molecules that offer less resistance to flow than entangled superstructures. The consistency index, K, which reflects the apparent viscosity of the gels at a shear rate of 1 s^{-1}, was highest for the BF pulp flour gel (56.9 Pa·s), followed by banana flour (52.9 Pa·s) and then BF peel flour (37.9 Pa·s). The higher K value of the BF pulp flour gel indicates a stronger internal structure and higher resistance to deformation. In contrast, the lower viscosity and K values observed in the BF peel gel may be attributed to its higher fiber content, which can compete with starch for water absorption, thus limiting the development of a cohesive

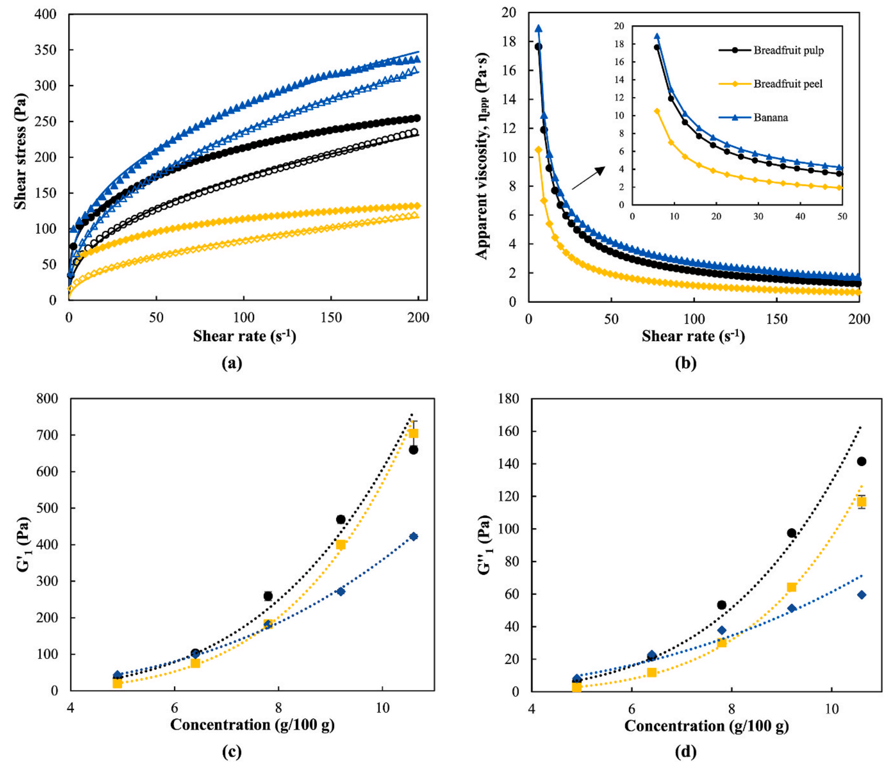

Fig. 2. Steady shear flow behavior of fruits flour pastes. (a) Flow curves of Breadfruit pulp flour (●), Breadfruit peel flour (♦) and banana flour (▲) during steady shear from 0.1 to 200 s^{-1} (full symbols) and 200 to 0.1 s^{-1} (empty symbols). Continuous line represents the adjust at power law; (b) Apparent viscosity (Pa·s) vs. shear rate (s^{-1}) in upward flow curve. Evolution of the elastic modulus (c) and viscous modulus (d) of gels made from Breadfruit pulp (●), Breadfruit peel (♦) and banana (▲) flours versus gel concentration. The error bars represent the standard deviation.

gel structure. Similar results have been reported by Bertolini et al. (2010), who found that banana peel flour suspensions, due their higher fiber content, exhibited lower viscosities compared to those made from banana pulp flour. During the downward curve, K values decreased while *n* values increased, showing a loss in consistency and a reduction in shear-thinning behavior over time. This is consistent with previous the time-dependent structural breakdown of the gel matrix, a behavior previously reported by Chen et al. (2021). All samples showed hysteresis loops, denoting a thixotropic behavior. Among them, the BF pulp gel exhibited the largest hysteresis loop area, which was 12 % smaller than that of the banana flour and 24 % smaller than that of BF peel. This suggests that the pulp gel was the most susceptible structural breakdown over time.

3.5.2. *Viscoelastic properties*

The viscoelastic properties of the gels prepared at different concentrations (from 4.9 to 10.6 %) were assessed trough dynamic oscillatory tests. Table 4 presents the maximum stress, τ_{max}, within the LVR and the crosspoint ($G' = G''$) obtained from strain sweep tests, as well as the parameters G'_1, G''_1, $(\tan\delta)_1$, and the exponents *a*, *b*, and *c* derived from fitting the power law model to the frequency sweep data within the LVR ($0.990 < R^2 < 1.000$, data not shown). Both flour concentration and botanical origin had statistically significant effects ($p < 0.05$) on τ_{max}, which increased with gel concentration. This trend aligns with, previous reports for gels made from several starchy matrices such as anchote starch (Wolde et al., 2023), tef flour (Abebe & Ronda, 2014), legume flours (Acevedo et al., 2013) and fonio flour (Deriu et al., 2022). The strain sweep tests revealed that the BF flours formed weaker and less stable gels compared to banana, with gels from BF peel being the most fragile. This behavior likely stems from the higher fiber content in the peel, consistent with the findings by Abebe and Ronda (2014), who attributed lower τ_{max} values in whole wheat flour gels to compositional differences compared to refined flours. The lower amylose content in BF flours may also contribute to the low τ_{max} observed in their gels, in agreement with findings from other studies that reported a positive correlation between amylose content and maximum stress before rupture (Mauro et al., 2023). The stress level at which gels transitioned from predominantly solid-like to liquid-like behavior (at the crosspoint) followed a trend similar to τ_{max}. In general, gels with lower τ_{max} values exhibit reduced resistance to shear forces, requiring less stress to undergo structural breakdown and shift to a viscous-dominated behavior (Calix-Rivera et al., 2023).

