International Journal of Food Science + Technology

Institute of Food Science +Technology ifst

International Journal of Food Science and Technology 2023, **58**, 5781–5795

Original article

Functionality of pre-cooked whole-grain corn, rice and sorghum flours for gluten-free bread

Raúl Comettant-Rabanal,[1,2,3]* Davy William Hidalgo Chávez,[1] José Luis Ramírez Ascheri,[4] Carlos Elías-Peñafiel[5] & Carlos W. Piler Carvalho[4]

1 Postgraduate Program in Food Science and Technology, Universidade Federal Rural do Rio de Janeiro, Rodovia BR 465, km 7, Seropédica, 23.890-000, Rio de Janeiro, Brazil

2 Escuela Profesional de Ingeniería Agroindustrial, Facultad de Ingenierías, Universidad Privada San Juan Bautista, Carretera Panamericana Sur Ex km 300, Ica, CP 11004, La angostura – Subtanjalla, Perú

3 Universidad Nacional Agraria La Molina, Av. La Molina s/n Lima 12, CP 15024, Lima, Perú

4 Food Extrusion and Physical Properties Lab, Embrapa Agroindústria de Alimentos, Avenida das Américas, 29501, Guaratiba, 23020-470, Guaratiba, Brazil

5 Departamento de Tecnología de Alimentos, Facultad de Industrias Alimentarias, Universidad Nacional Agraria La Molina, Av. La Molina s/n Lima 12, Lima, CP 15024, La Molina, Perú

(Received 5 May 2023; Accepted in revised form 21 August 2023)

Summary Extruded whole grain flours of corn, sorghum, and parboiled brown rice (PBR) and their blends were used to produce gluten-free (GF) multigrain bread. To determine the functionality of the flours, paste viscosity, farinography and oscillatory rheometry were evaluated as rheological methods, and for the bread, the texture profile, baking loss and specific volume of the breads were determined. The paste properties evidenced changes in the starch structure of the extruded samples, but these were not severe due to the absence of cold viscosity (CV) and formation of peak viscosity (PV), which evidenced the swelling capacity of the starch granules. The functionality of the samples was demonstrated by the increase in water absorption and farinographic consistency (PM), as well as by the development of dough viscoelasticity with continuous elastic (G') and viscous (G'') moduli when measured by oscillatory rheometry. The GF breads produced showed specific volume increases from 53.8 to 91.7% compared to the control, as well as high crumb hardness. However, the cereal blends did not generate significant increases in specific volume between samples ($P < 0.05$), but those made with higher proportions of extruded sorghum flour and its blend with corn had better crumb softness and lower baking loss ($P < 0.05$). On the other hand, the regression models for most of the dough rheological and bread textural variables were significant and presented good coefficients of determination (R^2 Adj = 0.60–0.99) with linear and quadratic fits, thus allowing prediction of the behaviours of these variables for future applications.

Keywords Dough rheology, extrusion cooking, mixture design, non-gluten flours, regression model, surface response.

Introduction

Gluten-free (GF) products are an attractive and challenging market for the baking industry, as the grains used do not possess the unique wheat characteristics. This market is mainly represented by a segment of the world's population, who may have some sensitivity to storage proteins (called gluten prolamins) found in the endosperm of wheat, barley, rye and in some cases may be found in oats by cross-contamination (Balakireva & Zamyatnin, 2016; Smulders *et al.*, 2018). Gluten sensitivities (GS) are classified into three groups, each mediated by various immunological mechanisms, including autoimmunogenic (including coeliac disease), allergic and innate (non-coeliac gluten sensitivity - NCGS) responses to wheat (Scherf *et al.*, 2016; Cabanillas, 2020). These disorders make up the main target market for the development of GF products. Additionally, there are groups of individuals who do not manifest GS, but who choose to adhere to GF diets due to trend alignment, unhealthy and misleading associations of wheat components of various indoles.

The development of GF bread requires the formation of an impermeable network with viscoelastic properties similar to those of wheat gluten to capture

*Correspondent: E-mail: raulttant@gmail.com; raul.cometttant@upsjb.edu.pe

doi:10.1111/ijfs.16676

CO_2 during fermentation to achieve light breads with soft crumbs and well-distributed cavities. Gluten-free bread (GFB) have a low nutritional value, since its formulas use refined cereals in combination with high proportions of potato, corn, rice and cassava starch and/or blends thereof to technologically contribute to the increase in viscosity and consistency of the dough by means of high-water absorption mechanisms (Mancebo *et al.*, 2015). For this reason, the use of pigmented corn, rice and sorghum as whole grains (WG) allows the nutritional and nutraceutical advantages of each of these GF cereals from different continents. Studies have focused on the bioaccessibility and digestibility of these grains and their relationship with bioactive compounds, dietary fibre, resistant starch and micronutrients have demonstrated their valuable contribution to the prevention of degenerative diseases (Pandey, 2022). Furthermore, its healthy aspects lie in its phytochemical constituents such as lignans, phenolic compounds, phytosterols, tocotrienols, phytates, sphingolipids, tannins, minerals (Fe and Zn), vitamins (B complex, C, D and E) present depending on the type of grain pigmentation, which have recognised antioxidant, anti-diabetic, anti-hypertensive, anti-inflammatory and analgesic effects (Allai *et al.*, 2022; Punia & Kumar, 2022).

Yellow corn (*Zea mays* (L.)), native to the Americas, is rich in carbohydrates (56–70%), dietary fibre (13%) with a slightly higher lipid content than other cereals, but the quality of its stored proteins (8–11%) is low due to a lack of essential amino acids such as lysine and tryptophan (Maqbool *et al.*, 2021; Kaushal *et al.*, 2023). The lipid fraction of this cereal is mainly found in the germ, which is composed of about 14% saturated fatty acids, 30% monounsaturated fatty acids (MUFA) and 56% polyunsaturated fatty acids (PUFA) (Rouf Shah *et al.*, 2016; Rochín *et al.*, 2019; Allai *et al.*, 2022). Brown rice (*Oryza sativa* (L.)), originally from Asia, is a hypoallergenic food by excellence due to its high protein digestibility (93%), which have a high biological value (74%) (Pantoa *et al.*, 2020; Zhao *et al.*, 2022). It is a rich source of carbohydrates (70–80%) consisting mainly of starch, with moderate amounts of protein (7%) and limited lipid content (~2.5%), as well as notable amounts of minerals such as Ca, Mg, P, Cu and Fe and vitamins (B y E) (Oliveira *et al.*, 2022). It also contains bioactives such as functional lipids, phytosterols, phenolic compounds, dietary fibre, γ-oryzanol and gamma-aminobutyric acid (GABA) (Mir *et al.*, 2020). Finally, sorghum (*Sorghum bicolor* (L.) Moench) is a gluten-free cereal originating from Africa, rich in nutrients, that contains significant amounts of resistant starch (Ratnavathi & Komala, 2016). Among the most important health-promoting phytochemicals in sorghum are phenolic compounds, including phenolic acids, flavonoids (3-deoxyanthocyanidins) and condensed tannins (proanthocyanidins and procyanidins) (Taylor & Kruger, 2019; Xiong *et al.*, 2019).

Whole grains can be thermally processed to develop technological properties that mimic the rheological characteristics of gluten and thus achieve nutritious GF bread with acceptable organoleptic attributes. To achieve this purpose, some authors such as Clerici *et al.* (2009), Comettant-Rabanal *et al.* (2021), Torbica *et al.* (2019) have used to extrusion cooking. This technology is characterised as a short time process with temperature and shear rate control applied to cereal starches and flours (refined and whole grain) to develop functionality by increasing the water absorption of extruded flours and the development of consistency and viscoelasticity of doughs when evaluated by farinography and dynamic oscillation rheometry for the manufacture of GF bread.

Previous studies carried out by Patil *et al.* (2016), Jafari *et al.* (2018b), Jafari *et al.* (2018a), Sun *et al.* (2019) have applied 10–40% extruded gluten-free flours from finger millet, corn, and sorghum in wheat composite breads. In these partial replacements, the sensory quality was improved and only in the replacements with extruded corn or finger millet in the wheat composite breads, the dough extensibility was increased; the volume, height and softness of the breadcrumbs were improved, as well as the contribution of phenolic compounds and a higher antioxidant capacity. Other efforts by Clerici *et al.* (2009) and Martínez *et al.* (2013) used partially extruded refined rice flour at 10%, while Pessanha *et al.* (2021) employed 50% of extruded whole pearl millet flour to produce GF breads. The partial additions of the extruded flours improved volume and texture by reducing the hardness of the GF breads. Additionally, extruded pearl millet flour produced hypoglycaemic GF bread with a significant improvement in antioxidant capacity.

However, few works such as Torbica *et al.* (2019), Comettant-Rabanal *et al.* (2021), Saito *et al.* (2022a), Saito *et al.* (2022b) and Saito *et al.* (2022c) have used 100% whole grains flours (corn, oat, millets, sorghum, rice, and rye) pre-treated by heated water and/or extrusion cooking to produce fibre-rich GF breads with volume, instrumental texture, and the sensory characteristics similar to counterparts obtained with partial replacement of extruded flour. The latter usually requires the addition of hydrocolloids, proteins, and other functional ingredients. On other hand, there are no reports on the effect of extrusion cooking on whole grain cereals to produce multigrain GF breads. Therefore, the aim of this work was to evaluate the functionality of extrusion pre-cooked WG flours and their blends to produce gluten- and additive-free multigrain bread, as well as to model the dough's rheological properties and the bread's physical and textural characteristics.

Materials and methods

Plant materials

Whole grains (WG) such as corn and parboiled brown rice (PBR) were generously donated by Indústrias de Alimentos Granfino (Nova Iguaçú, Brazil), while sorghum (red pericarp, low tannin) was kindly donated by Embrapa Milho e Sorgo (Sete Lagoas, Brazil). Non-hydrogenated palm fat, dehydrated yeast, white sucrose, and salt were acquired in the local market on Rio de Janeiro. WGs were cleaned on a Clipper grain cleaner (Clipper Separation Technologies, Bluff ton, United States) and ground using a hammer mill LM3100 (Perten Instruments, Huddinge, Sweden) equipped with a 0.8 mm opening screen for obtaining fine corn, PBR, and sorghum flours.

