



Nutritional, Antioxidant and Sensory Properties of Wheat–Oat Composite Sourdough Breads

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Abstract

Sourdough breads prepared from wheat and oat flours were evaluated for proximate composition, mineral profile, estimated mineral bioavailability, antioxidant activity, and sensory quality, while yeast-leavened breads served as controls. Five bread formulations were produced: 100% wheat yeast-leavened bread (WYD), 100% oat yeast-leavened bread (OYD), 100% wheat sourdough bread (WSD), 100% oat sourdough bread (OSD), and a 50:50 wheat–oat sourdough bread blend (WOSD). The bread samples exhibited moisture (23.54 ± 0.36 – $32.38 \pm 0.09\%$), ash (0.80 ± 0.01 – $1.32 \pm 0.12\%$), fat (8.55 ± 0.50 – $18.11 \pm 0.67\%$) contents, crude protein (7.34 ± 0.10 – $11.66 \pm 0.12\%$), crude fiber (0.18 ± 0.00 – $1.04 \pm 0.04\%$), and carbohydrate by difference (40.21 ± 0.70 – $55.27 \pm 0.97\%$). Sodium (31.19 ± 0.01 – 41.21 ± 0.00 ppm) and potassium (38.09 ± 0.01 – 44.21 ± 0.00 ppm) were the predominant minerals, with sourdough breads maintaining comparable mineral levels to yeast-leavened breads ($p < 0.05$). Phytate contents ranged from 8.15 to 12.10 mg/g, with WOSD exhibiting the lowest phytate level and the most favorable phytate-to-mineral molar ratios, indicating enhanced mineral bioavailability. Antioxidant assays demonstrated significantly higher DPPH radical scavenging activity, ABTS activity, and FRAP in sourdough breads than yeast controls, with WOSD showing the peak antioxidant activity. Sensory evaluation indicated that wheat yeast-leavened bread received the highest ratings for color and appearance, whereas sourdough breads were rated more favorably for flavor and aroma. Overall acceptability scores ranged from 7.60 ± 0.52 to 8.90 ± 0.32 on a nine-point hedonic scale. These findings indicate that the combination of enhanced antioxidant activity and acceptable sensory quality in WOSD highlights its potential as a nutritionally enriched bakery product.

Keywords:

antioxidants; bioavailability; DPPH radical scavenging activity; fermentation; phytate content; sourdough bread; wheat–oat composite

1. Introduction

Renewed interest in traditional food processing technologies has stimulated extensive research on sourdough fermentation as a natural approach to enhancing the nutritional and functional quality of cereal-based foods. Sourdough bread is produced through the metabolic activity of lactic acid bacteria (LAB) and yeasts, which collectively influence dough structure, flavor development, shelf stability, and nutrient bioavailability [1,2]. Compared with conventional yeast-leavened bread, sourdough bread is of-

ten associated with a lower glycemic response, improved mineral bioavailability, and enhanced sensory quality [3].

Sourdough fermentation improves mineral bioavailability primarily through acidification and microbial phytase activity, which hydrolyze phytic acid (inositol hexaphosphate) and reduce its capacity to chelate divalent minerals, such as Fe^{2+} , Zn^{2+} , and Ca^{2+} [4,5]. In vitro and animal studies have shown that sourdough fermentation significantly reduces phytate levels and enhances mineral solubility compared with yeast-leavened controls [4, 5]. Mechanistic reviews emphasize that effective phytate

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degradation depends on the optimization of fermentation parameters, including pH, fermentation time, and microbial composition. These conditions promote the activation of endogenous cereal phytases as well as microbial phytases produced by lactic acid bacteria [1,6–8].

Microbial fermentation facilitates the release of cell wall-bound phenolic compounds and may also generate novel antioxidant metabolites, thereby increasing total phenolic content and enhancing in vitro antioxidant activity as measured by DPPH, ABTS, and FRAP assays [9,10]. Multiple studies on cereal- and legume-based sourdough systems have consistently reported increases in radical scavenging capacity and reducing power following fermentation. The magnitude of these effects depends on substrate composition and starter culture microbiota [1,11].

