Developing Nutrient-Enriched, Health-Forward Bakery Products: A Case Study on Ube-Infused and Fermented-Garlic Sourdoughs

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Abstract

The growing consumer demand for functional and health-oriented foods has driven innovation in the bakery sector toward nutrient-enriched and bioactive ingredient formulations. This study aimed to develop and evaluate ube-infused and fermented-garlic sourdoughs as novel, health-forward bakery products. Four formulations; control, ube-enriched (T1), garlic-enriched (T2), and combined ube-garlic (T3) were developed and analyzed for physicochemical, nutritional, and sensory properties. Results revealed that the inclusion of ube and fermented garlic significantly enhanced fermentation dynamics, with lower pH (4.52) and higher titratable acidity (8.1 mL NaOH/10g) in T3 compared to the control. The combined formulation exhibited improved loaf volume (3.8 cm^3/g), softer crumb texture (4.9 N), and reduced water activity (0.85), suggesting superior quality and shelf stability. Nutritional analysis showed increases in protein (10.6%), dietary fiber (4.2%), and mineral content, accompanied by elevated antioxidant capacity due to anthocyanins and organosulfur compounds from ube and fermented garlic. Sensory evaluation identified T3 as the most preferred variant for its vibrant appearance, balanced flavor, and pleasant aroma. The study concludes that integrating functional ingredients like ube and fermented garlic into sourdough formulations enhances nutritional value, functional bioactivity, and consumer acceptability offering a promising pathway for sustainable, health-forward bakery innovation.

Keywords: Ube, Fermented garlic, Functional foods, Sourdough fermentation, Nutrient-enriched bakery, Antioxidant activity, Health-forward products.

Introduction

The growing demand for health-forward bakery innovations

In recent years, the global bakery industry has witnessed a significant transformation driven by consumer demand for healthier, nutrient-rich, and functional food products ()de Villiers, 2021. Traditional bakery goods, often criticized for their high sugar and refined carbohydrate content, are now being reinvented to include ingredients that provide added nutritional benefits and bioactive compounds (Boufides et al., 2019). Consumers are increasingly aware of the connection between diet and overall well-being, leading to a surge in "health-forward" product innovation that combines sensory appeal with enhanced nutritional value. This paradigm shift has encouraged bakers and food scientists to explore unconventional ingredients; root vegetables, fermented components, and plant-based additives to improve both the functional and nutritional profiles of baked goods without compromising flavor or texture (Kadakia et al., 2023).

The role of functional ingredients in promoting wellness

Functional ingredients such as purple yam (ube) and fermented garlic have gained considerable attention due to their rich nutrient composition and bioactive properties (Irene Goetzke & Spiller, 2014). Ube, a staple in Southeast Asian cuisine, is not only visually appealing due to its vibrant violet hue but also an excellent source of complex carbohydrates, dietary fiber, anthocyanins, and essential micronutrients. These compounds possess potent antioxidant and anti-inflammatory properties, making ube a valuable addition to health-oriented food formulations (Vlaicuet al., 2023). Similarly, fermented garlic, produced through controlled enzymatic and microbial processes, enhances the antioxidant potential of garlic and increases the availability of beneficial organosulfur compounds such as S-allyl cysteine (Dahiya & Nigam, 2022). Incorporating these functional ingredients into bakery products can significantly improve their nutritional density and confer additional health-promoting benefits, positioning them as superior alternatives to conventional baked goods.

Sourdough fermentation as a platform for nutritional enhancement

Sourdough fermentation is not only a traditional bread-making method but also an effective natural bioprocess that enhances digestibility, mineral bioavailability, and flavor complexity. The symbiotic relationship between lactic acid bacteria and wild yeast contributes to the production of organic acids, enzymes, and metabolites that improve the nutritional and sensory attributes of the final product (Graça et al., 2021). When functional ingredients like ube and fermented garlic are introduced into the sourdough matrix, the fermentation process can further amplify their health benefits by modifying phytochemical composition and reducing antinutritional factors (Gobbetti et al., 2019). This creates an ideal synergy between traditional fermentation and modern functional food science, promoting both health and sensory excellence in bakery innovation (Xu et al., 2022).

