



# Exploring the integration of orange peel for sustainable gluten-free flatbread making

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## ABSTRACT

In response to the growing demand for sustainable and nutritious gluten-free (GF) products, this study explores orange peel by-products as a breadmaking ingredient of GF rice or corn flatbreads. The orange peel powder exhibited remarkable water retention properties attributed to its high dietary fiber content. Partial pre-gelatinization of rice (64 g/100 g) and corn (67 g/100 g) flour allowed obtaining doughs with sufficient consistency and extensibility to obtain GF flatbreads. The inclusion of orange peel powder (0–9 g/100 g) influenced the consistency and thermal behavior of the dough. Modifying hydration levels mitigated the hardness resulting from orange peel powder substitution, leading to improved folding properties. Final products exhibited enhanced nutritional profiles, including higher ash and dietary fiber content. The optimum nutritional and technological outcomes were observed when employing the maximum substitution rate of 9 g/100 g, along with adjusted hydration (164 g/100 g for corn and 169 g/100 g for rice), with notable emphasis on the improved extensibility of the final products. Compared to rice-based flatbreads, corn-based flatbreads displayed more uniform dough consistency, lower gelatinization enthalpy, higher yellowness, and decreased extensibility due to the stiffer dough texture. This study suggests that orange peel residue holds significant promise as a nutritional and technological enhancer for gluten-free flatbreads.

## 1. Introduction

Since Willem-Karel Dicke published in 1941 his first report about the favorable effect of a wheat-free diet on celiac patients (Dicke, 1941), this therapeutic approach is still considered the only one scientifically recognized for treating gluten-related disorders. Lately, adhering to a strict gluten-free (GF) diet is not only confined to people affected by gluten-related disorders but it is also becoming a controversial trend among general consumers. Because of this, the market for GF products on a global scale had a valuation of almost USD 6 billion in 2021, and it is anticipated to exhibit a compound annual growth rate around 10% from 2022 to 2030, with the bakery segment as driving factor (Grand View Research, 2022, pp. 2022–2030). Consequently, there is a pressing need to develop innovative GF baked products that not only mimic the taste and texture of their gluten-containing counterparts but also offer enhanced nutritional value. Extensive research in the past two decades has explored novel GF flours, physical processes, and processing aids, aiming for close resemblance to wheat-containing products in texture

and sensory attributes (Gasparre & Rosell, 2023). Nonetheless, nutritional quality of GF bakery foods is still lower than that of their homologues made by wheat and different strategies are currently being developed to fill this gap (Matos Segura & Rosell, 2011; Roman et al., 2019).

One promising avenue for achieving this goal has been highlighted by previous research efforts focused on the incorporation of fruit and vegetables byproducts in GF baked goods. In this regard, Majzoobi et al. (2016) demonstrated that the addition of carrot pomace powder (up to 30 g/100 g) into GF rice and corn-based formulations improved crumb color, taste, texture and overall acceptability of final cakes. In GF mini sponge cake formulations, the substitution (2.5, 5 and 5 g/100 g) of corn and potato starch with broccoli leaf powder led to a decrease of the batter apparent viscosity. However, mini sponge cakes with the lowest substitution level (2.5 g/100 g) were characterized by an appealing green color, better crumb structure and higher general sensory acceptability (Krupa-Kozak et al., 2019). With the objective of developing a GF fiber-enriched cake formulations, Kirbaş et al. (2019) substituted rice

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flour with different levels of apple, orange and carrot pomace powders (5, 10 and 15 g/100 g). This incorporation caused a noticeable increase in total dietary fiber content in all the samples. Nevertheless, pomace powders addition had a negative impact on the specific volume of the GF cakes, except for the samples containing 5 g/100 g of orange pomace powder that also received the highest sensory test score. Conversely, O'Shea et al. (2013) reported a decrease in the apparent viscosity peak of the batter when adding orange pomace (5.5 g/100 g) to GF breads without leading to any significant difference in appearance, flavor and acceptability compared to the GF control. Therefore, it is quite clear that orange byproducts can be successfully applied as ingredients of GF leavened bakery products. However, there are other types of GF bakery products with more demanding technological functionality, where the absence of gluten is even more quality restrictive, like flatbreads. The consumption of GF flatbreads is on the rise because of their ease of carrying, and the versatility of being paired with a variety of fillings, transforming them into a complete meal option (Garzon et al., 2022). But gluten substitution in GF flatbread making is responsible for the loss of some key features of these products, such as elasticity, rollability, and ability to puff during baking (Patil et al., 2021). In fact, one of the most desirable features of GF flatbreads is the ability to maintain consistency, and its resistance to splitting when bent, also known as flexibility. To replace gluten and conferring some viscoelasticity to doughs, hydrocolloids are routinely incorporated in GF flatbreads. One of the alternatives to improve the handling of the GF doughs could be the orange peel (OP). So far, it has been incorporated in some GF bakery products, but its technological functionality has not been exploited. Generally, OP includes various components such as soluble sugars, starch, essential oils, dietary fiber encompassing cellulose, hemicellulose, lignin, and pectin, ash, fat, and protein (Ángel Siles López et al., 2010). Thus, developing more sustainable, clean labels and easier to wrap GF flatbreads with high fiber content by incorporating OP may offer a new option for consumers.