Wheat flour remains the dominant raw material for bread production worldwide due to its gluten-forming proteins and favorable baking properties. However, oats (*Avena sativa* L.) have attracted increasing attention due to their high dietary fiber content, balanced amino acid profile, and rich supply of bioactive compounds, including phenolic acids and avenanthramides [12,13]. Oats are a rich source of soluble dietary fiber, particularly β -glucan, as well as lipid-soluble antioxidants and unique phenolic compounds such as avenanthramides, which exhibit strong antioxidant and anti-inflammatory properties [14–17]. This is primarily attributed to the higher concentration of phenolic compounds in the outer kernel layers. In addition, milling fraction and particle size significantly influence phenolic content and its release during processing [14,18,19].

The incorporation of oat flour into wheat dough typically reduces loaf volume and modifies crumb structure due to gluten dilution. However, targeted use of sourdough fermentation or enzyme treatments can mitigate technological defects and improve sensory acceptance [20,21]. Sensory studies indicate that wheat-dominant breads are generally preferred for appearance and texture, whereas composite sourdough breads often receive higher scores for flavor acceptability and perceived healthfulness [22,23].

Although numerous studies have described the benefits of sourdough fermentation in single-grain matrices, limited data are available on wheat–oat composite sourdough bread systems. This study investigates the relationships among compositional changes, estimated mineral bioavailability, antioxidant capacity (DPPH, ABTS, and FRAP assays), and organoleptic acceptability in commercially relevant wheat–oat breads, thereby providing an integrated dataset linking compositional, nutritional, and sensory properties.

2. Materials and Methods

2.1. Ingredients and Reagents

Commercial wheat flour, sugar, salt, fat, and baking yeast were obtained from Uchi Market in Etsako-West Local Government Area, Edo State, Nigeria. Rolled oats were purchased from Jattu Market in the Etsako West Local Government Area. All analytical reagents used were of analytical grade and sourced from certified laboratory suppliers (Pascal Scientific, Akure, Ondo State, and Promise Medical Equipment and Supply, Ekpoma, Edo State).

2.2. Experimental Procedures

2.2.1. Sourdough Preparation and Bread Production

Sourdough fermentation was conducted according to the method described by Demirkesen-Bicak et al. [1], with minor modifications. Wheat and oat flours were separately dispersed in distilled water at a flour-to-water ratio of 187.5 g to 112.5 mL to obtain 300 g of dough. Spontaneous fermentation was carried out at ambient temperature (24–27 °C), with back-slopping every 24 h for 72 h. Fermentation was terminated when the dough pH reached approximately 4.0. Five bread samples were produced and coded as follows: WYD, 100% wheat yeast-leavened bread; OYD, 100% oat yeast-leavened bread; WSD, 100% wheat sourdough bread; OSD, 100% oat sourdough bread; and WOSD, 50:50 wheat–oat sourdough bread. The corresponding yeast-leavened breads served as controls. Doughs were proofed at 30 °C and 75% relative humidity for 45 minutes and then baked under standardized conditions. Baking was carried out in an electric oven for 45 minutes, with a bottom temperature of 190 °C and a top temperature of 215 °C.

2.2.2. Proximate and Mineral Analysis

Proximate composition was determined using standard AOAC methods [24]. Accordingly, each bread sample was milled into flour, and 1.0 g was weighed into a crucible. The samples were then transferred to a muffle furnace and ashed at 550 °C, after which they were placed in a desiccator to cool. A 0.1 M HCl solution (10 mL) was used to digest the ash residue, which was subsequently rinsed three times with 0.1 M HCl. The final solution was made up to 100 mL with deionized water. The calcium, magnesium, zinc, and iron contents of the samples were determined using an atomic absorption spectrophotometer (AAS). Standard stock solutions for each metal were prepared using appropriate metal salts, and calibration curves

were constructed for quantitative analysis. Sodium and potassium concentrations in the flour samples were determined using a flame photometer. The measured values were compared against corresponding standard calibration curves to quantify the elemental concentrations. Phosphorus content was determined using the vanadomolybdate method. A series of 100 mL volumetric flasks were prepared containing 0.0, 2.5, 5.0, 7.5, 11.0, 15.0, 20.0, 30.0, 40.0, and 50.0 mL of standard phosphate solution. Each solution was acidified by adding 2 mL of nitric acid (2:1), followed by the addition of 25 mL of vanadomolybdate reagent. The solutions were then diluted to the mark, thoroughly mixed, and allowed to stand for 10 minutes. Absorbance was measured at 470 nm. The Na:K ratio was also calculated as an indicator of dietary quality.

2.2.3. Estimation of Mineral Bioavailability

Relative mineral bioavailability was estimated using phytate-to-mineral molar ratios (phytate:Fe, phytate:Zn, and phytate:Ca), following established criteria for predicting mineral absorption [25].

