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Research article

Application of Frafra potato (*Solenostemon rotundifolius*) flour in the development of gluten-free bread

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ABSTRACT

The rising cost of wheat flour and incidences of celiac disease, an intolerance to gluten in wheat products, have created the need to explore ingredients, especially alternative flours, for developing gluten-free products. This study examined the performance of Frafra potato flour (FPF), a nutritious lesser-known indigenous crop, in the production of bread using a novel dough-conditioners (egg-gelatin combinations), and Transglutaminase blend to improve the product properties. The developed product was evaluated for physicochemical and sensory characteristics. The findings indicated that products with a single dough-conditioner (GFBE and GFBG) exhibited a weaker dough, prolonged development time, reduced stability, mixing tolerance, and increased cooking loss ($p < 0.05$). However, egg-gelatin dough-conditioner in GFBEG effectively improved the dough and bread structure, comparable to conventional bread (WTB). The dough stability and development time in GFBEG improved by 30 %, while bread volume increased by 10 %. SEM showed an improved network matrix and well-embedded starch granules in GFBEG, comparable to WTB. Sensory evaluation revealed GFBEG had a minor bitter flavour note, relative to WTB. Therefore, combining FPF with multiple dough-conditioners and TGase will produce bread with comparable characteristics to conventional bread. However, further optimization and consumer acceptability studies are imperative to provide food processors with a viable product for the market.

1. Introduction

Consumption of baked products keeps growing steadily [1–3]. Among bakery products, bread is the most consumed, and it is traditionally prepared with hard wheat flour as the major ingredient [4–6]. Wheat is essential in bread production because of its exceptional characteristics that impact the sensory attributes of bread, which is greatly appreciated by consumers [7–9]. However, wheat is an expensive ingredient, especially in the tropics where it is imported [10–12]. Furthermore, a rising number of consumers are beginning to show conditions of celiac disease (CD), an intolerance to gluten, which is a major protein formed from flour of many kinds of cereal, especially wheat, rye and related cereals, during dough formation [11].

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CD exhibits distinctive etiological aspects. Dietary exposure to gluten, especially in baked foods such as bread, is an identified environmental trigger for CD. This exposure can result in CD for a minority of individuals expressing DQ2 and/or DQ8 heterodimers. In North America and Europe, about 35 % of the general population possesses this immunogenetic predisposition to CD. In developing countries there is inadequate data on the phenomenon to better appreciate its impact. Nevertheless, celiac disease (CD) tends to be inadequately diagnosed, even in well-developed nations. Particularly in children, the ramifications of a missed or delayed diagnosis of celiac disease can be more severe than in adults. This is attributed to children's longer life expectancy and the fact that the onset of the disease occurs during their growth process [13,14]. This situation has created the need to explore ingredients and processes for the development of gluten-free flour and products [15,16].

Also, traditional hot air baking is the most common food processing technique, even though there are risks of acrylamide and hydroxymethylfurfural formation in baked goods subjected to high-temperature treatment. Given the adverse health implications associated with acrylamide and hydroxymethylfurfural, there is a pressing need to devise innovative baking technologies that can alleviate the presence of these detrimental components without compromising the sensory attributes of the end products [17]. However, these new technologies have not been widely adopted, especially in developing countries, hence studies in these areas are still limited to traditional baking techniques.

The adoption of alternative and composite flour blends in Sub-Saharan Africa has faced low consumer acceptance, primarily attributed to textural and other sensory differences compared to traditional bread [18]. Therefore, in the absence of advanced baking technologies [17], there is a critical requirement to investigate creative combinations of ingredients that can produce products with similar characteristics, offering a viable alternative to wheat bread for the market. Gluten-free pastry products have been developed using flour from tuber crops with the help of dough conditioners to improve dough processing and the overall quality of the baked products [19,20]. Dough conditioners help to improve dough handling properties, enabling a gluten-like matrix for gas retention, and improving the volume of bread, crumb structure and texture, and shelf-life by delaying the onset of staling [19,21,22]. There are different types of dough conditioners for gluten-free products, with different characteristics. Some, such as transglutaminase, serve technological functions and are used in minute concentrations. Others, such as egg and gelatin powder, add protein to products [23,24]. Some studies where microwave processing [25] and modelling of extrudates [26] were carried out showed that the effects of alternative ingredients and processes have implications for the physicochemical properties of the end products.

Frafra potato is a climate-resilient and underutilized root tuber crop grown for domestic consumption. The crop holds significant promise in alleviating malnutrition and improving food and nutrition security in Ghana and other developing nations. Starch, constituting approximately 80 % of the edible root's dry mass, is the primary biomolecule in Frafra potato. Notably, among tuber crops in Ghana, it stands out for its high protein content and micronutrients like iron. While not extensively studied for industrial applications, it could serve as a valuable flour source [27]. Frafra potato flour has been explored as a local alternative to wheat flour [28–30]. This study explored the potential of Frafra potato flour as an ingredient for gluten-free flour to produce consumer acceptable bread with the aid of dough conditioners. While gluten-free pastry products using alternative flours have been developed, studies on novel baking technologies [17], the adoption of these technologies in developing countries, and the use of innovative ingredient combinations remain limited. This research addresses these gaps, focusing on traditional hot air baking and utilizing Frafra potato flour with innovative ingredient combinations to provide a marketable alternative to wheat bread. The study's findings aim to empower food processors with viable options for the gluten-free bread market, particularly in Sub-Saharan African countries.

2. Materials and methods

2.1. Source of raw materials

Five accessions of Frafra potato flour were obtained locally, based on their availability, to produce gluten-free bread (GFB). The selected accessions include Maa-Lana Piesa, Manga Moya Piesa, Naachem-Tiir Piesa, Nutsugah Piesa and WAAPP Piesa. The accessions were obtained from the CSIR-Savana Agricultural Research Institute in Ghana. Commercially produced pastry dough conditioners, Egg and Gelatin powders, and Transglutaminase (TGase, 94 100 U/g) (Yiming Biologicals Company Limited, Jiangsu, China) were obtained from local suppliers in Ghana. Analytical grade chemicals and distilled water were also used.

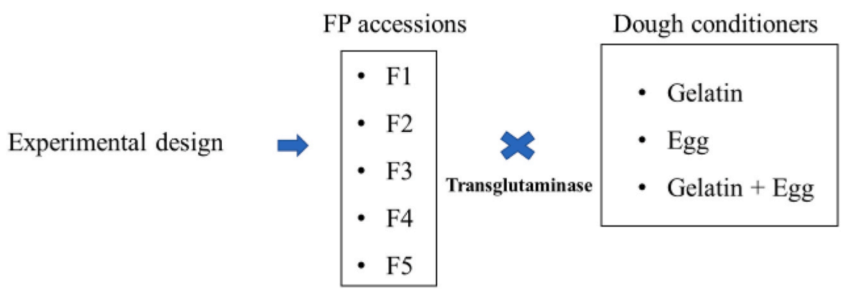


Fig. 1. Experimental design for gluten-free bread production.

2.2. Bread preparation

Based on the design in Fig. 1 and ingredients in Table 1, gluten-free bread (GFB) from each of the five Frafra potato accessions were made using equal amounts of the three dough conditioners and the enzyme Transglutaminase (TGase) as a protein cross-linking catalyst to mimic the characteristics (gluten-like matrix) and compared with typical wheat bread. The recipe used followed that of typical wheat bread, with the other ingredients being margarine, baker's yeast, and potable water, as shown in Table 1.

Bread samples were produced based on Fig. 1 and Table 1 and designated based on the type of dough conditioner used as follows: Samples made using egg powder only were designated as B1 – B5, samples containing only gelatin powder were B6 – B10, and samples made using egg-gelatin powder were B11 – B15. These were compared to wheat bread (WTB).

2.3. Characteristics of bread dough

Dough properties were characterised using the methods of Han et al. [31] with modifications, using a Mixolab rheometer (Chopin Technologies, France) and the Chopin^{+} protocol (Chopin Applications Laboratory, July 2009). Bread dough was made following the manufacturer's procedure with modifications using the proportion of ingredients in Table 1. The proportion of ingredients in Table 1, except for TGase, were poured into the rheometer and premixed for 1 min. Thereafter, a prescribed amount of TGase (1.2 %) was dispersed in 40 mL of distilled water and then added to the ingredients. The water distribution unit of the rheometer was filled with distilled water, after which 25 % was dispensed to remove air pockets and then topped up to mark before the commencement of the test. Parameters such as the amount of water absorbed during dough development, development time (the time required for all the compounds to be hydrated to form a dough), dough stability (time for which dough rheology remains constant during mixing after development and before breaking down) and mixing tolerance (rate of breakdown after development) were recorded.

