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Gluten-Free Baking: A Comparative Analysis of Rice, Corn, and Buckwheat Flours in Baking Technologies and the Biochemical Processes of Fermentation in Gluten-Free Dough

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Abstract

Gluten-free breadmaking is expanding rapidly. Yet the technological bottleneck remains the same: no gluten network means unstable gas retention, weak dough structure, and high batch-to-batch variability. This study examines how rice, corn, and buckwheat flours perform under comparable process conditions and which fermentation-centered decisions produce consistently acceptable quality.

The analytical framework combines raw-material profiling, rheological interpretation, and process-level fermentation control. Rice flour works as a neutral base and supports light crumb color, but it often needs extra structuring support. Corn flour improves flavor and crust appearance; however, brittleness risk rises when hydration is not tightly managed. Buckwheat flour increases nutritional density and micronutrient value, although high inclusion rates can produce an overly compact crumb. The results show that controlled fermentation is the key balancing mechanism: it aligns CO_2 generation kinetics, acidity trajectory, enzymatic starch hydrolysis, and water redistribution within the dough matrix.

A practical two-stage fermentation model with blended alternative flours is proposed for scalable use. The contribution is not limited to formulation choice; it provides a process logic that helps bakeries balance specific volume, texture elasticity, sensory acceptance, and nutritional quality in real production environments.

Keywords: *Gluten-Free Baking, Rice Flour, Corn Flour, Buckwheat Flour, Fermentation, Crumb Texture, Nutritional Value, Breadmaking Technology.*

PROBLEM STATEMENT IN GENERAL TERMS AND ITS CONNECTION WITH IMPORTANT SCIENTIFIC OR PRACTICAL TASKS

The market for gluten-free products is no longer a narrow medical niche. It has become mainstream. Today, the consumer does not expect a "compromise" product, but a full-quality loaf of bread with predictable characteristics. For the manufacturer, this means solving three tasks at the same time: achieving stable volume, controlled porosity, and a clear nutritional profile.

In traditional wheat dough, these functions are largely provided by gluten. In a gluten-free environment, the natural viscoelastic framework is absent, so the technologist has to build it artificially — through raw material selection, hydration control, the introduction of hydrocolloids, modification of fermentation, and management of the baking process [1; 2; 6]. Fermentation itself becomes a "critical control point": it is during this stage that the future loaf volume is established, the aromatic profile is formed, acidity develops, and the availability of nutrients changes.

The problem has a clearly applied significance for the American market. First, regulatory requirements for "gluten-free" labeling oblige manufacturers to control contamination risks and the stability of product composition. Second, retail chains require a longer shelf life without a significant loss of textural characteristics. Third, consumers are increasingly paying attention not only to the absence of gluten, but also to protein value, fiber content, glycemic response, and the "cleanliness" of the formulation.

Thus, the scientific and practical task is to develop a technologically grounded model that:

- combines the strengths of rice, corn, and buckwheat flours [8; 9];

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- minimizes their individual technological limitations;
- uses fermentation as a tool for controlling structure and quality;
- ensures reproducibility of results under scalable production conditions.

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS ON WHICH THE AUTHOR RELIES; IDENTIFICATION OF PREVIOUSLY UNRESOLVED PARTS OF THE GENERAL PROBLEM

In recent years, the amount of research has grown significantly. However, the knowledge remains divided between separate topics. For the review, it is appropriate to distinguish four groups of works.

Research on raw materials and compositions

This block is focused on the amino acid profile, starch fraction, water absorption capacity, and particle size of alternative types of flour. The conclusion of most works is that no type of flour can independently and steadily reproduce the functions of gluten. Therefore, mixing is a necessary strategy.

Rheology and structure formation

Most publications are devoted to the role of hydrocolloids: xanthan, guar, psyllium, HPMC, as well as protein concentrates and enzyme preparations. These works describe well the influence of ingredients on the viscosity and stability of dough, but they rarely integrate these data with the biochemistry of fermentation.

Fermentation and microbiological studies

It has been shown that yeast and sourdough fermentation improves aroma, may reduce antinutrients, and affects the rate of staling. At the same time, practice lacks unified regime recommendations for specific flour compositions.

Nutritional and sensory studies

Part of the works proves the advantages of pseudocereals and dark gluten-free crops in increasing the content of trace elements and polyphenols [11]. However, these advantages are often accompanied by a worsening of texture or a decrease in consumer acceptability.

Unresolved part of the problem.

Despite the thoroughness of separate studies, production practice lacks a complex model that would simultaneously connect:

- the choice of flour composition;
- fermentation parameters;
- prediction of textural and sensory results;
- assessment of the nutritional value of the finished product.

It is the elimination of this gap between the “ingredient” and “process” approaches that determines the scientific novelty of this work.

PURPOSE OF THE ARTICLE / STATEMENT OF THE TASK

The purpose of the article is to substantiate a technological model for the production of gluten-free bread based on rice, corn, and buckwheat flour, using controlled fermentation to optimize texture, volume, and nutritional value.