2.2.4. Antioxidant Activity Assays

An aqueous extract of the milled bread sample was prepared by macerating 500 g of flour in 2.5 L of distilled water, followed by filtration, concentration, and freeze-drying. Antioxidant activity was evaluated using DPPH radical scavenging, ABTS radical cation decolorization, and FRAP assays, following standardized analytical protocols [26–28].

2.2.5. Sensory Evaluation

Sensory evaluation was conducted using 30 untrained panelists, aged 18–50 years. Bread samples were evaluated for color, appearance, texture, aroma, taste, and overall acceptability using a nine-point hedonic scale, where 1 indicated “dislike extremely,” 2 “dislike very much,” 3 “dislike moderately,” 4 “dislike slightly,” 5 “neither like nor dislike,” 6 “like slightly,” 7 “like moderately,” 8 “like very much,” and 9 “like extremely.”. Water was provided for palate cleansing between samples. The bread samples were coded as WYD = 100% wheat yeast dough bread; OYD = 100% oat yeast dough bread; WSD = 100% wheat sourdough bread; OSD = 100% oat sourdough bread; WOSD = 50% wheat and 50% oat sourdough bread.

2.2.6. Statistical Analysis

All analyses were performed in triplicate using SPSS (version 26) and GraphPad Prism (version 5). Data were expressed as mean $\pm$ standard deviation. Statistical signifi-

cance was determined using one-way analysis of variance (ANOVA), and means were separated using Duncan’s multiple range test at $p < 0.05$.

3. Results and Discussion

3.1. Proximate Compositions

Moisture content varies markedly among the samples, ranging from 23.54% in 100% wheat yeast dough (WYD) to 32.38% in 100% oat sourdough (OSD) (Table 1). The higher moisture content observed in 100% oat yeast dough (OYD), 100% oat sourdough (OSD), and 50:50 wheat–oat sourdough (WOSD) samples can be attributed to the presence of soluble dietary fiber, particularly β -glucans in oats, which exhibit strong water-binding capacity [29]. Fermentation promotes the formation of organic acids and exopolysaccharides, which enhance water retention within the sourdough crumb matrix [30]. Doughs with high moisture content have been reported to exhibit reduced caloric density, improved crumb softness, enhanced digestibility, and greater ease of mastication, particularly benefiting elderly individuals and those with chewing difficulties [31]. These observations do not preclude the limitation that high-moisture doughs generally exhibit reduced shelf life due to increased susceptibility to microbial spoilage [32]. This effect is further influenced by enhanced water retention arising from fiber–starch interactions [33]. Ash content increased with oat inclusion, rising from $0.80 \pm 0.01\%$ in WYD to $1.32 \pm 0.12\%$ in OYD (Table 1). Ash reflects total mineral matter [34], indicating that oat flour contributed significantly to micronutrient density.

Similar trends have been reported for oat-composite breads in recent cereal nutrition studies [13,17]. Crude protein content was highest in WYD ($11.66 \pm 0.12\%$) and lowest in OSD (Table 1). These findings suggest that fermentation is associated with a general reduction in crude protein content across the dough samples. In comparison, wheat-based doughs exhibit higher protein content than oat-based sourdoughs. This reduction is expected, as oats contain fewer gluten-forming proteins, and sourdough fermentation promotes proteolysis through lactic acid bacteria activity [4]. Although this process reduces total protein content, it enhances protein digestibility by releasing bioactive peptides and free amino acids, thereby improving amino acid bioavailability. Recent studies have confirmed that fermentation improves protein quality in sourdoughs [35]. Crude fiber content increased substantially with oat inclusion, reaching $1.04 \pm 0.04\%$ in oat yeast-leavened bread and remaining elevated in oat sourdough bread. Wheat-based samples exhibited relatively low fiber

content. In contrast, oat-derived fiber, particularly β -glucan, is associated with approved cholesterol-lowering health claims. High-fiber formulations are also linked to increased market value and consumer acceptance, especially within functional and health-oriented food markets. These findings align with recent evidence on fiber enrichment in oat-based bakery products [14,36]. Fat content increased notably in oat-based breads, with the high-

est value ($18.11 \pm 0.67\%$) recorded in OSD. Oats naturally contain higher lipid levels, which confers a compositional advantage in baked products [17]. Carbohydrate content decreased with oat inclusion and sourdough fermentation, with the lowest value observed in OSD ($40.21 \pm 0.70\%$). Sourdough fermentation has been shown in recent in vitro and clinical studies to reduce starch digestibility and glycemic response [37].

