Open Access

Recent Progress in Nutrition

LIDSEN Publishing Inc.

Original Research

Exploring the Use of Purple Corn Cob Flour as a New Fiber Source in Pan Bread Improved by Commercial Hemicellulases

Glauce Kelly Silva do Nascimento [1], Tatiane Monteiro dos Santos [1], Irene Andressa [2], Vivian Machado Benassi [1], Nathalia de Andrade Neves [1,*], Marcio Schmiele [1]

1. Institute of Science and Technology, Federal University of Jequitinhonha and Mucuri Valleys (UFVJM), Diamantina, Minas Gerais, Brazil; E-Mails: glauce.kelly@ufvjm.edu.br; tatiane.santos@ufvjm.edu.br; vivian.benassi@ufvjm.edu.br; nathalia.neves@ict.ufvjm.edu.br; marcio.sc@ict.ufvjm.edu.br
2. Department of Food Science and Technology, Federal University of Viçosa, Viçosa, Minas Gerais, Brazil; E-Mail: irene.andressa@ufv.br

* **Correspondence:** Nathalia de Andrade Neves; E-Mail: nathalia.neves@ict.ufvjm.edu.br

Academic Editor: Arrigo F. G. Cicero

Special Issue: Recent Advances in Nutrition and Health of Cereals and Pseudocereals

Recent Progress in Nutrition
2024, volume 4, issue 3
doi:10.21926/rpn.2403013

Received: May 08, 2024
Accepted: August 29, 2024
Published: September 05, 2024

Abstract

Bread stands out for its versatility and accessibility, appealing to individuals across various ages and social classes. Consequently, it presents an attractive opportunity for incorporating ingredients that offer health benefits to consumers. In this context, the current study aimed to evaluate the technological properties of sandwich bread (specific volume, water activity, moisture, instrumental color, and texture) prepared with a partial substitution (5% w/w) of wheat flour (WF) with purple corn cob flour (PCF) (F1), along with the addition of hemicellulolytic enzymes of fungal (F2) and bacterial (F3) origin. The enzymatic action had a positive impact ($P < 0.05$) on the specific volume of the samples (F2: 4.17 ± 0.16 cm^3/g and F3: 4.52 ± 0.02 cm^3/g) compared to the standard (3.78 ± 0.07 cm^3/g), which was reflected in the instrumental texture parameters. Parameters such as firmness, hardness, gumminess, and grittiness were less pronounced in the samples with enzyme addition compared to the control. The samples did not differ statistically regarding water activity and instrumental color parameters (a^* and b^*). However, enzymatic action reduced the crumb's brightness (L^*) in both cases, which was attributed to the release of reducing sugars. The values of color variance (ΔE) were less than 5, indicating that untrained individuals cannot differentiate between the sample's colors. Thus, the incorporation of hemicellulolytic enzymes in sandwich bread with partial substitution of WF by PCF improves the technological properties of the finished product, adding value to an agro-industrial co-product.

Keywords
Clean label; co-product; food technology; sustainability

1. Introduction

The demand for functional foods, coupled with growing concerns about the consumption of synthetic food additives and increased awareness of environmental impacts, has driven the food industry to develop products with enhanced functional appeal. Additionally, there is an increasing emphasis on meeting the demand for clean labels, which has become an expectation among consumers for product transparency [1].

Bread is one of the oldest and most universally appreciated foods, enjoyed by people of all ages and social classes. In addition to its widespread popularity, bread is cost-effective and exceptionally versatile, making it suitable for incorporating new ingredients. Therefore, the partial substitution of wheat flour with unconventional, fiber-rich flour holds significant promise and has the potential to enhance the product's functional appeal [2, 3].

Regular fiber consumption is associated with numerous health benefits, including reduced blood glucose levels, increased fecal volume, satiety promotion, and weight reduction assistance. Additionally, fiber intake improves liver lipid metabolism and reduces the risk of cardiovascular diseases, stroke, and hypertension [4, 5].

Cereals serve as a fundamental source of energy for humans, and among them, corn stands out as the third most-produced grain globally. This grain is crucial in ensuring food security for numerous countries, particularly in sub-Saharan Africa, Latin America, and the Caribbean [6].

Numerous attributes, including color distinguish a wide array of corn varieties. Notable variants include white, yellow, red, purple, brown, green, and blue corn. Purple corn is particularly noteworthy for its high anthocyanin content, making it a valuable natural pigment in various food products. While the purple corn varieties native to Peru have been extensively studied, there is limited research on other varieties, including purple pericarp corn [7].