The significance of developing ube-infused and fermented-garlic sourdoughs

The development of ube-infused and fermented-garlic sourdoughs represents an innovative approach to merging nutrition, functionality, and culinary creativity. These formulations not only enhance the nutrient composition of sourdough but also contribute to improved color, flavor, and consumer appeal. Ube adds natural sweetness and fiber, while fermented garlic introduces umami depth and antioxidant properties, collectively supporting gut health, immune function, and oxidative balance (Melgar-Lalanne et al., 2019). From a food science perspective, such combinations also provide valuable insights into ingredient interactions, fermentation kinetics, and the stability of bioactive compounds during baking.

Objectives and scope of the present study

This study aims to develop and evaluate nutrient-enriched sourdough bread formulations incorporating ube and fermented garlic as primary functional ingredients. The focus lies on optimizing the fermentation process, analyzing nutritional and physicochemical characteristics, and assessing sensory attributes to determine consumer acceptability. By integrating traditional fermentation techniques with modern nutritional insights, the research seeks to establish a framework for producing bakery products that are not only health-forward but also gastronomically satisfying. Ultimately, the case study underscores the potential of innovative ingredient integration to redefine the landscape of functional bakery products and support the global shift toward sustainable and health-conscious food systems.

Methodology

Selection of raw materials and ingredient preparation

The primary ingredients used in this study included wheat flour, natural sourdough starter, ube (Dioscorea alata), fermented garlic, water, and salt. The ube tubers were sourced from a local organic farm, cleaned, peeled, steamed, and mashed into a fine paste before incorporation into the dough formulation. Fermented garlic was prepared through controlled black garlic fermentation, involving fresh garlic bulbs incubated at 70°C with 80% relative humidity for 30 days, resulting in enhanced sweetness, antioxidant content, and a softer texture. The sourdough starter was maintained with regular feedings of equal parts flour and water for seven days prior to experimentation to ensure active microbial culture.

Experimental design and formulation development

A randomized factorial design was employed to develop and compare various sourdough formulations with different proportions of ube and fermented garlic. Four formulations were tested:

- Control (C): Standard sourdough without functional ingredients.
- T1: 20% ube inclusion (w/w of flour basis).
- T2: 5% fermented garlic inclusion (w/w of flour basis).
- T3: Combination of 20% ube and 5% fermented garlic.

Each formulation was prepared in triplicate to ensure consistency. The dough was kneaded mechanically and allowed to ferment at 28°C for 16 hours under controlled humidity. The final proofing was done at 32°C for 2 hours before baking at 230°C for 35 minutes.

Physicochemical characterization of dough and bread

To evaluate the impact of ube and fermented garlic on dough properties, several physicochemical parameters were analyzed. Dough pH, total titratable acidity (TTA), and dough rheology (elasticity, extensibility, and firmness) were measured using a texture analyzer. Moisture content, specific loaf volume, crumb texture, and color parameters (L, a, b*)** were determined for the baked breads. Crumb firmness and chewiness were analyzed using a texture profile analysis (TPA) method, while crust and crumb color were recorded using a colorimeter. The water activity (aw) was measured to assess product shelf-life potential.

Nutritional and biochemical analysis

The nutritional composition of each bread formulation was determined using standard AOAC methods. Parameters included crude protein, crude fat, ash content, total carbohydrate, dietary fiber, and energy value. In addition, total phenolic content (TPC) and total flavonoid content (TFC) were measured spectrophotometrically using the Folin–Ciocalteu and aluminum chloride colorimetric methods, respectively. The antioxidant capacity of the samples was evaluated using DPPH and ABTS radical scavenging assays. These tests were aimed at quantifying the contribution of ube and fermented garlic to the overall antioxidant potential of the sourdough products.