Table 1: Proximate compositions of the samples.

Samples	Moisture (%)	Ash Content (%)	Crude Protein (%)	Crude Fibre (%)	Fat Content (%)	Carbohydrate By Difference (%)
WYD	23.54 ^a $\pm$ 0.36	0.80 ^a $\pm$ 0.01	11.66 ^c $\pm$ 0.12	0.18 ^a $\pm$ 0.00	8.55 ^a $\pm$ 0.50	55.27 ^d $\pm$ 0.97
OYD	26.15 ^b $\pm$ 0.48	1.32 ^d $\pm$ 0.12	9.77 ^c $\pm$ 0.13	1.04 ^d $\pm$ 0.04	13.57 ^c $\pm$ 0.82	48.15 ^b $\pm$ 1.09
WSD	26.25 ^b $\pm$ 0.02	0.85 ^{ab} $\pm$ 0.01	10.34 ^d $\pm$ 0.26	0.20 ^a $\pm$ 0.01	9.42 ^a $\pm$ 0.19	52.94 ^c $\pm$ 0.46
OSD	32.38 ^d $\pm$ 0.09	1.11 ^c $\pm$ 0.01	7.34 ^a $\pm$ 0.10	0.85 ^c $\pm$ 0.05	18.11 ^d $\pm$ 0.67	40.21 ^a $\pm$ 0.70
WOSD	27.83 ^c $\pm$ 0.05	0.95 ^b $\pm$ 0.05	8.11 ^b $\pm$ 0.03	0.33 ^b $\pm$ 0.04	10.92 ^b $\pm$ 0.33	51.86 ^c $\pm$ 0.36

Values are expressed as mean $\pm$ SD. Means within the same column bearing different superscript letters are significantly different ($p < 0.05$) according to Duncan's multiple range test. WYD = 100% wheat yeast dough bread; OYD = 100% oat yeast dough bread; WSD = 100% wheat sourdough bread; OSD = 100% oat sourdough bread; WOSD = 50% wheat and 50% oat sourdough bread.

3.2. Mineral Compositions

Table 2 shows the mineral compositions of yeast-based doughs and sourdoughs. Mineral analysis indicates that mineral bioavailability improves through both fermentation and composite flour formulation. Sodium content ranged from 31.19 ± 0.01 to 41.21 ± 0.00 ppm, with the lowest values observed in OSD. Reduced sodium intake has been associated with a lower risk of hypertension [38,39]. Potassium content is relatively high across all samples, with values up to 44.21 ± 0.00 ppm in WYD. High potassium intake has been reported to facilitate osmoregulation and support nerve and muscle function [40]. The World Health Organization (WHO) [41] emphasizes the importance of maintaining a low Na:K ratio for cardiovascular health, achieved through the simultaneous reduction of sodium intake and increased potassium consumption. Calcium and magnesium are high in WYD

and WSD, but remain nutritionally relevant in WOSD. Calcium contributes to bone health, whereas magnesium plays key roles in glucose metabolism and enzymatic activity. Iron and zinc contents were low across all samples, which is a common limitation of cereal-based products [42,43], largely attributed to the formation of phytate complexes that reduce their bioavailability. Recent evidence indicates improved iron and zinc bioavailability in sourdough-fermented products [5]. The differences in phosphorus content between yeast-leavened and sourdough breads reflect variations in phosphorus bioavailability [5]. The higher phosphorus content observed in wheat yeast-leavened bread suggests a greater proportion of indigestible phytate-bound phosphorus, whereas the lower phosphorus content in sourdough indicates increased levels of unbound, more bioavailable, and readily digestible phosphorus [4].

Table 2: Mineral compositions of the samples.