Owing to that, this study aims to develop novel GF flatbreads with acceptable technological and nutritional characteristics, shedding light on the impact of the OP in the GF food matrix and on the final products. To validate the viability of OP as clean ingredient in GF flatbreads, corn and rice flour were used as main commodities and the breadmaking process modified to allow obtaining GF doughs with adequate extensibility in the absence of any additive mimicking gluten functionality.

## 2. Materials and methods

### 2.1. Raw materials

Fresh orange bagasse was obtained after juice extraction in the pilot plant of the Institute of Agrochemistry and Food Technology (IATA) (Valencia, Spain). Drying was carried out using an electric oven ST-02 (Salva Industrial SA, Lezo, Guipuzcoa, Spain) at 45 °C for 18 h, until constant weight. Two insulated thermocouples (type K) were inserted, and wire leads were attached to the product and oven. Temperature changes were recorded hourly with a Comark N2014 multisensor temperature data logger (Comark Instruments, Norwich, Norfolk, UK). The dried residue was further processed into powder by utilizing a hammer mill (Fitzpatrick, Fitz Mill, Canada). Finally, the sample was placed into plastic containers and stored at -20 °C until further use. Flours from corn and rice were supplied by Harinera La Meta S.A (Lleida, Spain), while sunflower oil and salt were purchased from the local market.

### 2.2. Flour characterization

Chemical composition, including moisture, fat, protein and ash content of each flour were determined according to the AOAC (2012) methods (925.10, 922.06, 920.87, 923.03, respectively). Total dietary fiber and soluble fiber (TDF) contents were assessed following the official method 32-07.01 of the AACC (2010). Particle size analysis was

measured by a Malvern Mastersizer 2000 equipment (Malvern Instruments Limited, Worcestershire, U.K). The refractivity and absorption were 1.00. Volume-moment mean (D [4,3]) was obtained from the respective instrument's software and calculated as:  $D [4,3] = (\sum d^4) / (\sum d^3)$ , where  $d$  is the diameter of the sphere with a volume equivalent to that of the particles being measured:  $d$  (0.9),  $d$  (0.5) and  $d$  (0.1), which represent 90, 50 and 10% of sample volume with particle size below the size indicated, respectively. The polydispersity index (PDI) was calculated according to equation 1:

$$PDI = (d(0.9) - d(0.1)) / d(0.5)$$

Water activities were evaluated at room temperature using a water activity unit (Aqua Lab Series 3, Decagon devices, Pullman, USA).

### 2.3. Flour hydration properties

The water binding capacity (WBC) of the samples was assessed following the official method from AACC (2010) (56-30.01), wherein it refers to the quantity of water retained by the sample after centrifugation. The measurement was expressed as grams of water per gram of the sample, following equation 2:

$$WBC_{(g/g)} = \text{Weight of sediment after draining water (g)} / \text{Sample weight (g)}$$

The oil absorption capacity (OAC) of the sample was expressed as grams of oil bound per gram of the sample, following equation 3 (Cornejo & Rosell, 2015):

$$OAC_{(g/g)} = \text{Weight of sediment after draining oil (g)} / \text{Sample weight (g)}$$

### 2.4. Color evaluation

Color of samples was assessed using a Minolta Chromameter (Model CR-400, Minolta Co., Osaka, Japan) according to the CIELAB scale:  $L^*$  (lightness 0-100),  $a^*$  (positive values measure redness, negative values measure greenness) and  $b^*$  (positive values measure yellowness, negative values measure blueness). Each data represents an average of five measurements taken on the top part of the flat bread.

### 2.5. Physicochemical and thermal attributes of doughs

The hardness of dough was measured using a TA. TXT.Plus texture analyzer (Stable Microsystem, Surrey, U.K.) equipped with a 75 mm probe. The dough ball (25 g) was placed on the texture analyzer platform and subjected to a compression stress carried out by the probe. The test settings used were as follows: pre-test speed 2 mm/s, test speed: 4 mm/s, post-test speed 10 mm/s, distance: 15 mm, time 5 s. The force value (N) indicated the force required to compress the dough up to 70%.

The pH levels of the doughs were measured using a potentiometric method, employing a penetration electrode Crison PH25 + (Hach Lange Spain, S.L.U., Barcelona, Spain).

On the other hand, thermal behavior of the corn and rice-based doughs was determined using a differential scanning calorimeter (DSC) (Q2000, TA-Instruments Crawley, UK) with stainless-steel pans. Samples were heated from 30 to 125 °C at a heating rate of 5 °C/min. Gelatinization temperature ( $T_o$ ), peak temperature ( $T_p$ ), conclusion temperature ( $T_c$ ) and endothermic enthalpy ( $\Delta H$ ) were recorded using the supplier's software.