3. Bread baking capacity

Baking capacity was determined according to Cauvain's [19] method. To form a dough, a prescribed amount of TGase (1.2 %) was dispersed in 40 mL of water and then mixed with the ingredients for 10 min. The proportion of ingredients in Table 1 were mixed for 5 min in a mixer. The dough was rounded, covered with wrap film, and allowed to rest at 40 °C 2 h. This allowed the dough to undergo adequate protein crosslinking to mimic the gluten-like matrix in wheat dough. The rested dough was cut into 100 g pieces, rounded, and proofed at 30 °C for 60 min. The bread was baked in an electric oven at 180 °C for 30 min, thereafter, allowed to cool to about 25 ± 0.46 °C, then wrapped and stored in plastic bags.

4. Weight of bread

The weight of bread was determined using a digital scale (Escali Digital Scale, Burnsville, USA).

4.1. Baking loss

The baking loss was determined as loss in weight, according to Cauvain [19]. Loss in weight of bread after baking was estimated using the change in weight of dough before and after baking. This was expressed as per cent weight loss (LW).

4.2. Volume of bread

Bread volume (VB) was determined by modifying the rapeseed replacement method according to the procedure of AACC [32]. Millet was used in place of rapeseed. The loaves were put in a container of known volume (VN). The basin was filled to the top with millet, the bread was removed, and the volume of the millet (VM) was measured with a measuring cylinder. The bread volume was calculated as $VB\ (cm^3) = VN - VM$; Specific volume (SV) was expressed as $SV\ (cm^3/g) = V/LW$.

4.3. Density of bread

The density of bread (DB) was calculated using the weight (WB) and volume of bread with the formula:

Table 1
Proportion by weight of ingredients for GFB.

Ingredients	Baker's Percentage
Flour	100
Water	43.6
Margarine	16.6
Yeast	0.6
Egg powder	8
Gelatin powder	8
Transglutaminase	1.2

$$\mathrm{DB}\ (g/cm^3) = WB/VB$$

4.4. Colour analysis of bread

The Colour of the bread crumb and the crust was determined according to Popov-Raljić et al. [21] using a Chromameter (CR-400 Chroma Meter, Konica Minolta, Tokyo, Japan), equipped with C, D65 illuminant, and an integrated SpectraMagic NX software. The Chromameter was calibrated against a standard white tile (L*0 = 98.93, a*0 = 0.31, and b*0 = 4.63) before use. The samples were held in a clear Petri dish and covered. Bread crust and crumb colour were also described using C* (Chroma), h* (Hue angle), and Total change in colour (ΔE*) notations.

4.5. Proximate composition of bread

The proximate composition of the bread samples was determined according to AOAC methods [33]. Properties such as moisture (method 925.40), fat (method 948.22), protein concentration (method 955.52), ash (method 935.52), and fibre (method 985.29) were determined, and carbohydrate was estimated as the difference between the sum of the other components and 100 %. The energy was calculated using, E = (9 × fat) + (4 × carbohydrate) + (4 × protein).

4.6. Texture of bread

The texture profile of the bread crumb was determined according to Alencar et al. (2015) using three slices taken from the centre of each Bread of bread using a texture analyser (TA.XT2 Texture Analyzer, Stable MacroSystem, UK). The bread samples (3 × 3 × 3 cm) from the centre of each slice were compressed two times using the cylindrical 75 mm (P/75) probe with a pre-set speed of 1.5 mms^{-1}, the contact force of 0.05 N, a distance of 8 mm and a data acquisition rate of 100 pps. The parameters assessed include hardness, adhesiveness, cohesiveness and chewiness, and resilience.

4.7. Microstructure of bread

According to Aguilar et al. (2015), the morphology of bread samples was characterised by SEM (Phenom ProX World Desktop SEM + EDS, Thermo Fisher Scientific, USA) following the procedure established by the manufacturer. Samples were first coated with gold dust (15 nm thickness) using Emitech K550X Sputter Coater (Quorum Technologies Limited, Kent, UK). Imaging at ×2300 magnification was done at an accelerating voltage of 15 kV.

4.8. Sensory evaluation of bread

A panel of nine (9) trained assessors were used to assess the bread samples, five of which were gluten-free, and one was typical wheat bread (control), using the Quantitative Descriptive Analysis (QDA®) method. The assessors evaluated the crusts (top and bottom) and crumbs of the products for appearance, texture-in-hand, aroma, flavour, mouthfeel, and aftertaste/aftereffects. Assessors evaluated the samples one after the other in randomized order. Randomization was achieved using Williams Latin Square design [34]. Assessors used room temperature water as a palate cleanser and had a forced 30 s break after tasting each product.

Table 2
Characteristics of FPF dough.

Dough	WA (%)	DDT (min)	Dough Stability (min)	MT (BU)
D1	154.5 ± 0.03^a	10.56 ± 1.29^a	5.29 ± 2.08^d	12.67 ± 1.55^d
D2	159.6 ± 0.10^a	11.12 ± 0.96^a	4.89 ± 2.01^d	12.33 ± 1.53^d
D3	160.9 ± 0.07^a	10.67 ± 1.11^a	5.11 ± 2.43^d	11.67 ± 0.58^d
D4	164.5 ± 0.12^a	10.85 ± 1.34^a	4.99 ± 1.55^d	10.67 ± 1.55^d
D5	168.1 ± 0.09^a	11.09 ± 1.87^a	5.05 ± 1.34^d	12.33 ± 2.08^d
D6	116.8 ± 0.14^b	8.22 ± 1.53^b	6.19 ± 1.53^c	17.37 ± 0.58^c
D7	118.7 ± 0.05^b	8.83 ± 1.66^b	6.07 ± 0.98^c	16.33 ± 1.55^c
D8	120.2 ± 0.11^b	8.91 ± 1.72^b	6.01 ± 1.21^c	17.33 ± 2.08^c
D9	119.6 ± 0.12^b	8.65 ± 0.59^b	6.13 ± 1.62^c	16.67 ± 0.58^c
D10	119.8 ± 0.10^b	8.77 ± 0.96^b	6.04 ± 1.83^c	15.53 ± 0.58^c
D11	99.2 ± 0.07^c	6.92 ± 1.53^c	7.98 ± 0.58^b	21.33 ± 2.08^b
D12	100.3 ± 0.11^c	7.14 ± 1.72^c	7.26 ± 1.87^b	19.67 ± 0.58^b
D13	99.5 ± 0.13^c	7.05 ± 1.11^c	7.32 ± 1.55^b	20.33 ± 1.53^b
D14	100.2 ± 0.12^c	6.98 ± 1.87^c	7.19 ± 2.43^b	19.67 ± 0.58^b
D15	99.9 ± 0.03^c	7.01 ± 1.55^c	7.25 ± 0.96^b	19.53 ± 2.08^b
WTD	58.6 ± 0.01^d	1.73 ± 0.05^d	10.95 ± 0.20^a	32.67 ± 0.58^a

D1-D5 (GFBE) = Doughs with Egg conditioner only, **D6-D10 (GFBG)** = Doughs with Gelatin conditioner only, **D11-D15** (GFBEG) = Doughs with Egg-Gelatin conditioner, **WTD** = hard wheat flour dough, **WA** = Water absorption, **DDT** = Dough development time, **MT** = Mixing tolerance. Values are means of triplicates with standard deviation. Means in the same column with different superscripts are significantly different ($p \leq 0.05$).

4.9. Experimental design and statistical analysis

This study employed a completely randomized design, with the dough conditioners being the main factor. Analyses were conducted in triplicates, and the collected data were subjected to single-factor ANOVA, using "R" statistical software for Windows PC (version 4.1.1, R Project, Bell Laboratories, USA), for mean comparisons. The significance level was established ($p < 0.05$). Duncan multiple range test was performed to confirm samples with significant differences ($p < 0.05$). Principal component analyses (PCA) were executed on pertinent variables to explore variations in the physicochemical, morphological, and sensory properties of the samples (XLSTAT, 2019.2.2, Addinsoft USA).

5. Results and discussion

5.1. Characteristics of dough

Bread dough characteristics of FPF was determined to assess the performance of the dough conditioners used on the dough characteristics of gluten-free flours. Dough characteristics of FPF are presented in Table 2.

