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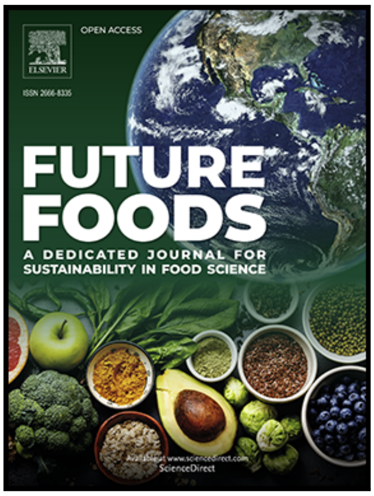

Effect of cornstarch partial substitution by millet flour and agro-industrial by-products on the development of gluten-free doughs

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Highlights:

- Potentiality of agro-industrial by-products as gluten free-dough ingredients.
- Rice bran and soybean extruded-expeller are source of dietary fibre and protein.
- Millet flour is a carbohydrate source alternative to cornstarch.
- Cornstarch replacement affects dough rheology and the optimal fermentation time.
- Understanding these effects contribute to future bakery products development.

Effect of cornstarch partial substitution by millet flour and agro-industrial by-products on the development of gluten-free doughs

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ABSTRACT

Agro-industrial by-products such as rice bran (RB) and soybean extruded-expelled meal (SEE), along with millet, contain nutrients that should be integrated to food-chain. The aim of this study was to characterise these raw-materials and evaluate their effect in the development of gluten-free doughs. A factorial design was used to evaluate the substitution of cornstarch up to 60% by RB, SEE and millet flour. RB and SEE contain 31.5 and 21 % dietary fibre (DF); 17.2 and 8.8 % lipids; 13.1 and 45.9 % protein; respectively. Millet flour presented 9.2% protein, 6.3% lipids and 5.3% DF. Surfaces areas of particles from RB and SEE were higher (63 and 94 m^2/kg, respectively) than those from millet flour (25m^2/kg). All these properties modified dough hydration, affecting the optimal fermentation time of dough as well as pasting properties. The minimum cornstarch substitution presented the highest peak viscosity (1750cP) and longer optimal fermentation time (53min). While system 4, with the maximum cornstarch substitution by 30% of RB, 15% of SEE and 15% millet, tended to the lowest setback value (134cP). Significant positive correlations among dough pasting properties and fermentation parameters were recorded. Partial substitution of cornstarch by RB, SEE and millet enhanced doughs development.

Keywords: by-products re-valorisation, dietary fibre content, dough rheology, fermentation behaviour.

Abbreviations:
RB: rice bran, SEE: soybean extruded-expelled meal, GF: gluten-free, GFDs: gluten-free doughs, GFBs: gluten-free breads, DF: dietary fibre, IDF: insoluble dietary fibre, HPMC: hydroxypropyl methylcellulose, OFTD: optimal fermentation time of dough determination, SC: swelling capacity, WHC: water holding capacity, WRC: water retention capacity, OHC: oil holding capacity.

1. Introduction

Gluten-free doughs (GFDs) present a technological challenge due to the absence of gluten, resulting in fluid consistency, high viscosity, lower cohesion, and limited elasticity (Ronda et al., 2017). Moreover, they often exhibit nutritional deficiencies, characterised mainly by low levels of dietary fibre (DF), vitamins, and minerals (Capriles and Arêas, 2014; Vici et al., 2016).

In recent years, a trend has emerged in the use of flours derived from alternative grains, seeds and agro-industrial by-products for the formulation of GF breads (GFBs), with the aim of diversifying these products and improving their nutritional value, technological and sensory quality (Genevois et al., 2020; Ammar et al., 2022; Korus et al., 2022; Chockchaisawasdee et al., 2023). The strategic inclusion of by-products such as rice bran (RB), soybean extruded-expelled meal (SEE), and others grains such as pearl millet, could be useful in addressing these challenges. RB is a valuable by-product and contains a significant amount of fat, proteins, DF (~31%), antioxidant compounds and minerals. While SEE is the by-product of the soy oil extraction free-solvent, a technology commonly adopted by small or medium sized Argentinian companies. SEE contains higher digestible energy, amino-acid availability, and lipid content than solvent meals. Few technological applications have been proposed regarding the addition of the SEE to food formulation (Accoroni et al., 2020; Genevois and de Escalada Pla, 2021). On the other hand, pearl millet (*Pennisetum glaucum*) is a cereal that is not commonly used in culinary preparations for western patter diet; it contains essential amino acids, primarily methionine, as well as iron, phosphorus, and phenolic compounds (Saleh et al., 2013, Rolandelli et al., 2023).