### 2.6. Gluten-free flatbread making

Rice and corn flour were pregelatinized according to Marco and Rosell (2008) with some modifications. The total amount of water ( $\pm 90$  °C) was added to the respective flour, mixed for 5 min with a mixer (Robot Coupe RM8, Robot Coupe, Vincenne, France) and subsequently

allowed to rest until reaching 25 °C. Following this, additional components like oil and salt (Table 2), were incorporated, and kneading continued for additional 5 min. Two different sets of samples were obtained from corn and rice flour, respectively. Then, different levels (0, 3, 6 and 9 g/100 g) of OP powder were incorporated, replacing corn or rice flour in the formulations. Preliminary assays were performed to determine the required water to hydrate the flours, obtaining a better handling of the dough and to allow the achievement of the expansion (double layer) during baking. From those assays, the hydration selected for the corn-based formulations was 120 g/100 g, while 125 g/100 g was used for those containing rice. Conversely, for doughs with adjusted hydration, levels of 164 g/100 g and 169 g/100 g of water addition were employed for corn and rice formulations, respectively. The dough was then divided into different balls (~75 g each). After that, each ball was laminated with an in-house prototype sheeting machine up to a thickness of 2 mm. Finally, the disk of dough was baked in an oven at 300 °C for 90 s on each side up to obtain a double layer structure.

## 2.7. Gluten-free flatbread characterization

Proximate composition was carried out following the AOAC (2012) and AACC (2010) methods previously described.

The water activity (aw) of the flatbreads was assessed at 22 °C using an Aqua Lab Series 3 instrument (Decagon Devices, Pullman, USA).

Baking loss of each flatbread during baking was calculated as follows:

$$\text{Baking loss (\%)} = (\text{weight before baking (g)} - \text{weight after baking (g)}) / \text{weight before baking (g)} \times 100$$

Two different texture analysis methods were employed using a TA. TXT.Plus texture analyzer (Stable Microsystem, Surrey, United Kingdom) equipped with a 5 kg load cell. The first one involved a half-

**Table 1**  
Chemical composition, hydration properties, color, particle size of rice, corn and OP flours.

	Corn Flour		Rice flour		OP powder	
aw	0.62 ± 0	a	0.59 ± 0	b	0.15 ± 0.01	c
<i>Chemical composition (g/100 g d.b.)</i>						
Moisture	13.70 ± 0.10	a	13.74 ± 0.21	a	9.51 ± 0.40	b
Total fat	2.04 ± 0.07	a	0.58 ± 0.01	c	1.43 ± 0.08	b
Ash	0.50 ± 0.02	b	0.44 ± 0	c	2.47 ± 0.03	a
Proteins	5.88 ± 0.30	c	8.85 ± 0.07	a	6.94 ± 0.03	b
Total Fiber	3.08 ± 0.80	b	4.28 ± 1.07	b	40.16 ± 0.30	a
Insoluble Fiber	1.20 ± 0.07	b	2.10 ± 0.55	b	31.29 ± 0.52	a
Soluble Fiber	1.21		2.18		8.86	
<i>Functional properties (g/g)</i>						
WBC (g/g)	1.78 ± 0.02	b	1.83 ± 0.08	b	4.91 ± 0.22	a
OBC (g/g)	1.36 ± 0.10	b	1.52 ± 0.01	b	1.88 ± 0.02	a
<i>Color</i>						
$L^a$	90.86 ± 0.01	b	90.91 ± 0.01	a	75.35 ± 0.01	c
$a^a$	-3.00 ± 0.01	c	-1.11 ± 0.01	b	2.73 ± 0.01	a
$b^a$	29.38 ± 0	b	6.90 ± 0.01	c	52.47 ± 0.01	a
<i>Particle size (µm)</i>						
D (4.3)	190 ± 1	b	183 ± 1	b	245 ± 6	a
D (0.1)	17 ± 0	c	64 ± 2	a	35 ± 1	b
D (0.5)	170 ± 0	c	174 ± 1	b	205 ± 10	a
D (0.9)	393 ± 3	b	316 ± 2	c	523 ± 6	a
Polydispersity index	2.2 ± 0	b	1.5 ± 0	c	2.4 ± 0.1	a

Significant differences among means within each column denoted by distinct letters, as determined by Fisher's test.

<sup>a</sup> 5.95 conversion factor was used for rice flour, while for corn flour and OP powder 6.25 conversion factor was applied.

inch spherical probe, which applied a compression up to break the sample. Extensibility (mm) and strength (N) parameters were obtained with twelve measurements taken for each half of the flatbread. The other method was carried out by using two clamps, one attached to the moving arm and the other attached to the platform. A 2 mm-wide flatbread strip was inserted fully into the clamps, aligning them vertically. The extensibility test was performed using the "return to start" option in tension mode, with a trigger force of 3 g. During the test, the flatbread strip was pulled until its rupture. The force required (N) to extend the flatbread strip, as well as the distance of extension (mm) (extensibility) were recorded. Sixteen measurements were taken for each formulation.

## 2.8. Statistical analysis

For each formulation, two batches were obtained, and each batch was analyzed in triplicate. The experimental data were subjected to statistical analysis using Statgraphics Centurion XVII software (Statistical Graphics Corporation, Rockville, MD, USA). The properties of the raw materials were assessed using multivariate analysis of variance (MANOVA). The results were reported as the mean ± standard deviation, and Fisher's least significant differences test (LSD) was used. Significance was determined at  $p \leq 0.05$ . To indicate correlations and their significance, Pearson correlation coefficient (r) was adopted. Principal Component Analysis (PCA) was employed as a multivariate data analysis technique to discern and differentiate among the samples.