Within the LVR, all BF gel samples exhibited predominantly elastic behavior, with $G'_1 > G''_1$ and $(\tan\delta)_1$ values below 1, and demonstrated slight frequency dependence. As expected, both G'_1 and G''_1 increased with flour concentration (1–10 Hz), in agreement with previous studies (Abebe & Ronda, 2014; Acevedo et al., 2013). However, the degree of this increase varied differently among the samples. The effect of concentration on both the elastic and viscous moduli was more pronounced in BF flour gels than in banana gels. At the lowest concentration (4.9 %), BF gels had significantly lower G'_1 and G''_1 values ($p < 0.05$). However, at highest concentration (10.6 %), BF pulp flour gels showed G'_1 and G''_1 values up to 36 % and 57 % higher, respectively, than those of banana flour gels, suggesting a greater dependency of BF gel strength on concentration. At the same concentration, differences in G'_1 and G''_1 between BF and banana flours could be attributed to variations in non-starch components and their interactions with starch, amylose content and granule integrity (Acevedo et al., 2013; Deriu et al., 2022; Ronda & Roos, 2011). The higher fiber content in BF flours may contribute to increased viscoelastic moduli by: i) competing with starch for water, thereby reducing water availability, or ii) acting as a filler within the viscoelastic matrix (Abebe & Ronda, 2014), while also promoting starch molecular reassociation (Lai et al., 2011). Conversely, the higher lipid content in BF peel sample could inhibit amylose leaching during gelatinization, weakening the continuous phase and reducing viscoelastic moduli, particularly at concentrations <8 % (Biliaderis &

Table 4
Rheological properties of samples analyzed at different concentrations.

Sample	Concentration (g/100 g)	G'_1 (Pa)	*a*	G''_1 (Pa)	*b*	$(\tan\delta)_1$	*c*	τ_{max} (Pa)	Crosspoint (Pa)
Breadfruit pulp	4.9	32 ± 1 aB	0.115 ± 0.002 aB	6.2 ± 0.1 aB	0.508 ± 0.009 eB	0.192 ± 0.006 aB	0.39 ± 0.01 eB	2.9 ± 0.1 aB	7.8 ± 0.1 aB
	6.4	102 ± 7 bB	0.143 ± 0.002 cB	22 ± 2 bB	0.412 ± 0.005 dB	0.211 ± 0.001 bcB	0.270 ± 0.003 dB	12.6 ± 0.7 bB	29 ± 2 bB
	7.8	259 ± 12 cB	0.136 ± 0.001 bB	53 ± 2 cC	0.334 ± 0.002 cB	0.206 ± 0.001 bB	0.198 ± 0.001 cB	31.4 ± 0.9 cB	80 ± 2 cB
	9.2	469 ± 10 dC	0.134 ± 0.002 bB	97 ± 1 dC	0.297 ± 0.001 bB	0.208 ± 0.004 bcC	0.163 ± 0.002 bA	56 ± 1 dB	168 ± 7 dB
	10.6	659 ± 7 eB	0.138 ± 0.001 bC	141 ± 1 eC	0.281 ± 0.004 aA	0.215 ± 0.001 cC	0.143 ± 0.003 aA	59 ± 1 dA	274 ± 1 eB
Breadfruit peel	4.9	19 ± 5 aA	0.07 ± 0.01 aA	2.7 ± 0.5 aA	0.53 ± 0.02 eB	0.140 ± 0.009 aA	0.47 ± 0.01 eC	1.7 ± 0.4 aA	3.9 ± 0.4 aA
	6.4	75 ± 1 bA	0.099 ± 0.001 bA	11.8 ± 0.1 bA	0.430 ± 0.001 dC	0.157 ± 0.001 bA	0.331 ± 0.002 dC	8.8 ± 0.1 bA	16.6 ± 0.1 bA
	7.8	182 ± 1 cA	0.106 ± 0.001 bA	30.1 ± 0.3 cA	0.364 ± 0.001 cC	0.165 ± 0.001 bA	0.26 ± 0 cC	21.7 ± 0.1 cA	46.5 ± 0.1 cA
	9.2	400 ± 4 dB	0.104 ± 0.004 bA	64 ± 2 dB	0.326 ± 0.004 bC	0.161 ± 0.007 bA	0.223 ± 0.001 bC	47.7 ± 0.4 dA	117 ± 1 dA
	10.6	704 ± 34 eB	0.103 ± 0.002 bB	117 ± 4 eB	0.292 ± 0.002 aB	0.166 ± 0.002 bB	0.190 ± 0.004 aB	61 ± 2 eA	198 ± 4 eA
Banana	4.9	43 ± 1 aC	0.120 ± 0.004 cB	8.2 ± 0.1 aC	0.421 ± 0.001 eA	0.190 ± 0.002 bB	0.301 ± 0.005 eA	7.7 ± 0.1 aC	12.6 ± 0.2 aC
	6.4	99 ± 3 bB	0.153 ± 0.002 eC	22.9 ± 0.3 bB	0.326 ± 0.001 dA	0.231 ± 0.003 dC	0.173 ± 0.002 bA	23.8 ± 0.4 bC	37.9 ± 0.7 bC
	7.8	181 ± 2 cA	0.133 ± 0.001 dB	37.8 ± 0.1 cB	0.295 ± 0.001 cA	0.209 ± 0.002 cB	0.162 ± 0.001 aA	82.4 ± 0.2 cC	122 ± 2 cC
	9.2	271 ± 5 dA	0.095 ± 0.003 bA	51.2 ± 0.2 dA	0.279 ± 0.002 aA	0.189 ± 0.004 bB	0.185 ± 0.004 cB	465 ± 6 dC	454 ± 12 dC
	10.6	422 ± 5 eA	0.033 ± 0.002 aA	59.5 ± 0.6 eA	0.284 ± 0.001 bA	0.141 ± 0.003 aA	0.250 ± 0.001 dC	775 ± 1 eB	796 ± 12 eC
Analysis of variance and significance (p-values)									
(F1) Concentration		***	*	***	***	**	***	***	***
(F2) Type of flour		**	**	***	**	***	***	**	***
(F1) X (F2)		***	***	***	***	***	***	***	***