Sample	Mineral (ppm)							Na:K
	Na	K	Ca	Mg	Fe	P	Zn	
WYD	41.21 ^a $\pm$ 0.00	44.21 ^a $\pm$ 0.00	8.32 ^a $\pm$ 0.00	14.06 ^b $\pm$ 0.02	0.03 ^b $\pm$ 0.01	8.95 ^a $\pm$ 0.00	0.21 ^d $\pm$ 0.01	0.96 ^b $\pm$ 0.00
OYD	33.10 ^d $\pm$ 0.01	39.50 ^c $\pm$ 0.00	5.96 ^e $\pm$ 0.00	15.50 ^a $\pm$ 0.01	0.04 ^a $\pm$ 0.00	7.54 ^c $\pm$ 0.00	0.45 ^a $\pm$ 0.00	0.84 ^d $\pm$ 0.00
WSD	36.00 ^c $\pm$ 0.00	41.30 ^b $\pm$ 0.00	7.17 ^c $\pm$ 0.00	10.06 ^d $\pm$ 0.01	0.02 ^d $\pm$ 0.01	7.81 ^b $\pm$ 0.00	0.19 ^d $\pm$ 0.00	0.87 ^c $\pm$ 0.00
OSD	31.19 ^e $\pm$ 0.01	38.09 ^e $\pm$ 0.01	6.00 ^d $\pm$ 0.00	7.79 ^e $\pm$ 0.00	0.02 ^e $\pm$ 0.00	6.80 ^d $\pm$ 0.00	0.26 ^c $\pm$ 0.01	0.82 ^e $\pm$ 0.00
WOSD	37.18 ^b $\pm$ 0.00	38.20 ^d $\pm$ 0.00	7.92 ^b $\pm$ 0.00	10.68 ^c $\pm$ 0.02	0.02 ^c $\pm$ 0.00	6.56 ^e $\pm$ 0.02	0.36 ^b $\pm$ 0.01	0.97 ^a $\pm$ 0.00

Values are expressed as mean $\pm$ SD. Means within the same column bearing different superscript letters are significantly different ($p < 0.05$) according to Duncan's multiple range test. WYD = 100% wheat yeast dough bread; OYD = 100% oat yeast dough bread; WSD = 100% wheat sourdough bread; OSD = 100% oat sourdough bread; WOSD = 50% wheat and 50% oat sourdough bread.

3.3. Phytate Content and Relative Mineral Bioavailability

Phytate content and relative mineral bioavailability of the bread samples are presented in Table 3. OSD exhibited the highest phytate content (12.10 ± 0.06 mg/g), whereas WYD and WSD showed moderate levels, and WOSD recorded the lowest phytate content (8.15 ± 0.08 mg/g). This observation suggests that sourdough fermentation exerts a greater overall effect in wheat–oat composites than

in oat-only systems, likely due to the presence of mixed substrates that provide a broader range of endogenous and microbial phytase activity. Phytase in wheat sourdough has been shown to be more active near the pH levels achieved in sourdough fermentation (3.8–4.2), whereas phytase in oat sourdough is less effective under the same conditions [4]. The phytate-to-iron (Phy:Fe) ratio is used as an indicator of iron bioavailability, with values below 1 generally considered favorable for improved absorption and bioavailability [44,45].

Table 3: Phytate contents and relative mineral bioavailability of the samples.

Samples	Phytate (mg/g)	Phy/Zn	Phy/Fe	Phy/Ca
WYD	$9.23^d \pm 0.00$	$4.40^c \pm 0.13$	$23.51^d \pm 0.84$	$0.07^d \pm 0.00$
OYD	$9.56^c \pm 0.01$	$2.10^d \pm 0.02$	$22.95^d \pm 0.34$	$0.10^b \pm 0.00$
WSD	$10.29^b \pm 0.01$	$5.25^a \pm 0.04$	$42.34^b \pm 2.27$	$0.09^c \pm 0.00$
OSD	$12.10^a \pm 0.06$	$4.99^b \pm 0.09$	$63.67^a \pm 2.39$	$0.11^a \pm 0.00$
WOSD	$8.15^e \pm 0.08$	$2.23^d \pm 0.08$	$28.43^c \pm 0.49$	$0.06^e \pm 0.00$

Values are expressed as mean $\pm$ SD. Means within the same column bearing different superscript letters are significantly different ($p < 0.05$) according to Duncan's multiple range test. WYD = 100% wheat yeast dough bread; OYD = 100% oat yeast dough bread; WSD = 100% wheat sourdough bread; OSD = 100% oat sourdough bread; WOSD = 50% wheat and 50% oat sourdough bread.