Extrusion conditions

An Evolum HT25 (Clextral Inc., Firminy, France) twin-screw, co-rotating geared extruder was employed to process the raw WG flours (corn, PBR and sorghum). It was explored the low shear, high moisture and moderate temperature extrusion conditions used by Comettant-Rabanal *et al.* (2021) in order to avoid complete starch breakdown and, under this new configuration to generate cohesive doughs of viscoelastic properties that would allow bread shaping under traditional breadmaking methods. For pre-cooking the samples, a Evolum HT25 (Clextral, Firminy, France) twin screw extruder, fitted with a 6 mm round die running at 200 rpm, set at 25, 40, 60, 80, 100, 110, 110, 90, 80 and 70 °C barrel heating zones from inlet to outlet, fed at 10 kg h^{-1} and added of deionised water injected between the first and the second zones (25% moisture content) was used. The unexpanded extrudates were dried at 55 °C for 5 h and milled in an LM3100 hammer mill (Perten Instruments, Huddinge, Sweden) equipped with a 0.8 mm sieve to obtain fine flours with 80–91% of particles ranging from 100 and 500 µm were used to produce GFBs.

Pasting viscosity properties

The viscosity of the extruded WG flours was analysed using a Rapid Visco Analyser series 4 RVA (Newport Scientific Pty Ltd., Warriewood, Australia) according to the methodology described by (Comettant-Rabanal *et al.*, 2021). Three grams of sample adjusted to 14% moisture (wet basis) along with 25 mL of distilled water were placed in the sample holder (aluminium beaker) of the equipment. The test conditions were mixing at 160 rpm at 25 °C for 2 min, heating to 95 °C at a constant rate of 14 °C min^{-1} and holding for 3 min and then cooling to 25 °C in 5 min at the same rate, with a total time of 20 min. Paste properties were measured: paste temperature (PTem, cP), cold viscosity at onset at 25 °C (CV, cP), peak viscosity (PV, cP), trough viscosity or holding strength (TV, cP), break viscosity (BDV = PV−TV, cP), final viscosity (FV, cP) and setback viscosity (SBV = FV-TV, cP).

Farinography properties

The farinographic 54-21.01 AACC (2000b) method was adapted for GF samples thermally and mechanically pre-treated by extrusion, based on the results reported by Comettant-Rabanal *et al.* (2021). This adaptation took 33 g of extruded flour and the average of the water absorption percentages (99.33%) of the three grains studied by the author in order to integrate the water absorption (WA) for use in binary and multigrain blends composed of corn, parboiled rice and sorghum, instead of the 500 Brabender units (BU) traditionally used for wheat. Beforehand, the moisture content of each sample was determined to calculate the amount of flour standardised to 14% moisture on a wet basis (wb) and the amount of water to be added, using the following eqns (1) and (2):

$$\text{Flour weight (g)} = \frac{33\ (\text{g}) \times 86(\%)}{100 - \text{moisture}\ (\%)} \tag{1}$$

$$\text{Water absoption (g)} = \frac{99.33 \times \text{flour weight (g)}}{100} \tag{2}$$

The farinograms yielded the following readings: water absorption (WA, %), arrival time (AT, min), departure time (DT, min), dough development time (DDT, min), dough stability time (DST, min), peak maximum of consistency (PM, BU) and mixing tolerance index determined at 5 min after peak (MTI).

Oscillatory rheometry properties

The oscillatory shear measurements were evaluated using a HAAKE Mars II rotational rheometer (Thermo Fisher Scientific, Karlsruhe, Germany) at 25 °C with a 35 mm diameter parallel plate geometry (PP35 Ti). In order to obtain the dough of each cereal, the flour samples were mixed with water in the farinograph, using WA and DDT obtained from the farinograms, as described by Comettant-Rabanal *et al.* (2021). Three grams of dough were loaded onto the bottom plate, and the top plate was then brought to the dough at a speed of 0.6 mm min^{-1} to a gap of 2 mm. Excess dough was carefully trimmed off, and mineral oil was applied to the edges to prevent dehydration of the doughs during measurement. An amplitude sweep was then conducted to determine the strain rate (γ) value within the linear viscoelastic region

(LVR). Subsequently, a frequency sweep determination was performed between 0.1 and 100 Hz, using the strain rate (γ) value of each sample. The values of elastic or storage modulus (G', Pa), viscous or loss modulus (G'', Pa), shear strain (γ), shear stress (τ, Pa) and the angle displacement ($\tan \delta = G''/G'$) were obtained at 1 Hz, with readings done in triplicate.

Formulation and bread making procedure

Using extruded WG flours, GFs were produced based on 100% of each cereal and their binary and multigrain blends, following the proportions of the simple centroid mix design (Table 1). The formulations were adapted from Comettant-Rabanal *et al.* (2021) and included non-hydrogenated palm fat (3%), sugar (3%), salt (1.5%), water (99.3%) and yeast (1%) on a flour weight basis. The dough was prepared in a 35 g micromixer (National MFG. CO., Lincoln, USA), with dry ingredients mixed for 2 min, followed by the incorporation of liquid ingredients during a kneading time of 3 min. 20 g portions were then fermented at 39 °C and 85% RH for 2 h and baked at 200 °C for 19 min in an electric oven, grill model (Fischer SA., Santa Catarina, Brazil). For comparison, a control bread composed of raw and extruded PBR (1:1) was included, as it could be sheeted and formed into rolled buns, as can be done with wheat flour according to traditional breadmaking procedures.

Texture profile analysis (TPA)

The TPA was conducted by cutting a slice 20 mm thick and applying a compression with a help of a 15 mm diameter aluminium cylindrical probe in the centre of the bread crumb using a Texture Analyser TA-XT Plus (Stable Micro Systems, Surrey, UK) equipped with a 5 kg load cell controlled by the Exponent software version 6.1.11.0 (Stable Micro Systems, Surrey, UK) according to Comettant-Rabanal *et al.* (2021). The device was configured to compress at 50% of the slice and waiting time of 30s between the first and second compression cycle. The TPA crumb hardness (N), adhesiveness (g·s), cohesiveness (–), springiness (–), chewiness (N), and resilience (–) were then considered are texture measurements.

Table 1 Simplex centroid mixture design for proportion of whole grain flours pre-treated by extrusion

Treatment	Corn (X_1)	Sorghum (X_2)	Parboiled brown rice (X_3)
T1	1	0	0
T2	0	1	0
T3	0	0	1
T4	0.5	0.5	0
T5	0.5	0	0.5
T6	0	0.5	0.5
T7*	0.3	0.3	0.3
T8*	0.3	0.3	0.3
T9*	0.3	0.3	0.3

*Centre point (CP).

Baking loss and bread specific volume

A modified standard seed displacement method 10–05.01, as outlined by the American Association of Cereal Chemists (AACC, 2000a), was used to determinate the specific volume of breads, with pearl millet seeds as displacement medium. The recipient used for the calculation was a parallelepiped dimension of 8.5 cm (width) × 8.4 cm (length) × 9.2 cm (height). The specific volume bread ($cm^3\ g^{-1}$) was calculated by dividing the volume of the bread its weight, measured 24 h after baking.

Statistical analysis

A simple centroid mixture design consisting of three components (cereals) was used. Seven different types of GFBs were generated with two replicates at the centre point (CP), as shown in Table 1. To assess the response variables, an analysis of variance (one-way ANOVA) was conducted, followed by a multicomparison Tukey's test. Furthermore, the Dunnett test was employed to compare treatments against the controls (raw cereals). In order to ensure homoscedasticity and normality, the Bartlett-test and Shapiro-test were performed. For variables that did not exhibit a normal distribution or homoscedasticity, the Box-Cox transformation was applied, utilising lambda (λ) to achieve a normal distribution (Box & Cox, 1964). Additionally, response variables were adjusted to polynomial models, and the adequacy of these models was evaluated using determination coefficients (R^2) following the criteria proposed by Toledo *et al.* (2020) as: low adjustment ($R^2 = 0.5$–0.69), well adjustment ($R^2 = 0.70$–0.89), optimum adjustment ($R^2 = 0.90$–0.99), and those adjusted models $\geq$0.70 were considered relevant. All statistical analyses were conducted using *R* software version 3.2.4 (R Foundation for Statistical Computing, Vienna, Austria), with a confidence level of 95%.

Results and discussion

Functionality of gluten-free whole grain flours pre-treated by extrusion

Paste viscosity properties

The paste profiles of the extrusion pre-cooked samples (Figure S1) showed changes compared to the raw flours (Table 2), but the absence of cold viscosity (CV) and formation of peak viscosity (PV) evidence the low fragmentation of starch during the process. However, a slight increase in CV was observed for samples T3 and T5 samples composed by PBR ($P < 0.05$; Table 2), which could be attributed to a combined effect of parboiling and extrusion process that caused a slight conversion of rice starch granules. Furthermore, the presence of peak viscosity (PV) in all pre-cooked flours by extrusion indicated that the starch granules maintained, at certain extent, its swelling capacity, representing remnants of their granular structure capable of absorbing water hence to swell. However, as expected PV readings of the pre-cooked samples were lower than raw flours, as reported by Comettant-Rabanal *et al.* (2021) for corn and sorghum flours, Cheng *et al.* (2020) for buckwheat flour and Liu *et al.* (2017) for rice starch, thus evidencing a moderate starch conversion under relatively high moisture extrusion cooking conditions.

Notably, extruded PBR showed significant increases in PV, due to a special behaviour of starch in this sample, associated with the increase in granular stiffness during the parboiling process, which can be observed in annealing and high moisture low shear extrusion-treated food starch products (Wang *et al.*, 2017; Cheng *et al.*, 2020). However, TV and BDV for T1 and T2 were found as evidence of starch disruption since these parameters were not present in the raw WG corn and sorghum (Figure S1). In addition, FV in T1 and T2 were lower than the raw samples, being T2 and T4 (which had the highest proportion of sorghum) those ones that exhibited the lowest FV (Table 2), probably due to the unique characteristics of sorghum starch that shows high retrogradation properties when compared to other cereals (dos Santos *et al.*, 2022).