G'_1 (elastic modulus), G''_1 (viscous modulus) and $(\tan\delta)_1$ (loss tangent) are the coefficients obtained from fitting the frequency sweeps data to power law model at a frequency of 1 Hz. The *a*, *b* and *c* exponents quantify the dependence degree of dynamic moduli and the loss tangent with the oscillation frequency. τmax represents the maximum stress tolerated by the sample in the LVR. Crosspoint represents the stress where $G' = G''$. Data are the mean ± standard deviation. Lowercase letters compare the effect of gel concentration within the same type of flour and capital letters compare the effect of type of flour within the same concentration. Analysis of variance and significance: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

Juliano, 1993). As noted by Náthia-Neves et al. (2024) the lipid composition (rather than content alone) significantly influences viscoelastic properties. For instance, the predominance of monoacylglycerols and polar lipids in BF peel favors amylose-lipid complex formation, which negatively impacts G' and G'' moduli.

Additionally, the higher amylose content in banana flour could account for its elevated G'_1 and G''_1 values at low concentrations, as amylose requires lower concentrations for gelation than amylopectin. These findings are in agreement with the positive correlation between viscoelastic moduli and amylose content reported by Biliaderis and Juliano (1993). Lower AP-M_W in BF starches may also contribute to reduced viscoelasticity at low concentrations (Calix-Rivera et al., 2025), as starches with lower AP-M_W tend to produce lower paste viscosities (Abebe & Ronda, 2014).

At high concentrations, however, amylose content plays a secondary role, and viscoelastic moduli are mainly influenced by the rigidity of swollen starch granules (Hoover, 2010). Therefore, the greater structural integrity of BF granules, as evidenced by lower BV values in the pasting test (Section 3.4), supports the elevated G'_1 and G''_1 values observed at higher concentrations.

The loss tangent of BF gels remained stable across all tested concentrations, except for a slight increase at the lowest concentration, suggesting a shift toward more viscous behavior (Deriu et al., 2022). In contrast, banana gels demonstrated a concentration-dependent decrease in $(\tan\delta)_1$, indicating a transition toward more elastic-dominated behavior and firmer gel formation at higher concentrations. The dependence of the elastic moduli on frequency (exponent *a*) was significantly lower for BF peel flour gels than BF pulp and banana gels, indicating a more stable gel-structure. Similar low *a* values have been reported for rice flour (Abebe & Ronda, 2014), legume flours (Acevedo et al., 2013) and anchote flour (Wolde et al., 2023). In contrast, BF peel flour gels presented the highest *b* exponent values, particularly at higher concentrations, indicating greater frequency dependence of the viscous modulus. The *c* exponent decreased with the increasing gel concentration, especially in BF peel gels, suggesting reduced frequency-dependence of the G''/G' ratio at higher concentrations (Ronda et al., 2011).

The strong dependence of G'_1 and G''_1 on flour concentration offers valuable insights into the gelation efficiency and the underlying network structure (Abebe & Ronda, 2014). This behavior fits well with the power law model: $G'_1 = x \cdot C^y$ and $G''_1 = w \cdot C^z$, where *x* and *w* denote the values of G'_1 and G''_1 at a gel concentration of 1 % and a frequency of 1 Hz, while *y* and *z* represent the exponents that quantify concentration-dependence of the moduli. These exponents also provide information about the nature of the associative behavior within the gel and the structural characteristics of its network (Acevedo et al., 2013). Table 5 summarizes the fitted parameters, while Fig. 2, graphs c and d show the model fits for G'_1 and G''_1, respectively.

The viscoelastic behavior of BF gels fit the power law model well ($R^2 > 0.97$), as shown in Table 5. Although banana gels also exhibited a

Table 5
Parameters obtained from fitting to the power-law model the experimental G′ and G″ data in function of the flour concentration in the gels ($G'_1 = x \cdot C^y$; $G''_1 = w \cdot C^z$).