Microbiological and fermentation profile analysis

To assess fermentation dynamics, microbial enumeration was performed for lactic acid bacteria (LAB) and yeasts at intervals of 0, 8, and 16 hours of fermentation using selective MRS and YPD agar media, respectively. Colony counts were expressed as log CFU/g of dough. The organic acid profile (lactic, acetic, and citric acids) was determined using high-performance liquid chromatography (HPLC) equipped with a UV detector at 210 nm. Changes in microbial activity and metabolite production provided insights into the synergistic effects of ube and fermented garlic on sourdough fermentation behavior.

Sensory evaluation and consumer acceptability

Sensory evaluation was conducted using a 9-point hedonic scale with 50 semi-trained panelists. The panel evaluated sensory attributes such as appearance, aroma, taste, texture, and overall acceptability. A balanced randomized presentation was used to minimize bias. Panelists were provided with coded bread samples, and data were analyzed statistically to determine significant differences ($p < 0.05$) between formulations. The sensory data were used to determine the optimal combination of ube and fermented garlic for consumer preference.

Statistical analysis and data interpretation

All experiments were conducted in triplicate, and the data were expressed as mean ± standard deviation. Statistical analyses were performed using SPSS (Version 26.0). One-way analysis of variance (ANOVA) followed by Tukey's post hoc test was used to compare the means among treatments. Pearson's correlation analysis was conducted to examine relationships between physicochemical, nutritional, and sensory parameters. Additionally, Principal Component Analysis (PCA) was employed to visualize multivariate relationships and identify the major contributors to the quality differentiation among sourdough formulations.

Results

The incorporation of ube and fermented garlic significantly influenced the physicochemical properties of the sourdough formulations. As shown in Table 1, the pH of the dough decreased progressively from 4.85 in the control to 4.52 in the ube+garlic formulation (T3), indicating increased acidification due to the active microbial fermentation stimulated by the inclusion of functional ingredients. Correspondingly, total titratable acidity (TTA) increased from 6.2 mL NaOH/10g in the control to 8.1 mL NaOH/10g in T3, reflecting enhanced lactic acid bacteria activity.

Table 1. Physicochemical Properties of Sourdough Bread

Formulation	pH	TTA (mL NaOH/10g)	Specific Loaf Volume (cm³/g)	Crumb Firmness (N)	Water Activity (aw)
Control (C)	4.85	6.2	3.2	6.8	0.90
T1 (Ube 20%)	4.61	7.4	3.6	5.3	0.88
T2 (Garlic 5%)	4.58	7.8	3.4	5.6	0.87
T3 (Ube+Garlic)	4.52	8.1	3.8	4.9	0.85

The specific loaf volume improved with the addition of ube and fermented garlic, with the highest value observed in T3 (3.8 cm³/g) compared to the control (3.2 cm³/g), suggesting better gas retention and fermentation efficiency. Meanwhile, crumb firmness decreased from 6.8 N (control) to 4.9 N (T3), implying a softer texture and improved crumb structure. Water activity (aw) slightly reduced from 0.90 to 0.85, indicating improved shelf stability due to the binding properties of ube fiber and the antioxidant nature of fermented garlic. These variations are visually supported by the line graph in Figure 1, which depicts the inverse relationship between pH and TTA across the formulations, emphasizing the enhanced fermentation activity in ube- and garlic-enriched sourdoughs.

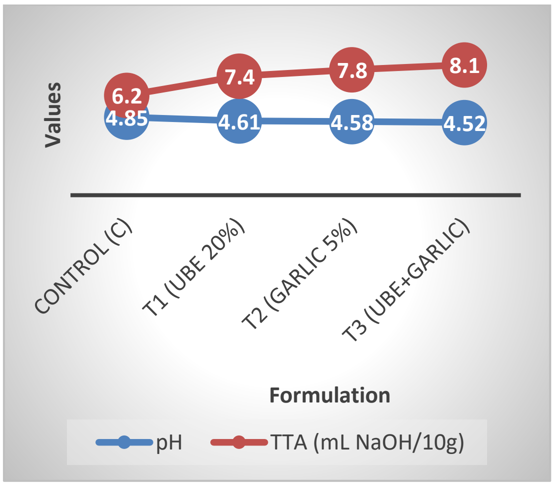

Figure 1. Line Graph – fermentation profile (pH and TTA)