In previous studies the addition of RB and SEE to GFBs were analysed up to 20% replacement (Genevois et al., 2020; Castellanos-Fuentes, et al., 2022). The combined impact of these ingredients with millet on dough quality remains unexplored. In order to improve the nutritional profile of dough formulation, the reduction of starchy raw material by those with higher DF and protein content is worth to be studied. Nevertheless, these latter components can notably affect dough rheology (Genevois et al., 2020). The aim of this work was to evaluate the effect of replacing, up to 60% of cornstarch, by RB, SEE and millet on the rheological properties and fermentation behaviour of GFDs.

2. Materials and methods

2.1. Materials

RB and rice flour from long-grain rice (78.0 of carbohydrates, 6.3 of proteins, 0.8 of lipids and 1.8 of DF), Gurí INTA CL cultivar (Cooperative Villa Elisa S.A., Entre Ríos, Argentina); SEE provided by Pet´s Group (Entre Ríos, Argentina); pearl millet (Yin-Yang, Argentina), cornstarch (82.2 g carbohydrates, 5.6 g proteins, 1.4 g lipids, 1.9 g DF; Maizena™, Argentina), sunflower oil (Natura, Argentina), hydroxypropyl methylcellulose (HPMC; Methocel K4M, Dow Chemical, USA), salt (Celusal, Argentina), sugar (Ledesma, Argentina), and dry yeast (LEVEX, Argentina) were used. The safety of SEE was ensured by aflatoxin levels of 0.30 μg kg^{-1} for AFB1 and <0.20 μg kg^{-1} for AFB2, AFG1, and AFG2. In addition, RB maintained a limit of <0.20 μg kg^{-1} for all aflatoxins, thus ensuring its safety. The gluten content was quantified using an enzyme immunoassay (Kit RIDASCREEN® Gliadin Competitive, r-Biopharm, Germany). All samples comply with the safety standards with requirements of local and international authorities (Cagnasso et al., 2023). The millet and SEE were milled (HC-1000Y, Arcano, China) at 32000 RPM for 15 min three times with an interval of 30 min to avoid flour overheating (Bekele and Emire, 2023a). Milled, SEE, and RB were sieved through 840 μm mesh (ASTM No. 20, Zonytest, Argentina).

2.2. Determination of particle size distribution

The particle size distribution of raw materials was determined using static light scattering with a Malvern Mastersizer 2000 analyser equipped with a Hydro 2000MU wet dispersion unit and its software (V6.01, Malvern Panalytical Ltd., UK). Particle sizes were expressed as: volume weighted mean (D[4.3], μm), surface weighted mean (D[3.2]), width of the distribution relative to the median value (span), mass median diameter [d(0.5)], particle size below which 10% of the sample lies [d(0.1)], particle size above which 90% of the sample lies [d(0.9)], and specific surface area (total area of particles divided by total weight, m²/kg).

$$D[4.3] = \frac{\sum di^4\, Vi}{\sum di^3 Vi} \quad \text{(Eq. 1)}$$

$$D[3.2] = \frac{\sum di^3\, Vi}{\sum di^2 Vi} \quad \text{(Eq. 2)}$$

Where Vi is the relative volume in class i with mean class diameter of di.

$$Span = \frac{d(0.9) - d(0.1)}{d(0.5)} \quad \text{(Eq. 3)}$$

2.3. Physicochemical, functional and hydration characterisation of raw materials

The moisture content was determined by drying at 105 °C until constant weight (AACC Method 44-15A, 2000), ash content in a muffle furnace at 550 °C, lipids by Soxhlet method, crude protein by the Kjeldahl method, total DF were determined as described in AOAC (2005) methods 936.07, 960.39, 984.13 and 991.43, respectively; total non-fibre carbohydrates were determined by difference. Apparent density (ρ, g/cm^3), specific volume (v, cm^3/g), oil holding capacity (OHC, g/g), swelling capacity (SC, mL/g), water retention capacity (WRC, g/g), and water holding capacity (WHC), were determined following the methodology outlined by Genevois et al., (2020).

Colour measurements were performed using a colorimeter (MiniScan EZ, HunterLab, USA) with D65 illuminant and an observer angle of 10°. The results were presented in the CIE Lab* colour space. Chroma value (Chr) and hue angle (h°) were obtained according to Eq. 4 and 5, respectively.

$$Chr = \sqrt{(a*)^2 + (b*)^2} \quad \text{(Eq. 4)}$$

$$h° = arctan\,(\frac{b*}{a*}) \times \frac{180}{\pi} \quad \text{(Eq. 5)}$$

2.4. Rheology behaviour and Pasting Properties

The viscous profiles of the systems were registered using a rheometer (MCR 302, Anton Paar, Graz, Austria) equipped with stirring cell (ST24-2D/2 V/2 V-30), following the method 61-02 (AACC, 2000) with slight modifications. Briefly, 3 g of the sample were dispersed in 25 mL of distilled water and homogenised for 1 minute at maximum speed using a vortex. A programmed heating and cooling cycle from 50°C to 95°C was used. Pasting temperature (°C) and viscosity parameters (cP) such as peak viscosity, holding strength, breakdown, final viscosity and setback were obtained from the analysis viscosity profiles.