Sample	Storage moduli (G'_1)			Loss moduli (G''_1)		
	x	*y*	R^2	*w*	*z*	R^2
Breadfruit pulp	0.06 ± 0.01 b	4.00 ± 0.02 b	0.973 ± 0.001 a	0.009 ± 0.001 a	4.11 ± 0.05 b	0.977 ± 0.007 b
Breadfruit peel	0.01 ± 0.01 a	4.69 ± 0.23 c	0.996 ± 0.004 a	0.001 ± 0.001 a	4.90 ± 0.20 c	0.995 ± 0.005 b
Banana	0.42 ± 0.03 c	2.94 ± 0.04 a	0.998 ± 0.001 a	0.16 ± 0.01 b	2.58 ± 0.03 a	0.938 ± 0.004 a

Data are the mean ± standard deviation. Values with a letter in common in the same column are not significantly different ($p < 0.05$).

good fit to this model, their viscoelastic behavior was equally well-described by a linear model (G'_1 or $G''_1 = a \cdot C + b$), especially for G''_1, where R^2 increased from 0.938 to 0.993 (data not shown). Similar linear relationships between G′ and concentration were reported by Biliaderis and Juliano (1993) for potato, wheat, corn, and rice starch gels. These findings support the idea that the higher fiber content in BF flours alters gel rheology by competing for water (Lazaridou et al., 2007), leading to a stronger concentration dependence of viscoelastic moduli.

The BF samples presented significantly ($p < 0.05$) lower *x* and *w* values and significantly ($p < 0.05$) higher *y* and *z* values than those of banana flour gels. This indicates a lower consistency at 1 % concentration and greater ability to increase gel strength with concentration. This flexibility makes BF flours, including peel-derived flour, promising ingredients for formulating gel-based gluten-free products. Furthermore, the detailed rheological characterization of BF gels provides essential information for designing transport and pumping systems and for evaluating their use as ingredients in fluid food products.

3.6. Retrogradation kinetics

The kinetics of amylopectin recrystallization in the gels made from BF and banana flours at refrigeration (4 ± 2 °C), along with the Avrami relationship fitted to the experimental data (continuous lines), are presented in Fig. 3. The parameters of the Avrami model are summarized in Table 6. Fig. 3 depicts curves with a rapid increase during the first 24 h, followed by a more gradual retrogradation phase until a plateau is reached (Li, 2022). Starch retrogradation is a kinetic process involving the reassociation of starch molecules into a partially crystalline, ordered structure (Ronda & Roos, 2011). The Avrami model provided an

Table 6
Values of Avrami model factors for gels amylopectin recrystallization in terms of melting enthalpy (H) of analyzed flours.

Sample	H_o (J/g, db)	H_∞ (J/g, db)	k (h^{-n})	n	R^2 (%)	$t_{1/2}$ (h)
Breadfruit pulp	−0.03 ± 0.3 a	7.6 ± 0.2 b	0.33 ± 0.06 b	0.48 ± 0.08 a	99.3	4.82 a
Breadfruit peel	−0.03 ± 0.3 a	6.5 ± 0.2 a	0.19 ± 0.05 a	0.66 ± 0.11 ab	99.2	7.03 b
Banana	0.03 ± 0.3 a	10.3 ± 0.2 c	0.18 ± 0.03 a	0.71 ± 0.07 b	99.7	6.60 b

H_∞: Enthalpy of retrogradation at infinite time, H_o: Enthalpy of retrogradation at initial time, k: constant of velocity, n: Avrami exponent, $t_{1/2}$: value of half-life, R^2: determination coefficient. Data are the mean ± standard deviation. Different letters in the same row indicate statistically significant differences ($p < 0.05$) between means.

excellent fit to the experimental data, as indicated by correlation coefficients, R^2, exceeding 0.99 and initial retrogradation enthalpy, H_o values close to zero. The negligible H_o value is consistent with theoretical predictions for freshly formed gels, indicating minimal amylopectin recrystallization immediately after gelatinization. This delay explains the absence of a staling endotherm during the early storage stages (Biliaderis & Juliano, 1993). The highest leveling-off enthalpy, H_∞, was found in banana gels, which was 35 % and 58 % higher than those found in BF pulp and BF peel flour gels, respectively. This could be due to the higher fiber content in BF samples (2–2.5 times higher than of banana flour), which reduces the proportion of starch available for retrogradation. Additionally, the elevated fiber content in BF flours may hinder the molecular reorganization required for amylopectin recrystallization (Abebe & Ronda, 2014). The rate constant, k, for amylopectin recrystallization at refrigeration temperatures was significantly higher in BF pulp gels (0.33 h^{-n}) compared to BF peel (0.19 h^{-n}) and banana gels (0.18 h^{-n}), denoting a faster amylopectin retrogradation. This trend is also reflected in the half-life time, $t_{1/2}$, which was 4.82 h for the BF pulp gel, significantly ($p < 0.05$) lower than for BF peel (7.03 h) and banana (6.60 h) samples. This suggests that the BF pulp gel required significantly less time to reach 50 % of the stabilization enthalpy compared to the other samples.

