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TECHNOLOGICAL APPROACHES TO THE PRODUCTION OF CEREAL-BASED FUNCTIONAL BEVERAGES

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Abstract

The increasing demand for healthy and sustainable food products has stimulated significant interest in cereal-based functional beverages as alternatives to traditional dairy and sugar-rich drinks. Cereals represent an important source of dietary fiber, bioactive compounds, vitamins, and minerals, making them suitable raw materials for the development of nutritionally enhanced beverages. Technological approaches such as fermentation, enzymatic treatment, and controlled processing play a crucial role in improving the functional, sensory, and digestive properties of cereal-based drinks.

This article analyzes modern technological approaches used in the production of cereal-based functional beverages, with particular emphasis on processing methods that enhance biological activity, nutrient bioavailability, and product stability. The interaction between cereal components and technological parameters is discussed in relation to beverage quality, digestibility, and functional potential. The study highlights the importance of selecting appropriate processing technologies to optimize the health-promoting properties of cereal-based beverages and support their application in functional nutrition.

Keywords: Cereal-based beverages; functional drinks; food technology; fermentation; enzymatic treatment; bioactive compounds; digestibility.

INTRODUCTION

In recent years, global trends in nutrition have increasingly shifted toward the consumption of functional foods and beverages that provide health benefits beyond basic nourishment. This shift is driven by growing consumer awareness of diet-related health issues, including digestive disorders, metabolic diseases, and nutrient deficiencies. As a result, there is a rising demand for innovative beverages that combine nutritional value, functional properties, and sustainable production practices. Cereal-based beverages have emerged as promising functional products due to the rich composition of cereal grains. Cereals such as oats, barley, wheat, rice, and millet contain significant amounts of dietary fiber, complex carbohydrates, proteins, vitamins, and biologically active compounds. These components contribute to improved digestive health, regulation of blood glucose levels, and overall metabolic balance. In addition, cereal-based beverages are suitable for consumers seeking plant-based, lactose-free, or low-allergen alternatives to dairy products.

The production of cereal-based functional beverages requires the application of appropriate technological approaches to ensure product safety, stability, and functional efficiency. Processing methods such as soaking, milling, enzymatic hydrolysis, fermentation, and thermal treatment are essential for improving nutrient availability, reducing antinutritional factors, and enhancing sensory characteristics. Among these methods, fermentation has gained particular attention due to its ability to increase biological activity through the formation of beneficial metabolites and the activation of probiotic microorganisms.

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Cereal-based functional beverages have gained increasing attention in food science due to their nutritional value, technological versatility, and potential health benefits. Cereals are widely recognized as essential sources of complex carbohydrates, dietary fiber, vitamins, minerals, and bioactive compounds that contribute to human health and disease prevention [1,2]. The utilization of cereals in beverage production has been driven by growing consumer demand for plant-based, lactose-free, and functional alternatives to conventional drinks [3].

Several studies emphasize that cereal grains such as oats, barley, rice, wheat, and millet are particularly suitable for beverage formulations due to their favorable composition and processing adaptability [4,5]. Oats and barley are rich in β-glucans, which have been associated with improved digestive health, cholesterol reduction, and glycemic control [6,7]. Rice-based beverages, on the other hand, are valued for their hypoallergenic properties and mild sensory profile, making them suitable for sensitive consumer groups [8].

Technological processing plays a critical role in determining the functional quality of cereal-based beverages. Traditional methods such as soaking, milling, and thermal treatment are commonly applied to improve extractability and microbiological safety [9]. However, these methods alone are often insufficient to maximize nutrient bioavailability and functional performance. As a result, modern technological approaches increasingly rely on enzymatic hydrolysis and fermentation to enhance the nutritional and biological value of cereal-based drinks [10].

Enzymatic treatment has been shown to effectively break down complex polysaccharides and antinutritional factors, thereby improving digestibility and nutrient absorption [11]. The application of amylases, cellulases, and proteases facilitates starch degradation and protein hydrolysis, resulting in smoother texture and improved mouthfeel of beverages [12]. Moreover, enzymatic processing contributes to the release of bioactive compounds that enhance the functional profile of cereal-based drinks [13].

Fermentation represents one of the most promising technological approaches in the production of cereal-based functional beverages. Numerous studies report that fermentation with lactic acid bacteria and yeast improves biological activity, enhances antioxidant capacity, and supports gut microbiota balance [14,15]. Fermented cereal beverages such as traditional cereal-based drinks and modern probiotic formulations demonstrate increased levels of organic acids, bioactive peptides, and vitamins [16].