Most mathematical models used to predict the effect of extruded corn, sorghum and PBR on paste properties (Figure S2a–f) fitted very well (R^2 Adj ≥ 0.90; Table S1). The pTemp, CV, TV and FV showed linear, whereas PV, BDV and SBV had quadratic models. The R^2 Adj varied between 0.90 and 0.99 for most variables, except for CV and TV (0.66 and 0.59, respectively), which indicate that the models for CV and TV can be taken only to explain the trends instead of predictions. Regarding FV and SBV, which are viscosity readings related to starch retrogradation, it was observed that samples composed of extruded parboiled rice (T3) and its blend with corn (T6) showed the highest values (Table 2), indicating that the starch in these samples after the extrusion process increased its molecular order and granular rigidity, which may have resulted in a high rate of short-term amylose retrogradation among the samples, as described by Liu *et al.* (2017). In contrast, FV and SBV in the extruded corn samples (T1) showed intermediate values, while extruded sorghum (T2) and its blend with corn (T4) exhibited a lower short-term retrogradation rate than the native starches previously studied by Comettant-Rabanal *et al.* (2021).This indicates that after extrusion, the molecular structure of amylose in sorghum starch granules had insignificant changes, which evidenced a reduction of short-term retrogradation, similar to those caused by the improved extrusion cooking technology (IECT) (Liu *et al.*, 2017, 2019b).

Increases in extruded sorghum (T2) promoted higher pTemp values (Figure S2a), which could be explained by the presence of phenolic compounds, particularly present in whole grain sorghum, which may have interacted through their hydroxyl and carboxyl groups with the water molecules in the suspension, limiting their availability for starch swelling leading to high gelatinisation temperature (Zhu, 2015). As reported by Chávez *et al.* (2017), the sorghum had higher amount of these compounds than other cereals, which in turn could affect the paste properties, as demonstrated by Chávez *et al.* (2021). In general, as the PBR increased in the blends, the resulting pasting profile became closer to T3, which was corroborated by PV, TV, BDV, FV and SBV contour plots (Figure S2b–f). A peculiar paste profile of T3 composed of PBR was evidenced, as well as its influence when blended with corn (T5) and sorghum (T6), which may be attributed to the intermediate gelatinisation and recrystallisation of rice starch produced by the hydrogen bond-mediated associations between dispersed amylose chains and water. Thus caused the rearrangement and association of the outermost short branches of rice starch granules (Hu *et al.*, 2017), when subjected to non-severe heat treatments of parboiling and extrusion as reported by Liu *et al.* (2020) and Comettant-Rabanal *et al.* (2021), respectively.

Farinographic measurement

The extrusion-treated T1 (extruded corn flour) and T2 (extruded sorghum flour) samples showed an increase in water absorption (WA) and dough consistency (PM) when compared to raw corn and sorghum samples (Table 3). On the other hand, non-extruded control rice sample (PBR) showed the highest WA leading to farinographic readings compared to the other controls (corn and sorghum raw flours). Interesting to see that after extrusion, the T3 rice sample showed lower WA than the PBR, but presented higher consistency levels (PM = 883 BU; Table 3). The water absorption (WA) of the samples was calculated based on their consistency levels reached AT between 0.98 and 1.75 min (Table 3) to form bread doughs with PM between 680 and 883 BU (Figure S3) that were similar to wheat doughs at 500 BU of PM. Such levels of WA and PM evidenced the farinographic functionality of extrusion-treated WG flours without the need to

Table 2 Paste viscosity properties of of raw and extrusion-pretreated gluten-free whole-grain flours

Treatment	PTemp (°C)	CV (cP)	PV (cP)	TV (cP)	BDV (cP)	FV (cP)	SBV (cP)
PBR	90 ± 6.25$^{\alpha,\gamma}$	62 ± 6.36	27 ± 3.5$^{\alpha,\gamma}$	276 ± 1.41$^{\alpha,\gamma}$	6 ± 3.54$^{\gamma}$	501 ± 12.7$^{\alpha,\gamma}$	210 ± 7.1$^{\alpha,\gamma}$
Raw corn	76 ± 1.31$^{\beta}$	57 ± 6.36	617 ± 8.5$^{\beta,\gamma}$	627 ± 9.9$^{\beta}$	4 ± 2.12$^{\gamma}$	2318 ± 46$^{\beta,\gamma}$	1676 ± 38.9$^{\beta,\gamma}$
Raw sorghum	78 ± 2.26$^{\beta}$	66 ± 7.78	705 ± 9.9$^{\alpha,\beta}$	612 ± 3.54$^{\beta}$	76 ± 7.78$^{\alpha,\beta}$	2234 ± 6$^{\alpha,\beta}$	1527 ± 15.2$^{\alpha,\beta}$
T1	57 ± 0.04 bc$^{\alpha,\beta,\gamma}$	49 ± 4.95 c$^{\gamma}$	469 ± 2.83 c$^{\alpha,\beta,\gamma}$	116 ± 0.00 de $^{\alpha,\beta,\gamma}$	353 ± 2.83 b$^{\alpha,\beta,\gamma}$	530 ± 0.00 e$^{\alpha,\gamma}$	414 ± 0.00 d$^{\alpha,\beta,\gamma}$
T2	62 ± 0.57 a$^{\alpha,\beta,\gamma}$	49 ± 4.95 c$^{\gamma}$	400 ± 5.66 e$^{\alpha,\beta,\gamma}$	90 ± 4.24 f$^{\alpha,\beta,\gamma}$	310 ± 1.41 d$^{\alpha,\beta,\gamma}$	355 ± 9.90 g$^{\alpha,\beta,\gamma}$	265 ± 5.66 f$^{\alpha,\beta,\gamma}$
T3	47 ± 0.07 e$^{\alpha,\beta,\gamma}$	106 ± 6.36 a$^{\alpha,\beta,\gamma}$	627 ± 9.90 a$^{\beta,\gamma}$	160 ± 7.07 b$^{\alpha,\beta,\gamma}$	467 ± 2.83 a$^{\alpha,\beta,\gamma}$	939 ± 3.54 a$^{\alpha,\beta,\gamma}$	779 ± 3.54 a$^{\alpha,\beta,\gamma}$
T4	59 ± 0.07 b$^{\alpha,\beta,\gamma}$	48 ± 6.36 c$^{\gamma}$	429 ± 9.19 d$^{\alpha,\beta,\gamma}$	98 ± 6.36 ef$^{\alpha,\beta,\gamma}$	331 ± 2.83 c$^{\alpha,\beta,\gamma}$	410 ± 4.24 f$^{\alpha,\beta,\gamma}$	313 ± 2.12 e$^{\alpha,\beta,\gamma}$
T5	51 ± 0.71 d$^{\alpha,\beta,\gamma}$	74 ± 1.41 b$^{\alpha}$	526 ± 5.66 b$^{\alpha,\beta,\gamma}$	191 ± 10.61 a$^{\alpha,\beta,\gamma}$	336 ± 4.95 c$^{\alpha,\beta,\gamma}$	779 ± 2.83 b$^{\alpha,\beta,\gamma}$	589 ± 7.78 b$^{\alpha,\beta,\gamma}$
T6	55 ± 1.38 c$^{\alpha,\beta,\gamma}$	59 ± 2.12 bc	430 ± 4.24 d$^{\alpha,\beta,\gamma}$	146 ± 4.24 bc$^{\alpha,\beta,\gamma}$	284 ± 0.00 ef$^{\alpha,\beta,\gamma}$	632 ± 5.66 c$^{\alpha,\beta,\gamma}$	486 ± 9.90 c$^{\alpha,\beta,\gamma}$
T7	54 ± 0.64 c$^{\alpha,\beta,\gamma}$	45 ± 1.41 c$^{\gamma}$	419 ± 2.12 de$^{\alpha,\beta,\gamma}$	122 ± 2.83 d$^{\alpha,\beta,\gamma}$	297 ± 4.95 de$^{\alpha,\beta,\gamma}$	581 ± 5.66 d$^{\alpha,\beta,\gamma}$	459 ± 8.49 c$^{\alpha,\beta,\gamma}$
T8	54 ± 0.67 c$^{\alpha,\beta,\gamma}$	44 ± 1.41 c	400 ± 2.12 e$^{\alpha,\beta,\gamma}$	119 ± 3.54 de$^{\alpha,\beta,\gamma}$	281 ± 5.66 f$^{\alpha,\beta,\gamma}$	582 ± 9.90 d$^{\alpha,\beta,\gamma}$	464 ± 13.44 c$^{\alpha,\beta,\gamma}$
T9	56 ± 0.07 c$^{\alpha,\beta,\gamma}$	54 ± 1.41 c	427 ± 7.07 d$^{\alpha,\beta,\gamma}$	135 ± 2.12 cd$^{\alpha,\beta,\gamma}$	293 ± 4.95 ef,$^{\alpha,\beta,\gamma}$	592 ± 2.83 d$^{\alpha,\beta,\gamma}$	458 ± 4.95 c$^{\alpha,\beta,\gamma}$
Shapiro (Norm.Res)	0.57	0.24	0.45	0.98	0.08	0.58	0.96
Durbin-Watson (Independence.Re)	0.94	0.37	0.73	0.94	0.36	0.84	0.91
LeveneTest (Var.Homoge)	–	–	–	–	–	–	–
Lambda (λ)	1.39	0.63	−0.30	0.06	1.88	1.88	0.51

Results represent the mean ± SD ($n = 3$). Lowercase letters indicate differences between extruded samples (T1–T9; $P < 0.05$). $^{\alpha,\beta,\gamma}$Indicates differences against raw corn, PBR and sorghum, respectively by Dunnett test ($P < 0.05$). Extruded pure flours (T1: corn, T2: sorghum and T3: parboiled brown rice), extruded binary blends 1:1 (T4: corn-sorghum, T5: corn-parboiled brown rice and T6: parboiled brown rice-sorghum) and extruded multigrain blends in equal proportions (T7–T9 = corn-parboiled brown rice-sorghum). Box-Cox transformation factor (λ) for non-parametric data. BDV, break down viscosity; CV, cold viscosity at beginning of the run at 25 °C; FV, final viscosity; PBR, parboiled brown rice; PTemp, pasting temperature; PV, maximum peak viscosity; SBD, setback viscosity; TV, through viscosity.