The differences in k and $t_{1/2}$ between BF pulp and banana gels correlate with the higher amylopectin content in BF pulp (89.1 g/100 g of starch vs. 82.3 g/100 g of starch in banana). The elevated amylopectin content provides more nucleation sites through its branched structure, thereby accelerating retrogradation (Li, 2022). In contrast, the

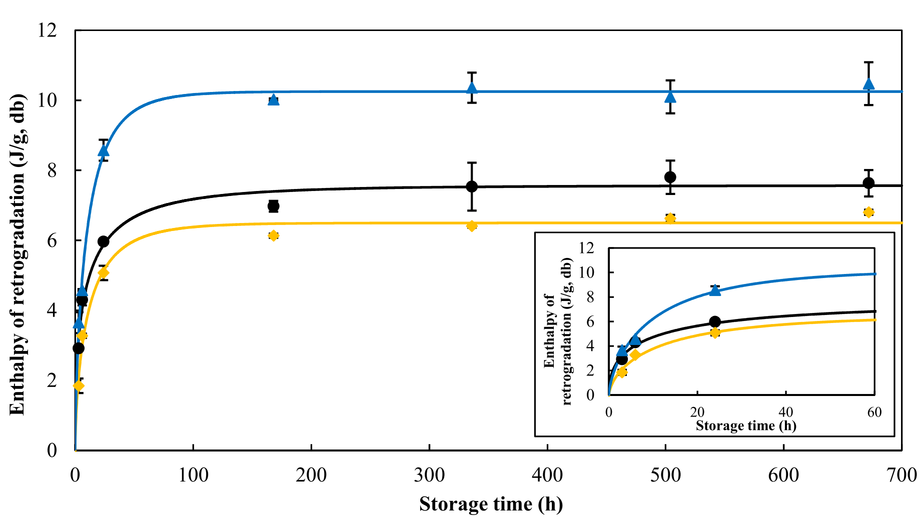

Fig. 3. Starch retrogradation kinetics of gels stored at 4 °C. The continuous lines resulted from fitting the experimental values to the Avrami equation. (●) Breadfruit pulp, (♦) Breadfruit peel, (▲) Banana. The values shown are mean ± standard deviation based on duplicate DSC measurements.

differences observed between BF pulp and peel appear to stem from other factors: while the peel contains moderately higher fiber, its two-fold higher lipid content (see section 2.1) could delay retrogradation (Chang et al., 2021). These lipids inhibit retrogradation by forming helical inclusion complexes (V-type) that hinder interchain associations and amylopectin crystallization (Biliaderis, 2009). This mechanism may also be influenced by the peel's distinct lipid profile, rich in monoacylglycerols and polar lipids (Viana et al., 2024), which exhibit a higher affinity for starch complexation and retrogradation inhibition, unlike pulp-derived triacylglycerols that interact minimally (Biliaderis, 2009).

Regarding to Avrami exponent, n, values were less than 1 for all samples, following the order: Banana (0.71) < BF peel (0.66) < BF pulp (0.48), suggesting that nucleation in starch recrystallization was instantaneous (nuclei formed simultaneously) and crystallite growth was one-dimensional (Niu et al., 2018). The lower n-value in BF samples compared to banana may be attributed to two factors: (1) its smaller AP-M_W (Calix-Rivera et al., 2025), which is consistent with the positive correlation between AP-M_W and n-values reported by (Mua & Jackson, 1998); and (2) its higher amounts of non-starch components such as fibers, proteins, lipids and low-molecular-weight compounds, which can interfere with starch chain alignment and water mobility, thus altering nucleation kinetics and crystal growth morphology (Chang et al., 2021). Based on these results, the faster retrogradation kinetics of BF pulp flours gels suggest their suitability for food products requiring quick texture stabilization, while the slower retrogradation in BF peel gels could help delay staling in starch-based foods. These insights support the tailored selection of starch sources to achieve specific textural properties in refrigerated food formulations.

4. Conclusions

This study demonstrates that BF flours possess distinctive techno-functional properties, influenced by their bimodal particle size distribution, higher fiber content, and lower amylose content compared to banana flour. The lower bulk density and higher water absorption capacity observed in BF flours are associated with their composition, which is rich in non-starch hydrophilic components. Additionally their highly concentration-dependent rheological behavior and faster retrogradation kinetics, particularly in BF pulp, as described by the Avrami model suggest potential advantages for food formulations requiring stable textures development. However, the high content of insoluble fibers in BF peel reduces its viscosity and emulsifying activity, limiting its application in systems where these properties are essential. Overall, these highlight BF flours, especially pulp flour, as a promising ingredient for improving the texture and shelf stability in functional food products such as baked goods, tortillas, dairy desserts or ready-to-eat meals. Nevertheless, further research is needed to evaluate the sensory attributes, digestibility, and compatibility of BF flours with other common food ingredients in complex formulations. In particular, studies assessing their behavior under processing conditions and storage over time will be key to confirming their industrial applicability.

CRediT authorship contribution statement

Caleb S. Calix-Rivera: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Grazielle Náthia-Neves:** Writing – review & editing, Validation, Conceptualization. **Marina Villanueva:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Felicidad Ronda:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank the financial support of the Ministerio de Ciencia, Innovación y Universidades (PID2023-153330OB-100). This work was supported by the Regional Government of Castilla y Leon and the EU-FEDER program (CLU 2019-04 – BIOECOUVA Unit of Excellence of the University of Valladolid). Authors thank Ana Benítez for providing the breadfruit fruits and Octavio Rivera-Flores, Karla Martínez and Genesis Nohal Limas for processing the flours analyzed. Caleb S. Calix-Rivera thanks the University of Valladolid for the doctorate grant.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodhyd.2025.111730.