Significant differences ($p \leq 0.05$) were observed in water absorption, dough development time, dough stability, and mixing tolerance among the various doughs (Table 2). Doughs exclusively conditioned with egg powder (D1 - D5) exhibited the highest ($p \leq 0.05$) water absorption and dough development time but the least ($p \leq 0.05$) stability and mixing tolerance. This was followed by doughs conditioned with gelatin powder (D6 - D10), which displayed lower stability due to a faster breakdown rate (Han et al., 2021; Cauvain, 2015). Doughs conditioned with an egg-gelatin powder blend (D11 – D15) demonstrated the least water absorption and dough development time but the highest stability compared to other gluten-free doughs (D1 – D10). Overall, wheat flour dough exhibited superior ($p \leq 0.05$) characteristics in comparison to the gluten-free doughs made with Frafra potato flour (FPF). Gluten plays a crucial role in imparting elasticity to pastry dough, allowing it to expand during proofing and baking. It prevents the escape of carbon dioxide produced by yeast, and at higher baking temperatures, gluten coagulates to form a sturdy structure, preventing the collapse of the bread Bread [35]. Similarly, studies [19,25,31] in which the viscoelastic behaviour of dough were measured, suggest that the dough's ability to store energy when subjected to deformation, and the ability to dissipate energy when subjected to deformation is largely dependent upon the functional and structural characteristics of the ingredients and the dough, respectively. Bread.

The development time, indicating the time required for thorough hydration of flour components during mixing, is a critical factor for producers, with shorter times being more favourable [31]. A prolonged development time implies lower gluten strength and increased water absorption by the flour components [8]. The extended development time observed in the doughs made from Frafra potato flours aligns with the higher water absorption and may be linked to a greater amount of damaged starch in Frafra potato flours, contributing to their higher water-binding capacity compared to wheat flour (Table 2). Consequently, producing Frafra potato flour bread required a lengthier development time and resulted in poor stability and mixing tolerance. This would impact negatively on producers by increasing their production cost and lowering productivity, however, some future optimizations may mitigate some of these setbacks.

Water-soluble proteins are a crucial factor during the mixing stage of dough formation, representing a desirable quality in bread doughs for enhanced performance and handling by producers [8,19,31]. The comparatively superior performance of the egg-gelatin doughs, relative to other Frafra potato flour doughs, may be attributed to more effective protein crosslinking upon hydration and during proofing. This could be due to a relatively superior protein mix provided by the egg-gelatin combination, promoting

Table 3
Baking capacity of bread.

Bread	WB (g)	VB (cm^3)	SV (cm^3/g)	DB (g/cm^3)	LW (%)
B1	91.97 ± 0.53^a	362.40 ± 1.01^c	3.94 ± 1.55^b	0.25 ± 0.02^a	8.03 ± 0.86^c
B2	91.99 ± 1.22^a	359.63 ± 0.93^c	3.91 ± 1.62^b	0.26 ± 0.05^a	8.01 ± 1.58^c
B3	91.93 ± 0.58^a	359.10 ± 1.58^c	3.91 ± 1.05^b	0.26 ± 0.85^a	8.07 ± 0.97^c
B4	91.96 ± 1.34^a	361.15 ± 1.05^c	3.93 ± 2.08^b	0.25 ± 0.55^a	8.04 ± 1.10^c
B5	91.94 ± 0.42^a	361.60 ± 2.05^c	3.93 ± 0.55^b	0.25 ± 0.41^a	8.06 ± 0.55^c
B6	91.16 ± 0.63^a	379.10 ± 2.58^c	4.16 ± 1.53^b	0.24 ± 0.56^a	8.84 ± 1.63^c
B7	91.24 ± 1.19^a	372.35 ± 1.08^c	4.08 ± 1.78^b	0.25 ± 0.63^a	8.76 ± 1.55^c
B8	91.09 ± 0.62^a	372.67 ± 1.58^c	4.09 ± 0.95^b	0.24 ± 0.57^a	8.91 ± 1.13^c
B9	91.35 ± 0.53^a	374.55 ± 2.08^c	4.10 ± 1.55^b	0.24 ± 0.48^a	8.65 ± 0.75^c
B10	91.21 ± 1.21^a	376.47 ± 1.55^c	4.13 ± 0.87^b	0.24 ± 0.29^a	8.79 ± 2.15^c
B11	88.66 ± 0.53^b	405.72 ± 0.93^b	4.58 ± 1.53^b	0.22 ± 0.21^a	11.34 ± 0.58^b
B12	89.38 ± 0.86^b	403.24 ± 0.62^b	4.51 ± 0.78^b	0.22 ± 0.18^a	10.62 ± 1.86^b
B13	89.46 ± 0.42^b	402.86 ± 0.67^b	4.50 ± 2.08^b	0.22 ± 0.09^a	10.54 ± 1.44^b
B14	89.29 ± 0.12^b	402.95 ± 0.54^b	4.51 ± 1.05^b	0.22 ± 0.23^a	10.71 ± 0.21^b
B15	89.15 ± 0.52^b	404.25 ± 0.71^b	4.53 ± 1.10^b	0.22 ± 0.17^a	10.85 ± 1.05^b
WTB	79.36 ± 0.58^c	458.52 ± 0.63^a	5.78 ± 1.53^a	0.17 ± 0.05^b	20.64 ± 2.08^a

GFBE (B1–B5) = Bread containing Egg only, GFBG (**B6–B10**) = Bread containing Gelatin only, GFBEG (**B11–B15**) = Bread containing Egg + Gelatin, **WTB** = wheat flour Bread, **WB** = Weight of Bread, **VB** = Volume of Bread, **SV** = Specific volume, **DB** = Specific density, **LW** = Weight loss. Values are means of triplicates with standard deviation. Means in the same column with different superscripts are significantly different ($p \leq 0.05$).

Transglutaminase activity [22,31]. These findings suggest that a combination of multiple pastry dough conditioners has the potential to yield bread with characteristics similar to conventional wheat bread, as observed in the egg-gelatin conditioned doughs (GFBEG).

5.2. *Baking capacity of bread*

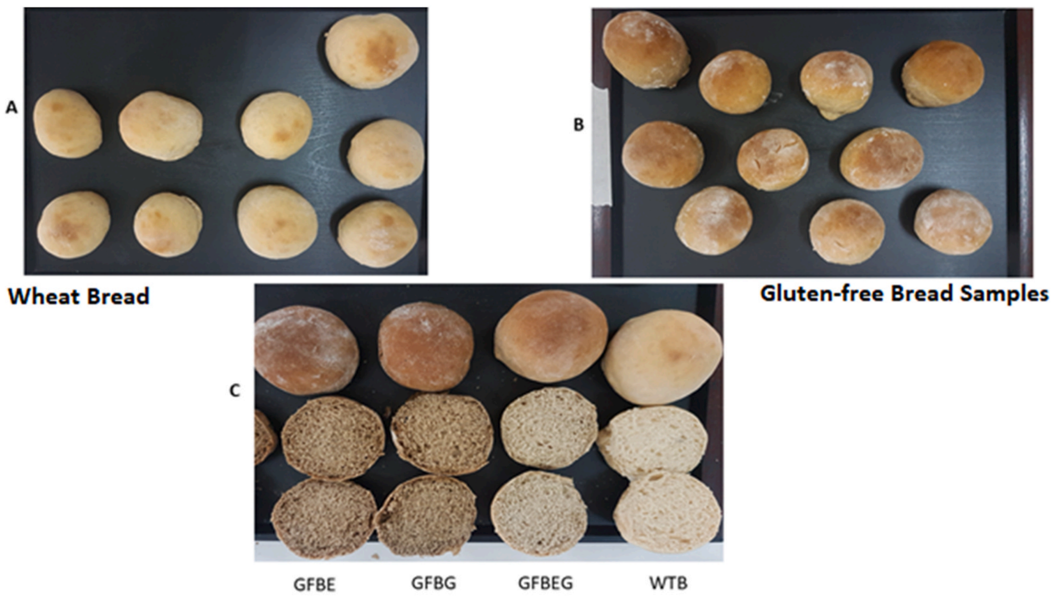
Baking capacity is a useful measure to evaluate the quality of alternative bread to conventional ones. Gluten-free FPF bread was made to compare their baking characteristics to conventional wheat flour bread. The baking capacity and cross-section of the bread are presented in Table 3 and Fig. 2. Fig. 2A shows bread samples made with wheat flour, and Fig. 2B shows samples of the gluten-free bread. Fig. 2C shows the cross-section of the bread samples.