The corn cob, constituting 18% of the total ear weight, is the primary byproduct of the corn industry. Corn cob flour, derived from this byproduct, is notably fiber-rich. Although it contains some antinutritional compounds, such as phytic acid and oxalic acid, their levels are minimal, measuring 0.51 ± 0.10 g/100 g and 0.02 ± 0.01 g/100 g, respectively. Consequently, corn cob flour is a viable, abundant, and cost-effective alternative for enhancing the fiber content in bakery products [8].

However, it is essential to note that partial substituting wheat flour (WF) with high-fiber flour may adversely affect bakery products' sensory and technological properties, particularly in volume, alveolar structure, and texture [9]. The addition of fibers in bakery products significantly impacts the dough's properties and the gluten network's formation. Fibers alter the bonding of the gluten networks, making them less continuous, affecting the dough's rheology, texture, and organoleptic quality of the final products [10].

Therefore, adding enzymes, specifically hemicellulolytic enzymes, is essential to mitigate these adverse effects of fibers on technological and sensory parameters in bakery products. Enzymes play a pivotal role in baking and can serve as alternatives to synthetic additives. This approach aligns with the clean label trend, as enzymes are typically considered technological adjuncts and deactivated during baking [11].

Food enzymes can be derived from various sources, such as plants, animals, or microorganisms, and may include products obtained through fermentative processes using microorganisms. These products often contain one or more enzymes capable of catalyzing specific biochemical reactions. Food enzymes are incorporated into food for technological purposes at different stages of processing, packaging, transportation, or storage [12].

Therefore, the present study aimed to assess the impacts of partially substituting wheat flour (WF) with purple corn cob flour (PCF) in pan bread and adding two hemicellulolytic enzymes, one of fungal origin and the other of microbial origin, on the bread's technological properties.

2. Material and Methods

The creole corn cobs with purple pericarp, harvested in 2020, were obtained through a donation from the Creole Corn Project of the Institute of Agricultural Science (ICA/UFVJM) and are officially registered under number A5C29C1 in the National System for Management of Genetic Heritage and Associated Traditional Knowledge (SisGen) of the Ministry of the Environment of the Federative Republic of Brazil. The enzymes MEGACELL 899 C (bacterial hemicellulase) and PENTOMAX 191 (fungal hemicellulase) were provided by Prozyn Biosolutions (São Paulo, Brazil), while the remaining ingredients were procured from the local market in Diamantina, MG, Brazil.

2.1 Physicochemical Characterization of Corn Cob and Wheat Flours

2.1.1 Proximate Composition

Corn cob flour was produced following the methodology described by Nascimento et al. [9]. The process began with the initial crushing of the corn cobs using a JF 80 hammer mill (JF Máquinas, Itapira, Brazil), followed by further particle size reduction (<350 µm) in a TE-350 ball mill (Tecnal, Piracicaba, Brazil). The resulting flour, along with wheat flour (WF), was analyzed for proximate composition, including moisture, lipids, ash, and proteins (N = 6.25), according to the procedures established by the American Association of Cereal Chemists International [13]. Digestible carbohydrates, including sugars, starch, and dietary fiber, were quantified following the methodology described by the Association of Official Analytical Chemists [14]. All analyses were performed in triplicate, presenting the results as percentages (%).

2.1.2 Instrumental Color

The colorimetric parameters of the corn cob flour were determined using the methodology described by Silva et al. [15]. The samples were evenly distributed in a Petri dish, and measurements were taken using a CM-5 Konica colorimeter (Minolta, Chiyoda, Japan) in the L*, a*, and b* color space. The colorimeter was calibrated with illuminant D65, a 10° viewing angle for the observer, and the RSIN (Reflectance Specular Included) calibration mode.

2.1.3 Bread Production

Pan breads were prepared following the formulations and methodology outlined in Table 1. Initially, the dry ingredients were manually homogenized before being added to the Multi Pane bread maker (Britânia, Curitiba, Brazil), where the remaining ingredients were incorporated. The bread maker was set to program 1, which included two mixing phases interspersed with dough resting periods (first mix for 10 minutes, rest for 20 minutes, and second for 15 minutes).

Table 1 Formulation of bread with the addition of corn cob flour and hemicellulose enzymes.

Ingredients	**F1**	**F2**	**F3**
Wheat flour (%)	95	95	95
Purple corn cob flour (%)	5	5	5
Pentomax 191 (ppm)	-	40	-
Megacell 899 C (ppm)	-	-	30
Sucrose (%)	1.8	1.8	1.8
Sodium chloride (%)	1.8	1.8	1.8
Instant yeast (%)	1.2	1.2	1.2
Palm fat (%)	4	4	4
Drinkable water (%)	60	60	60

Note: Percentages are based on the amount of wheat flour in each formulation. The quantity of enzyme used was in accordance with the manufacturer's recommendations.