Table 3 Farinographic properties of raw and extrusion-pretreated gluten-free whole-grain flours

Treatment	FW[†] (g)	WA[†] (mL)	AT (min)	PM (BU)	DT (min)	DDT (min)	DST (min)	MTI (–)
PBR	30	46	6.25 ± 0.12	525.10 ± 5.67	19.50 ± 0.41	11.5 ± 0.7	10.0 ± 2.1	21.0 ± 1.4
Raw corn[‡]	30	24	–	–	–	–	–	–
Raw sorghum[‡]	30	24	–	–	–	–	–	–
T1	31.3	31.1	1.45 ± 0.07 ab$^{\alpha}$	680 ± 0.01 g$^{\alpha}$	2.45 ± 0.07 bc$^{\alpha}$	2.05 ± 0.07 bc$^{\alpha}$	1.00 ± 0.14 bc$^{\alpha}$	116 ± 3.54 e$^{\alpha}$
T2	31.3	31.1	1.05 ± 0.07 bc$^{\alpha}$	761 ± 1.41 f$^{\alpha}$	2.05 ± 0.07 c$^{\alpha}$	2.00 ± 0.14 bc$^{\alpha}$	1.00 ± 0.00 bc$^{\alpha}$	169 ± 2.12 a$^{\alpha}$
T3	31.0	30.8	1.75 ± 0.07 a$^{\alpha}$	883 ± 3.54 a$^{\alpha}$	6.90 ± 0.14 a$^{\alpha}$	3.10 ± 0.14 a$^{\alpha}$	5.15 ± 0.21 a$^{\alpha}$	85 ± 0.00 f$^{\alpha}$
T4	31.2	31.0	1.05 ± 0.07 bc$^{\alpha}$	683 ± 1.41 g$^{\alpha}$	2.00 ± 0.28 c$^{\alpha}$	1.60 ± 0.14 c$^{\alpha}$	0.95 ± 0.21 c$^{\alpha}$	144 ± 0.00 c$^{\alpha}$
T5	31.2	30.9	0.98 ± 0.04 c$^{\alpha}$	848 ± 8.49 b$^{\alpha}$	2.60 ± 0.10 bc$^{\alpha}$	2.10 ± 0.14 b$^{\alpha}$	1.57 ± 0.11 b$^{\alpha}$	132 ± 6.36 d$^{\alpha}$
T6	30.9	30.8	1.35 ± 0.21 abc$^{\alpha}$	857 ± 2.12 b$^{\alpha}$	2.78 ± 0.04 b$^{\alpha}$	2.45 ± 0.07 b$^{\alpha}$	1.43 ± 0.25 bc$^{\alpha}$	156 ± 0.71 b$^{\alpha}$
T7	31.1	30.9	1.25 ± 0.07 bc$^{\alpha}$	799 ± 1.41 d$^{\alpha}$	2.50 ± 0 bc$^{\alpha}$	2.10 ± 0.14 b$^{\alpha}$	1.25 ± 0.07 bc$^{\alpha}$	140 ± 2.83 cd$^{\alpha}$
T8	30.9	30.7	1.10 ± 0.14 bc$^{\alpha}$	815 ± 7.07 c$^{\alpha}$	2.45 ± 0.07 bc$^{\alpha}$	2.35 ± 0.07 b$^{\alpha}$	1.40 ± 0.14 bc$^{\alpha}$	134 ± 2.12 cd$^{\alpha}$
T9	30.9	30.7	1.15 ± 0.07 bc$^{\alpha}$	780 ± 0.00 e$^{\alpha}$	2.25 ± 0.07 c$^{\alpha}$	2.15 ± 0.07 b$^{\alpha}$	1.10 ± 0.00 bc$^{\alpha}$	141 ± 1.41 cd$^{\alpha}$
P-anova	–	–	0	0	0	0	0	0
F-cal	–	–	11.3701	644.51	306.48	25.10	153.60	142.11
F-table (8,9)	–	–	3.23	3.23	3.438	3.23	3.23	3.23
CV	–	–	8.37	0.51	4.24	5.22	9.2	2.1
Shapiro (Norm.Res)	–	–	0.21	0.39	0.46	0.003	0.40	0.98
Durbin-Watson (Independence.Re)	–	–	0.7552	0.80	0.40	0.95	0.75	0.60
LeveneTest (Var.Homoge)	–	–	–	–	–	–	–	–
Lambda (λ)	–	–	−0.02	−2	1.15	1.19	0.70	1.35

Results represent the mean ± SD ($n = 3$). Extruded pure flours (T1: corn, T2: sorghum and T3: parboiled brown rice), extruded binary blends 1:1 (T4: corn-sorghum, T5: corn-parboiled brown rice and T6: parboiled brown rice-sorghum) and extruded multigrain blends in equal proportions (T7–T9 = corn-parboiled brown rice-sorghum). Lower case letters indicate differences between treatments ($P < 0.05$). $^{\alpha}$Indicates differences against control by Dunnett test ($P < 0.05$). Box-Cox transformation factor (λ) for non-parametric data. AT (min), arrival time; DDT (min), dough development time; DST (min), dough stability time; DT (min), departure time; FW, flour weight; MTI, mixing tolerance index, determined at 5 min after peak; PM (BU), peak maximum of consistency; WA, water absorption.

[†] Unique values without variability.

[‡] Control samples that did not exhibit farinographic properties.

incorporate hydrocolloids/starch and without the need to adapt special compartments to facilitate farinographic readings in GF flours, as was adapted by Sahin *et al.* (2020). These short TA values indicate a rapid WA of the flours due to increased hydrogen bonding caused by the thermal and shearing effect on starch fragmentation and solubility during the extrusion process (Espinosa-Ramírez *et al.*, 2021). This result highlights the potential of extrusion-treated WG flours to provide a viable alternative to traditional GF flours.

T1 and T2 showed the lowest AT ($P < 0.05$; Table 3), but they also have an initial peak at ~2 min, while T3 showed the highest values as result of its lower hydration capacity without an initial peak, suggesting greater component resistance and the ability to maintain its polymeric structure against mechanical stress during mixing. Regarding binary blends, T4–T6 carried the initial peak characteristic of T1 and T2. The T4 sample (without PBR) showed similar AT to the extruded corn (T3) and sorghum (T2) samples, while T5 and T6 samples with PBR were closed to the T3. For T7–T9 samples (multigrain), the AT and were intermediate but closer to T4 than T1 and T2 in the ease of WA.

Among the samples, T3 showed high stability during mixing, evidenced by its higher DT, DDT, DST and PM (Table 3) than T1 and T2 samples. All of them showed farinograms with PM levels above 500 BU emulating the characteristics of wholemeal wheat flour, as reported by Comettant-Rabanal *et al.* (2021), but this value was not possible to achieve in GF flours until the authors introduced a new technique to deal with GF flours to evaluate their functionality. The difficulty to achieve ~500 BU is evidenced in numerous works that have had the need to add additives like proteins or/and hydrocolloids (Ćurić *et al.*, 2007; van Riemsdijk *et al.*, 2011). The farinogram profiles corroborate to the effectiveness proposed by Comettant-Rabanal *et al.* (2021) for improving and measuring the viscoelastic properties of GF with better reproducibility.

Double heat processes, parboiling and extrusion, in brown rice (T3) may have led to special functionalities that conferred melting resistance their biopolymers even under mechanical work provided by extrusion cooking, possibly due to the formation of cross-linked complexes (starch annealing) and/or aggregates between starch and proteins/lipids. In comparison, T1 and T2 samples that were not pre-treated by parboiling showed lower DT, DDT, DST, PM, and higher MTI ($P < 0.05$), indicating that extruded corn and sorghum flours had lower tolerances to mechanical mixing work leading to rapid breaking of their viscoelastic properties. Recent progress in improving farinographic profiles was evidenced by Bian *et al.* (2022) in GF flours with the addition of soy protein isolate, particularly its contribution of cysteine in the interaction with water generates disulphide bonds, helped to improve dough stability and dough formation (van Riemsdijk *et al.*, 2011).

Among the binary blends, it was observed that the interaction between corn and sorghum (T4) had similar DT, DDT, DST and PM ($P > 0.05$) compared to corn and sorghum alone, which may be attributed to its high insoluble fibre fraction affecting dough conformation and its cohesiveness. Regarding T5 and T6, the presence of PBR contributed to similar farinographic properties (DDT, DST, and PM) than rice alone, demonstrating the strong influence of T1 sample on farinographic properties. In the multigrain samples, most properties slide low than T3, T5 and T6 (binary blends with PBR).

Farinography properties presented good adjustments of their mathematical models with R^2 Adj ranged from 0.73 to 0.99 and showed no lack of fit. Most of the variables (AT, DT, DST, and MTI) showed quadratic models (Figure S4a,b,d,f) with an optimum R^2 Adj (0.91–0.98; only AT showed 0.87) and DDT and PM showed linear models (Figure S4c,e) with a well R^2 Adj (0.73–0.80). The impact of T3 on farinographic properties and their modelling was found to be dominant, similar to its effect on paste properties. The results indicated that an increase in the proportion of T3 led to higher values of AT, DT, DDT, DST, and PM, while MTI decreased. High proportions of corn generated the lowest values for DDT, DST (together with sorghum), and PM. On the other hand, high proportions of sorghum resulted in the lowest values for DT and DST, with intermediate values of DDT and PM. In addition, high sorghum proportions and binary blends of corn and PBR generated the lowest AT values.

Oscillatory rheometry analysis

For all samples, a continuous development of elastic (G') and viscous (G'') modulus was observed with increasing of the angular velocity (Hz) compared to the raw samples (Figure S5a), where the elastic nature ($G' > G''$) was predominated (Figure S5b–d). These functional properties suggest that the use of heat treatment in combination with shearing can modify the components (starch, proteins, lipids and fibres) of the grains and/or establish cross-linked complexes between them, resulting in the formation of new structures with techno-functional characteristics useful in the GF industry, such as those require for the production of noodles and baking (Martínez *et al.*, 2014a, 2014b; Gómez & Martínez, 2016).