2.5. Dough Preparation and Optimal Fermentation Time of Dough determination (OFTD)

Based on the formulation reported by Genevois and de Escalada Pla, (2021), rice flour (22.5%), cornstarch (17.5-62.5%), RB (15-30%), SEE (0-15%) and millet (0-15%), HPMC (2%), sunflower oil (6%), salt (2%), sugar (5%), and dry yeast (3%) were used. The yeast was rehydrated in one-third of the total water volume (95%) at 30°C for approximately 2 minutes. All ingredients were mixed in a stand mixer (AEB-105, Alhias, China) equipped with a dough hook, for 2 minutes at the lowest speed setting (1 of 5). Approximately 10 g of dough was placed in graduated beakers and fermented at 30°C and 90% relative humidity (Memmert-HPP 108, Schwabach, Germany). The fermentation process was monitored, and the dough volume (*Y,* cm^3) was recorded at 10-minute intervals. Experimental data were fitted to Boltzmann sigmoid equation (Eq. 6). The OFTD was determined as the time at which the dough reached ¾ of its maximum volume, *P* (Bigne et al., 2016).

$$Y = Y_0 + \frac{(Y_0 - P)}{1 + exp^{\frac{(V50 - X)}{S}}} \qquad \text{(Eq. 6)}$$

Where: Y_0 corresponds to the initial volume of the fermented dough (cm^3), P is the maximum volume that the fermented dough can reach (cm^3); X is the time elapsed since the start of fermentation (min); V_{50} and S are fitting parameters that are related to the time at the halfway point between the P and Y_0 volumes (min), and to the slope that describes the steepness of the curve (min), respectively.

2.6. Experimental design and statistical analysis of experimental data

The impact of RB (X1), millet (X2), and SEE (X3) on pasting properties and OFTD parameters was investigated using a full factorial design 2^3, with a central point in triplicate (Table 1). Cornstarch was substituted with RB (15-30%), millet (0-15%), and SEE (0-15%), resulting in 11 systems that included central points by triplicate. ANOVA was performed to identify significant differences (α=0.05), followed by Fisher's LSD post hoc test. Model fit criteria included R^2adj > 80% and non-significant lack of fit ($p>0.05$). Pearson correlation analysis was used to examine significant ($p<0.05$) correlations between variables. Data analysis was performed using Design Expert 11 software (V11.1.2.0, USA). Results are reported as mean ± SD from at least three independent samples.

3. Results and discussion

3.1. Raw materials characterisation

The results corresponding to the physicochemical characterisation, particle size distribution, functional, hydration and pasting properties of the ingredients RB, SEE and millet flour are summarised in Table 2. RB showed the highest levels ($p<0.05$) of ash, lipids, and DF. The protein content was significantly higher in SEE, and millet flours exhibited the highest carbohydrate and moisture content ($p<0.05$). Similar values were observed by other authors (Shankaramurthy and Somannavar, 2019; Accoroni et al., 2020; Wu et al., 2022)

The ρ is a physicochemical property observed in flours that significantly impacts aspects related to the packaging efficiency, costs, and overall product quality (Chakraborty et al., 2016). Millet showed significantly lower ρ, larger mean particle size and higher moisture content (Table 2). A strong negative correlation was observed in ρ with d(0.5) ($r=-0.99$; $p<0.001$) and with moisture ($r=-0.85$; $p<0.001$). Siliveru et al., (2017) observed a consistent trend of ρ value decreasing with increasing moisture content of different wheat flours. This can be explained by the formation of porous structures which affect the arrangement of particles (Raigar and Mishra, 2015).

The hydration properties as SC plays a crucial role in both physiological processes and the functional properties in food, reflecting the extent to which the flour matrix swells following dispersion in water for 18 hours (Jiang et al., 2024). Significant differences in SC values were observed, with RB showing the highest value, primarily related to its high DF content, confirmed by a positive correlation with SC ($r=0.98$, $p<0.001$). The SC of insoluble dietary fibre (IDF) is due to the greater surface area and polar functional groups that interact with water molecules (Tejada-Ortigoza et al., 2017; Badia-Olmos et al., 2023). Others important properties are WRC and WHC, that were influenced by the presence of proteins and DF in the ingredient matrix (Al Maiman et al., 2021; Aryee et al., 2018). Positive correlations were found between WHC and proteins ($r=0.89$, $p<0.001$), and WRC and DF ($r=0.80$, $p<0.001$). SEE exhibited significantly higher values of WHC and WRC, consistent with previous values reported by Genevois et al., (2020). These properties are important since they can affect aspects such as rheological properties, texture, stability, and the final product quality.