The interaction between cereal substrates and microbial cultures during fermentation has been widely investigated. Research indicates that cereal fibers act as prebiotics, stimulating the growth and survival of beneficial microorganisms [17]. This probiotic–prebiotic synergy is considered a key factor in the development of functional beverages with enhanced health-promoting properties [18]. However, the effectiveness of fermentation largely depends on cereal type, starter culture selection, and processing conditions [19].

Despite significant progress, the literature highlights several challenges associated with cereal-based beverage technologies. Issues related to flavor development, sedimentation, viscosity control, and shelf-life stability remain major obstacles for industrial-scale production [20]. Additionally, the presence of antinutritional compounds such as phytic acid may limit mineral bioavailability if not adequately addressed through processing [21].

Recent studies increasingly focus on optimizing technological parameters and combining multiple processing methods to overcome these challenges. Integrated approaches that combine enzymatic

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treatment, fermentation, and controlled thermal processing have shown promising results in improving product stability, digestibility, and consumer acceptance [22,23]. Furthermore, the use of local cereal varieties and sustainable processing technologies is gaining attention as a strategy to enhance nutritional value and reduce environmental impact [24].

Overall, existing research confirms the strong potential of cereal-based functional beverages as health-oriented products. However, further studies are needed to optimize technological approaches, evaluate long-term health effects, and standardize processing conditions to support wider industrial application.

METHODS

This study employed an experimental and analytical research approach to investigate technological methods used in the production of cereal-based functional beverages and their influence on product quality and functional properties. The research focused on comparing traditional and modern processing techniques in order to evaluate their effectiveness in improving biological activity, digestibility-related characteristics, and overall beverage functionality.

Cereal grains commonly used in functional beverage production, including oats (*Avena sativa*), barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), and rice (*Oryza sativa*), were selected as the primary raw materials based on their nutritional composition, technological suitability, and relevance to plant-based beverage development. Potable water was used as the extraction medium, and food-grade starter cultures of lactic acid bacteria were applied in fermented formulations. All raw materials were prepared under controlled laboratory conditions to ensure consistency and reproducibility.

The technological process involved several sequential stages. Initially, cereal grains were cleaned and sorted to remove foreign materials, followed by soaking to improve hydration and soften the grain structure. The soaked cereals were then milled into a homogeneous slurry to enhance the release of nutrients and soluble components. Thermal treatment was applied to the cereal slurry to ensure microbiological safety, promote starch gelatinization, and stabilize the beverage matrix. In selected samples, enzymatic treatment using food-grade amylases and cellulases was applied to hydrolyze complex carbohydrates, reduce viscosity, and improve texture and mouthfeel.

For fermentation-based beverage formulations, the processed cereal substrates were inoculated with lactic acid bacteria and incubated under controlled temperature and time conditions. Fermentation was conducted until stable acidity and product consistency were achieved. Non-fermented cereal beverages produced under identical processing conditions were used as control samples to allow comparative evaluation of the effects of fermentation. Processing parameters such as temperature, duration, and enzyme dosage were carefully controlled throughout the experiments.

Functional properties of the cereal-based beverages were evaluated using physicochemical and structural indicators commonly reported in food science literature. Biological activity was assessed indirectly through indicators related to dietary fiber contribution, fermentation performance, and matrix structure. Digestibility-related characteristics were evaluated using a standardized in vitro digestion model simulating oral, gastric, and intestinal phases, allowing observation of structural changes and nutrient release behavior during digestion.

Data analysis was carried out using descriptive and comparative methods. Results obtained from different technological approaches were systematically compared to identify trends and relative improvements in functional quality and digestibility-related properties. Mean values were calculated

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where applicable, and the interpretation of results focused on technological relevance and nutritional implications rather than inferential statistical testing, in line with the exploratory nature of the study. The reliability of the research was ensured by maintaining standardized processing conditions, consistent raw material preparation, and repeatable experimental procedures. Validity was supported through the application of widely accepted technological models and analytical approaches documented in peer-reviewed scientific literature. The use of control formulations and reproducible methodologies strengthened the credibility and scientific rigor of the findings.

RESULTS AND DISCUSSION

The results of this study indicate that technological approaches applied during the production of cereal-based functional beverages significantly influence their functional quality, digestibility-related characteristics, and overall technological performance. Comparative analysis of beverages produced using thermal processing alone, enzymatic treatment, and fermentation revealed clear differences in biological activity, matrix stability, and digestibility behavior.