## 3. Results and discussion

### 3.1. Flour characterization

Raw materials were characterized according to their water activity, chemical composition, hydration properties, color, and particle size (Table 1). OP powder contained significantly ( $p \leq 0.05$ ) the lowest amount of free water followed by rice and corn flours. These outcomes were confirmed by the moisture content, in which OP powder also had the smallest value (9.51 g/100 g). Compared to corn and rice flour, OP powder had significantly ( $p \leq 0.05$ ) higher ash content (2.47 g/100 g) and total fiber (40.16 g/100 g). This outcome aligned with the fiber content reported in literature that was of 40.56 g/100 g (Han et al., 2021). The same trend was observed in the quantification of insoluble and soluble fiber, where OP powder still contained significant ( $p \leq 0.05$ ) higher amounts (31.29 and 8.86 g/100 g, respectively). According to Badaró et al. (2020), one of the most abundant component of OP is pectin, which is widely used by the food industry as thickener, stabilizer, gelling agent, and emulsifier thanks to its gelling and stabilizing capacities.

The ability of food raw materials to absorb water and oil is pivotal when it comes to design a gluten free bread formulation. The significant ( $p \leq 0.05$ ) highest capacity of OP in binding water (4.91 g/g) can be attributed to its higher content of pectin (Table 1). The polarity of the free hydroxyl groups of pectin is the basis for the formation of hydrogen bonds with water molecules, causing their absorption by the soluble polysaccharides (Einhorn-Stoll et al., 2015). Regarding the oil binding capacity, the same tendency was observed, in which significantly ( $p \leq 0.05$ ) more oil was retained by OP powder (1.88 g/g). This phenomenon could be explained by the higher dietary fiber content found in OP, that may retain more oil droplets through the roughness surface, van der Waals forces and hydrophobic interactions (Etale et al., 2023).

OP powder was darker than rice and corn flour, with significantly lower lightness and higher values for  $a^*$  (redness) and  $b^*$  (yellowness). This combination of values defines the typical orange color in OP, which is mainly due to the presence of the beta-carotene (Talens et al., 2017).

As part of the raw materials characterization, an assessment of particle size distribution was conducted. Findings showed that 90% of the total particles in the respective samples had sizes smaller than 316 µm for rice, 393 µm for corn, and 523 µm for OP. The uniformity of the

**Table 2**  
Formulations of gluten-free flatbreads.

Ingredients	0		3		6		9		9-AH	
	g/100 g	%	g/100 g	%	g/100 g	%	g/100 g	%	g/100 g	%
<b>Corn-based</b>										
Corn Flour	100	45	97	44	94	42	91	41	91	34
Salt	1	0	1	0	1	0	1	0	1	0
Oil	1	0	1	0	1	0	1	0	1	0
Water	120	54	120	54	120	54	120	54	164	62
Orange Peel	0	0	3	1	6	3	9	4	9	3
Total	222	100	222	100	222	100	222	100	266	100
<b>Rice-based</b>										
Rice Flour	100	44	97	43	94	41	91	40	91	34
Salt	1	0	1	0	1	0	1	0	1	0
Oil	1	0	1	0	1	0	1	0	1	0
Water	125	55	125	55	125	55	125	55	169	62
Orange Peel	0	0	3	1	6	3	9	4	9	3
Total	227	100	227	100	227	100	227	100	271	100

samples' particle size was evaluated by the polydispersity index, whose values are higher in case of broader size distribution. Rice flour presented significantly ( $p \leq 0.05$ ) more uniform particle size distribution, whereas OP powder was characterized by significant ( $p \leq 0.05$ ) higher heterogeneity.

3.2. Physicochemical attributes of doughs

For obtaining gluten free doughs with corn or rice flour with adequate consistency, pregelatinization treatment was selected as described by Marco and Rosell (2008). By adding boiling water to the GF flours, partial gelatinization of the starch was obtained with the consequent increase in consistency. To identify the extent of starch gelatinization, the thermal properties of the doughs were evaluated (Table 3). Corn based dough had higher peak temperature but significantly ( $p \leq 0.05$ ) lower gelatinization enthalpy than rice-based doughs. Using boiling water for hydrating the flour, 67 g/100 g and 64 g/100 g of the starch was gelatinized in the corn and rice doughs, respectively. Those levels of starch gelatinization led to doughs with enough consistency. Dough force was used to characterize the consistency of the doughs, corn-based doughs required higher force to be compressed compared to those made from rice flour.

When OP powder was replaced in increasing amounts (Table 3), rice dough hardness was only significantly increased when adding 9 g/100 g OP powder, but in the case of corn dough 6 g/100 g OP powder was sufficient to enhance dough hardness. Therefore, the impact of OP powder was much more intense in corn-based doughs. Similarly, the impact of OP powder, substituted at the highest level tested (9 g/100 g), on the starch gelatinization was assessed and a significant reduction in the enthalpy of gelatinization ( $\Delta H$ ) was observed in corn and rice doughs. The extension of the reduction was higher than that expected owing to starch dilution with OP powder. One of the factors behind this finding is the higher WBC of the soluble fiber in the OP powder, which