The RB presented a significantly higher OHC, which could be explained by its DF and lipid content (Table 2). A higher OHC positively influences the stability of foods with high-fat content by reducing the loss of lipids during processing, thereby enhancing the flavour and texture of the food (Benitez et al., 2019).

These findings suggest that the variations in these properties can be attributed to factors such as the source of raw materials, proximal composition and cellular structure, like porosity, particle size, density, surface area and microstructure (Elleuch et al., 2011; Chisenga et al., 2019). The particle size distribution of raw materials, expressed as volume (PSD-V) and numerical frequency (PSD-N) is shown in Fig. 1 a,b. The RB curve exhibited a mono-modal PSD-V, indicating that the particle population is concentrated at sizes ranging from 100-1000 μm, contrasting with the bimodal and multimodal distribution patterns observed in the curves for SEE and millet, respectively. The significant higher values of D[4,3] and d(0.9) volume percentiles, reflected a predominance of large particles in the SEE and millet samples (Table 2). Additionally, SEE presented Span of 13.4, indicating a wide and heterogeneous particle distribution. However, PSD-N was similar across all samples (Fig. 1b), suggesting that although there are fewer large particles in number, they contribute significantly to the total volume. The variation observed in the curves of SEE and millet could be attributed to the milling process, including parameters such as speed, time, and the type of grinding method used, and consequently affecting the properties of the flours (Loubes et al., 2018; Roa et al., 2019).

Additionally, a reduction in particle size increased the surface area per unit volume ($r=-0.99$, $p<0.001$). For instance, SEE exhibited a mass median diameter of 99 μm, with a significantly highest specific surface area (94 m^2/kg) (Table 2). These findings are consistent with those reported by Guan et al., (2020), who demonstrated the enhancing of the specific surface area of wheat flour by reducing particle size. Furthermore, larger surface area facilitates the water absorption (Bekele and Emire, 2023b), which was confirmed by a strong positive correlation ($r = 0.99$, $p<0.001$) between specific surface area and WRC of flours. The higher hydration properties observed in RB and SEE, compared to millet, can be attributed to their higher DF and protein content and larger surface area, which provide more sites for water binding (Bekele and Emire, 2023a; Zhao et al., 2017).

The strong negative correlation between D[3,2] and WHC ($r=-0.96$, $p<0.001$) and WRC ($r=-0.99$, $p<0.001$) shows that smaller average particle sizes are associated with higher water retention capacities. Understanding particle distribution is crucial in GF formulations, especially since the grinding process could modify the surface area and particle characteristics. Moreira et al., (2014) demonstrated that smaller particle sizes lead to doughs with lower values of G' and G'', affecting the rheological properties such as viscosity, elasticity and dough recoverability. This highlights the significant impact of particle size on the rheological properties and overall quality of GFDs.

Furthermore, particle characteristics, including size and distribution, could also influence the colour perception (Cotovanu and Mironeasa, 2022). As shown in Table 2, RB exhibited the lowest L* and Chr values ($p<0.05$), resulting in a darker and less intense colour compared to SEE and millet. All ingredients exhibited an h° close to 90°, suggesting a yellow tone.

3.2. Effect of RB, millet and SEE on the OFTD parameters and pasting properties

In GFDs, the OFTD plays a crucial role to ensure the gas retention and the expansion rate of the dough during the fermentation process. The OFTD values of the systems studied ranged from 25.2 to 53.1 min. The addition of RB and SEE significantly reduced the fermentation time, indicating a negative effect on the OFTD as can be observed in Pareto Chart in Fig. 2a. Millet also had a negative contribution on this parameter; however, its effect was not significant. The system 8, despite containing 15% RB, the high proportion (85%) of refined flours in the formulations could counteract the influence of DF from RB, increasing the OFTD. On the other hand, System 4, presented the shortest ($p<0.05$) OFTD. A significant negative correlation was observed between OFTD and the DF content in GFDs ($r=-0.92$; $p<0.05$) of the systems studied. A positive correlation ($r=0.88$, $p<0.01$) was observed between *S* and OFTD. In Fig. 2b, it was observed that RB, as well as its interaction with millet, negatively impacted on the *S* parameter. On the contrary, the interaction between SEE and millet showed a synergistic effect.