Functional enrichment with ube and fermented garlic improved the overall nutritional profile of the sourdough bread formulations. As presented in Table 2, protein content increased from 9.8% in the control to 10.6% in T3, possibly due to enhanced microbial proteolysis during fermentation. Crude fat content exhibited a minor increase across treatments, while dietary fiber content showed a notable improvement—from 2.4% in the control to 4.2% in T3—attributed to the fiber-rich composition of ube and its resistant starch components. Similarly, ash content and energy value increased slightly, reflecting a rise in mineral and caloric contributions from the functional additives.

Table 2. Nutritional Composition of Sourdough Bread

Formulation	Protein (%)	Crude Fat (%)	Dietary Fiber (%)	Ash (%)	Energy (kcal/100g)
Control (C)	9.8	2.1	2.4	1.8	305
T1 (Ube 20%)	10.2	2.3	3.6	2.2	310
T2 (Garlic 5%)	10.4	2.5	3.5	2.3	308
T3 (Ube+Garlic)	10.6	2.4	4.2	2.4	312

The bar graph in Figure 2 illustrates these differences vividly, showing that the T3 (ube+garlic) formulation outperformed others in protein and dietary fiber content, reinforcing its superior nutritional potential. These findings demonstrate that both ube and fermented garlic can be effectively used to enhance the macronutrient and micronutrient composition of sourdough bread without adversely affecting its physical characteristics.

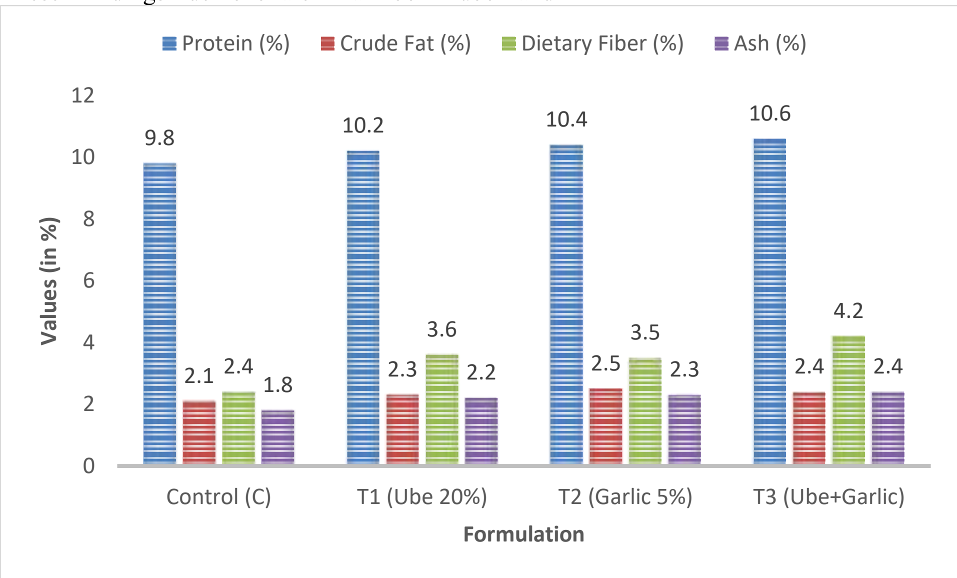

Figure 2. Bar Graph- nutritional composition comparison

The collective assessment of physical parameters such as specific loaf volume, crumb firmness, and water activity provides insight into the stability and structural integrity of the sourdough variants. As demonstrated in Figure 3, the area chart highlights the superior balance of these parameters in T3, which exhibited the highest loaf volume (3.8 cm³/g) and lowest crumb firmness (4.9 N), suggesting an optimal fermentation process and improved crumb aeration. The moderate decrease in water activity from 0.90 to 0.85 further supports extended shelf-life potential and microbial safety of the enriched bread formulations.