Data availability

Data will be made available on request.

References

AACC. (2010). Approved methods of analysis. *In cereals & grains association* (11th ed.).

Abebe, W., Collar, C., & Ronda, F. (2015). Impact of variety type and particle size distribution on starch enzymatic hydrolysis and functional properties of tef flours. *Carbohydrate Polymers, 115*, 260–268. https://doi.org/10.1016/j.carbpol.2014.08.080

Abebe, W., & Ronda, F. (2014). Rheological and textural properties of tef [Eragrostis tef (Zucc.) Trotter] grain flour gels. *Journal of Cereal Science, 60*(1), 122–130. https://doi.org/10.1016/j.jcs.2014.02.001

Acevedo, B. A., Avanza, M. V., Cháves, M. G., & Ronda, F. (2013). Gelation, thermal and pasting properties of pigeon pea (Cajanus cajan L.), dolichos bean (Dolichos lablab L.) and jack bean (Canavalia ensiformis) flours. *Journal of Food Engineering, 119*(1), 65–71. https://doi.org/10.1016/j.jfoodeng.2013.05.014

Adebo, J. A., & Kesa, H. (2023). Evaluation of nutritional and functional properties of anatomical parts of two sorghum (Sorghum bicolor) varieties. *Heliyon, 9*(6), Article e17296. https://doi.org/10.1016/j.heliyon.2023.e17296

Adebowale, K. O., Olu-Owolabi, B. I., Olawumi, E. K., & Lawal, O. S. (2005). Functional properties of native, physically and chemically modified breadfruit (Artocarpus artilis) starch. *Industrial Crops and Products, 21*(3), 343–351. https://doi.org/10.1016/j.indcrop.2004.05.002

Appiah, F., Oduro, I., & Ellis, W. O. (2016). Nutritional composition of breadfruits (Artocarpus spp. and Treculia africana) in Ghana. *Acta Horticulturae, 1128*, 15–20. https://doi.org/10.17660/ActaHortic.2016.1128.3

Bakare, H. A., Osundahunsi, O. F., & Adegunwa, M. O. (2012). Composition and pasting properties of breadfruit (Artocarpus communis forst) from south-west states of Nigeria. *Nigerian Food Journal, 30*(1), 11–17. https://doi.org/10.1016/S0189-7241(15)30008-4

Bento, J. A. C., Morais, D. K., de Berse, R. S., Bassinello, P. Z., Caliari, M., & Soares Júnior, M. S. (2022). Functional, thermal, and pasting properties of cooked carioca bean (Phaseolus vulgaris L.) flours. *Applied Food Research, 2*(1). https://doi.org/10.1016/j.afres.2021.100027

Bertolini, A. C., Bello-Pérez, L. A., Méndez-Montealvo, G., Almeida, C. A. S., & Lajolo, F. (2010). Rheological and functional properties of flours from banana pulp and peel. *Starch/Staerke, 62*(6), 277–284. https://doi.org/10.1002/star.200900216

Bi, Y., Zhang, Y., Jiang, H., Hong, Y., Gu, Z., Cheng, L., Li, Z., & Li, C. (2017). Molecular structure and digestibility of banana flour and starch. *Food Hydrocolloids, 72*, 219–227. https://doi.org/10.1016/j.foodhyd.2017.06.003

Biliaderis, C. G. (2009). Structural transitions and related physical properties of starch. In R. W. James BeMiller (Ed.), *Starch* (3rd ed., pp. 293–372). Academic Press. https://doi.org/10.1016/B978-0-12-746275-2.00008-2.

Biliaderis, C. G., & Juliano, B. O. (1993). Thermal and mechanical properties of concentrated rice starch gels of varying composition. *Food Chemistry, 48*, 243–250. https://doi.org/10.1016/0308-8146(93)90134-2

Calix-Rivera, C. S., Náthia-Neves, G., Mauro, R. R., Villanueva, M., & Ronda, F. (2025). Physico-chemical and nutritional properties of breadfruit pulp and peel flours: Insights into starch molecular characteristics and their impact on starch digestibility. *International Journal of Biological Macromolecules, 305*, Article 141224. https://doi.org/10.1016/j.ijbiomac.2025.141224

Calix-Rivera, C. S., Villanueva, M., Náthia-Neves, G., & Ronda, F. (2023). Changes on techno-functional, thermal, rheological, and microstructural properties of tef flours induced by microwave radiation—development of new improved gluten-free ingredients. *Foods, 12*(6), 1345. https://doi.org/10.3390/foods12061345

Chang, Q., Zheng, B., Zhang, Y., & Zeng, H. (2021). A comprehensive review of the factors influencing the formation of retrograded starch. *International Journal of Biological Macromolecules, 186*, 163–173. https://doi.org/10.1016/j.ijbiomac.2021.07.050