The DF content was calculated based on the proximal composition of the ingredients: 7.31, 7.29, 7.36, 11.58, 7.50, 4.34, 7.64, 3.53, 10.03, 7.50, and 7.39 g/100 g w.b. for systems 1 to 11, respectively. Bigne et al., (2018) observed that increasing mesquite flour levels led to a gradual increase in DF content and resulted in shorter OFTD. DF increases water absorption, which could hinder dough expansion and result in lower volume of dough development (Chevallier et al., 2012). The DF from RB is predominantly composed by 90-95% IDF such as cellulose, hemicellulose, and lignin (Wen et al., 2017; Wu et al., 2022). While the DF from SEE and millet are composed approximately by 81-82% IDF and 18-19% soluble fibres (β-glucans, arabinoxylans, pectins) (Rodriguez et al., 2020; Jacob et al., 2024). Martínez et al., (2014) observed that by combining starch with polydextrose, the cohesion of the dough and gas retention improved. In contrast, IDF from oats and bamboo affected the gas retention and cohesion during fermentation. IDF absorbs and retains water but does not improve the viscosity, potentially weakening the dough structure and affecting the rheology. This behaviour of IDF could lead to reduce the OFTD and the final product volume under consistent hydration conditions (Cappa et al., 2013).

The influence of DF on the dough properties includes its effects on the fermentation parameters and rheological characteristics. RB and SEE showed ($p<0.05$) lower peak viscosity, holding strength, breakdown, final viscosity, and setback values (Table 2), mainly explained by its lower starch content. In Fig. 3 are represented the pasting curves of rice flour, cornstarch, RB, SEE and millet, and the systems from experimental design. These curves are essential to understand the gelatinisation and retrogradation behaviour of these materials and illustrates how the different raw materials and their combinations affect the viscoelastic properties and thermal stability of the evaluated systems, providing a clear reference for comparisons between the different formulations. As shown in Table 1 and Fig. 2c, the addition of RB increased the pasting temperature, which is the minimum temperature at which viscosity rises during heating. The presence of DF creates a physical barrier that hinders the swelling of starch granules by competing for water within the dough matrix.

This barrier reduces the water availability, thereby requiring higher temperatures for starting the starch gelatinisation process (Güler and Sensoy, 2023; Wang et al., 2024). In Fig. 2d, SEE and RB negatively affected the peak viscosity, probably due to the reduction of water availability for starch swelling. These ingredients showed minimal swelling and maintained a constant viscosity throughout the assay (Table 1). The maximum viscosity refers to the maximum value of viscosity during the swelling of the starch granules. System 8 had the highest ($p<0.05$) peak viscosity, possibly it could be explained because this formulation has only 15% of cornstarch replacement. A negative correlation was observed in peak viscosity with protein content ($r=-0.85$, $p<0.01$) and DF ($r=-0.90$, $p<0.01$). According to Wu et al., (2021) the presence of DF from RB increased the pasting temperature and decreased peak viscosity, setback, and breakdown values. The holding strength, characterised by the viscosity at the end of the heating step at 95°C, was negatively affected by SEE and RB (Fig. 2e), mainly due to their higher protein and DF content. These components increase the water retention, thereby impacting the dough's consistency and viscosity during heating. Consequently, this could affect the dough's ability to maintain its structure and viscosity, which are critical for holding strength (Rosell et al., 2009).

The breakdown parameter, is the viscosity decreasing due to the swollen granule rupture, and was negatively affected by RB (Fig. 2f). This suggests a significant changes in dough structure during heating at 95°C (van Rooyen et al., 2022). Fig. 2g, shows that raw materials had a negative effect on the final viscosity, probably due to an effect of starch dilution, associated to the replacement of cornstarch by non-starchy by-products and millet flour. Additionally, higher values of setback viscosity showed a faster retrogradation, affecting the final characteristics of GFDs (Ronda et al., 2017). Substitution cornstarch by 30% of RB, 10.5% of SEE and 15% of millet, was statistically estimated for achievement the minimum setback value of 100.6 cP (R^2_{adj}: 90.1%, lack of fit > 0.05). System 4 showed a trend to the lowest experimental setback value, close to that statistically estimated, 134 cP, and as can be observed cornstarch substitution was 30% of RB, 15% of SEE and 15% of millet (Table 1). It must be highlighted that in this condition, the maximum DF was also achieved.