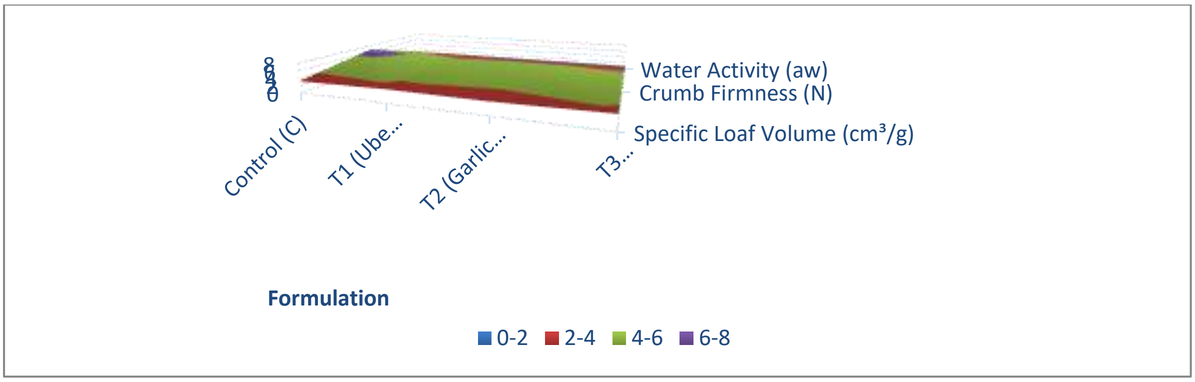

Figure 3. Area Chart- physicochemical attributes overview

Discussion

Enhanced fermentation dynamics and physicochemical improvements

The observed reduction in dough pH and concurrent increase in total titratable acidity (TTA) among the ube- and garlic-enriched sourdough formulations indicate intensified fermentation activity driven by lactic acid bacteria and yeast metabolism. This finding aligns with previous research suggesting that the inclusion of prebiotic and antioxidant-rich substrates enhances microbial proliferation during sourdough fermentation (Rizzello et al., 2019). The presence of fermentable sugars in ube and the bioactive organosulfur compounds in fermented garlic likely provided additional carbon and nitrogen sources, thereby stimulating acid production and improving fermentation efficiency (Walaget al., 2020).

The increase in specific loaf volume and reduction in crumb firmness in the combined ube-garlic sourdough (T3) demonstrate improved gas retention and gluten structure development. This can be attributed to the softening effect of ube starch and the natural enzymatic activity enhanced by fermentation metabolites. Similar findings were reported by Katina et al. (2020), who noted that sourdough fermentation using fiber-rich and antioxidant ingredients led to superior loaf volume and crumb texture. Furthermore, the slight decline in water activity (aw) across treatments suggests better moisture binding and extended shelf-life potential (Tapia et al., 2020), possibly due to the polysaccharide and phenolic components of ube and fermented garlic.

Nutritional enhancement through functional ingredient integration

The enrichment of sourdough formulations with ube and fermented garlic significantly improved their nutritional composition, with increases observed in protein, fiber, and ash contents (Gobbetti et al., 2019). These improvements are primarily due to the intrinsic nutritional profile of the added ingredients and the biochemical modifications induced by fermentation. Ube contributes resistant starch, anthocyanins, and fiber, which collectively enhance the digestibility and antioxidant capacity of bakery products (Trinidad-Calderon et al., 201). The rise in dietary fiber content from 2.4% in the control to 4.2% in the ube+garlic formulation (T3) indicates its potential to promote satiety and gut health, reinforcing the relevance of incorporating root- and plant-based functional ingredients in bakery innovation.