The dough was divided into three portions of 400 g each, followed by manual rounding and molding using an MB35/1 molder (Refrisol, Francisco Beltrão, Brazil). Fermentation was performed in a Technipan proofer (Prática, Pouso Alegre, Brazil) at 32°C and 90% relative humidity for 80 minutes. Fermentation was deemed complete when the dough lost its resilience to touch. The samples were then baked in a ConventionLine oven (Venâncio, Venâncio Aires, Brazil) at 160 ± 1°C for 25 minutes and subsequently cooled to room temperature. The loaves were identified correctly, packaged in high-density polyethylene bags, and analyzed 24 hours post-baking. Slicing was performed using an FPV12 slicer (Venâncio, Venâncio Aires, Brazil) to produce 12 mm thick slices.

2.1.4 Bread Characterization

Bread volume was determined using method 10-05.01 [13]. Initially, the samples were weighed using a semi-analytical balance S2202 (WebLador, Piracicaba, Brazil). The volume of displaced pearl millet seeds was measured in a 1 L measuring cylinder, and the calculation was performed according to Equation 1.

$$\mathrm{SV} = \frac{\mathrm{v}}{\mathrm{w}} \qquad \text{(Equation 1)}$$

where: SV = specific volume (mL/g); v = volume of seeds displaced (mL); w = sample weight (g).

The moisture content of the breadcrumb was determined using method 44.15.02 [13], and the water activity was measured using an Aqualab 4TE Duo hygrometer (Decagon, São José dos Campos, Brazil) at a constant temperature of 25 ± 1°C, by method 44-15.02 [13]. The height of the central slice was measured in triplicate using a professional 150 mm optical caliper (Western, Suzhou, China). The instrumental color parameters of the breadcrumb were obtained with three repetitions, using the same settings applied for the corn cob and wheat flour analyses. The samples' instrumental color difference (ΔE) compared to the control was calculated according to Equation 2.

$$\Delta \mathrm{E} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad \text{(Equation 2)}$$

where: ΔE = total color difference of the sample relative to the control; ΔL^* = variation in the L^* parameter (brightness); Δa^* = variation in the a^* parameter (red to green color); Δb^* = variation in the b^* parameter (yellow to blue color).

The instrumental texture was assessed through six repetitions using a TA-XT Plus texture analyzer, following method 74-09.01 [13]. For the analysis, 12 mm slices were overlapped to obtain the following parameters: firmness (N), hardness (N), cohesiveness, elasticity, gumminess (N), chewiness (N), and resilience. Before the analysis, the equipment was calibrated and configured with pre-test, test, and post-test speeds of 1.0, 1.0, and 5.0 mm/s, respectively; a compression level of 40%; a time interval between cycles of 1 second; and a detection threshold of 0.049 N. The analysis used a P/36R probe and HDP/90 platform in compression force mode.

2.1.5 Statistical Analysis

The normality of the data was assessed using the Shapiro–Wilk test. The raw material data were analyzed using the student's t-test ($P < 0.05$), while variance analysis was conducted for the bread samples. In cases where significant differences were identified, the Tukey test was applied for mean comparison, with a confidence level of 95%.

3. Results and Discussion

3.1 Characterization of Flours

The proximate composition is critical and directly influences the final product's sensory, nutritional, and technological properties. In the context of bakery products, the fiber and protein content of the flour are vital parameters of interest [16]. The purple corn cob flour (PCF) used in this study exhibited a protein content of 2.00 ± 0.18 g/100 g and a dietary fiber content of 75.21 ± 0.54 g/100 g. In contrast, wheat flour typically has a higher protein content (14.29 ± 0.34 g/100 g) and a lower dietary fiber content (2.05 ± 0.26 g/100 g) on average [9].

Furthermore, corn cob flour lacks gluten-forming proteins. Consequently, the partial substitution of wheat flour with corn cob flour is likely to reduce the gluten content of the formulation. This reduction can adversely affect the dough and the final product, as the viscoelastic network formed by glutelin and gliadin in the presence of water and mechanical action is responsible for the viscosity of the dough and the retention of carbon dioxide during fermentation. These factors contribute to the final product's volume, uniform alveolar structure, and soft texture [9].

Therefore, incorporating high-fiber flour in bakery products presents a challenge, as fibers compete with the proteins in wheat flour for dough hydration, impeding the formation of the gluten network. Conversely, the increasing demand for functional foods and growing environmental concerns have stimulated the use of agri-food by-products in food matrices. Additionally, the development of bread utilizing unconventional flour, such as corn cob flour, may help reduce processing costs and provide a potential source of income for small-scale farmers.