The higher content of DF, protein and lipid in RB and SEE notably reduced ($p<0.05$) the setback values (Fig. 2h, Table 1), affecting the retrogradation process. This effect was also observed in system 7 and 10 (Table 1). Lipid complexes could act as barriers, preventing the amylose retrogradation giving as result a softer crumb during storage. Furthermore, protein-starch interactions stabilised the starch granule structure, thereby delaying the gelatinisation, therefore reducing the subsequent retrogradation process. It must be highlighted that amylose retrogradation is generally associated to the bread staling process due to crumb hardening, reducing the shelf life of the final product (de Escalada Pla et al., 2013).

4. Conclusion

These results contribute to the agro-industrial by-products valorisation, since nutrients like DF and protein can be recycled in GFDs mixes. For nutritional purposes, cornstarch replacement by non-starchy by-products as RB and SEE along with millet flour, enhance DF content of GFDs. In addition, the inclusion of these raw materials in GFDs formulations had a significant impact on pasting properties, and dough fermentation development. Along with DF, lipids and protein from RB and SEE reduced the setback values, that is related to amylose retrogradation. Understanding these effects contribute to the development of novel bakery formulations. Future studies should be performed to optimise final gluten-free bread quality, searching correlation between dough characteristics with the yield and efficiency as well as the staling of the bread final product. Profiting nutrients from agro-industrial by-products along with the enhancement food shelf life, trends to be key tools for improving food manufacturing sustainability.

CRediT authorship contribution statement

Karen F. Irigoytia: Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Writing – original draft**; Carolina E. Genevois:** Visualization, Supervision Methodology, Investigation, Formal analysis, Funding acquisition, Resources, Writing – review & editing**; Marina F. de Escalada Pla:** Conceptualization, Supervision, Methodology, Investigation, Formal analysis, Funding acquisition, Writing – review & editing.

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Ethics declarations

This work did not involve the use of human and animal subjects.

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.

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FIGURE CAPTIONS

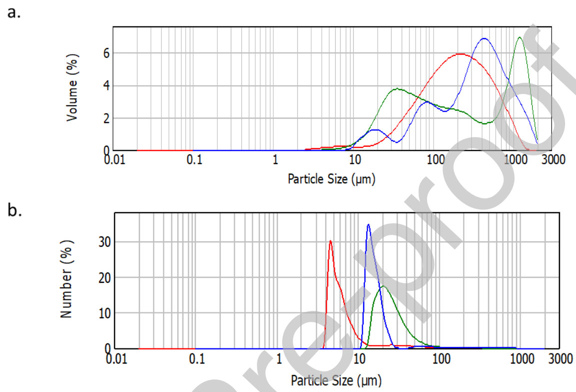


Figure 1. Figure 1. Particle size distribution, expressed as volume (a) and number frequency (b) of raw materials. The red line represents rice bran, the green line soybean extruded-expelled meal, and the blue line millet.

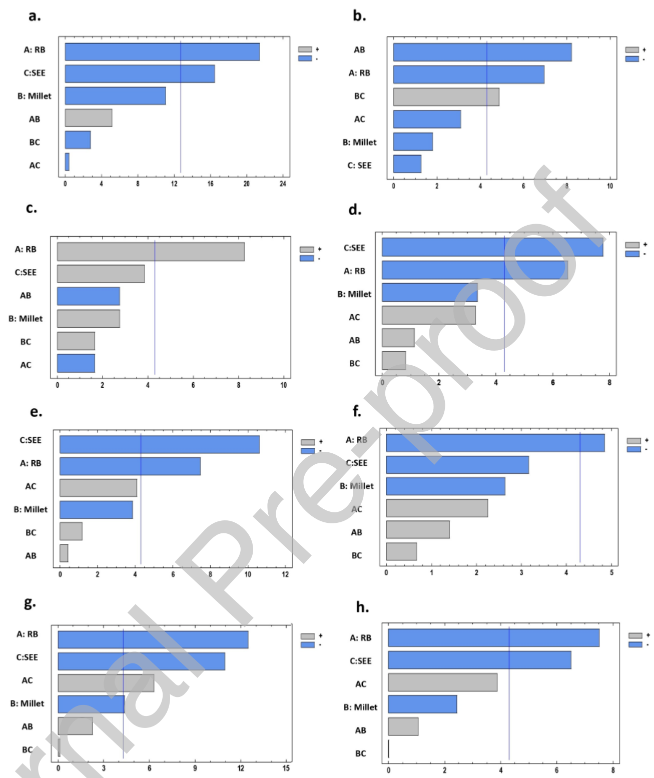
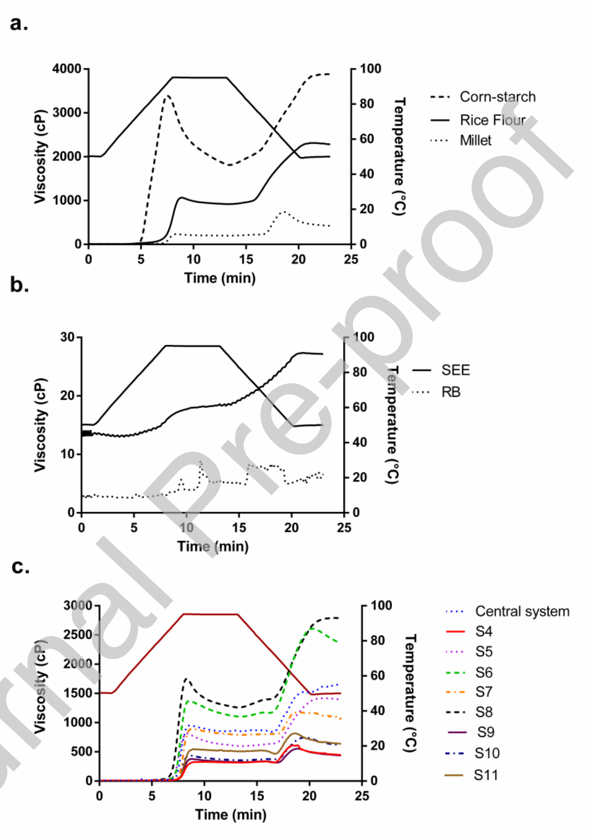