Cereal-based beverages produced using basic thermal treatment showed acceptable microbiological stability; however, their functional characteristics were limited by higher viscosity, sedimentation tendency, and reduced nutrient availability. In contrast, enzymatic treatment improved starch and fiber breakdown, resulting in smoother texture and enhanced extractability of soluble components. Fermentation-based beverages demonstrated the most pronounced functional improvements, including enhanced biological activity, improved matrix stability, and favorable digestibility-related properties.

A comparative summary of the main functional and technological indicators observed for different processing approaches is presented in Table 1.

Table 1.

Effect of technological approaches on functional and digestibility-related properties of cereal-based beverages

Processing approach	Biological activity level	Digestibility characteristics	Matrix stability	Functional value
Thermal treatment only	Moderate	Limited nutrient release	Moderate sedimentation	Moderate
Enzymatic treatment	High	Improved nutrient availability	Improved homogeneity	High
Fermentation	Very high	Gradual and controlled digestion	High stability	Very high

The data in Table 1 demonstrate that fermentation is the most effective technological approach for enhancing the functional properties of cereal-based beverages. The increased biological activity observed in fermented samples can be attributed to microbial metabolism, which promotes the formation of organic acids, bioactive compounds, and improved availability of nutrients. These findings are consistent with previous studies reporting the positive role of fermentation in improving the nutritional and functional quality of cereal-based products.

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Digestibility-related analysis revealed that enzymatic and fermented beverages exhibited more controlled nutrient release during simulated digestion compared to thermally treated samples. Enzymatic hydrolysis reduced the complexity of polysaccharides, facilitating enzymatic access during digestion and improving gastrointestinal tolerance. Fermented beverages further enhanced this effect by modifying the food matrix through microbial activity, resulting in gradual breakdown and improved digestibility without compromising product structure.

In addition to quantitative comparison, qualitative observations highlighted important technological differences. Thermally treated beverages showed phase separation during storage, indicating limited matrix stability. Enzymatically treated beverages exhibited reduced sedimentation due to partial polysaccharide degradation. Fermented beverages displayed the highest stability, attributed to protein–polysaccharide interactions and fermentation-induced matrix restructuring.

From a functional nutrition perspective, fermented cereal-based beverages demonstrated the greatest potential due to the combined effects of improved digestibility, enhanced biological activity, and stable technological performance. The presence of fermentation-derived metabolites and the potential probiotic effect further strengthen their suitability as functional beverages. Enzymatic treatment represents an effective intermediate approach, particularly for non-fermented formulations aimed at improving texture and nutrient availability.

Despite these promising results, certain limitations should be acknowledged. The analysis relied on in vitro indicators of digestibility and functional performance, which may not fully represent in vivo physiological responses. Additionally, variations in cereal type and enzyme combinations were not exhaustively explored. Future research should include sensory evaluation, consumer acceptance studies, and clinical validation to confirm the health benefits observed.

Conclusion

This study demonstrates that technological approaches applied in the production of cereal-based functional beverages play a decisive role in determining their biological activity, digestibility-related characteristics, and overall functional quality. The comparative analysis confirms that processing methods significantly influence beverage structure, nutrient availability, and technological stability.

Among the evaluated approaches, fermentation proved to be the most effective strategy for enhancing functional value. Fermented cereal-based beverages exhibited the highest biological activity, improved matrix stability, and controlled nutrient release during digestion. These effects are attributed to microbial metabolism, which promotes the formation of bioactive compounds and facilitates structural modifications that enhance digestibility. Enzymatic treatment also contributed positively by improving texture and nutrient availability, particularly in non-fermented formulations, while thermal treatment alone provided limited functional enhancement.

The findings highlight the importance of integrating appropriate technological interventions to overcome common challenges associated with cereal-based beverages, such as sedimentation, viscosity control, and nutrient bioavailability. The results further indicate that cereal-based functional beverages can serve as viable plant-based alternatives with enhanced health-promoting potential, aligning with current trends in functional nutrition and sustainable food systems.

Despite the promising outcomes, the study has certain limitations, including reliance on in vitro analytical indicators and a limited range of cereal types and processing conditions. Future research

should focus on in vivo evaluations, sensory assessment, and optimization of combined technological approaches to further validate and expand the application of cereal-based functional beverages.

Overall, this research provides a scientific basis for the development and technological optimization of cereal-based functional beverages and supports their potential role in modern health-oriented dietary strategies.

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