As indicated in Table 3, all the bread crafted from Frafra potato flours exhibited a significant ($p \leq 0.05$) increase in weight (approximately 89–92 g) but a decrease in volume (around 359–404 cm^3) compared to the Bread made from wheat flour, which had an average weight and volume of about 79 g and 459 cm^3, respectively (Table 4). Loaves prepared with either egg or gelatin were notably ($p \leq 0.05$) heavier but smaller in size compared to those incorporating both egg and gelatin. Frafra potato flour (FPF) loaves demonstrated a significant ($p \leq 0.05$) denseness in comparison to wheat flour bread. These variations in the baking characteristics of FPF loaves can be attributed to the insufficient presence of a gluten-like matrix, leading to differences in crumb structure, which is more pronounced in wheat bread due to the gluten content of wheat flour [8,35]. Consequently, the lack of adequate gluten levels, as found in wheat flour, results in a weaker and less elastic dough, diminishing leavening ability and yielding bread with reduced Bread volume and higher density.

The weight loss in the wheat flour Bread was at least twice ($p \leq 0.05$) the loss observed in FPF bread samples. Loaves containing either egg or gelatin alone recorded the lowest weight loss (approximately 9 %). This variance in weight loss could be attributed to lower water absorption in wheat dough relative to FPF doughs [22,36,37]. It is conceivable that the higher protein concentration in FPF contributed to a relatively greater water-binding capacity in the resulting bread. The results are consistent with studies [19,31] in which similar parameters were measured for wheat and alternative flour products. The development of gluten-free bread with characteristics similar to those of wheat bread (WTB) holds promising prospects for creating and promoting viable alternative bread in markets where consumers have previously shown reluctance towards alternative flour products.

5.3. *Colour of bread*

Colour plays a critical role in pastry products such as bread because it impacts consumer acceptance and overall acceptability [7,21]. The colour of FPF bread crust and the crumb was measured and compared to wheat flour bread. The colour characteristics of the



A = samples of wheat flour loaves, **B** = samples of gluten-free Frafra potato bread, **C** = Cross-section of bread samples. **GFBE (B1-B5)** = Bread containing Egg only, GFBG (**B6-B10)** = bread containing Gelatin only, GFBEG (**B11-B15)** = Bread containing Egg+Gelatin, **WTB** = wheat flour Bread. This figure shows the bread samples made and image **C** shows the cross-sectional view of each type of bread.

Fig. 2. Images of bread samples
A = samples of wheat flour loaves, **B** = samples of gluten-free Frafra potato bread, **C** = Cross-section of bread samples. GFBE (**B1–B5**) = Bread containing Egg only, GFBG (**B6–B10**) = bread containing Gelatin only, GFBEG (**B11–B15**) = Bread containing Egg + Gelatin, **WTB** = wheat flour Bread. This figure shows the bread samples made and image **C** shows the cross-sectional view of each type of bread.

Table 4
Colour of bread crust.

Bread	L*	a*	b*	h*	C*	ΔE*
B1	50.42 ± 1.14^{b}	12.28 ± 0.21^{a}	23.53 ± 0.06^{a}	62.44 ± 0.13^{b}	26.54 ± 0.09^{a}	26.54 ± 0.15^{a}
B2	51.13 ± 0.08^{b}	12.87 ± 0.13^{a}	24.43 ± 0.11^{a}	62.57 ± 0.10^{b}	27.94 ± 0.07^{a}	27.95 ± 0.06^{a}
B3	50.65 ± 0.07^{b}	12.84 ± 0.05^{a}	23.05 ± 0.15^{a}	60.88 ± 0.14^{b}	26.39 ± 0.08^{a}	26.38 ± 0.12^{a}
B4	51.29 ± 0.23^{b}	11.91 ± 0.32^{a}	22.67 ± 0.24^{a}	62.28 ± 0.10^{b}	25.61 ± 0.09^{a}	25.61 ± 0.14^{a}
B5	51.58 ± 0.15^{b}	12.22 ± 0.16^{a}	22.48 ± 0.28^{a}	61.47 ± 0.12^{b}	25.59 ± 0.06^{a}	25.59 ± 0.10^{a}
B6	51.12 ± 0.27^{b}	12.28 ± 0.33^{a}	23.43 ± 0.53^{a}	62.34 ± 0.58^{b}	26.45 ± 0.22^{a}	26.54 ± 0.19^{a}
B7	51.13 ± 0.13^{b}	12.37 ± 0.17^{a}	24.16 ± 0.93^{a}	63.49 ± 0.62^{b}	27.71 ± 0.58^{a}	27.71 ± 0.13^{a}
B8	51.15 ± 0.37^{b}	12.24 ± 0.23^{a}	23.05 ± 0.16^{a}	62.03 ± 0.53^{b}	26.10 ± 0.28^{a}	26.10 ± 0.23^{a}
B9	51.18 ± 0.23^{b}	12.31 ± 0.62^{a}	22.65 ± 0.27^{a}	61.48 ± 0.18^{b}	25.78 ± 0.53^{a}	25.80 ± 0.58^{a}
B10	51.18 ± 0.19^{b}	12.22 ± 0.45^{a}	22.48 ± 0.15^{a}	61.47 ± 0.10^{b}	25.59 ± 0.62^{a}	25.59 ± 0.14^{a}
B11	51.22 ± 0.21^{b}	12.28 ± 0.23^{a}	23.61 ± 0.58^{a}	62.52 ± 0.47^{b}	26.61 ± 0.23^{a}	26.54 ± 0.12^{a}
B12	51.13 ± 0.62^{b}	12.27 ± 0.58^{a}	23.70 ± 0.22^{a}	62.63 ± 0.12^{b}	26.69 ± 0.58^{a}	26.69 ± 0.53^{a}
B13	51.15 ± 0.43^{b}	12.24 ± 0.55^{a}	23.05 ± 0.19^{a}	62.03 ± 0.62^{b}	26.10 ± 0.37^{a}	26.10 ± 0.28^{a}
B14	51.29 ± 0.58^{b}	12.22 ± 0.18^{a}	22.78 ± 0.47^{a}	61.79 ± 0.28^{b}	25.85 ± 0.32^{a}	25.75 ± 0.19^{a}
B15	51.28 ± 0.25^{b}	12.23 ± 0.58^{a}	22.48 ± 0.21^{a}	61.45 ± 0.53^{b}	25.59 ± 0.23^{a}	25.59 ± 0.37^{a}
WTB	61.63 ± 0.23^{a}	9.01 ± 0.32^{b}	22.67 ± 0.24^{a}	68.33 ± 0.11^{a}	21.40 ± 0.08^{b}	25.84 ± 0.05^{a}

L* - lightness from dark (0–100), **a***/-a* = redness/greenness, **b***/-b* = yellowness/blueness, **h*** = Hue angle, **C*** = Chroma (colour intensity), **ΔE*** = Total colour change. **B1–B5** (GFBE) = Bread containing Egg only, **B6–B10** (GFBG) = Bread containing Gelatin only, **B11–B15** (GFBEG) = Bread containing Egg + Gelatin, **WTB** = Bread from hard wheat flour. Values are means of triplicates with standard deviation. Means in the same column with different superscript are significantly different ($p \leq 0.05$).

samples are presented in Tables 4 and 5.

The colour analysis of the Frafra potato flour (FPF) loaves (B1 – B15) reveals that their crusts appeared darker than the crust of wheat flour bread (WTB) (Table 4). This is indicated by the lower L* value, while higher c* and a* values were observed in the crusts of FPF loaves compared to WTB. Wheat flour bread exhibited a significantly ($p \leq 0.05$) brighter crust colour than FPF loaves, as evidenced by the higher h* value in WTB. This suggests that the browning process, mainly due to dextrinization and partly involving caramelization and Maillard reactions, was more extensive in FPF loaves than in wheat bread [8,38]. The analysis did not show a clear ($p \leq 0.05$) trend in colour differences (ΔE*) and b* between the dough and the final baked bread in the crust.

As anticipated, the crusts of Frafra potato flour (FPF) loaves (B1 – B15) exhibited a darker color compared to the crumb, mirroring the trend observed in wheat flour bread (Tables 4 and 5). This is evident in the higher L* values, along with lower C* and a* values in the FPF loaves' crumb in contrast to the crust. A similar pattern emerged when comparing the color of FPF loaves with that of wheat flour Bread. Wheat flour bread displayed a significantly ($p \leq 0.05$) brighter crumb color than FPF loaves, as indicated by the higher h* values in WTB (Table 5). The darker coloration observed in the FPF loaves' crumb also suggests extensive browning, partially attributed to caramelization and Maillard reactions, compared to wheat bread [8,38]. No distinct ($p \leq 0.05$) trend in color differences (ΔE*) and b* between the dough and the final baked bread was noted in the crumb of FPF loaves. However, there was a noticeable colour change in the crumb of wheat flour bread, shifting from a whitish hue to an off-white shade. Research has indicated that the colour of bread plays a significant role in determining consumer acceptance. In traditional markets like Sub-Saharan Africa, the appeal of Frafra potato bread may be heavily influenced by its colour, as consumers are more inclined to be deterred by a darker crust colour

Table 5
Colour of bread crumb.