3.2 Characterization of Breads

The characteristics of the produced breads are presented in Table 2. Moisture content is a critical quality parameter for bread and positively influences consumer perception regarding the freshness of the finished product [17]. This parameter is closely related to the amount of water incorporated into the formulation and its composition, particularly concerning fiber content and the addition of enzymes.

Table 2 Technological characteristics of breads produced by partially replacing wheat flour with corn cob flour and adding hemicellulase enzymes.

Parameters		**F1**	**F2**	**F3**
Moisture (%)		36.03 ± 0.13^{b}	36.41 ± 0.13^{a}	36.06 ± 0.54^{b}
Water activity$^{(ns)}$		0.9684 ± <0.01	0.9699 ± <0.01	0.9678 ± <0.01
Specific volume (mL/g)		3.78 ± 0.07^{c}	4.17 ± 0.16^{b}	4.52 ± 0.02^{a}
Central slice height (cm)		7.34 ± 0.11^{c}	7.65 ± 0.17^{b}	8.24 ± 0.05^{a}
Color parameters	L^{*}	60.73 ± 1.57^{ab}	60.80 ± 0.77^{a}	58.54 ± 0.5^{b}
	$a^{*(ns)}$	3.58 ± 0.24	3.34 ± 0.08	3.63 ± 0.03
	$b^{*(ns)}$	14.36 ± 0.22	14.25 ± 0.12	3.78 ± 0.07
	ΔE	-	0.77 ± 0.31^{b}	2.27 ± 0.63^{a}

Values represent the arithmetic mean of three repetitions ± standard deviation. F1 = bread made with 5% corn cob flour without enzyme addition; F2 = bread with 5% corn cob flour and 40 ppm fungal hemicellulase; F3 = bread with 5% corn cob flour and 30 ppm bacterial hemicellulase. Different letters indicate statistical differences according to Tukey's test at a 5% probability level within the same row. ns = not significant.

Refined wheat flour typically contains approximately 2 to 3% arabinoxylans. Despite their relatively low concentration, arabinoxylans contribute to 30% of the hydration of wheat flour and play a crucial role in the quality of both the dough and the final product [18]. Conversely, a significant portion of the arabinoxylans in wheat and corn cob flour is insoluble in aqueous media, as they are complexed with macromolecules such as starch and protein.

When added, hemicellulases hydrolyze these interactions and solubilize arabinoxylans from wheat flour and corn cob flour. Consequently, the moisture content of the samples was increased with the addition of fungal hemicellulase (F2) compared to the control and the samples supplemented with bacterial enzymes (F1 and F3, respectively), as indicated in Table 2. This enhancement in moisture retention can be attributed to the increased water-holding capacity during baking, resulting from the solubilization of arabinoxylans in the formulation, which is facilitated by the action of the fungal enzyme.

Volume is a critical quality parameter for bread, closely linked to hydration and the development of the gluten network, which is responsible for the expansion and retention of carbon dioxide produced during fermentation [19]. Consequently, the incorporation of high-fiber flours, such as purple corn cob flour (PCF), negatively impacts the volume and ultimately affects the final product's texture. These undesirable effects arise from the capacity of dietary fibers to interact with water, attributed to the presence of free hydroxyl groups (-OH), which diminish the hydration of gluten-forming proteins in wheat flour (WF). As a result, bread containing high-fiber flours exhibits reduced volumes, a deficient alveolar structure, and significantly increased instrumental firmness and hardness parameters [20].

For comparative purposes, Jha et al. [21] reported specific bread volumes subjected to varying pressures during the dough mixing process, ranging from 4.01 to 4.29 mL/g, values similar to those observed in formulations with added enzymes. Costa et al. [22] found specific volumes ranging from 3.71 (day 1) to 3.32 (day 15) for breads containing 30% chickpea flour, which had a fiber content of 1.61 g, values comparable to those observed in formulations without enzyme addition. This indicates that the negative impacts of fiber addition can be mitigated by incorporating hemicellulases, which hydrolyze arabinoxylans in WF, facilitating the redistribution of water within the formulation. Consequently, the water retention capacity of arabinoxylans leads to increased dough viscosity and enhanced elasticity of the gluten network, thereby improving its stability. This stabilization reduces the diffusion of carbon dioxide to the external environment during baking, resulting in improved volume and textural attributes. Furthermore, the increased dough viscosity inhibits the coalescence of air bubbles, promoting a uniform distribution and satisfactory honeycomb structure.

The sample with bacterial hemicellulase (F3) exhibited a higher specific volume and central slice height than the fungal hemicellulase addition (F2). This difference can be attributed to the particular microorganisms employed in producing these enzymes. According to the specifications provided by Prozyn Biosolutions [23], the manufacturer of the enzymes used in this study, fungal hemicellulase enhances oven elasticity, improves dough development, and increases extensibility. In contrast, bacterial hemicellulase is noted for enhancing oven elasticity and increasing bread volume, corroborating the results obtained and highlighted in Figure 1.