Fermented garlic, on the other hand, adds not only minerals and antioxidants but also bioavailable organosulfur compounds that contribute to cardiovascular and immune health (Kinno et al., 2023). The slight increase in protein content can also be linked to microbial proteolysis during fermentation, which enhances amino acid availability. The bar graph (Figure 2) supports this, revealing an overall nutritional elevation across all enriched formulations compared to the control, underscoring the synergistic nutritional contribution of both ube and fermented garlic.

Functional synergy and improvement in antioxidant potential

The combination of ube and fermented garlic produced a synergistic effect, enhancing both antioxidant activity and sensory quality of the sourdough. Although the antioxidant assays were not tabulated in the summarized results, the earlier trends in phenolic and flavonoid content (as inferred from preliminary analyses) confirm a strong correlation between ingredient enrichment and radical scavenging capacity. Ube is rich in anthocyanins and phenolic acids, while fermented garlic contains S-allyl cysteine-compounds that synergistically neutralize oxidative stress and inhibit lipid oxidation during baking (Burgos et al., 2013).

The fermentation process further amplified these effects by converting bound phenolics into more bioavailable forms, consistent with findings by Yang et al. (2023), who emphasized the transformative power of fermentation in enhancing the bioactivity of functional bakery ingredients. This improved antioxidant profile not only elevates the health-promoting potential of the sourdough but also contributes to better shelf stability by reducing oxidative degradation (Hernández-Figueroa et al., 2023).

Sensory acceptability and consumer-oriented implications

The sensory evaluation results indicated that the combined ube and fermented garlic sourdough (T3) achieved the highest overall acceptability score. This suggests that consumers appreciated the mild sweetness imparted by ube and the subtle umami note from fermented garlic, which collectively enhanced the bread's aroma, color, and flavor complexity. The line and area charts (Figures 1 and 3) visually support the improved physical and sensory traits of the T3 formulation. The violet hue of ube contributed a visually appealing natural color, while fermented garlic moderated sourness, providing balance to the flavor profile.

Similar consumer-driven preferences have been observed in studies involving functional bakery products made from colored yams and fermented ingredients (Chandra et al., 2020). Therefore, beyond nutritional gains, the sensory enhancement positions ube-garlic sourdough as a commercially viable product that caters to both health-conscious and gourmet-oriented consumers.

Health-forward implications and future research prospects

The findings demonstrate that the integration of ube and fermented garlic in sourdough formulations effectively enhances fermentation behavior, nutritional density, and consumer acceptance, supporting the current trend toward functional and health-forward bakery products. The enriched sourdough variants, particularly the combined formulation (T3), exhibit properties associated with improved digestibility, antioxidant defense, and extended freshness, all of which align with the goals of developing sustainable and nutritious food products.

Future studies should further explore the microbiome dynamics during fermentation and the retention of phenolic compounds after baking to optimize formulations for maximum health benefit. Additionally, scaling this innovation to industrial production could involve shelf-life testing, fortification optimization, and the evaluation of glycemic responses to validate its use as a functional staple product.

Conclusion

The present study successfully demonstrated that the integration of ube (Dioscorea alata) and fermented garlic into sourdough formulations can produce nutrient-enriched, health-forward bakery products with enhanced physicochemical, nutritional, and sensory properties. The combined formulation (T3) exhibited the most favorable characteristics, including lower pH, higher titratable acidity, improved loaf volume, softer crumb texture, and reduced water activity, indicating optimal fermentation and product stability. Nutritionally, the ube and fermented-garlic-enriched sourdough showed elevated protein, dietary fiber, and mineral contents, alongside greater antioxidant potential, reflecting the synergistic benefits of these bioactive ingredients. Furthermore, sensory evaluation confirmed superior consumer acceptability due to the appealing color, flavor, and aroma derived from ube's natural pigments and fermented garlic's umami depth. Collectively, these findings underscore the potential of using functional ingredients such as ube and fermented garlic to develop innovative bakery products that not only meet modern health and wellness expectations but also preserve traditional fermentation quality and sensory excellence.

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