T1 presented the highest G' (62 543.33 Pa), followed by T2 (47 680 Pa; Table 4), but both samples had similar G'' (Figure S5a) to wheat according to Comettant-Rabanal *et al.* (2021). While T3 based on PBR showed

Table 4 Oscillatory rheometry properties of raw and extrusion-pretreated gluten-free whole-grain flours

	Amplitude sweep								**Frequency sweep**
	LVR plateau	**End of LVR**		**Critical value**		**Crossover**			
Treatment	**G' (Pa)**	**γ**	**τ (Pa)**	**γ**	**τ (Pa)**	**$G' = G''$ (Pa)**	**γ**	**τ (Pa)**	**tan δ (G''/G') at 1 Hz**
PBR	84 466.7 ± 908.4$^{\alpha,\gamma}$	0.025 ± 0.003$^{\alpha,\gamma}$	1739.7 ± 73.7$^{\alpha,\gamma}$	0.02 ± 0.001$^{\alpha,\gamma}$	1491.7 ± 73.1$^{\alpha,\gamma}$	20 480 ± 1021.3$^{\gamma}$	0.32 ± 0.01$^{\alpha}$	8589.3 ± 340.6$^{\alpha,\gamma}$	0.129 ± 0$^{\alpha,\gamma}$
Raw Corn	152 466.7 ± 5909.6$^{\beta,\gamma}$	0.008 ± 0.0002$^{\beta}$	1007.4 ± 70$^{\beta,\gamma}$	0.008 ± 5e-05$^{\beta}$	971.6 ± 32.4$^{\beta,\gamma}$	20 190 ± 321.9$^{\gamma}$	0.09 ± 0.00$^{\beta}$	2269.7 ± 36.5$^{\beta}$	0.372 ± 0.004$^{\beta,\gamma}$
Raw Sorghum	209 366.7 ± 5186.8$^{\alpha,\beta}$	0.008 ± 0.0001$^{\beta}$	1279.3 ± 50.8$^{\alpha,\beta}$	0.008 ± 3e-05$^{\beta}$	1287 ± 49$^{\alpha,\beta}$	12 714.7 ± 1828 4$^{\alpha,\beta}$	0.18 ± 0.03	3105 ± 92.7$^{\beta}$	0.332 ± 0.003$^{\alpha,\beta}$
T1	62 543.3 ± 317.2 a$^{\alpha,\beta,\gamma}$	0.02 ± 0 d$^{\alpha,\beta,\gamma}$	1056.33 ± 39.3 f$^{\beta,\gamma}$	0.02 ± 0.00 d$^{\alpha,\gamma}$	1361.0 ± 19.9 f$^{\alpha,\beta}$	7355.3 ± 46.6 a$^{\alpha,\beta,\gamma}$	1.34 ± 0.04 e$^{\alpha,\beta,\gamma}$	13 756.6 ± 151.8 fg$^{\alpha,\beta,\gamma}$	0.13 ± 0 cd$^{\alpha,\gamma}$
T2	47 680.0 ± 1558.9 c$^{\alpha,\beta,\gamma}$	0.02 ± 0 d$^{\alpha,\beta,\gamma}$	775.67 ± 4.0 g$^{\gamma}$	0.03 ± 0.00 d$^{\alpha,\gamma}$	1139.0 ± 67.8 g$^{\alpha,\beta,\gamma}$	5569.7 ± 56.5 e$^{\alpha,\beta,\gamma}$	1.74 ± 0.07 d$^{\alpha,\beta,\gamma}$	14 203.3 ± 30.6 f$^{\alpha,\beta,\gamma}$	0.15 ± 0 a$^{\alpha,\beta,\gamma}$
T3	25 473.3 ± 989.9 h$^{\alpha,\beta,\gamma}$	0.17 ± 0.01 a$^{\alpha,\beta,\gamma}$	3968.67 ± 64.4 a$^{\alpha,\beta,\gamma}$	0.21 ± 0.01 a$^{\alpha,\beta,\gamma}$	4644.3 ± 88.5 a$^{\alpha,\beta,\gamma}$	3617.7 ± 52 g$^{\alpha,\beta,\gamma}$	4.71 ± 0.22 a$^{\alpha,\beta,\gamma}$	23 816.7 ± 72.3 a$^{\alpha,\beta,\gamma}$	0.15 ± 0 a$^{\alpha,\beta,\gamma}$
T4	50 266.7 ± 135.8 b,$^{\alpha,\beta,\gamma}$	0.02 ± 0 d$^{\alpha,\beta,\gamma}$	682.00 ± 22.1 g$^{\alpha,\beta,\gamma}$	0.02 ± 0.00 d$^{\alpha,\gamma}$	1021.3 ± 21.0 g$^{\beta\gamma}$	6071.3 ± 36.8 d$^{\alpha,\beta,\gamma}$	1.54 ± 0.02 de$^{\alpha,\beta,\gamma}$	13 126.7 ± 355.6 g$^{\alpha,\beta,\gamma}$	0.14 ± 0 b$^{\alpha,\beta,\gamma}$
T5	41 280.0 ± 294.6 ef$^{\alpha,\beta,\gamma}$	0.06 ± 0 b$^{\alpha,\beta,\gamma}$	2105.67 ± 57.1 b$^{\alpha,\beta,\gamma}$	0.08 ± 0.00 b$^{\alpha,\beta,\gamma}$	2913.3 ± 35.2 b$^{\alpha,\beta,\gamma}$	6103.3 ± 72.3 cd$^{\alpha,\beta,\gamma}$	2.65 ± 0.14 b$^{\alpha,\beta,\gamma}$	22 043.3 ± 510.0 b$^{\alpha,\beta,\gamma}$	0.13 ± 0 d$^{\alpha,\gamma}$
T6	38 366.7 ± 1062.3 g$^{\alpha,\beta,\gamma}$	0.06 ± 0 b$^{\alpha,\beta,\gamma}$	1961.33 ± 35.2 c$^{\alpha,\beta,\gamma}$	0.08 ± 0.00 b$^{\alpha,\beta,\gamma}$	2601.3 ± 21.2 c$^{\alpha,\beta,\gamma}$	5387.0 ± 79 f$^{\alpha,\beta,\gamma}$	2.92 ± 0.07 b$^{\alpha,\beta,\gamma}$	21 753.3 ± 581.6 b$^{\alpha,\beta,\gamma}$	0.14 ± 0 c$^{\alpha,\beta,\gamma}$
T7	44 466.7 ± 489.9 d$^{\alpha,\beta,\gamma}$	0.04 ± 0 c$^{\alpha,\beta,\gamma}$	1577.33 ± 15.7 d$^{\alpha,\beta,\gamma}$	0.06 ± 0.00 c$^{\alpha,\beta,\gamma}$	1990.3 ± 80.1 de$^{\alpha,\beta,\gamma}$	6266.0 ± 60.3 b$^{\alpha,\beta,\gamma}$	2.32 ± 0.11 c$^{\alpha,\beta,\gamma}$	19 790 ± 20 c$^{\alpha,\beta,\gamma}$	0.15 ± 0 a$^{\alpha,\gamma}$
T8	42 733.3 ± 118.5 de$^{\alpha,\beta,\gamma}$	0.04 ± 0 c$^{\alpha,\beta,\gamma}$	1583.00 ± 18.5 d$^{\alpha,\beta,\gamma}$	0.06 ± 0.00 c$^{\alpha,\beta,\gamma}$	2092.3 ± 4.2 d$^{\alpha,\beta,\gamma}$	6245.0 ± 11.5 bc$^{\alpha,\beta,\gamma}$	2.86 ± 0 b$^{\alpha,\beta,\gamma}$	18 873.3 ± 50.3 d$^{\alpha,\beta,\gamma}$	0.14 ± 0 b$^{\alpha,\beta,\gamma}$
T9	39 780.0 ± 439.6 fg$^{\alpha,\beta,\gamma}$	0.04 ± 0 c$^{\alpha,\beta,\gamma}$	1441.33 ± 20.5 e$^{\alpha,\beta,\gamma}$	0.06 ± 0.00 c$^{\alpha,\beta,\gamma}$	1949.3 ± 6.6 e$^{\alpha,\beta,\gamma}$	5692.7 ± 23.1 e$^{\alpha,\beta,\gamma}$	2.23 ± 0 c$^{\alpha,\beta,\gamma}$	17 070 ± 86.6 e$^{\alpha,\beta,\gamma}$	0.14 ± 0 b$^{\alpha,\beta,\gamma}$
P-anova	0.00	0	0	0	0	0	0	0	0
F-cal	518.31	1541.73	2242.41	388.76	1570.79	1071.65	301.51	550.17	92.41
F-table (8,9)	2.51	2.51	2.51	2.51	2.51	2.51	2.51	2.51	3.23
CV	1.74	4.13	2.14	7.35	2.23	0.91	4.07	1.6	0.88
Shapiro (Norm.Res)	0.17	6e-04	0.86	0.00	0.15	0.50	0.06	0.01	0.45
Durbin-Watson (Independence.Res)	0.30	0.14	0.69	0.97	0.51	0.22	0.99	0.96	0.61
LeveneTest (Var.Homoge)	0.76	0.11	0.69	0.09	0.47	0.93	0.18	0.30	–
Lambda (λ)	–	–	–	−0.26	–	–	–	0.02	2

Results represent the mean ± SD (n = 3). Lowercase letters indicate differences between extruded samples (T1–T9; $P < 0.05$). $^{\alpha,\beta,\gamma}$indicates differences against raw corn, PBR and raw sorghum, respectively by Dunnett test ($P < 0.05$). Extruded pure flours (T1: corn, T2: sorghum and T3: parboiled brown rice), extruded binary blends 1:1 (T4: corn-sorghum, T5: corn-parboiled brow rice and T6: parboiled brown rice-sorghum) and extruded multigrain blends in equal proportions (T7–T9: corn-parboiled brown rice-sorghum). Box-Cox transformation factor (λ) for non-parametric data. G'', viscous or loss modulus; γ, shear strain or strain rate; G', elastic or storage modulus; LVR, linear viscoelastic region; tan δ, angle of displacement; τ, shear stress.

the lowest G′ and G″ values close to those reported by Bian *et al.* (2022) for wheat flour (Figure S5c). In the binary blends, samples which corn T4 and T5 (50 266.67 and 41 280 Pa, respectively) had higher G' and G'' ($P < 0.05$; Table 4), due to the influence of extruded corn, while T6 showed the lowest G' due to the presence of PBR. The multigrain samples T7-T9 had G′ values ranged from 39 780–44 466.67 Pa, indicating that the elastic modulus values were intermediate and similar to the binary samples T5 and T6 ($P > 0.05$).