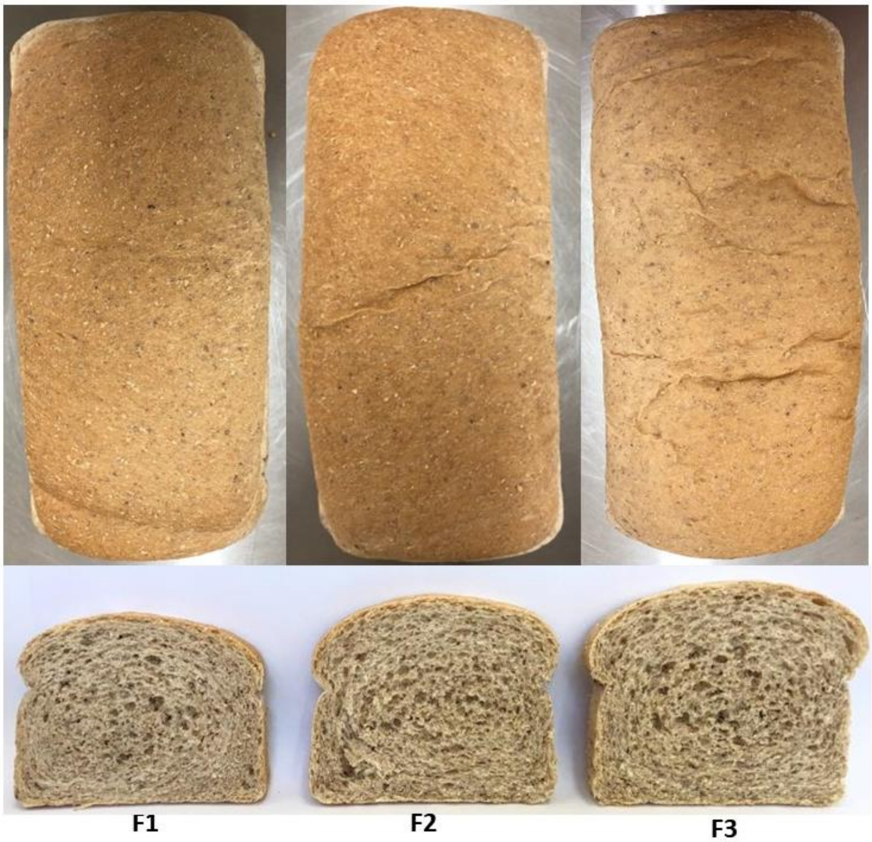

Figure 1 Bread samples were made by partially replacing wheat flour with corn cob flour and adding hemicellulase enzymes. F1 = Bread made with the addition of 5% corn cob flour without the addition of enzymes. F2 = Bread with 5% corn cob flour and 40 ppm fungal hemicellulase. F3 = Breads with 5% corn cob flour and 30 ppm bacterial hemicellulase.

Microbial-origin enzymes are derived from bacteria, fungi, and yeasts, each exhibiting specific actions resulting from their intrinsic ability to catalyze hydrolysis reactions. Different hemicellulolytic enzymes act on various structures of hemicellulose. For instance, certain fungi secrete high concentrations of a diverse array of hemicellulases that function synergistically. Aerobic bacteria produce several polysaccharide-degrading enzymes that yield relatively large oligosaccharide products. These variations may account for the differing results observed in this study, which can be attributed to the origin of the enzymes used [24].

According to Dahiya et al. [11], the application of hemicellulases in traditional bread contributes to the formation of the gluten network, enhances the rheological properties of the dough, and increases the overall volume. These factors may have played a significant role in achieving the characteristics observed in the bread samples with enzyme addition.

The color of the ingredients primarily influences the crumb color in the formulation. According to Nascimento et al. [9], the incorporation of corn cob flour into pan bread results in a significant darkening (indicated by a reduction in the L^* value) of the crumb compared to traditional products, which is considered undesirable since a lighter-colored crumb (higher L^* value) is generally more appealing to consumers. This effect on the hue is illustrated in Figure 2, which demonstrates the color difference between purple corn cob flour (PCF) and wheat flour (WF), directly impacting the instrumental color parameters of the bread.

Figure 2 Wheat flour (at left) and purple corn cob flour (at right).

The data obtained for the color of the bread indicate that the action of hemicellulases diminished the luminosity of the samples, likely due to the release of reducing sugars through the hydrolysis of fibers in both PCF and WF. This release favors the development of pigments through the Maillard reaction, contributing to the observed changes in color.