Chen, X., Liu, Y., Xu, Z., Zhang, C., Liu, X., Sui, Z., & Corke, H. (2021). Microwave irradiation alters the rheological properties and molecular structure of hull-less barley starch. *Food Hydrocolloids, 120*, Article 106821. https://doi.org/10.1016/j.foodhyd.2021.106821

de Souza Oliveira, E., Lovera, M., Rios Pires, V., da Silva Mendes, F. R., Lima Peixoto Maia, N. V., Viana Rodrigues, J. P., Rocha Bastos, M. do S., Cheng, H. N., Biswas, A., de Azevedo Moreira, R., & de Oliveira Monteiro Moreira, A. C. (2022). Effect of acid catalyst on pyroconversion of breadfruit (Artocarpus altilis) starch: Physicochemical and structural properties. *Journal of Food Processing and Preservation, 46*(3). https://doi.org/10.1111/jfpp.16408

Deriu, A. G., Vela, A. J., & Ronda, F. (2022). Techno-functional and gelling properties of acha (fonio) (Digitaria exilis stapf) flour: A study of its potential as a new gluten-free starch source in industrial applications. *Foods, 11*(2). https://doi.org/10.3390/foods11020183

Dickinson, E. (2012). Use of nanoparticles and microparticles in the formation and stabilization of food emulsions. *Trends in Food Science and Technology, 24*(1), 4–12. https://doi.org/10.1016/j.tifs.2011.09.006

Harsanto, B. W., Pranoto, Y., Supriyanto, & Kartini, I. (2022). Breadfruit (Artocarpus altilis) starch-based nanoparticle formation through dropwise mixing nanoprecipitation. *Food Research, 6*(3), 34–41. https://doi.org/10.26656/fr.2017.6, 3).308.

Hoover, R. (2010). The impact of heat-moisture treatment on molecular structures and properties of starches isolated from different botanical sources. *Critical Reviews in Food Science and Nutrition, 50*(9), 835–847. https://doi.org/10.1080/10408390903001735

Huang, L., Liu, J., Addy, M., Ding, B., Cheng, Y., Peng, P., Wang, Y., Liu, Y., Chen, P., & Ruan, R. (2020). Physicochemical and emulsifying properties of Orange fibers stabilized oil-in-water emulsions. *Lwt, 133*(March), Article 110054. https://doi.org/10.1016/j.lwt.2020.110054

Huang, S., Martinez, M. M., & Bohrer, B. M. (2019). The compositional and functional attributes of commercial flours from tropical fruits (breadfruit and banana). *Foods, 8*(11), 586. https://doi.org/10.3390/foods8110586

Irakli, M., Lazaridou, A., & Biliaderis, C. G. (2020). Comparative evaluation of the nutritional, antinutritional, functional, and bioactivity attributes of rice bran stabilized by different heat treatments. *Foods, 10*(1), 57. https://doi.org/10.3390/foods10010057

Jones, A. M. P., Ragone, D., Aiona, K., Lane, W. A., & Murch, S. J. (2011). Nutritional and morphological diversity of breadfruit (Artocarpus, moraceae): Identification of elite cultivars for food security. *Journal of Food Composition and Analysis, 24*(8), 1091–1102. https://doi.org/10.1016/j.jfca.2011.04.002

Kaushal, P., Kumar, E., & Sharma, H. K. (2012). Comparative study of physicochemical, functional, antinutritional and pasting properties of taro (Colocasia esculenta), rice (Oryza sativa) flour, pigeonpea (Cajanus cajan) flour and their blends. *LWT - Food Science and Technology, 48*(1), 59–68. https://doi.org/10.1016/j.lwt.2012.02.028

Kumar, S. R., Sadiq, M. B., & Anal, A. K. (2020). Comparative study of physicochemical and functional properties of pan and microwave cooked underutilized millets (proso and little). *LWT, 128*. https://doi.org/10.1016/j.lwt.2020.109465

Lai, P., Li, K. Y., Lu, S., & Chen, H. H. (2011). Physicochemical characteristics of rice starch supplemented with dietary fibre. *Food Chemistry, 127*(1), 153–158. https://doi.org/10.1016/j.foodchem.2010.12.116

Lazaridou, A., Duta, D., Papageorgiou, M., Belc, N., & Biliaderis, C. G. (2007). Effects of hydrocolloids on dough rheology and bread quality parameters in gluten-free formulations. *Journal of Food Engineering, 79*(3), 1033–1047. https://doi.org/10.1016/j.jfoodeng.2006.03.032

Li, C. (2022). Consecutive reaction kinetics model reveals the nature of long-term rice amylopectin retrogradation characteristics. *Food Chemistry, 369*, Article 131000. https://doi.org/10.1016/j.foodchem.2021.131000

Li, B., Wang, Y., Zhu, L., Huang, C., Zhang, Y., Zhao, Y., Wu, G., & Tan, L. (2022). Starch characterizations of two kinds of seedless Artocarpus altilis (Parkinson) Fosberg originated from China. *Food Hydrocolloids, 123*, Article 107145. https://doi.org/10.1016/j.foodhyd.2021.107145

Mauro, R. R., Vela, A. J., & Ronda, F. (2023). Impact of starch concentration on the pasting and rheological properties of gluten-free gels. Effects of amylose content and thermal and hydration properties. *Foods, 12*(12), 2281. https://doi.org/10.3390/foods12122281

Mehta, K. A., Quek, Y. C. R., & Henry, C. J. (2023). Breadfruit (Artocarpus altilis): Processing, nutritional quality, and food applications. *Frontiers in Nutrition, 10*, 433. https://doi.org/10.3389/fnut.2023.1156155