The parameters γ and τ determined at the end of the LVR (beginning of loss of integrity) and in the critical state (Table 4), demonstrate the degree of structuring of the constituents of each sample against oscillatory stresses. Notable, sample T3 showed the highest $\tau = 4644.33$ Pa (with $\gamma = 0.21$; $P < 0.05$), indicating a higher degree of structuring or strength of its constituents than T1 and T2. Among the binary samples, T5 showed the highest $\tau = 2913.33$ Pa ($\gamma = 0.08$), followed by T6 with a $\tau = 2601.33$ ($\gamma = 0.08$), indicating the strong influence of extruded PBR on rheological parameters, maybe due to its double cooking process (parboiling and extrusion), which caused atypical modifications rarely reported in starch and its other components, associated with phenomena of starch granular stiffness (Liu *et al.*, 2019a; Yeum *et al.*, 2021) and starch/protein or starch/lipid cross-linking (Wu *et al.*, 2010). Multigrain blends (T7–T9) showed intermediate τ values between 1990.33–2092.33 Pa, because those blends contain equal proportions of the three GF grains.

T1 and T5 showed the lowest values (0.13) of tan δ, which is an indicative of the elasticity, as the smaller is tan δ, the higher is the elasticity of a sample. Finally, the crossover ($G' = G''$) and its equivalents in γ and τ measured in the non-linear region indicate the behaviour of the samples, when their components (mainly polymers) are affected by stresses that cause their lack of structure but can give important information in those investigations that focus on this type of parameters in the non-linear region. The models for properties of oscillatory rheometry were significant (G', γ, τ, and $G' = G''$) and had no lack of fit (Table S1), except for tan δ (G''/G') where the model was non-significant. The variables G' together τ on the end of LVR and γ, τ at the critical limit showed optimum R^2Adj (0.90–0.99) with linear (Figure S6a,e–i) and quadratic models (Figure S6b–d), while in the non-linear region as $G' = G''$ and τ (crossover) had a well R^2 Adj of 0.78 and 0.82, respectively.

Higher T1 proportions led to higher G' (LVR) and $G' = G''$, and lower γ and τ (both at the LVR, critical and crossover ends; Figure S6a–i), indicating that extruded corn sample loses its structure more easily than the T2 and T3 samples, due to its higher fibre content, which exerts a shearing effect between the continuous network of the dough, thus decreasing the cohesive forces of the dough conformation (Comettant-Rabanal *et al.*, 2021). While the T3 showed the highest γ and τ (LVR), indicating its predominant and interesting contribution to the dough resistance to oscillatory stresses.

Bread characterisation

Texture profile analysis (TPA) of gluten-free bread

All extrusion-treated samples showed higher hardness and chewiness compared to the control ($P < 0.05$; Table 5). While between extruded samples, sorghum with PBR (T6) and multigrain (T7 and T8) blends in terms of cohesiveness were similar to the control ($P > 0.05$), due to the strong consistency caused by the PBR. Furthermore, it was observed that the hardness, cohesiveness, chewiness and resilience of the extruded samples were significant and showed no lack of fit (Table S2), thus they could be used as reliable and accurate models in predicting and explaining the behaviour of these variables. Among these variables, hardness showed a linear behaviour (Figure S7a), but with a low R^2 Adj = 0.60; hence, it could be considered to explain trends, while other authors as Santos *et al.* (2018) and Genevois & de Escalada Pla (2021) did not achieve significance in this parameter which is the most relevant instrumental texture for GF breadcrumb. In this sense, we could estimate that the higher the proportion of T2, the lower the hardness of the breads evaluated ($P < 0.05$; Table 5). While high proportions of T1 or T3 led to increases in hardness as reported by Mancebo *et al.* (2015) for GF breads with predominant rice starch incorporation. The hardness of bread crumbs can be influenced by the type of starch (A or B) and the degree of amylose polymerisation (Roman *et al.*, 2020), which are related to the ability to form air-liquid interfaces a phenomenon known as Pickering stabilisation. This property allows the dough to retain carbon dioxide during fermentation, resulting in an increase in the bread specific volume and a reduction in its hardness (Roman *et al.*, 2018). On the other hand, after extrusion cooking, the molecular order of starch was modified (Figure S1), leading to sorghum starch presented the lowest parameters associated with retrogradation, such as FV and SBV, which may be related to a lower crumb hardness, since the specific volume in this study did not vary significantly ($P < 0.05$) between samples.

Likewise, cohesiveness and chewiness showed a linear behaviour (Figure S7c,e) and a well R^2 Adj of 0.83 for both, where the highest cohesiveness was reached with the highest proportion of T3. Yet intermediate values with high proportions of T2 and the lowest with high proportions of T1, which due to its high fibre content, affected the strength of the breadcrumb and caused a higher crumbling. The highest chewiness was

Table 5 Texture profile, baking loss and specific volume analysis of gluten-free breads

Treatment	Hardness (N)	Adhesiveness (g.s)	Cohesiveness (–)	Springiness (–)	Chewiness (N)	Resilience (–)	Baking loss (g)	Specific volume (cm^3 g^{-1})
Control	13.38 ± 0.82	−1.19 ± 0.33	0.22 ± 0.03	0.75 ± 0.05	2.04 ± 0.25	0.12 ± 0.02	16.25 ± 0.23	0.63 ± 0.02
T1	38.78 ± 3.64 bc[†]	−2.98 ± 0.43 bc[†]	0.08 ± 0.01 g[†]	0.88 ± 0.1 b	2.63 ± 0.29 e	0.04 ± 0.01 e[†]	13.17 ± 0.38 b[†]	1.13 ± 0.03 ab[†]
T2	26.85 ± 3.33 d[†]	−3.75 ± 0.53 c[†]	0.12 ± 0.02 f[†]	0.78 ± 0.09 b	2.73 ± 0.39 e	0.06 ± 0.01 de[†]	11.58 ± 0.18 c[†]	1.03 ± 0.06 ab[†]
T3	40.62 ± 4.7 ab[†]	−5.23 ± 0.79 d[†]	0.37 ± 0.04 a[†]	5.72 ± 0.64 a[†]	16.11 ± 2.06 a[†]	0.17 ± 0.02 a[†]	13.23 ± 0.38 b[†]	1.09 ± 0.06 ab[†]
T4	32.7 ± 3.32 cd[†]	−2.1 ± 0.37 b	0.14 ± 0.01 ef[†]	0.90 ± 0.08 b	4.17 ± 0.83 de[†]	0.07 ± 0.01 d[†]	15.17 ± 1.15 a	1.15 ± 0.05 a[†]
T5	45.25 ± 3.7 a[†]	−0.62 ± 0.08 a	0.15 ± 0.02 ef[†]	0.92 ± 0.05 b	6.19 ± 0.88 bc[†]	0.06 ± 0.01 de[†]	15.00 ± 0.50 a[†]	1.00 ± 0.01 b[†]
T6	26.66 ± 2.88 d[†]	−3.35 ± 0.51 bc[†]	0.25 ± 0.02 b	0.96 ± 0.04 b	6.51 ± 0.67 bc[†]	0.12 ± 0.01 b	14.33 ± 0.29 ab[†]	1.02 ± 0.05 ab[†]
T7	33.53 ± 3.02 c[†]	−7.3 ± 1.03 e[†]	0.23 ± 0.03 bc	0.90 ± 0.07 b	6.94 ± 0.89 bc[†]	0.06 ± 0.01 de	14.67 ± 0.29 a[†]	1.05 ± 0.06 ab[†]
T8	40.81 ± 2.49 ab[†]	−6.2 ± 0.96 de[†]	0.20 ± 0.03 cd	0.89 ± 0.09 b	7.48 ± 1.44 b[†]	0.09 ± 0.01 c[†]	13.97 ± 0.16 ab[†]	1.05 ± 0.06 ab[†]
T9	37.42 ± 2.57 bc[†]	−6.43 ± 1.32 de[†]	0.18 ± 0.02 de[†]	0.90 ± 0.08 b	5.46 ± 0.81 cd[†]	0.07 ± 0.01 cd[†]	13.93 ± 0.08 ab	1.10 ± 0.04 ab[†]
P-anova	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
F-cal	21.79	50.79	84.71	300.56	88.01	64.86	15.95	3.69
F-table (8,9)	2.15	2.15	2.15	2.15	2.15	2.15	2.51	2.51
CV	9.36	−18.06	11.98	15.96	16.23	14.19	3.48	4.44
Shapiro (Norm.Res)	0.10	0.51	0.45	0	0.11	0.30	0.03	0.19
Durbin-Watson (Independence.Res)	0.09	0.92	0.76	0.99	0.99	0.43	0.67	0.19
LeveneTest (Var.Homoge)	0.98	0.005	0.03	0.001	0.06	0.11	0.82	0.96
Lambda (λ)	–	x_negativo	−0.101	−0.101	–	–	−2	–

Results represent the mean ± SD (*n* = 8 for texture and *n* = 6 for physical properties). Lower case letters indicate differences between treatments ($P < 0.05$). Control: blend of raw rice/PBR flours (1:1). Extruded pure flours (T1: corn, T2: sorghum and T3: parboiled brown rice), extruded binary blends 1:1 (T4: corn-sorghum, T5: corn-parboiled brow rice and T6: parboiled brown rice-sorghum) and extruded multigrain blends in equal proportions (T7–T9: corn-parboiled brown rice-sorghum).

[†] Indicates differences against control by Dunnett test ($P < 0.05$). Box-Cox transformation factor (λ) for non-parametric data.

achieved with higher proportions of T3 (Figure S7e), while with higher proportions of T1 or T2, the lowest values for this parameter were reached. Resilience had a quadratic behaviour with an optimum R^2 Adj equal to 0.91 and reached its highest values at high proportions of T3 (Figure S7f), indicating a better crumb recovery capacity; the opposite effect was caused by high proportions T2 and intermediate values by majority proportions of T1. Adhesiveness and springiness were texture parameters that had a lack of fit, hence they were not considered in the interpretation of the regression models (Figure S7b,d), but for both texture parameters, it was T3 that expressed outstanding values.

Baking loss and specific volume of gluten-free bread

The baking loss values of most of the extruded samples were lower than the control ($P < 0.05$) and only the mixture between corn and extruded sorghum (T4) had statistically similar values ($P > 0.05$; Table 5). Meanwhile, T2 showed the lowest baking loss among all the samples ($P < 0.05$), which indicates a better water retention of the extruded sorghum during the baking process. This behaviour is associated with the water release rate and is consistent with the low FV and SBV values of T2 sample, which are associated with the lower short-term retrogradation rate mentioned above. Furthermore, the modelling of this variable was not significant with a low R^2 Adj = 0.39 (Figure S8a). The specific volume of the samples treated by extrusion was higher than the control ($P < 0.05$) between 53.8 to 91.7%. But among the extruded samples, the specific volume was very low (1–1.15 cm^3/g) and did not produce significant contributions ($P > 0.05$) contributing to this parameter. These specific volume values resulted in a high crumb hardness (26.66–45.25 N), which are typical of dense breads compared to those reported by Comettant-Rabanal *et al.* (2021), where researchers used a GF bread formulation with twice the fat and 3 times the amount of yeast. In addition, our results were close to those found by Centeno *et al.* (2021) for sorghum bread and Sandri *et al.* (2017) when incorporating a fibre-rich ingredient such as chia, resulted in denser GF breads. However, both the specific volume and the baking loss of the GF breads could not be modelled because the effect of each extruded cereal on the blends did not produce appreciable changes in these parameters. But these results may be useful for interpreting slight trends in these variables, produced by the incorporation of each GF grain.

Conclusions

The paste properties of the samples after extrusion were altered, but the absence of cold viscosity (CV) and peak viscosity (PV) formation showed moderate changes in the starch granular structure. These changes resulted in viscoelastic functional flours that showed increased water absorption capacity and farinographic consistency, as well as the development of elastic (G') and viscous (G'') moduli under dynamic oscillation stress. The GF breads produced using the extruded whole grain flours and their blends showed considerable increases of 53.8–91.7% in specific volume compared to the control. However, in terms of texture, the extruded sorghum flour (T2) and its blend with parboiled rice (T6) had softer crumbs, a more continuous crust with fewer fissures. Furthermore, the regression models were able to explain with optimal (R^2 Adj = 0.90–0.99) linear and quadratic fits the behaviour of the dough rheological variables (except for tan δ) and well fits (R^2 Adj = 0.60–0.90) for the textural variables of the GF bread (except for adhesiveness and springiness). This allowed to establish that the GF bread with a higher proportion of sorghum (excluding PBR), results in breads with a lower crumb hardness and a lower baking loss. Therefore, each type of extruded grain in different proportions can generate GF breads with a variety of textural and nutritional profiles that contribute to the diet of target consumers.

Acknowledgments

The authors thank FAPERJ for the financial support and CAPES and CNPq for the scholarships granted.

Author contributions

Raul Comettant-Rabanal: Conceptualization (lead); formal analysis (lead); investigation (lead); writing – original draft (lead). **Davy William Hidalgo Chávez:** Data curation (equal); methodology (equal); software (equal); supervision (equal); visualization (equal); writing – review and editing (equal). **José Luis Ramírez Ascheri:** Project administration (equal); supervision (equal); writing – review and editing (equal). **Carlos Elías-Peñafiel:** Formal analysis (equal); methodology (equal); validation (equal). **Carlos W. Piler Carvalho:** Conceptualization (equal); formal analysis (lead); funding acquisition (lead); project administration (lead); resources (equal); supervision (equal); writing – review and editing (supporting).

Ethical guidelines

Ethics approval was not required for this research.

Peer review

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/ijfs.16676.

Data availability statement

The data will be made available if required by the journal.

References

AACC (2000a). Method 10-05.01 specific volume (rapeseed). In: *Approved Methods of the American Association of Cereal Chemist*, 10th edn. St. Paul: AACC.

AACC (2000b). Method 54-21.01 farinograph method for flour. In: *Approved Methods of the American Association of Cereal Chemist*, 10th edn. St. Paul: AACC.

Allai, F.M., Azad, Z., Gul, K. & Dar, B.N. (2022). Wholegrains: a review on the amino acid profile, mineral content, physicochemical, bioactive composition and health benefits. *International Journal of Food Science & Technology*, **57**, 1849–1865.

Balakireva, A.V. & Zamyatnin, A.A. (2016). Properties of gluten intolerance: gluten structure, evolution, pathogenicity and detoxification capabilities. *Nutrients*, **8**, 2–27.

This article is one of the few that deals comprehensively with gluten-related disorders. For this reason, it was chosen for citation as it provides comprehensive information summarised in a single article.

Bian, X., Xing, T.-L., Yang, Y. *et al.* (2022). Effect of soy protein isolate on physical properties of quinoa dough and gluten-free bread quality characteristics. *Journal of the Science of Food and Agriculture*, **103**, 118–124.

Box, G.E.P. & Cox, D.R. (1964). An analysis of transformations. *Journal of the Royal Statistical Society: Series B (Methodological)*, **26**, 211–243.

This article belongs to the authors who proposed the technique of converting variables by the method that bears their own name "Box-Cox". Since we used this method in our results, it was pertinent to cite them.

Cabanillas, B. (2020). Gluten-related disorders: celiac disease, wheat allergy, and nonceliac gluten sensitivity. *Critical Reviews in Food Science and Nutrition*, **60**, 2606–2621.

Centeno, A.C.L., Aguiar, E., Santos, F. *et al.* (2021). Defining whole grain sorghum flour and water levels to improve sensory and nutritional quality of gluten-free bread—a factorial design approach. *Applied Sciences*, **11**, 1–13.

This article was cited because it is one of the few that used whole grains to produce gluten-free breads. It was therefore used to compare their results with ours.

Chávez, D.W.H., Ascheri, J.L.R., Carvalho, C.W.P. *et al.* (2021). Physicochemical properties, characteristics, and consumer acceptance of whole grain sorghum expanded extrudates. *Journal of Food Processing and Preservation*, **45**, e15837.

Chávez, D.W.H., Ascheri, J.L.R., Carvalho, C.W.P., Godoy, R.L.O. & Pacheco, S. (2017). Sorghum and roasted coffee blends as a novel extruded product: bioactive compounds and antioxidant capacity. *Journal of Functional Foods*, **29**, 93–103.

Cheng, W., Gao, L., Wu, D. *et al.* (2020). Effect of improved extrusion cooking technology on structure, physiochemical and nutritional characteristics of physically modified buckwheat flour: its potential use as food ingredients. *LWT*, **133**, 109872.

Clerici, M.T.P.S., Airoldi, C. & El-Dash, A.A. (2009). Production of acidic extruded rice flour and its influence on the qualities of gluten-free bread. *LWT - Food Science and Technology*, **42**, 618–623.

This is one of the first articles that used extrusion on flours to produce gluten-free breads. It is therefore a key work that forms part of the state of the art in the introduction.

Comettant-Rabanal, R., Carvalho, C.W.P., Ascheri, J.L.R., Chávez, D.W.H. & Germani, R. (2021). Extruded whole grain flours and sprout millet as functional ingredients for gluten-free bread. *LWT*, **150**, 112042.

Ćurić, D., Novotni, D., Tušak, D., Bauman, I. & Gabrić, D. (2007). Gluten-free bread production by the corn meal and soybean flour extruded blend usage. *Agriculturae Conspectus Scientificus*, **72**, 227–232.

dos Santos, T.B., da Silva Freire Neto, R., Collantes, N.F., Chávez, D.W.H., Queiroz, V.A.V. & de Carvalho, C.W.P. (2022). Exploring starches from varied sorghum genotypes compared to commercial maize starch. *Journal of Food Process Engineering*, **46**, e14251.

Espinosa-Ramírez, J., Rodríguez, A., De la Rosa-Millán, J., Heredia-Olea, E., Pérez-Carrillo, E. & Serna-Saldívar, S.O. (2021). Shear-induced enhancement of technofunctional properties of whole grain flours through extrusion. *Food Hydrocolloids*, **111**, 106400.

Genevois, C.E. & de Escalada Pla, M.F. (2021). Soybean by-products and modified cassava starch for improving alveolar structure and quality characteristics of gluten-free bread. *European Food Research and Technology*, **247**, 1477–1488.

Gómez, M. & Martínez, M.M. (2016). Changing flour functionality through physical treatments for the production of gluten-free baking goods. *Journal of Cereal Science*, **67**, 68–74.

Hu, Z., Tang, X., Liu, J., Zhu, Z. & Shao, Y. (2017). Effect of parboiling on phytochemical content, antioxidant activity and physicochemical properties of germinated red rice. *Food Chemistry*, **214**, 285–292.

Jafari, M., Koocheki, A. & Milani, E. (2018a). Functional effects of xanthan gum on quality attributes and microstructure of extruded sorghum-wheat composite dough and bread. *LWT*, **89**, 551–558.

Jafari, M., Koocheki, A. & Milani, E. (2018b). Physicochemical and sensory properties of extruded sorghum–wheat composite bread. *Journal of Food Measurement and Characterization*, **12**, 370–377.

Kaushal, M., Sharma, R., Vaidya, D. *et al.* (2023). Maize: an underexploited golden cereal crop. *Cereal Research Communications*, **51**, 3–14.

Liu, K., Hao, Y., Chen, Y. & Gao, Q. (2019a). Effects of dry heat treatment on the structure and physicochemical properties of waxy potato starch. *International Journal of Biological Macromolecules*, **132**, 1044–1050.

Liu, Q., Kong, Q., Li, X. *et al.* (2020). Effect of mild-parboiling treatment on the structure, colour, pasting properties and rheology properties of germinated brown rice. *LWT*, **130**, 109623.

Liu, Y., Chen, J., Luo, S. *et al.* (2017). Physicochemical and structural properties of pregelatinized starch prepared by improved extrusion cooking technology. *Carbohydrate Polymers*, **175**, 265–272.

Liu, Y., Chen, J., Wu, J. *et al.* (2019b). Modification of retrogradation property of rice starch by improved extrusion cooking technology. *Carbohydrate Polymers*, **213**, 192–198.

Mancebo, C.M., Merino, C., Martínez, M.M. & Gómez, M. (2015). Mixture design of rice flour, maize starch and wheat starch for optimization of gluten free bread quality. *Journal of Food Science and Technology*, **52**, 6323–6333.