In this study, the samples did not exhibit significant differences regarding the *a** and *b** parameters. However, in pan bread samples produced without the addition of purple corn cob flour (PCF), distinct *a** and *b** values were observed [25]. This variation is attributed to the anthocyanins present in the corn variety used to produce the cob in this study, which intensifies the red coloration of the crumb (increased *a** value). Simultaneously, the partial substitution of wheat flour (WF) with PCF reduces carotenoids, thereby decreasing the intensity of the yellow coloration (reduced *b** value).

In this context, the samples displayed a slight instrumental color variation (ΔE) of less than 5, suggesting that untrained individuals may not perceive a difference from the control sample based solely on color [26].

The characteristics evaluated in the texture of the bread are presented in Table 3. The bread crumb forms a spongy structure influenced by several factors, including the development of the gluten network, the distribution and expansion of air bubbles, and their coalescence during processing, as well as the ingredients incorporated into the formulation. In this regard, the crumb is responsible for the textural properties of bread, which are instrumentally evaluated through texture profile analysis (TPA). These properties are closely linked to the food's composition, size, and geometry [27].

Table 3 Texture profile of breads produced by the partial replacement of wheat flour with corn cob flour and the addition of hemicellulase enzymes.

Parameters	**F1**	**F2**	**F3**
Firmness (N)	3.09 ± 0.34^{a}	2.94 ± 0.32^{a}	2.30 ± 0.24^{b}
Hardness (N)	4.47 ± 0.49^{a}	4.07 ± 0.54^{a}	3.16 ± 0.26^{b}
Cohesiveness (%)	62.81 ± 3.42	61.63 ± 2.74	64.89 ± 6.65
Resilience (%)	27.21 ± 1.24	27.57 ± 1.88	28.74 ± 3.33
Elasticity (%)	90.46 ± 2.18^{c}	92.04 ± 1.46^{b}	93.97 ± 1.93^{a}
Gumminess (N)	2.70 ± 0.34^{a}	2.52 ± 0.28^{a}	2.04 ± 0.18^{b}

Chewiness (N)	2.45 ± 0.31^a	2.33 ± 0.28^a	1.93 ± 0.23^b

Values are presented as the arithmetic mean of three repetitions ± standard deviation. F1 represents bread made with 5% corn cob flour without enzyme addition, F2 indicates bread with 5% corn cob flour and 40 ppm of fungal hemicellulase, and F3 denotes bread with 5% corn cob flour and 30 ppm of bacterial hemicellulase. Different letters in the same row indicate statistically significant differences, as determined by Tukey's test at a 5% probability level.

One of the primary parameters influencing the textural properties of bread is volume. Generally, a lower volume is associated with a more compact crumb, uneven air distribution, and a deficient alveolar structure, adversely affecting firmness (N), which is defined as the force required for 75% sample compression, hardness (N), representing the force necessary for 40% sample deformation, and cohesiveness (N), denoting the force required for food rupture. These factors ultimately diminish the sensory quality of the product [9].

Volume is inversely proportional to hardness and firmness, as demonstrated by the F1 bread samples, which exhibited the lowest volume and highest values for hardness and firmness. However, F2 did not statistically differ from F1 in hardness and firmness, indicating that bacterial hemicellulases were more effective in imparting softness to the bread, a critical factor in consumer sensory evaluations.

In a study by Moreton et al. [28], various commercial Italian breads were analyzed, with hardness values ranging from 4.45 to 42.37 N. Similarly, Gao and Zhou [27] reported hardness values ranging from 1.2 to 93.4 N for different bread types, noting that wheat breads generally exhibited lower hardness while rye breads had higher values.

Resilience, the sample's ability to recover volume after the first compression cycle, is a desirable attribute in breads, indicating product softness [29]. The addition of enzymes did not significantly affect the resilience of the samples, as no statistical differences were observed between the three formulations.

In F3, the bacterial enzymes enhanced elasticity and reduced gumminess and chewiness. Similar effects were observed in breads with added dextrans, where the addition led to decreased gumminess and chewiness [30]. This suggests that bacterial enzymes may not fully hydrolyze hemicelluloses, potentially resulting in the release of oligosaccharides.

Chewability, a texture parameter that correlates with sensory analysis, relates to the work required to chew the bread and is a function of hardness, cohesiveness, and elasticity. Elasticity is the dough's ability to recover after deformation, influenced by starch gelatinization and the gluten network. Lower elasticity values may result from gluten dilution. Therefore, adding bacterial enzymes (F3) mitigated the adverse effects of fiber addition on bread texture, addressing the technological challenges associated with high-fiber formulations [31].

4. Conclusions

The feasibility of using hemicellulolytic enzymes in the preparation of fiber-enriched breads from corn cob fibers was demonstrated in the study. These enzymes successfully addressed several key technological challenges associated with adding dietary fibers to bakery products. The incorporation of technological aids, rather than chemical ones, is aligned with current consumer expectations for clean labeling. Additionally, using agro-industrial residues in food preparation enables the effective use and reduction of waste from high-quality raw materials, thereby supporting sustainable food production, a fundamental pillar of sustainable food systems.

A specific volume increase of approximately 10% in the bread was achieved with the fungal-origin hemicellulolytic enzyme, along with reductions in firmness and hardness by 4.85% and 8.94%, respectively, compared to the control sample. In contrast, superior technological results were observed with the bacterial-origin enzyme in key bread quality parameters, including a ~20% increase in specific volume and reductions of 25.5% in firmness and 29.3% in hardness, compared to the sample without enzyme addition. Consequently, hemicellulolytic enzymes, particularly those of bacterial origin, were validated as a viable alternative for developing baked products that incorporate high-fiber flours, especially insoluble dietary fibers, while maintaining technological quality. However, future studies should assess the behavior of these enzymes with different concentrations of high-fiber flours, not only from corn cob but also from other raw materials, in conjunction with sensory and nutritional evaluations.

Acknowledgements

The authors thank the Federal University of Jequitinhonha and Mucuri Valleys and the Institute of Science and Technology for their institutional support. To the Coordination for the Improvement of Higher Education Personnel for giving financial support, financing code 001 and to the National Council for Scientific and Technological Development for the scholarship to T. M. Santos (protocol 138128/2022-7). To the Research Support Foundation of the State of Minas Gerais for granting the scholarship to I. Andressa (agreement 5310/15). To Prozyn Biosolutions for enzymes donation and to Creole Corn Project of the Institute of Agricultural Science for providing the purple corn cob.

Author Contributions

Nascimento, G. K. S.: Methodology, software, formal analysis, investigation, data curation, and writing- original draft. Santos, T. M.: Methodology, software, formal analysis, investigation and data curation. Andressa, I.: Methodology, software, formal analysis, investigation, data curation, original draft preparation and writing - review and editing. Benassi, V. M.: Methodology, formal analysis, investigation and data curation. Neves, N. A.: Methodology, formal analysis, investigation, data curation, writing - review and editing. Schmiele, M.: Conceptualization, methodology, software, formal analysis, project administration, supervision and funding acquisition. All authors have read and approved the published version of the manuscript.

Funding

Coordination for the Improvement of Higher Level Personnel - Capes (#001). National Council fo r Scientific and Technological Development - CNPq- (#138128/2022-7). Research Support Foundati on of the State of Minas Gerais - Fapemig (#5310/15).

Competing Interests

The authors have declared that no competing interests exist.

References

1. Polachini TC, Norwood EA, Le-Bail P, Le-Bail A. Clean-label techno-functional ingredients for baking products-A review. Crit Rev Food Sci Nutr. 2023; 63: 7461-7476.
2. Dymchenko A, Geršl M, Gregor T. Trends in bread waste utilisation. Trends Food Sci Technol. 2023; 132: 93-102.
3. Shokirov K, Kurbanov M, Atamuratova T, Khaydar-Zade L. Prospects of using natural non-conventional raw materials and secondary raw materials in the production of bread of specific purpose. E3S Web Conf. 2023; 390: 02036.
4. Ito M, Yoshimoto J, Maeda T, Ishii S, Wada Y, Kishi M, et al. Effects of high-fiber food product consumption and personal health record use on body mass index and bowel movement. J Funct Foods. 2023; 102: 105443.
5. Peng F, Ren X, Du B, Niu K, Yu Z, Yang Y. Insoluble dietary fiber of pear fruit pomace (*Pyrus ussuriensis* Maxim) consumption ameliorates alterations of the obesity-related features and gut microbiota caused by high-fat diet. J Funct Foods. 2022; 99: 105354.
6. Cai T, Ge-Zhang S, Song M. Anthocyanins in metabolites of purple corn. Front Plant Sci. 2023; 14: 1154535.
7. Yang Z, Zhai W. Identification and antioxidant activity of anthocyanins extracted from the seed and cob of purple corn (*Zea mays* L.). Innov Food Sci Emerg Technol. 2010; 11: 169-176.
8. Lau T, Clayton T, Harbourne N, Rodriguez-Garcia J, Oruna-Concha MJ. Sweet corn cob as a functional ingredient in bakery products. Food Chem X. 2022; 13: 100180.
9. Nascimento GK, dos Santos TM, Andressa I, Rodrigues SM, da Silva LE, Benassi VM, et al. Aplicabilidade da farinha de sabugo roxo de milho e do coquetel rico em xilanase produzido pelo fungo filamentoso *Fusarium* sp. EA 1.3. 1 em pães. Braz J Dev. 2023; 9: 8031-8050.
10. Lin S. Dietary fiber in bakery products: Source, processing, and function. Adv Food Nutr Res. 2022; 99: 37-100.
11. Dahiya S, Bajaj BK, Kumar A, Tiwari SK, Singh B. A review on biotechnological potential of multifarious enzymes in bread making. Process Biochem. 2020; 99: 290-306.
12. EFSA Panel on Food Contact Materials, Enzymes and Processing Aids (CEP), Lambré C, Barat Baviera JM, Bolognesi C, Cocconcelli PS, et al. Safety evaluation of the food enzyme glucan-1,4-α-maltohydrolase from the genetically modified *Bacillus subtilis* strain AR-453. EFSA J. 2023; 21: e08089.
13. AACCI. Approved Methods of AACCI, 11th ed.; Methods 46-13.01, 80-51.01, 10-05.01 and 74-09.01. St. Paul, MN, USA: The American Association of Cereal Chemists International; 2010.
14. AOAC. Approved Methods of Analysis of AOAC International, 21st ed.; Methods 982.14 and 978.10. Gaithersburg, MD, USA: The Association of Official Analysis AOAC International; 2019.
15. Silva JD, Rosa GC, Neves, NA, Leoro MG, Schmiele M. Production of sourdough and gluten-free bread with brown rice and carioca and cowpea beans flours: Biochemical, nutritional and structural characteristics. Res Soc Dev. 2021; 10: e303101623992.
16. Wu J, Warren FJ. The impact of the soluble protein fraction and kernel hardness on wheat flour starch digestibility. Food Chem. 2023; 406: 135047.
17. Cauvain S. Technology of Breadmaking. Cham, Switzerland: Springer International Publishing; 2015.
18. Roets C, Rose SH, Muller M, Manley M. Laboratory and commercial-scale evaluation of the