OSD exhibited the highest Phytate (mg/g) ratio (12.10 ± 0.06), suggesting potential inhibition of iron absorption despite fermentation. In contrast, WOSD showed the lowest Phy:Fe ratio (8.15 ± 0.08), indicating comparatively higher iron bioavailability among all bread samples, whereas WYD and WSD demonstrated a moderate phytate effect. Zinc bioavailability is particularly sensitive to phytate, with values greater than 15 widely recognized as inhibitory [46]. In the same trend, OSD exhibited the highest phytate-to-zinc (Phy:Zn) ratio (4.99 ± 0.09), suggesting poor zinc bioavailability, whereas WOSD showed the lowest ratio (2.23 ± 0.08), indicating the most favorable zinc bioavailability among the samples. These findings indicate that zinc is highly reactive with phytate, such that even a modest reduction in phytate can substantially improve zinc bioavailability. This effect is evident in WOSD, suggesting that sourdough fermentation in composite flours can markedly reduce the phytate-to-zinc ratio below inhibitory thresholds, thereby enhancing zinc accessibility [4]. In contrast, this effect appears less pronounced in single-grain oat sourdough bread. Calcium bioavailability is less sensitive to phytate than Fe or Zn, but high ratios still negatively impact absorption. WOSD exhibited the lowest phytate-to-calcium (Phy:Ca) ratio (0.06 ± 0.00), indicating improved potential calcium bioavailability. In contrast, OSD showed the highest ratio (0.11 ± 0.00), whereas WSD and WYD displayed intermediate values, suggesting a moderate phytate impact on calcium availability. The improved phytate-to-calcium (Phy:Ca) ratio in WOSD reflects a balance between phy-

tate degradation and moderate calcium levels, which enhances mineral solubility and potential bioavailability. In contrast, the higher phytate levels observed in oat sourdough may hinder calcium interactions, thereby potentially reducing calcium uptake [47]. Overall, sourdough fermentation improves relative mineral availability compared with yeast leavening, primarily due to phytate degradation and the acidic conditions generated during fermentation [5]. Blending wheat with oats before sourdough fermentation yields the most nutritionally advantageous profile, balancing enhanced cereal diversity with optimized enzyme activity.

3.4. Antioxidant Activities

Figures 1–4 illustrate the quality of the bread samples based on three antioxidant assays—FRAP, DPPH, and ABTS—and α -amylase inhibition, which serves as an indicator of glycemic modulation. Each assay reflects a distinct antioxidant mechanism: FRAP measures reducing power, DPPH and ABTS evaluate radical scavenging capacity, while α -amylase inhibition assesses the ability of bioactive compounds to slow starch hydrolysis [5,48]. FRAP values were lowest in WYD and OYD, whereas sourdough breads, particularly WOSD, exhibited significantly higher reducing power (Figure 1). These findings indicate that WOSD outperforms single-grain sourdough formulations. The enhanced performance of WOSD may be attributed to the release of bound phenolic acids and the formation of low-molecular-weight phenolic metabolites through microbial biotransformation, as

well as the release of avenanthramides, oat-specific antioxidants known for their strong reducing capacity [4,17]. Similarly, WOSD and OSD exhibited higher DPPH radical scavenging activity, indicating greater radical scavenging capacity compared with the other bread samples (Figure 2).

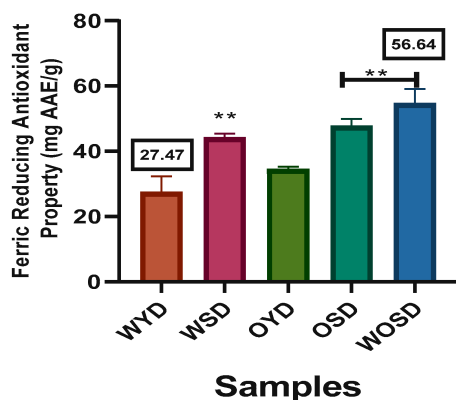


Figure 1: Activity of FRAP of the samples. (** $p < 0.05$).

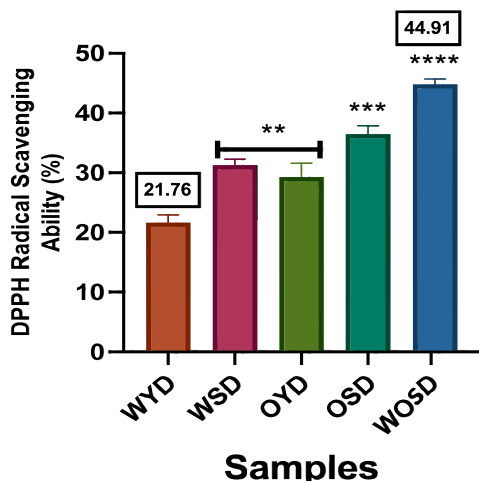


Figure 2: DPPH reduced scavenger ability of the samples. (** $p < 0.05$; *** $p < 0.01$; **** $p < 0.001$).

Sourdough breads consistently outperformed yeast-leavened breads, with WOSD exhibiting the highest DPPH radical scavenging activity. These results demonstrate an improvement in DPPH activity following sourdough fermentation, consistent with reports of a 2–3-fold increase in antioxidant activity during sourdough processing [35]. ABTS values are generally higher than DPPH values across all samples (Figure 3), indicating a broader spectrum of antioxidant activity, particularly for both hydrophilic and lipophilic compounds. WOSD exhibited the highest ABTS radical scavenging activity, followed closely by OSD, whereas WYD and OYD showed comparatively limited activity. The elevated ABTS activity

in WOSD may suggest a diverse antioxidant profile, enhanced by mixed-flour fermentation [48]. α -Amylase inhibition was lowest in WYD and highest in WOSD, while oat-based sourdoughs also exhibited stronger inhibitory effects compared with the wheat-based samples (Figure 4). This inhibitory effect may be attributed to the presence of soluble dietary fiber (β -glucan) in oats, which physically restricts enzyme–substrate interactions. This finding is consistent with reports that sourdough fermentation promotes the formation of bioactive peptides that can interfere with enzyme activity [5,37]. Collectively, the antioxidant and α -amylase inhibition data indicate that WOSD may improve oxidative stress protection, increase metabolic regulation, reduce glycemic impact, and provide greater functional food value. This study demonstrates that the synergistic interaction of wheat–oat composite flours enhance antioxidant activity compared with the individual effects of each flour alone.

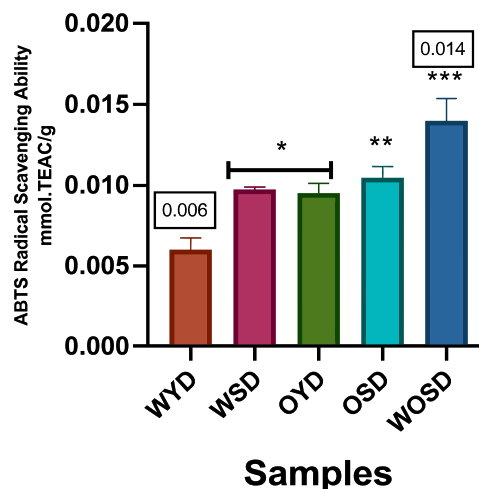


Figure 3: ABTS radical scavenging ability of the samples. (* $p > 0.05$; ** $p < 0.05$; *** $p < 0.01$).

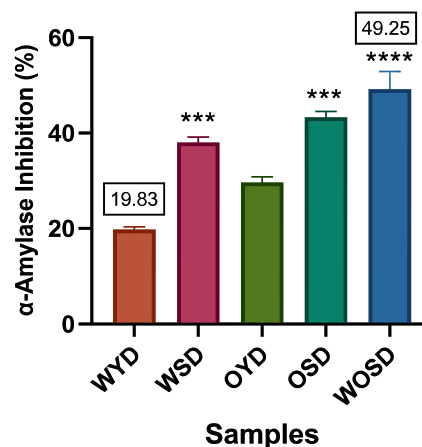


Figure 4: α -amylase inhibition of the samples. (*** $p < 0.01$; **** $p < 0.05$).

3.5. Sensory Evaluation

Sensory evaluation indicated that WYD achieved the highest scores for color, appearance, texture, and overall acceptability, reflecting consumer familiarity with conventional wheat bread (Table 4). In contrast, sourdough breads, particularly WSD and WOSD, received higher scores for aroma and flavor. Lower color and appearance scores for OYD and OSD may be attributed to their darker

crumb color and denser texture, characteristics commonly reported in oat-based products [21]. Despite this, overall acceptability scores for all samples range from 7.60 ± 0.52 to 8.90 ± 0.32 , indicating good consumer acceptance. Sensory acceptability is essential for sustained consumption of nutritionally enhanced foods, providing a potential alternative to wheat-based sourdough breads and wheat yeast-leavened breads.

Table 4: Sensory attributes of the samples.