Figure 2. Pareto chart of the standardized effect of rice bran (RB), soybean extruded-expelled meal (SEE) and millet, on the optimal fermentation time of dough (a); S, Boltzmann fitting parameter (b); pasting temperature (c); peak viscosity (d); holding strength (e); breakdown (f); final viscosity (g) and setback from trough (h).

Factors (horizontal bars) that cross the reference blue line are statistically significant ($p<0.05$).



Caption for on-line version of **Figure 3.** Pasting curves of cornstarch, rice flour, and millet (a); agro-industrial by-products (RB: rice bran, SEE: soybean extruded–expelled meal) (b); and systems from experimental design.

Table 1. Response variables from full factorial design 2^3 with 3 central points to study the effects of the rice bran, soybean extruded-expelled meal and millet levels.

Systems	RB (%)	SEE (%)	Millet (%)	Response variable							
				OFTD[1] (min)	S[1] (min)	Pasting temperature (°C)	Peak viscosity[2] (cP)	Holding strength[2] (cP)	Breakdown[2] (cP)	Final viscosity[2] (cP)	Setback from trough[2] (cP)
*1	22.5	7.5	7.5	38.3±0.5[d]	5.9±0.8[cd]	91.2±0.7[c]	971±20[c]	830±69[c]	146±47[cd]	1273±120[bc]	448±75[de]
*2	22.5	7.5	7.5	39.2±0.4[d]	5.4±0.7[cd]	90±0.6[c]	906±50[c]	842±72[c]	114±30[cd]	1282±110[bc]	400±67[de]
*3	22.5	7.5	7.5	39.0±0.4[d]	6.5±0.6[cd]	90±0.6[c]	955±34[c]	718±60[c]	137±60[cd]	1500±140[bc]	319±43[de]
4	30	15	15	25±1[f]	4.5±0.8[d]	93.2±0.5[ab]	328±20[g]	315±26[f]	13±4[e]	449±43[d]	134±22[f]
5	15	15	0	43.9±0.8[b]	8.9±0.6[bc]	88.2±0.6[d]	814±30[d]	603±50[d]	211±60[bc]	1395±133[b]	791±132[c]
6	15	0	15	42.6±0.5[bcd]	7.1±0.1[bcd]	88.2±0.7[d]	1370±50[b]	1099±90[b]	271±88[b]	2360±224[a]	1261±211[b]
7	30	0	0	39±1[d]	10±2[ab]	92.2±0.5[b]	894±32[c]	788±66[c]	106±35[cd]	1062±100[b]	273±43[def]
8	15	0	0	53±4[a]	9.2±0.2[b]	87.2±0.8[e]	1750±61[a]	1258±106[a]	492±160[a]	2790±265[a]	1532±257[a]
9	30	15	0	39±1[cd]	7±1[cd]	92.2±0.6[b]	378±13[g]	470±25[e]	79±25[d]	670±63[cd]	509±85[d]
10	15	15	15	43.8±0.9[bc]	12.4±0.3[a]	92.2±0.5[b]	438±15[f]	356±20[f]	82±26[d]	618±58[cd]	262±43[ef]
11	30	0	15	34.4±0.6[e]	5.1±0.8[cd]	93.2±0.6[a]	549±20[e]	324±13[f]	54±17[d]	440±41[d]	765±128[c]

*Replicated systems from the experimental design.

RB: rice bran; SEE: soybean extruded–expelled meal; OFTD: optimal fermentation time of dough; S: slope.