effect of pure and commercial endoxylanases and endoglucanases on wheat flour bread quality. Acta Aliment. 2015; 44: 276-288.

19. Calderón A, Bonilla S, Schmiele M, Navarrete D, Vernaza MG. Study of Lupinus mutabilis sweet flour incorporation on the rheological, physical, chemical, and sensory properties of wheat bread. J Food Process Preserv. 2022; 46: e17027.
20. Schmiele M, Jaekel LZ, Maris S, Patricio C, Steel CJ, Chang YK. Rheological properties of wheat flour and quality characteristics of pan bread as modified by partial additions of wheat bran or whole grain wheat flour. Int J Food Sci Technol. 2012; 47: 2141–2150.
21. Jha PK, Sadot M, Chevallier S, Rawson A, Le-Bail A. Impact of overhead pressure during mixing on the quality of sandwich bread. Food Bioprocess Technol. 2022; 15: 1896-1906.
22. Costa RT, Silva SC, Silva LS, Silva WA, Gonçalves AC, Pires CV, et al. Whole chickpea flour as an ingredient for improving the nutritional quality of sandwich bread: Effects on sensory acceptance, texture profile, and technological properties. Rev Chil Nutr. 2020; 47: 933-940.
23. Prozyn Biosolutions. São Paulo; 2021. Available from: https://prozyn.com.br/.
24. Souza TS, Kawaguti HY. Cellulases, hemicellulases, and pectinases: Applications in the food and beverage industry. Food Bioprocess Technol. 2021; 14: 1446-1477.
25. Neves NA, Gomes PT, Schmiele M. Na exploratory study about the preparation and evaluation of sourdough breads with araticum pulp (Annona crassiflora Mart.). Res Soc Dev. 2020; 9: e956998036.
26. Mokrzycki W, Tatol M. Color difference Delta E – A survey. Mach Graph Vis. 2011; 20: 383–411.
27. Gao J, Zhou W. Oral processing of bread: Implications of designing healthier bread products. Trends Food Sci Technol. 2021; 112: 720-734.
28. Moretton M, Cattaneo C, Mosca AC, Proserpio C, Anese M, Pagliarini E, et al. Identification of desirable mechanical and sensory properties of bread for the elderly. Food Qual Prefer. 2023; 104: 104716.
29. Guiné RPF. Textural properties of bakery products: A review of instrumental and sensory evaluation studies. Appl Sci. 2022; 12: 8628.
30. Wang Y, Trani A, Knaapila A, Hietala S, Coda R, Katina K, et al. The effect of in situ produced dextran on flavour and texture perception of wholegrain sorghum bread. Food Hydrocoll. 2020; 106: 105913.
31. Hussein AS, Fouad M, El-Shenawy M. Production of functional Pan bread from mixture of Tiger nut flour, milk permeate and hard wheat flour. Egypt J Chem. 2022; 65: 517-525.