Samples	Colour	Appearance	Texture	Aroma	Taste	General Acceptability
WYD	$8.80^a \pm 0.42$	$8.60^a \pm 0.70$	$8.32^a \pm 1.03$	$8.40^b \pm 0.70$	$8.30^a \pm 0.67$	$8.90^a \pm 0.32$
OYD	$6.80^{bc} \pm 1.03$	$7.20^{ab} \pm 1.14$	$7.40^a \pm 1.35$	$7.30^a \pm 0.95$	$8.50^b \pm 0.53$	$8.50^{ab} \pm 0.71$
WSD	$7.50^{ab} \pm 1.35$	$7.10^b \pm 1.52$	$7.50^a \pm 1.27$	$7.50^a \pm 1.43$	$7.60^b \pm 0.52$	$8.00^{bc} \pm 0.67$
OSD	$5.80^{cd} \pm 1.93$	$6.40^{bc} \pm 1.78$	$5.90^b \pm 1.79$	$7.50^a \pm 1.43$	$7.50^b \pm 0.53$	$7.60^c \pm 0.52$
WOSD	$5.20^d \pm 2.35$	$5.40^c \pm 2.22$	$5.50^b \pm 2.01$	$6.00^b \pm 1.41$	$8.20^a \pm 0.42$	$8.10^{bc} \pm 0.57$

Values are expressed as mean $\pm$ SD. Means within the same column bearing different superscript letters are significantly different ($p < 0.05$) according to Duncan's multiple range test.

4. Conclusions

This study demonstrates that sourdough fermentation and the incorporation of wheat–oat composite flours substantially improve the nutritional, antioxidant, and sensory properties of breads, enhancing their overall consumer acceptability. Compared with yeast-leavened controls, sourdough breads exhibited improved compositional attributes, including higher moisture retention, increased dietary fiber and lipid contents in oat-based formulations, and modified protein profiles consistent with enhanced digestibility. Mineral analysis showed that sodium and potassium were the predominant minerals across all samples, while sourdough fermentation retained overall mineral contents and improved nutritionally relevant Na:K ratio. Notably, the wheat–oat composite sourdough bread exhibited the lowest phytate content and the most favorable phytate-to-mineral molar ratios, indicating comparatively higher bioavailability of iron, zinc, and calcium among the samples. This improvement highlights the synergistic effect of wheat–oat composite flours in reducing the inhibitory impact of phytate on mineral absorption. Antioxidant evaluation further revealed that sourdough breads, particularly the wheat–oat composite (WOSD), possessed significantly higher ferric reducing power, radical scavenging activity, and α -amylase inhibition capacity, which could improve oxidative stress protection and potential glycemic modulation. Sensory evaluation showed that conventional wheat bread was most preferred for appearance and texture, whereas sourdough breads were rated more favorably for aroma and flavor. All samples achieved good overall acceptability.

Collectively, these findings indicate that wheat–oat composite sourdough bread provides a balanced profile of improved mineral bioavailability, enhanced antioxidant activity, and acceptable sensory quality. The study highlights the potential of wheat–oat sourdough bread as a nutritionally enriched bakery product.

List of Abbreviations

AAS	Atomic Absorption Spectrophotometer
ABTS	2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid)
ANOVA	Analysis of Variance
AOAC	Association of Official Analytical Chemists
DPPH	2,2-diphenyl-1-picrylhydrazyl
FRAP	Ferric Reducing Antioxidant Power
OSD	Oat-based Sourdough Bread (100%)
OYD	Oat-based Yeast-dough Bread (100%)
WHO	World Health Organization
WOSD	Wheat–oat (50:50) Sourdough Bread
WSD	Wheat-based Sourdough Bread (100%)
WYD	Wheat-based Yeast-dough Bread (100%)

Author Contributions

Conceptualization, methodology: A.A.O.; Investigation, resources, formal analysis, writing—original draft, visualization, supervision, and writing—review & editing: A.O.O. All authors have read and agreed to the published version of the manuscript.

Availability of Data and Materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Ethics Committee Approval and Consent to Participate

Ethical approval was not required by the institution, Auchi Polytechnic, Auchi, Nigeria, where the sensory evaluation was conducted, as the study involved a non-invasive sensory assessment of food products. Informed consent was obtained from all panelists prior to participation, including consent for the use and publication of the collected data.

Human Rights

The study adhered to ethical research practices and was conducted in accordance with the Declaration of Helsinki (2024).

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AI Declaration

The authors used ChatGPT to assist with the clarification and refinement of ideas during the preparation of this manuscript. All generated content was thoroughly reviewed, verified, and revised to ensure accuracy, originality, and scientific integrity. The authors assume full responsibility for the accuracy and integrity of the manuscript.

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