Bread	L*	a*	b*	h*	C*	ΔE*
B1	61.39 ± 1.14^{b}	3.28 ± 0.21^{a}	12.53 ± 0.06^{a}	75.33 ± 0.05^{b}	12.95 ± 0.10^{a}	12.95 ± 0.05^{a}
B2	63.58 ± 0.08^{b}	3.87 ± 0.13^{a}	12.80 ± 0.11^{a}	71.84 ± 0.03^{b}	12.42 ± 0.14^{a}	12.42 ± 0.10^{a}
B3	64.32 ± 0.07^{b}	3.84 ± 0.05^{a}	13.05 ± 0.15^{a}	70.84 ± 0.09^{b}	11.70 ± 0.12^{a}	12.01 ± 0.12^{a}
B4	62.29 ± 0.23^{b}	3.01 ± 0.32^{a}	12.67 ± 0.24^{a}	75.54 ± 0.06^{b}	12.05 ± 0.09^{a}	12.05 ± 0.08^{a}
B5	61.58 ± 0.15^{b}	4.22 ± 0.16^{a}	12.98 ± 0.28^{a}	70.60 ± 0.08^{b}	12.70 ± 0.13^{a}	12.64 ± 0.09^{a}
B6	63.58 ± 2.08^{b}	3.77 ± 0.33^{a}	12.80 ± 0.17^{a}	72.28 ± 0.05^{b}	12.39 ± 0.22^{a}	12.39 ± 0.08^{a}
B7	64.21 ± 0.63^{b}	3.64 ± 0.55^{a}	13.05 ± 0.18^{a}	71.78 ± 0.03^{b}	11.63 ± 0.62^{a}	12.63 ± 0.05^{a}
B8	61.34 ± 1.05^{b}	4.01 ± 0.47^{a}	12.87 ± 0.08^{a}	71.33 ± 0.08^{b}	12.53 ± 0.47^{a}	12.63 ± 0.09^{a}
B9	61.35 ± 0.97^{b}	3.68 ± 0.13^{a}	12.61 ± 0.23^{a}	73.73 ± 0.06^{b}	13.14 ± 2.53^{a}	13.06 ± 0.07^{a}
B10	62.23 ± 2.08^{b}	3.91 ± 0.53^{a}	12.65 ± 0.62^{a}	71.45 ± 0.05^{b}	12.29 ± 0.08^{a}	12.31 ± 0.03^{a}
B11	63.51 ± 1.13^{b}	3.87 ± 0.27^{a}	12.21 ± 0.16^{a}	72.41 ± 0.02^{b}	12.81 ± 1.08^{a}	12.42 ± 0.11^{a}
B12	64.14 ± 0.67^{b}	3.93 ± 0.58^{a}	12.05 ± 0.05^{a}	70.42 ± 0.07^{b}	11.73 ± 0.53^{a}	12.73 ± 0.22^{a}
B13	61.62 ± 1.53^{b}	4.12 ± 0.62^{a}	11.99 ± 0.21^{a}	71.04 ± 0.04^{b}	12.68 ± 0.97^{a}	12.67 ± 0.38^{a}
B14	61.63 ± 0.58^{b}	3.88 ± 0.15^{a}	12.53 ± 0.09^{a}	71.40 ± 0.09^{b}	12.17 ± 0.62^{a}	12.17 ± 0.21^{a}
B15	62.05 ± 2.05^{b}	3.65 ± 0.11^{a}	12.66 ± 0.06^{a}	72.62 ± 0.11^{b}	12.22 ± 0.53^{a}	12.23 ± 1.08^{a}
WTB	73.15 ± 0.23^{a}	1.01 ± 0.32^{b}	8.67 ± 0.24^{b}	84.01 ± 0.05^{a}	9.72 ± 0.11^{b}	10.93 ± 0.07^{b}

L* - lightness from dark (0–100), **a***/-a* = redness/greenness, **b***/-b* = yellowness/blueness, **h*** = Hue angle, **C*** = Chroma (colour intensity), **ΔE*** = Total colour change. **B1–B5** (GFBE) = Bread containing Egg only, **B6–B10** (GFBG) = Bread containing Gelatin only, **B11–B15** (GFBEG) = Bread containing Egg + Gelatin, **WTB** = Bread from hard wheat flour. Values are means of triplicates with standard deviation. Means in the same column with different superscript are significantly different ($p \leq 0.05$).

[4]. On the contrary, research conducted by Osei Tutu et al. [28] and Tortoe et al. [29] indicates that consumers in certain Sub-Saharan African countries may not be easily discouraged by the unconventional colour of bread made from alternative flours.

5.4. Proximate composition of bread

Compositional analysis of bread made from gluten-free Frafra potato flours, using dough conditioners, was determined, and compared to typical wheat flour bread. The proximate composition of the bread is presented in Table 6.

Table 6 indicates that there are no significant differences ($p \leq 0.05$) in the concentrations of dietary fiber, carbohydrates, and energy among all the bread samples. Within the FPF loaves, there were no significant differences observed. However, when compared to wheat flour bread, FPF loaves exhibited significantly higher levels of ash and fat. The increased protein content in FPF loaves, surpassing that of wheat flour bread ($p \leq 0.05$), can be attributed to the additional proteins introduced, such as egg albumin and gelatin powders. Specifically, FPF loaves containing both egg and gelatin (B11 – B15) demonstrated higher protein content compared to the other Bread samples (B1 – B10). Although the fat content in FPF loaves was similar, it was also higher ($p \leq 0.05$) than in wheat flour bread. This elevated fat content in FPF loaves is linked to the added egg powder, known for its fatty yolk [31], and the high oil absorption capacity of Frafra potato flours. Flours with high water and oil binding capacities, such as those from Frafra potato, tend to absorb and retain more water and oil in the final products [8,35]. Therefore, FPF and multiple dough conditioner blends can be efficiently used to prepare bread with improved nutritional characteristics. Bread.

5.5. Texture profile of bread

Texture profile analysis of the bread samples was measured to mimic what happens when the bread is bitten into or pressed between the molars. The texture profile of the bread samples is presented in Table 7.

Bread samples made with Frafra potato flour (FPF) with egg conditioner alone (GFBE) exhibited significantly ($p \leq 0.05$) greater hardness (2289–2410.7 g force) compared to those containing solely gelatin (GFBG) (1817.4–1867.2 g force) or a combination of egg and gelatin (GFBEG) (1201.2–1239.0 g force) (Table 7). These samples were also notably ($p \leq 0.05$) harder than WTB, which recorded an average hardness of 856 g force. Nevertheless, FPF loaves were less chewy than wheat bread. Wheat bread was ($p \leq 0.05$) more adhesive than B1 – B15, potentially due to the superior gluten matrix in wheat flour bread, rendering it gummy [8,35]. However, GFBEG exhibited greater adhesiveness compared to GFBE and GFBG. The cohesiveness of GFBEG (B11 – B15) was comparable to wheat bread. GFBEG and wheat bread shared similar ($p \leq 0.05$) resilience but significantly ($p \leq 0.05$) differed from GFBE (B1–B5) and GFBG (B6–B10). This suggests that GFBEG and wheat bread had a superior ability to regain their height after compression than loaves containing only gelatin or egg. The alveoli structure formed by a combination of egg and gelatin conditioners in GFBEG demonstrated comparable stability to that of bread made from wheat flour [4,8,35], which was more stable compared to the structure formed by loaves containing either only egg or only gelatin. In contrast to earlier research [28,29], these findings represent a noteworthy enhancement in the textural attributes recorded for bread and other pastry items derived from Frafra potato-wheat flour combinations. Therefore, the present study is poised to revive local enthusiasm and spur further exploration of innovative ingredient blends to refine the production of gluten-free bread using indigenous, underutilized, and nutritious crops, such as Frafra potato.

Table 6
Proximate composition of bread (g/100g).

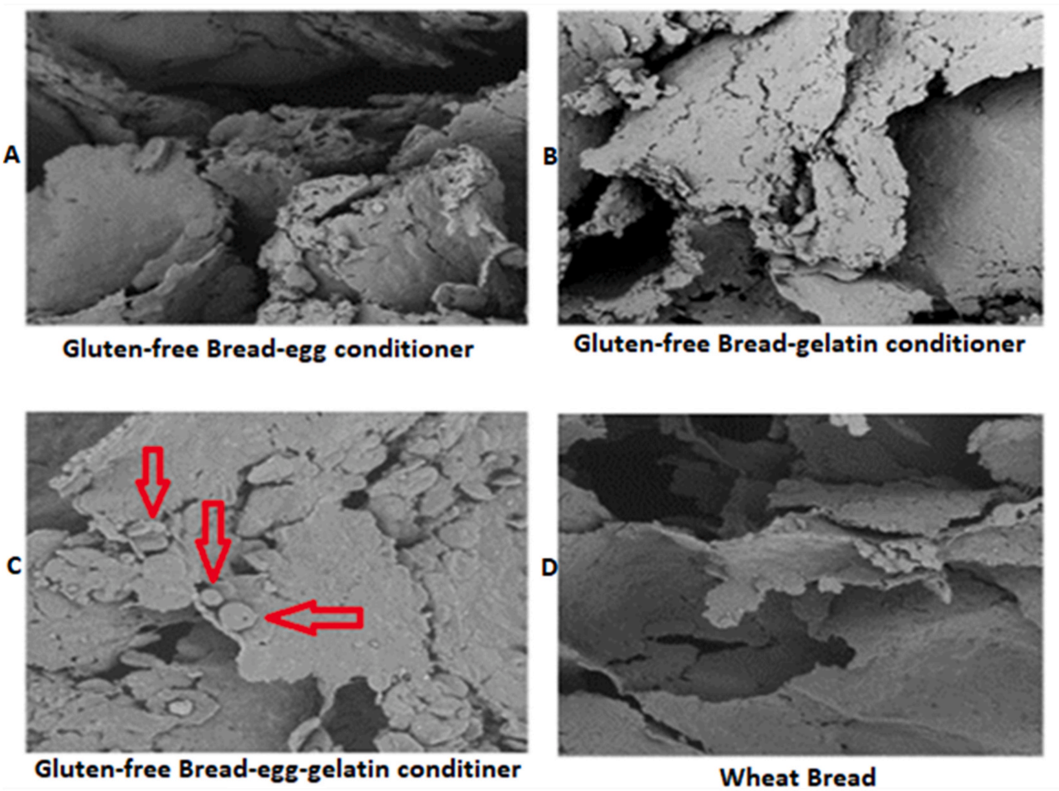
Bread	Ash	Fat	Protein	Dietary fibre	Carbohydrate	Energy (kcal)
B1	4.05 ± 1.08^a	12.13 ± 1.63^a	19.42 ± 0.32^b	2.32 ± 0.09^a	61.88 ± 1.15^a	435.17 ± 0.65^a
B2	3.89 ± 0.62^a	12.11 ± 1.62^a	19.35 ± 0.58^b	2.21 ± 0.21^a	62.44 ± 1.52^a	459.35 ± 0.22^a
B3	3.75 ± 0.28^a	12.24 ± 1.13^a	19.22 ± 0.04^b	2.24 ± 0.37^a	62.55 ± 0.63^a	437.24 ± 0.58^a
B4	4.02 ± 0.34^a	13.05 ± 0.53^a	18.23 ± 0.23^c	2.31 ± 0.53^a	62.39 ± 1.18^a	439.93 ± 0.62^a
B5	4.01 ± 0.26^a	13.63 ± 0.14^a	18.19 ± 0.15^c	2.02 ± 0.02^a	62.15 ± 1.27^a	444.03 ± 0.33^a
B6	4.36 ± 0.54^a	12.86 ± 0.12^a	20.02 ± 0.58^a	2.43 ± 0.32^a	60.33 ± 2.58^a	446.14 ± 0.54^a
B7	3.54 ± 1.08^a	12.71 ± 0.11^a	19.96 ± 0.62^{ab}	2.35 ± 0.06^a	61.44 ± 1.37^a	439.99 ± 0.58^a
B8	3.61 ± 0.58^a	12.62 ± 0.32^a	20.01 ± 0.37^a	2.39 ± 0.13^a	61.37 ± 1.09^a	439.10 ± 0.63^a
B9	4.23 ± 0.63^a	13.01 ± 0.62^a	19.98 ± 0.10^{ab}	2.38 ± 0.09^a	60.40 ± 2.30^a	438.61 ± 0.21^a
B10	4.19 ± 0.09^a	13.76 ± 0.43^a	20.01 ± 0.32^a	2.11 ± 0.12^a	59.93 ± 1.24^a	443.60 ± 0.52^a
B11	4.41 ± 1.18^a	12.15 ± 1.04^a	24.15 ± 0.01^a	2.49 ± 0.13^a	63.80 ± 0.74^a	465.15 ± 1.40^a
B12	3.67 ± 0.34^a	12.01 ± 1.01^a	22.67 ± 0.23^a	2.39 ± 0.05^a	61.45 ± 1.66^a	444.57 ± 2.17^a
B13	3.51 ± 0.09^a	12.12 ± 1.04^a	23.22 ± 0.21^a	2.42 ± 0.22^a	62.12 ± 1.10^a	450.44 ± 1.12^a
B14	4.42 ± 0.29^a	13.31 ± 0.23^a	20.23 ± 0.04^a	2.43 ± 0.05^a	60.31 ± 2.20^a	441.95 ± 1.45^a
B15	4.13 ± 0.15^a	13.06 ± 0.23^a	20.19 ± 0.04^a	2.05 ± 0.05^a	60.15 ± 2.14^a	447.90 ± 1.08^a
WTB	1.49 ± 0.03^b	10.08 ± 0.35^b	16.86 ± 0.01^d	2.17 ± 0.04^a	68.51 ± 0.30^a	469.70 ± 2.06^a

B1–B5 (GFBE) = Bread containing Egg only, **B6–B10** (GFBG) = Bread containing Gelatin only, **B11–B15** (GFBEG) = Bread containing Egg + Gelatin, **WTB**= Bread from hard wheat flour. Values are means of triplicates with standard deviation. Means in the same column with different superscripts are significantly different ($p \leq 0.05$).

Table 7
Texture profile of bread samples.

Bread	Hardness (N)	Adhesiveness (Nmm)	Cohesiveness	Chewiness (Ns)	Resilience
B1	2289.30 ± 1.24[a]	−1.86 ± 2.13[a]	0.14 ± 1.01[b]	124.23 ± 2.26[c]	0.09 ± 0.76[b]
B2	2356.29 ± 1.67[a]	−1.73 ± 3.24[a]	0.15 ± 0.56[b]	112.14 ± 1.09[c]	0.09 ± 0.15[b]
B3	2410.66 ± 1.74[a]	−1.58 ± 2.67[a]	0.13 ± 0,83[b]	123.27 ± 2.01[c]	0.08 ± 0.32[b]
B4	2339.71 ± 1.53[a]	−1.55 ± 4.91[a]	0.16 ± 1.22[b]	106.03 ± 0.73[c]	0.09 ± 0.49[b]
B5	2339.71 ± 1.92[a]	−1.62 ± 3.82[a]	0.14 ± 0.91[b]	119.15 ± 1.01[c]	0.08 ± 0.92[b]
B6	1845.08 ± 1.81[b]	−5.02 ± 3.48[b]	0.32 ± 1.15[b]	179.47 ± 1.05[b]	0.11 ± 0.53[b]
B7	1867.19 ± 1.79[b]	−4.87 ± 4.16[b]	0.28 ± 0.76[b]	164.55 ± 0.82[b]	0.10 ± 0.45[b]
B8	1828.52 ± 1.55[b]	−4.98 ± 3.58[b]	0.21 ± 0.31[b]	181.26 ± 2.13[b]	0.12 ± 0.34[b]
B9	1834.35 ± 1.88[b]	−5.08 ± 3.55[b]	0.23 ± 1.01[b]	168.95 ± 1.19[b]	0.10 ± 0.66[b]
B10	1817.44 ± 0.97[b]	−5.23 ± 2.94[b]	0.28 ± 0.65[b]	194.23 ± 1.74[b]	0.11 ± 0.53[b]
B11	1201.23 ± 1.16[c]	−7.12 ± 3.09[b]	0.61 ± 1.05[a]	262.13 ± 1.68[a]	0.15 ± 0.18[a]
B12	1208.31 ± 1.45[c]	−6.15 ± 3.11[b]	0.62 ± 0.85[a]	254.46 ± 2.13[a]	0.16 ± 0.13[a]
B13	1226.25 ± 1.61[c]	−6.13 ± 4.02[b]	0.58 ± 0.93[a]	257.62 ± 1.95[a]	0.15 ± 0.29[a]
B14	1214.19 ± 1.94[c]	−6.09 ± 3.89[b]	0.61 ± 0.72[a]	259.93 ± 1.14[a]	0.17 ± 0.11[a]
B15	1239.04 ± 1.76[c]	−7.10 ± 3.63[b]	0.63 ± 0.90[a]	261.34 ± 1.08[a]	0.15 ± 0.13[a]
WTB	856.06 ± 0.53[d]	−10.62 ± 1.10[c]	0.57 ± 0.15[a]	286.09 ± 0.09[a]	0.18 ± 0.06[a]

B1–B5 (GFBE) = Bread containing Egg only, **B6–B10** (GFBG) = Bread containing Gelatin only, **B11–B15** (GFBEG) = Bread containing Egg + Gelatin, **WTB** = Bread from hard wheat flour. Values are means of 5 reps with standard deviation. Means in the same column with different superscripts are significantly different ($p \leq 0.05$).