could have reduced the availability of water for the starch gelatinization. Another plausible explanation is related to the polyphenols present in the OP powder. Different authors convened that the interaction between the side chains of amylopectin and the hydroxyl groups of polyphenols could bind the amorphous region of starch granules, altering the crystallinity of the structure, leading to an easier hydration with consequent reduction in the thermal energy required for gelatinization (Wu et al., 2009; Xiao et al., 2013). In fact, a higher degree of gelatinization (80–82%) was reached in the presence of 9 g/100 g OP powder in both GF doughs. The role of polyphenols in reducing the enthalpy for starch gelatinization has also been related to the restriction of water availability caused by the interaction established between phenolic compound hydroxyl groups and water molecules (Han et al., 2020). Knowing the importance of constant hydration or constant consistency in gluten free doughs performance (Morreale et al., 2018), doughs were also prepared adapting the amount of water for keeping the dough hardness like the one in the absence of OP powder. In the samples containing corn flour, it was observed that an increase in water availability, achieved through adjusted hydration (sample identified as 9-AH in Table 3), resulted in a corresponding increase in  $\Delta H$ . This would also strengthen the significant ( $p \leq 0.05$ ) decrease of the onset and peak temperature for the starch gelatinization observed in the sample made by corn flour. However, an inverse trend was recorded when rice-based doughs were tested. In addition, rice-based dough with adapted hydration in the presence of 9 g/100 g OP showed higher gelatinization enthalpy than its counterpart without adapted hydration but it was lower than the one observed in the absence of OP. Hence, OP at the highest level impacted dough thermal properties differently whether rice or corn flour was used.

When OP was introduced in the formulations, the dough's pH decreased. This pH drop amounted to about 18 and 16% in the samples containing rice and corn, respectively.

**Table 3**  
Physicochemical attributes of gluten-free doughs.

Flour	OP (g/100 g)	Dough force (N)	Gelatinized flour (g/100 g)	Onset T <sup>a</sup> (°C)	Peak T <sup>a</sup> (°C)	$\Delta H$ (J/g)	pH					
Corn	0	25.9 ± 1.5	b	67	85 ± 1	b	92 ± 2	b	0.77 ± 0.03	a	5.6 ± 0	b
	3	27.7 ± 3.1	b		–	–	–	–	–	–	5.2 ± 0	c
	6	32.0 ± 2.1	a		–	–	–	–	–	–	4.8 ± 0.1	d
	9	34.0 ± 3.3	a	82	82 ± 1	d	85 ± 0	f	0.26 ± 0.03	f	4.6 ± 0.1	e
	9-AH	24.6 ± 0.8	bc	69	79 ± 0	f	85 ± 1	e	1.24 ± 0.08	b	4.8 ± 0	d
Rice	0	16.7 ± 2.8	e	64	82 ± 1	e	89 ± 1	d	1.43 ± 0.23	a	5.8 ± 0.2	a
	3	17.6 ± 1.5	de		–	–	–	–	–	–	5.5 ± 0.1	b
	6	17.9 ± 5.1	de		–	–	–	–	–	–	5.2 ± 0	c
	9	20.7 ± 2.3	cd	80	84 ± 0	c	89 ± 0	c	0.39 ± 0.13	e	5.0 ± 0	d
	9-AH	16.0 ± 0.8	e	73	86 ± 0	a	97 ± 1	a	0.88 ± 0.13	c	5.0 ± 0.1	cd

Significant differences among means within each column denoted by distinct letters, as determined by Fisher's test.

### 3.3. Flatbreads assessment

GF flatbreads were evaluated for their nutritional and technological attributes (Table 4). The presence of OP in the recipes did not affect the baking loss of the flatbreads, neither in the case of corn or rice. When doughs containing 9 g/100 g OP were made with adapted hydration, there was a significant increase in the baking loss. Thus, the added water for ensuring the hydration of all the constituents is released during baking, leading to flatbreads with similar moisture content.

The type of flour used significantly ( $p \leq 0.05$ ) impacted the final moisture of the GF flatbreads. Samples made from rice presented significant ( $p \leq 0.05$ ) higher moisture content than their corn-based homologues. Moreover, the moisture content in corn-based flatbreads showed a steady significant ( $p \leq 0.05$ ) increase with the level of OP. Total fat and ash content were significantly ( $p \leq 0.05$ ) influenced by OP incorporation. Flatbreads made by corn flour were higher in fat, while those obtained from rice flour contained greater ash content. In both set of samples, a significant ( $p \leq 0.05$ ) linear increase of fat and ash amount was observed after the incorporation of OP powder. As expected, this incorporation led to a significant ( $p \leq 0.05$ ) increment of the total fiber in all the samples. The same trend has been described following the addition of OP powder into pearl millet formulations for the production of biscuits (Obafaye & Omoba, 2018). With a total fiber content above 9 g/100 g, samples containing the highest substitution rate (9 g/100 g) of OP powder could easily benefit the nutritional claim “high in fiber”, according to the EU regulation (Regulation - 1924/2006 - EN - EUR-Lex (Regulation, 2024)). However, it is necessary to consider that a theoretical estimation of the fiber content expected in the bread was carried out based on the fiber content present in the raw materials. In the case of corn, the estimated fiber content stood at 2.05, 2.68, 3.33, and 3.93 g/100 g for flat breads with 0, 3, 6, and 9 g/100 g replacement with OP, respectively. Meanwhile, for rice, the estimated fiber values were 2.59, 3.22, 3.86, and 4.50 g/100 g respectively. This suggested that the method employed for determining the total dietary fiber might not have been the most suitable due to either sample characteristics or components of the OP that could have overestimated the total fiber content. Therefore, further analyses should be conducted to address this concern.

Certainly, the color of the raw materials had a significant ( $p \leq 0.05$ ) effect on the final tone of GF flatbreads, as well as the OP incorporation, which significantly ( $p \leq 0.05$ ) made them less luminous (Fig. 1). Meanwhile, corn flour GF flatbreads significantly ( $p \leq 0.05$ ) presented fewer green shades but higher yellowness, compared to their counterparts made by rice flour. In both groups, the flour substitution with OP resulted in a statistically significant ( $p \leq 0.05$ ) increase in the  $b^*$  values, indicating a shift towards higher yellowish color (Fig. 1). A distinct pattern emerged when examining the effect of OP incorporation on the red-green axis ( $a^*$ ). Results demonstrated a significant ( $p \leq 0.05$ ) decrease in the  $a^*$  values for the rice-based samples when OP was added, whereas the values significantly ( $p \leq 0.05$ ) increased in the corn flour-based samples (Fig. 1).

Texture evaluation of the GF flatbreads was carried out using two different methods, with a spherical probe and tensile grips to better assess extensibility. The choice of flour and the inclusion of OP played a significant ( $p \leq 0.05$ ) role in influencing the mechanical properties of the samples. Results indicated that GF flatbreads obtained from rice flour showed higher extensibility (from 16 to 29 mm) than those made by corn (from 11 to 17 mm). Opposite findings came from the strength test, in which samples containing corn flour were harder (from 2 to 25 N) compared to those rice-based (from 3 to 12 N). The outcomes from the test carried out with the spherical probe were confirmed when tensile grips were implemented. Consequently, the GF flatbreads formulated with corn flour exhibited a stiffer structure (from 2 to 11 N), resulting in reduced extensibility (from 3 to 5 mm) compared to the rice-based samples that held greater extensibility (from 5 to 9 mm) and a softer texture (from 1 to 4 N). Overall, the texture parameters of corn-based flatbreads incorporating OP were comparatively lower. This

qualitative deterioration occurred in samples with constant hydration could have been caused by the higher fiber content of OP, which would have led to a dilution of starch with a reduction of its swollen granules (O'Shea et al., 2013). In fact, the application of the adjusted hydration restored the extensibility (17 mm) and dramatically reduced the strength in corn flour flatbreads (2 N). Conversely, OP powder incorporation did not significantly affect the extensibility of rice-based flatbreads measured by penetration, although they showed a progressive reduction in uniaxial extensibility (tensile grips). Rice flatbreads containing 9 g/100 g OP and made with adapted hydration were more extensible (29 mm) with a noticeable decrease in strength (3 N). Interesting findings were found when Pearson correlation coefficient was calculated to find connections between variables. Extensibility determined by penetration was inversely related ( $r = -0.98$ ) to the baking losses. Same results were found by Gujral et al. (2004) in which the addition of 0.5 g/100 g of different hydrocolloids (hydroxypropylmethylcellulose, guar gum and locust bean gum) increased the extensibility and lowered baking losses in rice-based chapatis. Moreover, strong negative correlations existed between moisture content and both strengths measured with spherical probe ( $r = -0.96$ ) and tensile grips ( $r = -0.99$ ). Hence, lower moisture contents were associated with stiffer structures, pointing out the crucial role of hydration in GF systems.

### 3.4. Principal component analysis

To show differences and similarities among the GF flatbread samples, PCA was carried out and samples were separated and categorized into different subgroups (Fig. 2). The first principal component (PC 1), represented along the x-axis, accounted for 49.1% of the overall variation in the dataset. The second one (PC 2), represented along the y-axis, explained 27.3% of the total variation. The combined contribution of the first two principal components amounted to 76.4% of the total variation, indicating that they captured a substantial majority of the variability in the data. GF flatbreads split into two major groups along the PC 1 axis. The rice-containing ones (R0, R3 and R6) were found in the positive x-quadrant (lower right) and showed similar protein content, water activity, tensile grips extensibility and  $L^*$ . Rice flatbreads containing the highest OP incorporation (R9 and R9-AH) were grouped by high extensibility (tensile strain), moisture content, baking loss and ash amount. On the other hand, GF flatbreads containing corn flour with higher level of OP substitution (C6, C9 and C9-AH) occupied the negative x-quadrant (upper left), being similar in terms of color attributes ( $a^*$  and  $b^*$ ) and fat content. In the negative x and y quadrant, the remaining corn flatbreads (C0 and C3) were brought together by their strengths.

## 4. Conclusion

The study focused on the technological influence of substituting corn and rice flour with OP powder in the obtention of GF flatbreads with higher nutritional profile in terms of fiber content. This unconventional flour, attained from the citrus industry by products, resulted rich in fat and minerals, exhibiting intense yellow color and high fiber content (especially the soluble fraction), which contributed to its excellent water retention capacity. GF flatbreads were formulated by varying the hydration level (120 g/100 g for corn and 125 g/100 g for rice), gelatinizing the starch to increase dough consistency and incorporating different contents (from 0 to 9 g/100 g) of OP powder. Based on the obtained findings, OP powder influenced the consistency and the thermal behaviors of the doughs. The hardening effect of OP in the doughs was restored by adjusting the hydration level in the sample containing the highest level of substitution, also assuring better folding properties that are key for this category of food products. The resulting flatbreads displayed an enriched nutritional profile in terms of fat, ash and above all dietary fiber, standing out for their intense yellow color, which may attract consumers' attention. Compared to rice flatbreads, those made

**Table 4**  
Characteristics of gluten-free flatbreads: water activity, baking loss, proximate composition, color, and texture.

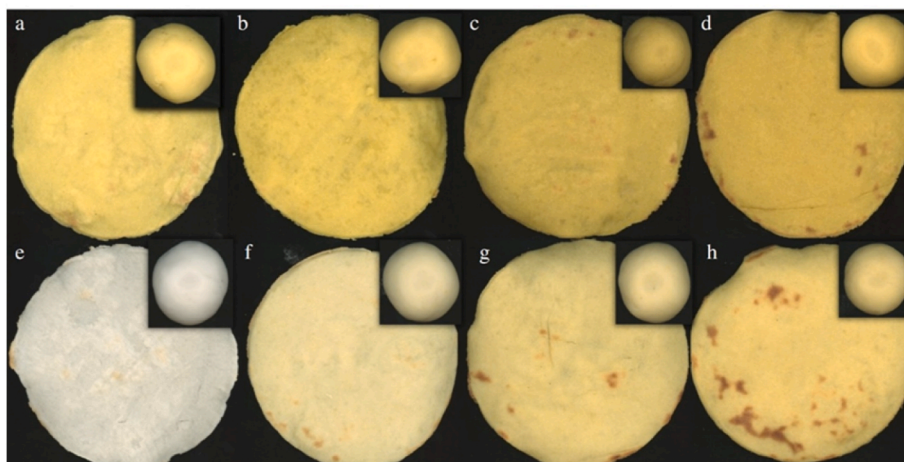
	Corn								Rice											
	OP (g/100 g)	0	3	6	9	9-AH <sup>f</sup>			0	3	6	9	9-AH <sup>f</sup>							
aw	0.95 ± 0.02	ab	0.96 ± 0.01	ab	0.97 ± 0.00	ab	0.97 ± 0.00	a	0.94 ± 0.00	b	0.97 ± 0.00	a	0.97 ± 0.00	a	0.97 ± 0.01	ab	0.98 ± 0.01	a		
Baking loss (%)	30.24 ± 1.90	bc	31.95 ± 1.87	bc	32.12 ± 2.41	bc	32.95 ± 3.02	b	48.40 ± 4.74	a	30.50 ± 2.77	bc	31.37 ± 1.16	bc	29.40 ± 2.95	c	31.35 ± 3.17	bc	51.09 ± 0.63	
<b>Composition (g/100 g w.b)</b>																				
Moisture	33.55 ± 2.29	b	36.14 ± 1.85	ab	37.28 ± 1.67	ab	38.71 ± 0.97	a	41.53 ± 0.37	a	39.56 ± 2.81	a	39.94 ± 1.55	a	39.98 ± 2.67	a	40.10 ± 2.13	a	39.71 ± 0.86	
Ash	0.90 ± 0.05	h	1.13 ± 0.05	g	1.22 ± 0.03	f	1.26 ± 0.07	e	1.20		1.31 ± 0.08	d	1.36 ± 0.01	c	1.43 ± 0.09	b	1.47 ± 0.05	a	1.48	
Protein <sup>a</sup>	5.26 ± 0.07	c	5.31 ± 0.15	c	5.22 ± 0.07	c	5.20 ± 0.05	c	4.96		8.24 ± 0.09	a	8.17 ± 0.03	ab	8.14 ± 0.04	ab	8.03 ± 0.08	b	8.09	
Fats	0.35 ± 0.10	g	0.86 ± 0.02	c	0.92 ± 0.01	b	1.08 ± 0.17	a	1.03		0.31 ± 0.03	h	0.41 ± 0.15	f	0.44 ± 0.30	e	0.71 ± 0.04	d	0.71	
Total fiber	4.83 ± 0.24	h	5.84 ± 0.47	f	7.36 ± 0.62	c	9.38 ± 0.09	a	8.95		5.14 ± 0.30	g	6.12 ± 0.52	e	7.10 ± 0.38	d	9.14 ± 0.43	b	9.20	
Carbohydrate	93.50 ± 0.02	a	92.71 ± 0.12	b	92.62 ± 0.06	c	92.45 ± 0.20	d	92.81		90.14 ± 0.14	e	90.06 ± 0.12	f	89.93 ± 0.25	g	89.76 ± 0.18	h	89.72	
<b>Color</b>																				
<i>L</i> <sup>d</sup>	72.57 ± 1.51	bc	68.81 ± 1.03	de	66.64 ± 3.24	ef	65.65 ± 2.29	f	69.96 ± 1.37	cd	76.45 ± 1.87	a	73.19 ± 3.16	b	71.04 ± 3.94	cd	70.78 ± 1.56	cd	72.33 ± 0.64	
<i>a</i> <sup>d</sup>	-1.42 ± 0.33	c	-1.07 ± 0.22	c	-0.57 ± 0.10	ab	-0.37 ± 0.05	a	-0.40 ± 0.03	a	-0.72 ± 0.18	b	-2.91 ± 0.46	d	-3.04 ± 0.39	d	-1.23 ± 0.08	c	-1.25 ± 0.06	
<i>b</i> <sup>d</sup>	48.21 ± 1.22	d	51.12 ± 1.99	c	52.53 ± 1.45	bc	53.60 ± 1.63	b	56.99 ± 2.42	a	9.89 ± 1.62	h	26.73 ± 2.25	g	34.29 ± 1.75	f	39.22 ± 1.77	e	41.30 ± 0.90	
<b>Texture</b>																				
<i>Sphere (penetration)</i>																				
Extensibility (mm)	17 ± 2	b	14 ± 2	cd	12 ± 1	de	11 ± 1	e	17 ± 2	b	17 ± 1	b	16 ± 1	b	16 ± 1	b	16 ± 1	bc	29 ± 5	a
Strength (N)	25 ± 3	a	13 ± 3	b	10 ± 2	cde	9 ± 2	e	2 ± 0	f	12 ± 1	bc	11 ± 1	bcd	9 ± 1	de	9 ± 1	e	3 ± 0	f
<i>Tensile grips</i>																				
Extensibility (mm)	5 ± 2	c	3 ± 1	d	3 ± 1	d	3 ± 1	d	5 ± 1	bc	9 ± 1	a	8 ± 1	a	6 ± 1	b	5 ± 1	bc	8 ± 1	a
Strength (N)	11 ± 3	a	9 ± 1	a	7 ± 1	b	5 ± 1	c	2 ± 0	ef	4 ± 1	cd	4 ± 0	d	3 ± 1	de	3 ± 1	de	1 ± 0	f