Maqbool, M.A., Beshir Issa, A. & Khokhar, E.S. (2021). Quality protein maize (QPM): importance, genetics, timeline of different events, breeding strategies and varietal adoption. *Plant Breeding*, **140**, 375–399.

Martínez, M., Díaz, Á. & Gómez, M. (2014a). Effect of different microstructural features of soluble and insoluble fibres on gluten-free dough rheology and bread-making. *Journal of Food Engineering*, **142**, 49–56.

Martínez, M.M., Calviño, A., Rosell, C.M. & Gómez, M. (2014b). Effect of different extrusion treatments and particle size distribution on the physicochemical properties of Rice flour. *Food and Bioprocess Technology*, **7**, 2657–2665.

Martínez, M.M., Marcos, P. & Gómez, M. (2013). Texture development in gluten-free breads: effect of different enzymes and extruded flour. *Journal of Texture Studies*, **44**, 480–489.

Mir, S.A., Shah, M.A., Bosco, S.J.D., Sunooj, K.V. & Farooq, S. (2020). A review on nutritional properties, shelf life, health aspects, and consumption of brown rice in comparison with white rice. *Cereal Chemistry*, **97**, 895–903.

Oliveira, M.E.A.S., Coimbra, P.P.S., Galdeano, M.C., Carvalho, C.W.P. & Takeiti, C.Y. (2022). How does germinated rice impact starch structure, products and nutrional evidences? – a review. *Trends in Food Science & Technology*, **122**, 13–23.

Pandey, S. (2022). Nutritional aspects and health implications of gluten-free products. In: *Challenges and Potential Solutions in Gluten Free Product Development* (edited by N. Singh Deora, A. Deswal & M. Dwivedi). Pp. 17–34. Cham: Springer International Publishing.

Pantoa, T., Baricevic-Jones, I., Suwannaporn, P. *et al.* (2020). Young rice protein as a new source of low allergenic plant-base protein. *Journal of Cereal Science*, **93**, 102970.

Patil, S.S., Rudra, S.G., Varghese, E. & Kaur, C. (2016). Effect of extruded finger millet (Eleusine coracan L.) on textural properties and sensory acceptability of composite bread. *Food Bioscience*, **14**, 62–69.

Pessanha, K.L.F., Menezes, J.P.d., Silva, A.d.A., Ferreira, M.V.d.S., Takeiti, C.Y. & Carvalho, C.W.P. (2021). Impact of whole millet extruded flour on the physicochemical properties and antihyperglycemic activity of gluten free bread. *LWT*, **147**, 111495.

Punia, S. & Kumar, M. (2022). *Functionality and Application of Colored Cereals: Nutritional, Bioactive, and Health Aspects*. Amsterdam: Elsevier.

Ratnavathi, C.V. & Komala, V.V. (2016). Chapter 1 - sorghum grain quality. In: *In: Sorghum Biochemistry* (edited by C.V. Ratnavathi, J.V. Patil & U.D. Chavan). Pp. 1–61. San Diego: Academic Press.

Rochín, S.M., Noris, A.K.M. & Carrillo, J.M. (2019). Maize. In: *Whole Grains* (edited by A. Manickavasagan, M.A. Shah & S.A. Mir). Pp. 87–102. Boca Raton: CRC Press.

Roman, L., Cal, E.d.l., Gomez, M. & Martinez, M.M. (2018). Specific ratio of A-to B-type wheat starch granules improves the quality of gluten-free breads: optimizing dough viscosity and Pickering stabilization. *Food Hydrocolloids*, **82**, 510–518.

Roman, L., Reguilon, M.P., Gomez, M. & Martinez, M.M. (2020). Intermediate length amylose increases the crumb hardness of rice flour gluten-free breads. *Food Hydrocolloids*, **100**, 105451.

Rouf Shah, T., Prasad, K. & Kumar, P. (2016). Maize—a potential source of human nutrition and health: a review. *Cogent Food and Agriculture*, **2**, 1166995.

Sahin, A.W., Wiertz, J. & Arendt, E.K. (2020). Evaluation of a new method to determine the water addition level in gluten-free bread systems. *Journal of Cereal Science*, **93**, 102971.

Saito, K., Okouchi, M., Yamaguchi, M. *et al.* (2022a). Effect of the addition of high-temperature water on the properties of batter and bread made from gluten-free rice flour. *Journal of Food Science*, **87**, 576–584.

Saito, K., Okouchi, M., Yamaguchi, M. *et al.* (2022b). Effects of the addition of high-temperature water on the bubble structure, rheological properties, and sensory characteristics of gluten-free rice flour bread. *Journal of Food Processing and Preservation*, **46**, 1–18.

Saito, K., Okouchi, M., Yamaguchi, M. *et al.* (2022c). Quality improvement of gluten-free rice flour bread through the addition of high-temperature water during processing. *Journal of Food Science*, **87**, 4820–4830.

Sandri, L.T.B., Santos, F.G., Fratelli, C. & Capriles, V.D. (2017). Development of gluten-free bread formulations containing whole chia flour with acceptable sensory properties. *Food Science & Nutrition*, **5**, 1021–1028.

Santos, F.G., Fratelli, C., Muniz, D.G. & Capriles, V.D. (2018). Mixture design applied to the development of chickpea-based gluten-free bread with attractive technological, sensory, and nutritional quality. *Journal of Food Science*, **83**, 188–197.

Scherf, K.A., Koehler, P. & Wieser, H. (2016). Gluten and wheat sensitivities – an overview. *Journal of Cereal Science*, **67**, 2–11.

Smulders, M.J.M., van de Wiel, C.C.M., van den Broeck, H.C. *et al.* (2018). Oats in healthy gluten-free and regular diets: a perspective. *Food Research International*, **110**, 3–10.

Sun, H., Ju, Q., Ma, J. *et al.* (2019). The effects of extruded corn flour on rheological properties of wheat-based composite dough and the bread quality. *Food Science & Nutrition*, **7**, 2977–2985.

Taylor, J.R.N. & Kruger, J. (2019). Chapter 7 - sorghum and millets: food and beverage nutritional attributes. In: *Sorghum and Millets* (edited by J.R.N. Taylor & K.G. Duodu). Pp. 171–224, 2nd edn. St. Paul, MN: AACC International Press.

Toledo, V.C.S., Carvalho, C.W.P., Vargas-Solórzano, J.W., Ascheri, J.L.R. & Comettant-Rabanal, R. (2020). Extrusion cooking of gluten-free whole grain flour blends. *Journal of Food Process Engineering*, **43**, e13303.

Torbica, A., Belovic, M. & Tomic, J. (2019). Novel breads of non-wheat flours. *Food Chemistry*, **282**, 134–140.

van Riemsdijk, L.E., van der Goot, A.J. & Hamer, R.J. (2011). The use of whey protein particles in gluten-free bread production, the effect of particle stability. *Food Hydrocolloids*, **25**, 1744–1750.

Wang, S., Wang, J., Wang, S. & Wang, S. (2017). Annealing improves paste viscosity and stability of starch. *Food Hydrocolloids*, **62**, 203–211.

Wu, M., Li, D., Wang, L.-J., Özkan, N. & Mao, Z.-H. (2010). Rheological properties of extruded dispersions of flaxseed-maize blend. *Journal of Food Engineering*, **98**, 480–491.

Xiong, Y., Zhang, P., Warner, R.D. & Fang, Z. (2019). Sorghum grain: from genotype, nutrition, and phenolic profile to its health benefits and food applications. *Comprehensive Reviews in Food Science and Food Safety*, **18**, 2025–2046.

Yeum, J.H., Choi, H.-W., Kim, H.-y. *et al.* (2021). Effect of hydrothermal treatment on physicochemical properties of amorphous granular potato starch (AGPS). *International Journal of Biological Macromolecules*, **168**, 816–822.

Zhao, F., Li, Y., Li, C. *et al.* (2022). Insight into the regulations of rice protein on the gluten-free bread matrix properties. *Food Hydrocolloids*, **131**, 107796.

Zhu, F. (2015). Interactions between starch and phenolic compound. *Trends in Food Science & Technology*, **43**, 129–143.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Paste profile of raw and extrusion-pretreated gluten-free whole-grain flours. Pure flours (T1: corn, T2: sorghum and T3: parboiled brown rice), binary blends 1:1 (T4: cornsorghum, T5: corn-parboiled brown rice and T6: parboiled brown rice-sorghum) and multigrain blends in equal proportions (T7-T9 = corn-parboiled brown rice-sorghum).

Figure S2. Contour plot for each paste properties of gluten-free whole grain flours pretreated by extrusion. (a) PTemp: pasting temperature, (b) PV: maximum peak viscosity, (c) TV: through viscosity, (d) BDV: break down viscosity, (e) FV: final viscosity and (f) SBD: setback viscosity.

Figure S3. Farinograms of gluten-free whole grain flours pre-treated by extrusion and control (PBR). Pure flours (T1: corn, T2: sorghum and T3: parboiled brown rice), binary blends 1:1 (T4: corn-sorghum, T5: corn-parboiled brown rice and T6: parboiled brown rice-sorghum) and multigrain blends in equal proportions (T7-T9 = corn-parboiled brown rice-sorghum).

Figure S4. Contour plot for each farinographic properties of gluten-free whole grain flours pre-treated by extrusion. (a) arrival time (AT), (b) departure time (DT), (c) dough development time (DDT), (d) dough stability time (DST), (e) peak maximum of consistency (PM) and (f) mixing tolerance index determined at 5 min after peak (MTI).

Figure S5. Oscillatory rheometry properties of raw and extrusion-pretreated gluten-free whole-grain flours.

Figure S6. Contour plot for each oscillatory rheometric properties of gluten-free whole grain flours pretreated by extrusion. LVR: linear viscoelastic region, ɣ: shear strain or strain rate, τ: shear stress, tan δ: angle of displacement, G′: elastic or storage modulus, G″: viscous or loss modulus.

Figure S7. Contour plot for texture properties of gluten-free bread.

Figure S8. Contour plot for baking loss and specific volume of gluten-free bread.

Table S1. Regression models for rheology characteristics of gluten-free whole grain flours pre-treated by extrusion.

Table S2. Regression models for texture properties, baking loss and specific volume of gluten-free bread.