Different letters in the same parameter denote significant difference ($p<0.05$) with a confidence level of 95%.

[1] Mean values ± SD are reported (n = 3).

[2] Values represent the average ± relative error.

Table 2. Physicochemical characterization, particle size distribution, and functional, hydration and pasting properties of rice bran, soybean extruded-expelled meal and millet.

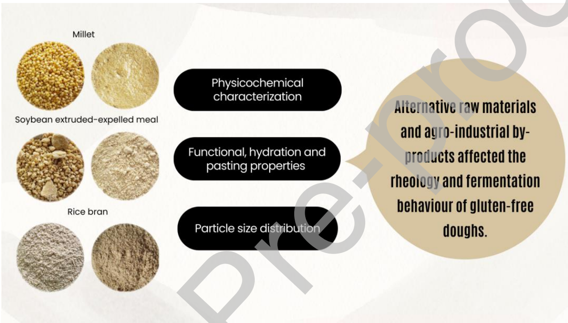
Properties	**RB[1]**	**SEE[2]**	**Millet**
Proximal composition (w.b)			
Ash (%)	8.46±0.02[a]	5.6±0.5[b]	2.9±0.1[c]
Moisture (%)	8.64±0.04[b]	5.9±0.3[c]	11.12±0.01[a]
Protein (%)	13.1±0.5[b]	45.9±0.2[a]	9.2±0.2[c]
Lipids (%)	17.20±0.02[a]	8.8±0.3[b]	6.3±0.5[b]
Dietary fibre (%)	31.50±0.04[a]	21±5[b]	5.3±0.2[c]
Carbohydrates (%)	21.1±0.2[b]	22±6[b]	71.6±1.5[a]
Physical and functional properties			
ρ (g/cm^3)	0.500±0.001[a]	0.500±0.001[a]	0.460±0.001[b]
v (cm^3/g)	1.00±0.01[b]	1.00±0.01[b]	1.10±0.01[a]
SC (mL/g)	7.0±0.1[a]	6.0±0.1[b]	3.0±0.1[c]
WRC (g/g)	5.3±0.4[b]	6.29±0.2[a]	2.5±0.2[b]
WHC (g/g)	5.1±0.2[b]	7.0±0.2[a]	2.5±0.1[c]
OHC(g/g)	2.5±0.2[a]	1.7±0.4[b]	1.8±0.1[b]
Particle size parameter (µm) (volume percentiles)			
d(0.1)	51±2[b]	26±1[c]	117±3[a]
d(0.5)	197±4[b]	99±12[c]	855±60[a]
d(0.9)	630±21[b]	1342±31[a]	1430±75[a]
D[4.3][3]	270±7[c]	420±47[b]	832±63[a]
D[3.2][4]	99±4[b]	70±6[c]	240±13[a]
Span	2.6±0.3[b]	13.4±0.6[a]	2.6±0.1[b]
Specific surface area (m^2/kg)	63±6[b]	94±7[a]	25±5[c]
Colour			
L*	63±3[b]	72.1±0.2[a]	72±1[a]
a*	3.0±0.8[a]	0.9±0.1[b]	2.5±0.3[a]
b*	17±3[b]	25.5±0.2[a]	24±2[a]
Chr	19±1[b]	25.7±0.2[a]	23.9±0.2[a]
h°	79.9±0.1[c]	88.0±0.1[a]	84.3±0.3[b]
Pasting properties			
Pasting temperature (°C)	95.5±0.2[a]	95.2±0.1[a]	88.6±0.3[b]
Peak viscosity (cP)	33±4[b]	20±2[b]	254±29[a]
Holding strength (cP)	15±1[b]	19±1[b]	217±25[a]
Breakdown (cP)	19±3[b]	1.9±0.1[c]	37±4[a]
Final viscosity (cP)	25±3[b]	29±3[b]	456±48[a]
Setback from trough (cP)	7±2[b]	4±1[b]	419±44[a]

RB: rice bran; SEE: soybean extruded–expelled meal. w.b: wet basis
[1] Proximal composition determined by Genevois et al., 2021
[2] Proximal composition determined by Genevois et al., 2021 and Castellanos Fuentes et al., 2020
[3] Volume weighted mean
[4] Surface weighted mean
Different letters in the same parameter denote significant difference (p<0.05) with a confidence level of 95%.
Mean values ± SD are reported (n = 3)

Ethical Statement - Studies in humans and animals

Authors declare that no animals no humans were involved in the studies described in this research work.

Graphical Abstract



Declaration of interests

☒ 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.

☐ The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for *[Journal name]* and was not involved in the editorial review or the decision to publish this article.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: