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Original article

Physicochemical and sensory attributes of gluten-free sourdough breads produced from underutilised African cereal flours and flour blends

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Summary To seek potential alternative(s) for imported wheat in the African baking industry, the physicochemical parameters and sensory attributes of sourdough breads developed from locally sourced underutilised cereals and their blends were assessed. Processed sorghum (*Sorghum bicolour*), finger millet (*Eleusine coracana*) and pearl millet (*Pennisetum glaucum*) and their composites (50:50) were used to produce sourdough. Sourdough and flour-sourdough blends (30% sourdough) were used in making gluten-free breads. The protein content of the breads ranged from 16.29% to 39.26%, whereas the fat, crude fibre, ash and carbohydrate contents fell between 14.02–18.80%, 0.55–1.22%, 1.90–3.32% and 42.16–65.61%, respectively. The calculated energy value of the gluten-free breads (405.99–446.39 Kcal per 100 g) exceeded that of wheat bread (396.43 Kcal per 100 g), while the specific loaf volume varied from 1.46 to 1.80 cm^3 g^{-1}. Although the produced gluten-free breads have improved nutritional content compared to conventional wheat bread, they were at best moderately liked. This is perhaps due to the non-cohesive nature of the crumbs and psychological preference for known products. Further research targeted at improving the organoleptic properties of these sourdough breads is recommended.

Keywords Africa economy, bread, food choice, gluten-free cereals, organoleptic quality, product development, sourdough technology.

Introduction

Consumers' acceptability of food products is dependent on nutritional, economic, cultural, and social factors, among others. In addition, organoleptic perception, performance, convenience, affordability, and product image are very important in the consumer's choice of food. For bread, it is largely dependent on certain important qualities, such as good shelf-life, soft and elastic crumb structure, high loaf volume, and microbiological safety of product (Cauvain, 2003). The presence of gluten, which gives the dough a viscoelastic quality and gas-holding texture for the leavening of the wheat bread during fermentation plays a significant role in its global acceptability (Taylor & Emmambux, 2007). Although bread is a daily consumable for nearly-all African populace, most countries of the continent largely rely on wheat importation to meet their baking needs. Reliable data shows that between 2014 and 2021, Egypt topped the list of wheat and wheat products importers globally with an annual average value of well over 12 million metric tonnes (MMT) (Shahbandeh, 2021; USDA, 2021a). Algeria and Nigeria stand in the sixth and tenth positions with mean annual wheat importation that exceeds 7 MMT and 4 MMT, respectively, within the same period.

Notwithstanding, the deteriorating state of most African nations' economies, it is worrisome that a general increase in wheat importation is a norm. The high rate of importation of food items and other consumables does not only drain the economy but denies cultivators of alternative but underused cereals the benefits of finding a market for their produce. It is a well-established fact that nations that can be self-dependent in feeding their populations have a better chance to thrive economically than their counterparts

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that depend solely on importation. Gluten intolerance is a major allergy that has also been reported among consumers of wheat products (Catassi & Fasano, 2008). Similarly, the flour used for bread production is manufactured from the wheat's endosperm, which is less nutritious compared to the whole grain kernel, and research have revealed that whole grain food plays a protective role against many western diseases (Jacobs *et al*., 1998; Liu *et al*., 2000; Pereira *et al*., 2002; Adepehin *et al*., 2015, 2016).

Pearl millet, finger millet, and sorghum are gluten-free cereals grown in abundance in Nigeria and other African countries because they are drought-tolerant and resistant to soil salinity, elevated temperature, and climatic changes (Adepehin, 2017). For example, thirteen African countries (Niger, Nigeria, Mali, Sudan, Ethiopia, Burkina Faso, Chad, Tanzania, Uganda, Guinea, Ghana, Zimbabwe, and Cameroon) ranked among the highest twenty producers of millet globally (USDA, 2021b). Unfortunately, these cereals are grossly underutilised, mainly for feeding livestock. The capabilities of these cereals to thrive under harsh climatic conditions can be harnessed to combat the scourge of regional, national, and global food insecurity. Additionally, potential coeliac patients can also consume gluten-free breads without the danger of gluten-related allergies, and the whole grain nature of these cereals makes them better nutritional and healthy consumables.

Earlier studies have identified that sourdough technology generates healthy lactic acid bacteria (LAB) that are of nutritional value and usable as starter cultures when applied to gluten-free cereals (Table 1). Sourdough produced from finger millet contains *Pediococcus acidilactici* and *Candida glabrata*, which are LAB and yeast, respectively, while pearl millet sourdough was found to be highly populated with *Pediococcus pentosaceus* (Table 1). *Weissella confusa* and *Pediococcus pentosaceus* have been identified in sorghum sourdough batter (Ogunsakin *et al*., 2015). Sourdoughs produced from composite pearl millet-sorghum flour and finger millet-sorghum flour are rich in substrates that support the growth of *Weissella confusa* and *Pediococcus pentosaceus* (see, Adepehin *et al*., 2018; Adepehin, 2020). Different sourdoughs have been used in the production of different leavened baked products (e.g., white pan bread, rye bread, Panettone cake and San Francisco bread) (Corsetti, 2013) and unleavened food products (e.g., Sudanese kisra, Sudanese khamir, Ghanian kenkey, Ethiopian injera and Mexican pozol) (Arendt & Moroni, 2013).

However, significant attention has not been given to proximate composition, consumers' perception and acceptability (e.g., taste, aroma, texture, colour) of breads developed from these gluten-free cereals relative to wheat bread. Hence, this current study is a pilot test targeted at maximising the strengths of indigenously sourced grains (finger millet, pearl millet, sorghum, and their blends) as raw materials for bread production using the sourdough technique, which is known to improve the baking properties of gluten-lacking cereals in addition to other benefits. This study is part of continuous research that seeks to promote the use of underutilised gluten-deficient cereals as alternatives for wheat flour in the African baking industry, thereby reducing importation and the possibility of gluten-related allergies.

Material and methods

Sample collection and preparation

The KNE 1149 variety of finger millet (*Eleusine coracana*), ICMV 221-White variety of pearl millet (*Pennisetum glaucum*) and KARI MTAMA 1 variety of

Table 1 Isolated microfloral strains identified from finger millet, pearl millet, sorghum sourdoughs and their blends (adapted from Adepehin *et al*., 2018)

Sourdough	Closest relative[a]	Identity (%)	Accession no	Query cover
Finger millet sourdough	*Pediococcus acidilactici* strain KTNA3010M	99	KT968348.1	100
	Candida glabrata strain OJ18	99	KM103027.1	98
Pearl millet sourdough	*Pediococcus pentosaceus* strain WiKim20	100	KX890131.1	99
Sorghum sourdough	*Pediococcus pentosaceus* strain WiKim20	100	KX890131.1	99
Finger millet- Pearl millet sourdough	*Pediococcus acidilactici* strain KTNA3010M	99	KT968348.1	100
Pearl millet- Sorghum sourdough	*Weissella confusa* strain bcpcaqj1	99	KX247764.1	100
	Pediococcus pentosaceus strain WiKim20	99	KX890131.1	100
	Pediococcus acidilactici strain KTNA3010M	99	KT968348.1	100
Finger millet- Sorghum sourdough	*Weissella confusa* strain bcpcaqj1	99	KX247764.1	100
	Pediococcus pentosaceus strain WiKim20	99	KX890131.1	100

[a]Species showing the closest identity to the strains isolated from the six sourdoughs. Determination of the % identity was done using multiple-sequence alignments in BLAST. Identification was carried out using 16S rRNA and 26S rDNA gene sequencing for bacteria and yeast, respectively.

sorghum (*Sorghum bicolour*) were obtained from International Crops Research Institute on Semi-Arid Tropics (ICRISAT), Nairobi, Kenya. The grains were cleaned, milled through a knife mill (8 0-55743, Fritsch Industriestr, Idaroberstein, Germany), and sieved to a particle size ≤ of 0.2 mm. The flours were stored in well-labelled air-tight containers.

Sourdough preparation

Sourdough was prepared without the use of starter culture(s) and bakers' yeast. The cereals were used both singly and mixed for sourdough production. Composite flours, pearl millet-sorghum, finger millet-sorghum and finger millet-pearl millet were mixed in a ratio of 50:50, to allow for the equal expression of their unique properties, such that none predominate the other quantitatively. Sourdough preparation was done according to Adepehin *et al*. (2018). Thorough mixing of the flour and tap water was done and this was fermented naturally at room temperature (27 °C) for a duration of 48 h. Dough preparation was carried out in triplicate.

Sourdough breads

Sourdough bread was produced from the various flour samples as highlighted in Fig. 1. The ingredients used were 30% sourdough, 5% baking fat, 75% flour, 1.5% salt, 10% sugar, 5% egg white, 2% yeast, 0.5% ascorbic acid and 30 mL water based on preliminary experiments (Edema *et al*., 2013; Adepehin, 2017). An amount (5 g) of sugar and 2 g of yeast were mixed with 10 mL of water to check the viability of the yeast. The dry ingredients (flour, salt, remaining sugar, and ascorbic acid) were initially mixed with an electric mixer (Binatone electric mixer: Model 350S, United Kingdom) in a mixing bowl at low speed after which, the baking fat was added and mixed. This was followed by the addition of the egg white, sourdough, and remaining water. On gentle mixing, a batter was formed having the colour of the flour used. The mixture was transferred into a greased baking pan and proofed for 20 min. The proofed dough was moved into a heated oven at a temperature of 160 °C and baked for 20 min. The baked sourdough bread was cooled to room temperature and stored in a labelled and sealed polythene nylon for further analyses.

Measurement of physical properties of the various sourdough breads

The crumb and crust colours of the breads were determined by comparing observed colours with the International Commission on Illumination colour chart (International Commission on Illumination (CIE), 1976). The $L^*a^*b^*$ values of the crust and crumb colour were also recorded to aid descriptive terminologies. The height of the sourdough breads was measured with a metre rule and recorded in centimetres (cm), while their weight (measured in grams) was determined using an electronic weighing balance (PTY-B4000, Huazhi (Fujian) Electronic Technology Co., Ltd., Fujian, China). The loaf volume and specific loaf volume were calculated using the Rosales-Juárez *et al*. (2008) method. All the measurements were taken in triplicates.

Determination of proximate composition and energy value

The proximate composition (dry matter basis) for the different flours and flour blends was obtained using AOAC (2005) method. The carbohydrate was calculated by difference. All determinations were carried out in triplicate. Energy value was estimated using the Crisan & Sands (1978) method.

Sensory assessment of the sourdough breads and wheat bread

Sensory evaluation of the various sourdough breads and wheat bread was carried out after 3 h of cooling by a 30-member semi-trained panel. The panellists were randomly recruited from the students and staff members in the Department of Food Science and Technology, the Federal University of Technology Akure, Nigeria. Gender and age were not prerequisites for panellists' recruitment, rather, likeness for eating bread was the major criterion for selection. This evaluation was carried out in three sensorial sections that each seated ten panellists in a well-lightened and spacious sensory booth. Parameters considered include colour, taste, texture, aroma, and overall acceptability with the sensory characteristics rated on a 9-point

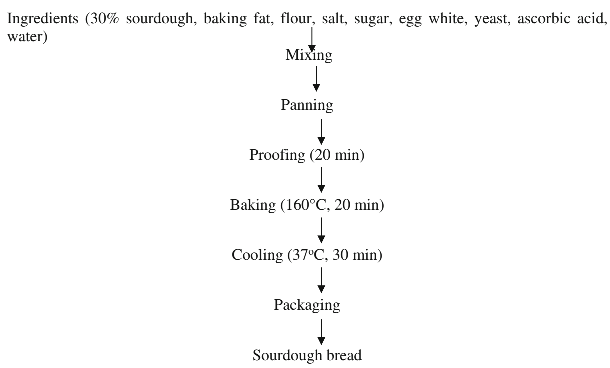

Figure 1 Flowchart for the production of sourdough bread (Modified after Edema *et al*., 2013).

hedonic scale, with 9 connoting extremely liked and 1 meaning extremely disliked (Appendix S1). Panellists were spaciously seated to prevent external influence on the individual's perception. The participants were trained on the usage of the printed sensory evaluation form and what each of the terms indicated so they could give unbiased judgement (Appendix S1). Water was made available for the panellists to rinse their mouths after tasting each bread. Alphanumerically coded slices (containing crumb and crust) of the produced sourdough breads and wheat bread were presented to the panellists. The data obtained were subjected to statistical analysis as detailed (Statistical analyses section).

Statistical analyses

The analyses were carried out in triplicate and their mean ± standard deviations were determined. The obtained data were subjected to a one-way analysis of variance (ANOVA) at the 5% level of significance using the Statistical Package for the Social Sciences (SPSS) 23.0 for Windows (International Business Machines Corp., Chicago, IL, USA). The means were separated using Duncan's multiple range tests.

Results and discussion

Physical properties of produced gluten-free sourdough breads

The crust and crumb of the finger millet and finger millet-pearl millet sourdough breads (Fig. 2a, d) are characteristically reddish-brown ($L^* = 17.35$, $a^* = 118.72$, $b^* = 39.08$). Though with crumb colour that differs from that of the crust (Fig. 2c, e, f; Table 2), the sorghum bread and the other two breads produced from its blend are of brownish crust ($L^* = 24.49$, $a^* = 55.22$, $b^* = 97.69$). The sorghum and the pearl millet-sorghum breads both displayed cream crumb colour ($L^* = 58.16$, $a^* = 57.98$, $b^* = 78.15$) (Fig. 2c, e). The fact that the resultant crumb colour for the developed sourdough breads generally reflects the colour of the grains used for their production indicates that sourdough fermentation and the adopted baking procedures had insignificant impacts on crumbs colour.

Colour impacts consumers' perception of food products in diverse ways (Spence, 2018), it stimulates appetite by appealing to the sense of sight (Dias *et al.*, 2012). Bread colour has an unprecedented impact on its acceptability and by implication, its commercial importance, and of the numerous factors posited to control crumb colour, the colour of grains from which it was produced is the singular most important (Pomeranz, 1960). The preference for the wheat bread crumb followed by the light-brownish crumb of the sorghum, pearl millet, and pearl millet-sorghum breads somewhat indicate consumers' preferences for light brownish breadcrumbs (Fig. 2, Table 4). The converse slightly disliked dispositions towards the dark brownish crumbs of the other whole-grain breads, suggest the need to lighten-up these gluten-free breads to meet consumers' needs (Bakke & Vickers, 2010). This is because food product choice is largely contingent on existing sensory preferences (importantly colour), age-long habits, and psychosocial factors that are difficult to do away with (Dias *et al.*, 2012). Thus, establishing that variation in bread crumb and crust colour from what consumers are used to has a strong influence on their flavour/taste perception and general acceptability (Spence *et al.*, 2010; Spence, 2015).

The finger millet bread is characterised by a flat crust with some slight bulging and slightly big pores (Fig. 2a). The crust of the pearl millet bread is flat with some slight bulging like the finger millet bread (Fig. 2a, b). This notwithstanding, the pearl millet bread pores were relatively smaller than those of the finger millet sourdough bread. The pearl millet-sorghum sourdough bread possessed tiny pores, whereas the finger millet-sorghum blend sourdough bread is characterised by large pores mainly. The sorghum bread crust is similar to the finger millet and the pearl millet sourdough breads, although its pores are typically smaller than those of the former but similar to that of the latter (Fig. 2). Sourdough breads are reportedly characterised by large pores, and well-developed pore sizes in bread crumb have a direct influence on textural improvement (Sanni *et al.*, 1998). A direct correlation could not be established between the qualitatively expressed pore sizes and the texture of the bread (Fig. 2, Table 4). However, the three breads with significantly larger pore sizes generally recorded textural perception between 5.44 and 5.88, suggesting they were neither liked nor disliked (Table 4). This data indicates that crumb texture is influenced by other factors (e.g., grain sizes of flour particles, flour fibre, and baking conditions *etc.*) other than pore sizes and quantities. The predomination of large pores observed in the finger millet, finger millet-pearl millet, and finger millet-sorghum breads is indicative of the presence of trapped CO_2 gas within their doughs during fermentation (Fig. 2). These gas bubbles were possibly formed by the yeast, *Candida* species and heterofermentative lactic acid bacteria present in the sourdoughs (Table 1). The significant population of small-sized pores in other sourdough breads notwithstanding the occurrence of *Candida* species is attributed to the variation of this microflora in the products.

The loaf volume of the single flour sourdough breads fell within the range of 270.00–295.00 cm^3

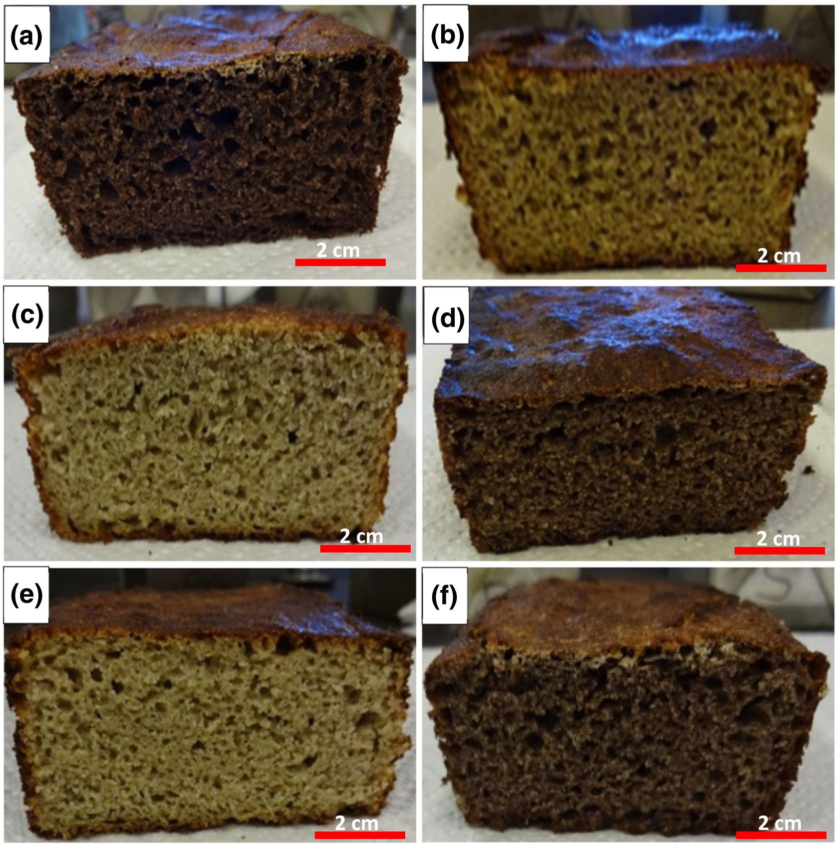

Figure 2 Different sourdough bread produced from underused gluten-free flour and flour-blends (a) Darkish brown finger millet sourdough bread with small-large sized pores, (b) Brownish Pearl millet sourdough bread showing dominantly small pores, (c) Light brownish sorghum sourdough bread with small pore sizes, (d) Dark brownish composite finger millet-pearl millet sourdough bread with medium to large pores, (e) Composite pearl millet- sorghum sourdough bread showing light brown colour and tiny pores, (f) Finger millet- sorghum blend sourdough bread with dark brownish colour and mainly large pores.

Table 2 Physical properties of the sourdough breads

Sample code	Crust colour			Crumb colour			Weight (g)	Height (cm)	Loaf volume (cm^3)	Specific loaf volume ($cm^3\ g^{-1}$)
	*L**	*a**	*b**	*L**	*a**	*b**				
F	17.35	118.72	39.08	17.35	118.72	39.08	$178.44^{b} \pm 1.99$	$2.75^{bc} \pm 0.06$	$287.00^{c} \pm 0.82$	$1.61^{ab} \pm 0.14$
P	18.37	118.72	39.08	59.18	99.39	78.15	$184.98^{a} \pm 0.45$	$2.65^{cd} \pm 0.17$	$270.00^{d} \pm 8.16$	$1.46^{b} \pm 0.01$
S	24.49	55.22	97.69	58.16	57.98	78.15	$178.73^{b} \pm 1.01$	$2.55^{d} \pm 0.17$	$295.00^{b} \pm 0.82$	$1.65^{ab} \pm 0.34$
FP	17.35	118.72	39.08	17.35	118.72	39.08	$166.50^{d} \pm 1.52$	$2.85^{ab} \pm 0.06$	$294.00^{b} \pm 0.00$	$1.77^{a} \pm 0.16$
PS	24.49	55.22	97.69	58.16	57.98	78.15	$170.48^{c} \pm 0.00$	$2.75^{bc} \pm 0.06$	$274.00^{d} \pm 0.82$	$1.61^{ab} \pm 0.22$
FS	24.49	55.22	97.69	24.49	55.22	97.69	$169.09^{c} \pm 2.77$	$3.00^{a} \pm 0.12$	$305.00^{a} \pm 0.82$	$1.80^{a} \pm 0.11$

*L*a*b** values were obtained based on the CIELAB colour space (International Commission on Illumination (CIE), 1976). Each value of weight, height loaf volume and specific loaf volume is a mean ± standard deviation of three replicates; values followed by the same letter(s) are not significantly different ($P > 0.05$) by New Duncan's Multiple Range Test (along column).

F, Finger millet sourdough bread; FP, Finger millet-Pearl millet sourdough bread; FS, Finger millet-Sorghum sourdough bread; P, Pearl millet sourdough bread; PS, Pearl millet-Sorghum sourdough bread; S, Sorghum sourdough bread.

(Table 2). The peak loaf volume (295.00 cm^3) and specific loaf volume (1.65 $cm^3\ g^{-1}$) were observed in the sorghum sourdough bread (Table 4). Hence, the specific loaf volume of the sorghum sourdough bread is higher than that of the finger millet and the pearl millet, although no significant difference could be construed for the values of the specific loaf volume of all the sourdough breads produced from single flours. A similar observation was noticed in the sourdough bread made from composite flours. This can be attributed to the fact that all the cereals used for bread making were gluten-free cereals thereby indicating a similar process of fermentation, leavening and acidification. The specific loaf volumes of the various sourdough breads obtained in this current study (1.46–1.80 $cm^3\ g^{-1}$) are lower than those reported by Falade *et al.* (2017) for sour maize bread (2.1 $cm^3\ g^{-1}$), but well above the (0.84–1.05 $cm^3\ g^{-1}$) documented for sorghum sourdough bread by Ogunsakin *et al.* (2015). In this current study, the addition of sorghum to finger millet and pearl millet notably increased the specific loaf volume from 1.61 to 1.80 and 1.46 to 1.61 $cm^3\ g^{-1}$, respectively (Table 4). Hence, this indicates the advantage of composite flour over single flour for use as raw material for producing sourdough baked foods.

Proximate composition and energy value of the gluten-free and wheat breads

The protein content of the sourdough bread produced from the single flours fell within the range of 16.29–39.26%, with pearl millet sourdough bread possessing the highest value (Table 3). The protein content of the finger millet, pearl millet, and sorghum sourdough breads show a significant difference ($P > 0.05$). Of the three single flour sourdough breads, the protein content of the pearl millet (39.26%) and sorghum (28.28%) breads exceeds that of the wheat bread (18.60%), although the latter is slightly higher than that of the finger millet sourdough bread (16.29%) (Table 3). The sourdough loaves produced from composite flours have protein content ranging from 28.83% to 33.30%. Except for the finger millet-sorghum sourdough bread, other breads produced from composite gluten-free flours recorded a significant difference ($P > 0.05$) in their protein contents. The protein content of all the composite sourdough breads was observed to exceed the recorded value for wheat bread (Table 3).

This observation shows that these indigenous gluten-free breads offer promising and cheaper sources of protein to the ~93 million Nigerians who consume protein-lacking diets daily (Ramoni, 2021), since bread is almost a daily consumable in most African homes. Thus, promoting the consumption of these gluten-free breads could potentially reduce nutritional and health challenges associated with protein deficiency. In children, a shortage of protein in diets is associated with body swelling, skin degeneration, fatty liver, stunted growth, and increasing severity of infections, whereas low protein intake in maternal diets could result in intrauterine growth restriction, embryonic losses, and reduction of postnatal growth (Sukhatme, 1970; Waterlow & Payne, 1975; Abrahams *et al.*, 2011). In sub-Saharan Africa, a direct link has been established between high infant mortality and factors such as poor protein consumption and exclusive breastfeeding, especially in low-income countries with very low nutrition transition scores (table 2 in Abrahams *et al.*, 2011).

There was a significant difference ($P > 0.05$) in the fat contents of all the sourdough bread made from finger millet, pearl millet and sorghum sourdough bread (Table 3). The fat content of the produced sourdough breads (14.02–18.80%) was higher than that of wheat bread (1.91%) (Table 3). The documented higher fat content in sourdough breads has the potential of increasing energy and as well as boosting immunity (Yao *et al.*, 2022). This, validates the higher energy value documented in all the gluten-lacking breads than the wheat bread (Table 3), suggesting that derivable chemical energy for important human metabolic processes in wheat bread is lesser than those in gluten-free breads (Tomassi & Merendino, 2006). The crude fibre content of the single flour sourdough breads ranged from 0.55 to 1.06%, while the value for the composite breads varied from 0.95% to 1.22% (Table 3). This data demonstrated that blended whole grain gluten-lacking breads offer higher crude fibre content than the single flour, except for the pearl millet bread. Comparatively, these whole grain sourdough loaves are richer sources of crude fibre than wheat bread (Table 3). However, these values were less than that of pumpernickel bread (1.10%) but higher than the crude fibre of sour maize bread (0.00%) (Mrdeza, 1978; Sanni *et al.*, 1998).

Table 3 Proximate composition and energy value of the various sourdough breads and wheat bread

Sample code	Protein (%)	Fat (%)	Crude fibre (%)	Ash (%)	CHO (%)	Energy value (Kcal per 100 g)
F	$16.29^{e} \pm 0.63$	$15.31^{c} \pm 0.56$	$0.73^{c} \pm 0.10$	$2.06^{cd} \pm 0.14$	$65.61^{b} \pm 0.29$	$446.39^{a} \pm 0.42$
P	$39.26^{a} \pm 0.85$	$15.06^{c} \pm 0.31$	$1.06^{b} \pm 0.09$	$2.46^{bc} \pm 0.13$	$42.16^{f} \pm 0.92$	$405.99^{d} \pm 0.65$
S	$28.28^{c} \pm 0.44$	$14.02^{d} \pm 0.51$	$0.55^{d} \pm 0.02$	$1.90^{d} \pm 0.05$	$55.25^{c} \pm 0.41$	$423.49^{c} \pm 0.45$
FP	$31.68^{b} \pm 1.16$	$16.41^{b} \pm 0.65$	$0.95^{b} \pm 0.04$	$2.22^{cd} \pm 0.13$	$48.75^{e} \pm 0.60$	$425.10^{b} \pm 0.80$
PS	$33.30^{b} \pm 1.22$	$18.80^{a} \pm 0.43$	$0.99^{b} \pm 0.09$	$3.32^{a} \pm 0.56$	$43.58^{e} \pm 1.35$	$427.64^{b} \pm 1.00$
FS	$28.83^{c} \pm 1.17$	$15.41^{c} \pm 0.46$	$1.22^{a} \pm 0.13$	$2.87^{b} \pm 0.09$	$51.66^{d} \pm 0.75$	$421.49^{c} \pm 0.79$
W	$18.60^{d} \pm 0.11$	$1.91^{e} \pm 0.54$	$0.00^{e} \pm 0.02$	$0.81^{e} \pm 0.13$	$78.98^{a} \pm 0.19$	$396.43^{e} \pm 0.28$

Each value is a mean ± standard deviation of three replicates; values followed by the same letter(s) are not significantly different ($P > 0.05$) by New Duncan's Multiple Range Test (along column).

F, Finger millet sourdough bread; FP, Finger millet-Pearl millet sourdough bread; FS, Finger millet-Sorghum sourdough bread; P, Pearl millet sourdough bread; PS, Pearl millet-Sorghum sourdough bread; S, Sorghum sourdough bread; W, Wheat bread.

Table 4 Sensory attributes of the various sourdough breads and wheat bread

Sample code	Colour	Aroma	Taste	Texture	Overall acceptability
F	$4.94^{c} \pm 1.69$	$5.38^{b} \pm 1.93$	$5.06^{b} \pm 1.95$	$5.88^{b} \pm 1.96$	$5.31^{b} \pm 1.58$
P	$6.38^{bc} \pm 1.50$	$5.25^{b} \pm 1.39$	$5.25^{b} \pm 1.29$	$5.38^{b} \pm 1.54$	$5.56^{b} \pm 1.10$
S	$6.81^{ab} \pm 1.05$	$5.25^{b} \pm 1.39$	$4.88^{b} \pm 1.02$	$5.69^{b} \pm 1.82$	$5.66^{b} \pm 0.92$
FP	$5.38^{bc} \pm 1.86$	$5.94^{ab} \pm 1.69$	$4.94^{b} \pm 1.24$	$5.56^{b} \pm 1.50$	$5.45^{b} \pm 1.36$
PS	$6.31^{bc} \pm 1.58$	$6.25^{ab} \pm 0.86$	$5.75^{b} \pm 0.77$	$5.69^{b} \pm 1.30$	$6.00^{b} \pm 0.68$
FS	$4.75^{c} \pm 2.21$	$5.81^{ab} \pm 1.76$	$5.63^{b} \pm 1.41$	$5.44^{b} \pm 1.67$	$5.41^{b} \pm 1.47$
W	$8.10^{a} \pm 0.11$	$7.00^{a} \pm 0.21$	$7.40^{a} \pm 0.14$	$7.50^{a} \pm 0.26$	$7.50^{a} \pm 0.34$

Each value is a mean ± standard deviation of three replicates; values followed by the same letter(s) are not significantly different ($P > 0.05$) by New Duncan's Multiple Range Test (along column).

F, Finger millet sourdough bread; FP, Finger millet-Pearl millet sourdough bread; FS, Finger millet-Sorghum sourdough bread; P, Pearl millet sourdough bread; PS, Pearl millet-Sorghum sourdough bread; S, Sorghum sourdough bread; W, Wheat bread.

The ash content of all the sourdough breads is higher than that of the wheat bread (~1%), there was no significant difference ($P > 0.05$) in the ash content of the finger millet, pearl millet, the finger millet-sorghum sourdough breads (Table 3). The ash content of food produce/products is an indicator of their mineral composition. Hence, it can be deduced that all the produced sourdough breads are generally better sources of minerals for the body compared to processed wheat flour. Although whole-wheat grains are documented to be richer in minerals such as phosphorus, potassium, and magnesium compared to these gluten-free cereals (Adepehin *et al.*, 2015; Allai *et al.*, 2022), the recorded lower values of ash content for wheat in this study probably resulted from its processing (e.g., debranning).

Among the single-flour sourdough breads, the finger millet bread had the highest carbohydrate content which was less than that of wheat bread. This indicates that the sourdough introduced in the dough during mixing aided in the breakdown of carbohydrates during the fermentations. Although carbohydrate is known to provide energy that fuel all needed anabolic and catabolic activities in the body, including the functionality of all the cells, tissues and organs as well as promoting intestinal health, the ridiculously high consumption of carbohydrate-rich foods by Africans (specifically Nigerians) vis-à-vis the high level of recorded incidence of diabetes require all measure that could reduce unnecessary ingestion of complex carbohydrates. The consumption of bread products containing lactic acid, whether generated during fermentation or added had been reported by Ostman *et al.* (2002) to reduce insulin responses and postprandial glucose in humans without ill-health records. Hence, relatively lower carbohydrates recorded in the produced bread promised a better alternative for diabetic patients and others with relatively lower insulin capacity, especially in Nigeria where more than four million cases of diabetes have been reported (Fasanmade & Dagogo-Jack, 2015).

Sensory attributes of the sourdough breads and wheat bread

The preference of the panellists for wheat bread over the gluten-free breads in this study was expected, and as posited in (Physical Properties of Produced Gluten-free Sourdough Breads section), it somewhat reflects consumers' psychological biases for products they are accustomed to (Pomeranz, 1960; Dias *et al.*, 2012; Spence, 2018). Of all the considered organoleptic parameters, it interesting to note that only colour (finger millet and finger millet-sorghum) and taste (sorghum and finger millet-pearl millet) were slightly disliked (Table 4, Fig. 2), notwithstanding the established prejudice for the conventional wheat bread. This understanding is crucial, as it offers promising acceptance for the gluten-free sourdough breads in Africa, although the need for further studies that would improve on this current work is sacrosanct. Interestingly, the choice of nutritious and healthy foods is not only contingent on existing biases, age-long childhood habits and social factors, but also on adequate nutritional information and psychological factors (Dias *et al.*, 2012; Singh, 2014), which can be positively altered through targeted awareness, orientation, and advocacy. As such, concerted efforts by relevant government agencies and policymakers to educate the masses on the health, nutritional, and economic benefits of gluten-free sourdough breads hold the potential to increase its overall acceptability.

Conclusion

Gluten-free sourdough breads offer higher protein, fat, energy value, crude fibre, and ash contents relative to conventional wheat breads, whereas their physical and sensory attributes and overall acceptability of the sourdough breads remains on the average. Light coloured gluten-free breads have more acceptability than darker ones. The preference of the panellists for the physical and sensory attributes of wheat bread confirms existential preferences for known products. The limitation of the sensory panellists size to thirty elites might have introduce some statistical bias, given the 1.40 billion population of Africa. Consequently, future studies should be completed with larger sample size to confirm these results. Further research to enhance crumb cohesiveness, storability, and organoleptic qualities of the gluten-free bread. Deliberate awareness on the economic, nutritional, and health benefits of consuming these breads is expected to increase their acceptability, and thus initiate a paradigm shift in the African baking industry. Overall, this shift will improve the livelihoods of persons involved in the production and supply chain of these whole-grains as raw materials. Thereby reducing the gross dependence of the African baking industry on wheat importation, while making more nutritious and healthy alternatives available for consumers.

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Author contributions

Jemima Omonigho Adepehin: Conceptualization (lead); data curation (lead); methodology (lead); project administration (lead); writing – original draft (lead); writing – review and editing (lead). **Victor N Enujiugha:** Supervision (equal). Resources (equal); supervision (equal). **Glenn M. Young:** Supervision (equal). **Damaris Achieng Odeny:** Resources (equal); supervision (equal).

Conflict of interest

Authors declared that they have no conflict of interest regarding the work detailed in this manuscript.

Ethical approval

Prior to its execution, this research received approval from the research ethics committee, Department of Food Science and Technology, the Federal University of Technology Akure, Nigeria.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Supporting Information

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

AppendixS1