Mua, J. P., & Jackson, D. S. (1998). Retrogradation and gel textural attributes of corn starch amylose and amylopectin fractions. *Journal of Cereal Science, 27*(2), 157–166. https://doi.org/10.1006/jcrs.1997.0161

Náthia-Neves, G., Calix-Rivera, C. S., Villanueva, M., & Ronda, F. (2023). Microwave radiation induces modifications in the protein fractions of tef flours and modulates their derived techno-functional properties. *International Journal of Biological Macromolecules, 253*(August), Article 126908. https://doi.org/10.1016/j.ijbiomac.2023.126908

Náthia-Neves, G., Villanueva, M., & Ronda, F. (2024). Impact of lipids on the functional, rheological, pasting and thermal properties of ultrasound-processed canary seed flours. *Food Hydrocolloids, 150*(January). https://doi.org/10.1016/j.foodhyd.2024.109727

Niu, H., Zhang, M., Xia, X., Liu, Q., & Kong, B. (2018). Effect of porcine plasma protein hydrolysates on long-term retrogradation of corn starch. *Food Chemistry, 239*, 172–179. https://doi.org/10.1016/j.foodchem.2017.06.103

Nwokocha, L. M., & Williams, P. A. (2011). Comparative study of physicochemical properties of breadfruit (Artocarpus altilis) and white yam starches. *Carbohydrate Polymers, 85*(2), 294–302. https://doi.org/10.1016/j.carbpol.2011.01.050

Odeku, O. A., & Itiola, O. A. (2007). Compaction properties of three types of starch. *Iranian Journal of Pharmaceutical Research, 6*(1), 17–23.

Olawoye, B., Fagbohun, O. F., Popoola, O. O., Gbadamosi, S. O., & Akanbi, C. T. (2022). Understanding how different modification processes affect the physiochemical, functional, thermal, morphological structures and digestibility of cardaba banana starch. *International Journal of Biological Macromolecules, 201*, 158–172. https://doi.org/10.1016/j.ijbiomac.2021.12.134

Puncha-Arnon, S., & Uttapap, D. (2013). Rice starch vs. rice flour: Differences in their properties when modified by heat-moisture treatment. *Carbohydrate Polymers, 91*(1), 85–91. https://doi.org/10.1016/j.carbpol.2012.08.006

Ragone, D. (2018). Breadfruit— Artocarpus altilis (Parkinson) fosberg. In *Exotic fruits* (pp. 53–60). Elsevier. https://doi.org/10.1016/B978-0-12-803138-4.00009-5.

Ronda, F., Oliete, B., Gómez, M., Caballero, P. A., & Pando, V. (2011). Rheological study of layer cake batters made with soybean protein isolate and different starch sources. *Journal of Food Engineering, 102*(3), 272–277. https://doi.org/10.1016/j.jfoodeng.2010.09.001

Ronda, F., & Roos, Y. H. (2011). Staling of fresh and frozen gluten-free bread. *Journal of Cereal Science, 53*(3), 340–346. https://doi.org/10.1016/j.jcs.2011.02.004

Salazar, D., Arancibia, M., Lalaleo, D., Rodríguez-Maecker, R., López-Caballero, M. E., & Montero, M. P. (2021). Physico-chemical properties and filmogenic aptitude for edible packaging of Ecuadorian discard green banana flours (Musa acuminanta AAA). *Food Hydrocolloids, 122*. https://doi.org/10.1016/j.foodhyd.2021.107048

Turi, C. E., Liu, Y., Ragone, D., & Murch, S. J. (2015). Breadfruit (Artocarpus altilis and hybrids): A traditional crop with the potential to prevent hunger and mitigate diabetes in oceania. *Trends in Food Science and Technology, 45*(2), 264–272. https://doi.org/10.1016/j.tifs.2015.07.014. Elsevier Ltd.

Viana, L. M., Rodrigues, F. S. R., Santos, M. C. B., Lima, A., dos, S., Nabeshima, E. H., Leite, M. de O., Martins, M. A., Carvalho, C. W. P. de, Maltarollo, V. G., Azevedo, L., Ferreira, M. S. L., Martino, H. S. D., Felisberto, M. H. F., & Barros, F. A. R. de. (2024). Green banana (Musa ssp.) mixed pulp and peel flour: A new ingredient with interesting bioactive, nutritional, and technological properties for food applications. *Food Chemistry, 451*(October 2023). https://doi.org/10.1016/j.foodchem.2024.139506

Wang, X., Chen, L., Li, X., Xie, F., Liu, H., & Yu, L. (2011). Thermal and rheological properties of breadfruit starch. *Journal of Food Science, 76*(1). https://doi.org/10.1111/j.1750-3841.2010.01888.x

Wolde, Y. T., Emire, S. A., Zeleke, W. A., & Ronda, F. (2023). Gel rheological properties and storage texture kinetics of starches isolated from Anchote (Coccinia abyssinica (Lam.) Cogn.) cultivars. *Gels, 9*(8), 631. https://doi.org/10.3390/gels9080631

Yang, M., Chang, L., Jiang, F., Zhao, N., Zheng, P., Simbo, J., Yu, X., & Du, S. kui. (2022). Structural, physicochemical and rheological properties of starches isolated from banana varieties (Musa spp.). *Food Chemistry X, 16*(September), Article 100473. https://doi.org/10.1016/j.fochx.2022.100473