Significant differences among means within each column denoted by distinct letters, as determined by Fisher's test.

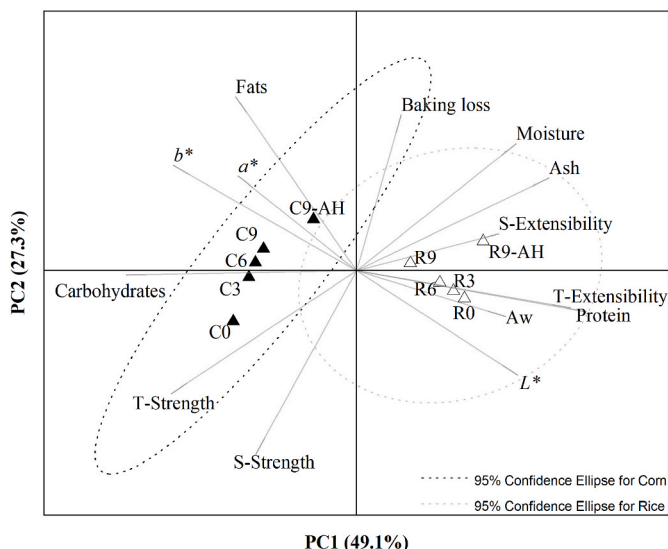
The carbohydrate content was calculated as the difference [100 - (protein + fat + ash)].

<sup>a</sup> 6.25 has been applied as conversion factor.

<sup>c</sup> The calculations were derived from the composition of their counterparts without adjusting for hydration, while considering the moisture bread factor.



**Fig. 1.** Gluten-free doughs and flatbreads made from corn (a-d) and rice (e-h), with increasing orange peel substitution (0, 3, 6, and 9 g/100 g) from left to right. The bread's appearance with 9 g/100 g orange peel content and adapted hydration was identical to that without adaptation.



**Fig. 2.** Principal component analysis of gluten-free flatbreads. Gluten-free flatbreads containing corn flour were labelled as C0, C3, C6, C9, with the number indicating the level of orange peel substitution. Sample C9-AH is referred to sample with the highest orange peel substitution and adapted hydration.

Gluten-free flatbreads containing rice flour were labelled as R0, R3, R6, R9, with the number indicating the level of orange peel substitution. Sample R9-AH is referred to sample with the highest orange peel substitution and adapted hydration.

S-Extensibility and S-Strength refer to texture parameters measured by a spherical probe, while T-Extensibility and T-Strength were obtained through tensile grips.

by corn flour exhibited a more consistent dough, lower enthalpy of gelatinization, higher yellowness, lower mineral content, and decreased extensibility due to the stiffer consistency of the doughs. The best results in terms of nutritional and technological features were achieved when the highest substitution rate (9 g/100 g) was applied in addition to the adjusted hydration (164 g/100 g for corn and 169 g/100 g for rice) with a special mention to the GF flatbreads made by rice flour that showed higher extensibility.

According to the results proposed by this study, OP residue has great potential as a nutritional and technological enhancer for GF flatbreads, offering an economical bakery alternative while promoting sustainability. By transforming OP into a valuable food ingredient, food waste

can be effectively reduced and the production of a new generation of fiber-rich GF flatbreads may represent a healthier choice for consumers.

For future studies, integrating a sensory analysis component would provide valuable insights into the consumer acceptability and preferences, enhancing the overall understanding of the OP-enhanced GF flatbreads' market potential.

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**CRediT authorship contribution statement**

**Nicola Gasparre:** Writing – original draft, Formal analysis, Data curation. **Raquel Garzon:** Writing – review & editing, Supervision, Formal analysis, Data curation, Conceptualization. **Cristina M. Rosell:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Conceptualization.

**Declaration of competing interest**

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

On behalf of all the authors I declare that none have conflict of interest.

**Data availability**

Data will be made available on request.

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