A = Gluten-free bread samples made with egg conditioner only (B1 – B5), **B** = Gluten-free bread samples made with gelatin conditioner only (B6 – B10), **C** = Gluten-free bread samples made with egg-gelatin conditioner (B11 – B15), **D** = Wheat flour bread. This figure shows the morphology of gluten-free bread samples relative to wheat bread.

Fig. 3. Microstructure of Bread Samples (×2300 magnification @ 15 kV)
A = Gluten-free bread samples made with egg conditioner only (B1 – B5), **B** = Gluten-free bread samples made with gelatin conditioner only (B6 – B10), **C** = Gluten-free bread samples made with egg-gelatin conditioner (B11 – B15), **D** = Wheat flour bread. This figure shows the morphology of gluten-free bread samples relative to wheat bread.

5.6. Microstructure of bread

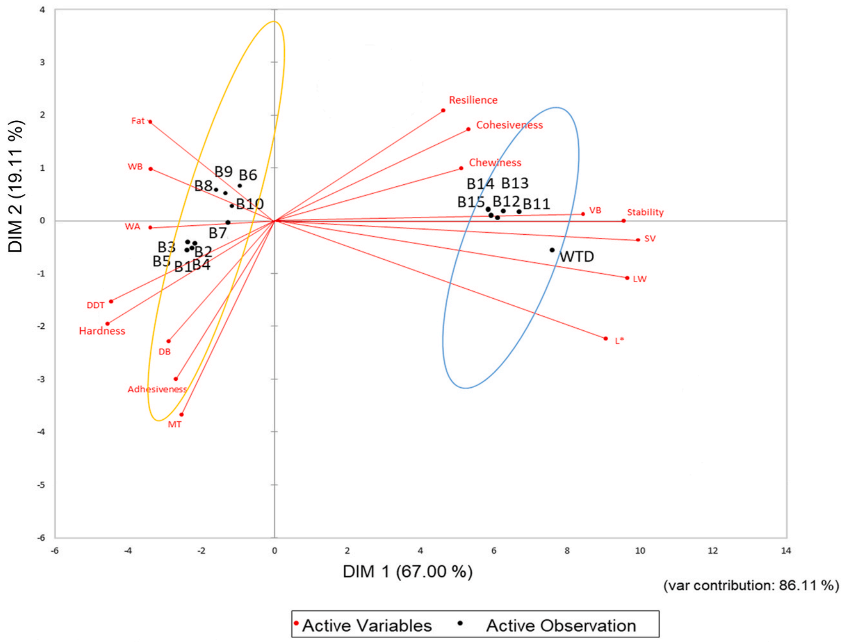
The alveoli structure of FPF bread samples were imaged and compared to that of typical wheat flour bread. Fig. 3.

SEM imaging (Fig. 3) and Fig. 2**C** revealed an open crumb structure with denser walls in Fig. 3A(GFBE) compared to the other samples. Fig. 3B (GFBG) also had an open crumb structure with dense walls compared to Fig. 3C (GFBEG) and 3D (WTB). The morphological characteristics observed in GFBE and GFBG are indicative of the fact that the dough conditioners used could not mimic the gluten-like matrix found in conventional wheat bread adequately withing the parameters of the study. In the structure of bread produced with the egg-gelatin conditioner combination (GFBEG), there were observable almost intact starch granules, as indicated by arrows. It is plausible that the more robust gel network formed by this combined conditioner may have chelated the starch granules, consequently limiting the swelling of starch granules during the dough-forming stages [27,35,39]. SEM also revealed a more open crumb structure consisting of thinner walls in bread made from wheat flour compared to those made with egg or gelatin only (GFBE and GFBG, respectively), which showed a denser network (Fig. 3). These morphological characteristics observed are consistent with other gluten-free [6] and composite bread [28,29] studies, where bread made with alternative flours exhibited similar characteristics of denser crumb network. However, bread with egg-gelatin conditioner had a crumb structure similar to wheat flour bread compared to those made with either egg or gelatin only.

5.7. Principal component analyses of physicochemical characteristics of dough and bread

The Principal Component Analysis (PCA) was adopted to determine which features significantly impacted the differences and similarities amongst the dough and bread samples. The PCA map generated displays the positioning of the bread based on their physicochemical characteristics. Majority of the variance (86.11 %) was explained in the first 2 dimensions (DIM1 = 67.00 %, DIM2 = 19.11 %) as shown in Fig. 3.

From Fig. 4, PCA clustered the samples of bread into two main groups, with GFBEG and WTB in one group (area of the blue ellipse), and GFBE and GFBG in another (area of the yellow ellipse). GFBEG and wheat flour bread were mainly characterised by their dough stability, bread volume, the colour of bread, loss in weight, cohesiveness, chewiness, and resilience (area of the blue ellipse). In contrast, the second group (B1 – B10) was characterised by their fat concentrations, the weight of bread, water absorption, development time and mixing tolerance of their doughs, density, Bread hardness, and adhesiveness (area of the yellow ellipse). The



B1-B5 (GFBE) = Gluten-free bread samples made with egg conditioner only, **B6-B10** (GFBG) = Gluten-free bread samples made with gelatin conditioner only, **B11-B15** (GFBEG) = Gluten-free bread samples made with Egg + Gelatin conditioner, **WTB** = Wheat flour bread. The yellow and blue ellipses indicate the grouping of the samples. This figure describes how the gluten-free bread samples compare to each other and wheat bread in terms of physicochemical and textural characteristics.

Fig. 4. PCA Plot for Bread Characteristics

B1-B5 (GFBE) = Gluten-free bread samples made with egg conditioner only, **B6–B10** (GFBG) = Gluten-free bread samples made with gelatin conditioner only, **B11–B15** (GFBEG) = Gluten-free bread samples made with Egg + Gelatin conditioner, **WTB** = Wheat flour bread. The yellow and blue ellipses indicate the grouping of the samples. This figure describes how the gluten-free bread samples compare to each other and wheat bread in terms of physicochemical and textural characteristics.

grouping by PCA suggests that bread made with egg and gelatin combination (B11 – B15) was more likely to compare with typical bread than the other FPF bread (B1 – B10). These results differ significantly from prior investigations [14,28,28,40] into the integration of alternative flours in pastry production, as the characteristics observed were notably inferior to those of their wheat flour counterparts. Thus, GFBEG (B11 – B15) may be considered for advanced selection for further investigation and optimization studies to provide the bread production industry in Sub-Sahara Africa and other developing countries a marketable alternative to what flour pastry products with improved physicochemical, sensory, and nutritional characteristics.

Also, some studies on gluten-free flour [28,40] and those investigating enzymatic gluten degradation [41] have consistently demonstrated health benefits. These findings indicate that alternative flour-based food products, even those containing wheat, can offer improved health outcomes compared to their gluten-based counterparts, with satisfactory sensory acceptance. The underdiagnosis of celiac disease and the consequent underestimation of its epidemiological impact can be attributed to various factors. These include limited disease awareness among physicians and patients, restricted access to diagnostic resources, inappropriate use or interpretation of serological tests, the absence of standardized diagnostic and endoscopic protocols, and insufficient expertise in histopathological interpretation [2,13,14]. These studies advocate for the development and consumption of gluten-free products, emphasizing the need to enhance their formulations to address the health challenges posed by CD [42]. This approach could significantly impact CD management, particularly in developed countries where gluten intake, primarily through bread, has contributed to the increasing burden of CD in recent years.

5.8. Sensory characterisation of bread

GFBEG (B11–B15) and WTD (control) were selected for sensory evaluation based on the superior physicochemical and morphological characteristics of the bread samples. Additionally, among the attributes used to describe the bread, five features exhibited significant differences ($p \leq 0.05$). These comprised four appearance attributes and one flavor attribute: brown top crust, brown bottom crust, smooth bottom crust, homogenous color, and bitter aftertaste. No significant differences ($p \leq 0.05$) were noted in aroma, flavor (excluding bitter), hand texture, mouthfeel, and aftertaste. The distinct attributes are depicted in Fig. 4.

The top and bottom crusts of both WTB and B14 exhibited the lightest intensity of brown colour in the sample set, and there was no statistically significant difference ($p \leq 0.05$) between them (Fig. 5). The top crusts of products B11, B12, B13, and B15 displayed higher brown colour intensities, and they were not significantly different ($p \leq 0.05$) from one another. The brown color of the bottom crust of B11 did not significantly differ from that of products B12, B13, and B15. However, B13 had a significantly higher brown bottom crust color than all the products except B11 ($p \leq 0.05$). The bottom crusts of WTB and B14 appeared significantly smoother than those of B13 and B15. The smoothness of the bottom crusts of WTB and B14 was significantly different ($p \leq 0.05$) from the other bread types in the sample set. The overall homogeneity of the bottom crusts for all products was generally low, ranging between 3 and 4 out of 10. The homogeneous color scores of B11, B14, and WTB were significantly higher than those of B12, B13, and B15. A bitter aftertaste was detected in the FPB products (B11, B12, B13, and B15) except for B14. However, this bitter aftertaste was very mild (less than 1 on a 10 cm line scale). The bitterness perceived in B11 was significantly more intense than in the others ($p \leq 0.05$). The bitter aftertaste might be attributed to the relative concentrations of components [42] and compounds, such as hydroxymethylfurfurals, furfurals, and melanoidins, formed during the Maillard reaction in the baking process, leading to a subtle bitter aftertaste in baked and toasted foods subjected to high-temperature treatment [2,17]. Research conducted by Tortoe et al. [29] and Osei Tutu et al. [28] revealed consistent findings, except for the mild bitter note identified in the present study. Discrepancies in these studies can be ascribed to variations in ingredients [42], the types of assessors employed, and the nature of sensory tests conducted.

6. Product map of bread samples

The Principal Component Analysis (PCA) map illustrates the arrangement of the six bread samples within the sensory space. Nearly all of the variance (96.94 %) was accounted for by the first two dimensions (DIM1 = 71.25 % and DIM2 = 25.69 %), as depicted in Fig. 5.

From Fig. 6, B12 and B13 were mainly characterised by brown colours of both the top and bottom crusts and appeared close to B11 and B15 (area of green ellipses). On the other hand, B14 and WTB were primarily characterized by the smooth appearance of the bottom crusts (area outlined by blue ellipses). The arrangement of the six products can be categorized into two distinct groups, with B14 and WTB forming one group and the remaining products constituting another group. The drawback of this assessment is that while it provides data on the product characteristics, it does not provide data about consumer preference or acceptability.

7. Conclusion

Bread made with two dough conditioners (B11–B15) and typical wheat bread exhibited some similar properties and were grouped together in PCA analysis. The combination of egg and gelatin produced dough with characteristics closer to wheat flour, showing improved baking capacity. However, bread made with a single conditioner (B1–B10) differed significantly from wheat flour bread. The key finding is that, for gluten-free bread from FPF, the use of multiple dough conditioners is recommended over one, as it provides a better substrate for mimicking a gluten-like matrix. All five released accessions of FPF performed similarly in gluten-free bread, suggesting their suitability for further studies in gluten-free bread development. Furthermore, future research can gain advantages from innovative baking technologies and consumer acceptability assessments. This will enhance the ability to more accurately assess the potential success of this gluten-free bread as a suitable substitute for traditional bread in conservative markets like Sub-Saharan

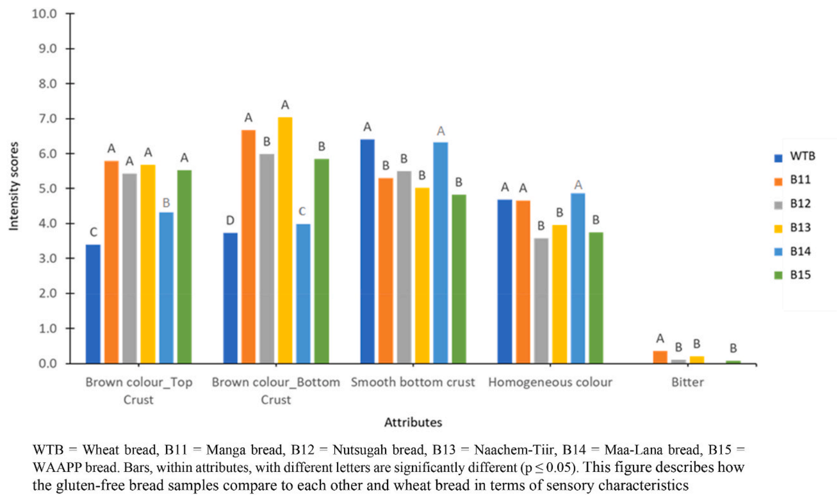


Fig. 5. Bar chart showing differences between bread formulations for discriminating attributes
WTB = Wheat bread, B11 = Manga bread, B12 = Nutsugah bread, B13 = Naachem-Tiir, B14 = Maa-Lana bread, B15 = WAAPP bread. Bars, within attributes, with different letters are significantly different ($p \leq 0.05$). This figure describes how the gluten-free bread samples compare to each other and wheat bread in terms of sensory characteristics.

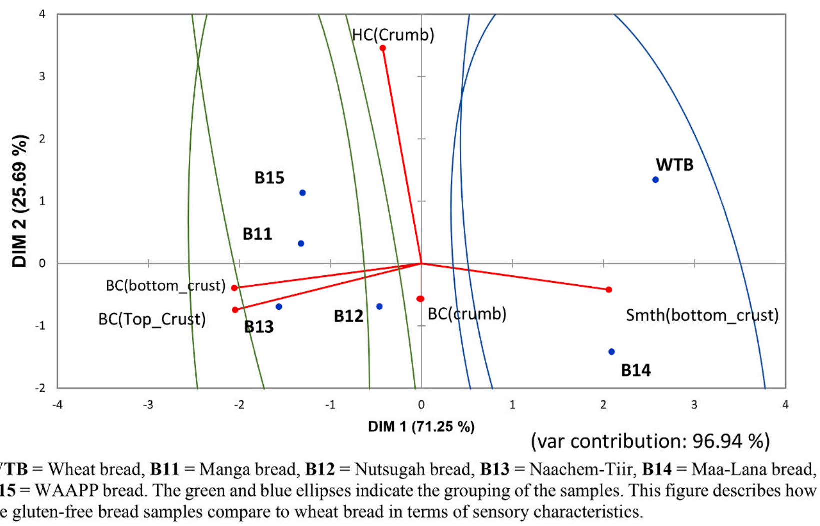


Fig. 6. PCA biplot display of the bread types in the sensory space
WTB = Wheat bread, **B11** = Manga bread, **B12** = Nutsugah bread, **B13** = Naachem-Tiir, **B14** = Maa-Lana bread, **B15** = WAAPP bread. The green and blue ellipses indicate the grouping of the samples. This figure describes how the gluten-free bread samples compare to wheat bread in terms of sensory characteristics.

Africa.

Declarations

The authors report no known conflict of interest. Ethics approval (*certified protocol ECBAS 048/15–16*) by the Ethics Committee for Basic and Applied Sciences (ECBAS), University of Ghana, was obtained for this study because there were trained panel of human assessors used for sensory evaluation. The trained panel of assessors gave informed consent before conducting the sensory evaluation.

Data availability statement

The data associated with this study has not been deposited into any publicly available repository. The data associated with this study are included in article/supp. material/referenced in article.

CRediT authorship contribution statement

Crossby Osei Tutu: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Joris Gerald Niilante Amissah:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Jacqueline Naalamle Amissah:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Paa Toah Akonor:** Writing – review & editing, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation. **Agnes Simpson Budu:** Writing – review & editing, Supervision, Resources, Project administration, Methodology. **Firibu Kwesi Saalia:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, 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.

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