To achieve this purpose, the following tasks were set:

- to conduct a comparative analysis of the functional and technological properties of rice, corn, and buckwheat flour;
- to determine the key biochemical processes of fermentation in gluten-free dough and their connection with the rheological behavior of the system;
- to evaluate the influence of fermentation regimes on crumb structure, product volume, and sensory indicators;
- to analyze changes in nutritional characteristics as a result of fermentation;
- to form practical recommendations for craft and industrial bakeries oriented toward the requirements of the American market.

METHODOLOGICAL PRINCIPLES OF THE STUDY

The methodology is built according to the principle “raw material — process — result.” At the first stage, the functional characteristics of each type of flour are carried out. At the second stage, fermentation regimes are modeled: temperature, duration, humidity, and mixing intensity. At the third stage, integral indicators of product quality are evaluated.

The work uses the following groups of indicators:

- Technological: dough moisture, stability of structure during proofing, specific volume, uniformity of porosity.
- Rheological: dough viscosity, gas-retention capacity, deformation stability.
- Biochemical: pH dynamics, titratable acidity, activity of yeast fermentation, level of enzymatic hydrolysis of starch [3; 4; 5].
- Nutritional: approximate content of protein, dietary fiber, minerals, and the share of antinutrients after fermentation.
- Sensory: taste, aroma, crumb elasticity, aftertaste, and general acceptability.

For comparison of the compositions, the principle of multi-criteria assessment was applied, where the final technological rating is determined not by one indicator, but by the coordination of textural, sensory, and nutritional parameters.

PRESENTATION OF THE MAIN RESEARCH MATERIAL WITH FULL JUSTIFICATION OF THE OBTAINED SCIENTIFIC RESULTS

Functional Role of Rice, Corn, and Buckwheat Flour

Rice Flour

It has a high share of starch, a relatively neutral taste, and a light color, which makes it a basic component for gluten-free mixtures. The technological advantage is predictable behavior during mixing. The main disadvantage is low protein functionality, which is why hydrocolloids or protein additives are needed to form a stable framework.

Corn Flour

It improves organoleptic properties, adds characteristic taste and aroma notes, and gives an attractive crust color. At the same time, with an excessive share, it can increase crumb brittleness and accelerate the loss of freshness because of the features of the starch phase.

Buckwheat Flour

It is characterized by higher protein and mineral density and contains polyphenolic compounds that positively affect the biological value of the product. The technological limitation is the risk of excessive structure compaction at high dosage without correction of water and fermentation regime.

Table 1. Comparative Analysis of Flour in Gluten-Free Baking Technology

Parameter	Rice flour	Corn flour	Buckwheat flour
Crumb texture	Soft, but prone to crumbling without hydrocolloids	Moderately dense, more grainy	Denser, requires hydration optimization
Flavor profile	Neutral	Slightly sweet and grain-like	Pronounced, nutty
Technological risks	Low gas retention	Brittleness at low moisture	Excessive structural density
Nutritional potential	Basic	Moderate (carotenoids)	Higher (protein, polyphenols, minerals)

BIOCHEMICAL PROCESSES OF FERMENTATION IN GLUTEN-FREE DOUGH

In gluten-free systems, fermentation stops being only a stage of "dough rising" and becomes a central mechanism of structure formation. The main processes can be reduced to four interconnected blocks.

Gas Formation and CO_2 Retention

Yeast metabolizes available sugars with the formation of carbon dioxide. Unlike wheat dough, the gas is retained not by a gluten network, but by a starch-hydrocolloid matrix. Therefore, the viscosity of the liquid phase, hydration of hydrocolloids, and the rate of acidification of the medium are critically important.

Acid Formation and pH Regulation

A decrease in pH affects the activity of endogenous enzymes, the state of protein-polysaccharide complexes, and the water-binding capacity of the dough. Moderate acidification improves aroma and structural stability, while excessive acidification may cause weakening of the framework.

Enzymatic Hydrolysis of Starch

Partial hydrolysis increases the availability of substrates for yeast and promotes more uniform fermentation. At the same time, excessive hydrolysis leads to a sticky crumb and the risk of a "gummy" texture after baking.

Formation of the Aromatic Profile

Fermentation generates volatile compounds that compensate for the sensory "flatness" typical of some gluten-free products. The combination of compressed yeast with a mild sourdough phase is especially effective.

In general, the dynamics of the process can be presented as:

$$Q = f(C\_, H, T, t, pH, S),$$

where Q is an integral quality indicator; C_ is the composition of the flour blend; H is hydration; T is fermentation temperature; t is duration; pH is the acidity of the medium; S is structure-forming agents.

FERMENTATION AND THE TEXTURAL PROFILE OF FINISHED PRODUCTS

Fermentation processes have a decisive influence on the structural and mechanical indicators of gluten-free bread through three main mechanisms.

First, stable kinetics of gas formation determines the quality of porosity, creating a uniform system of small cells without large voids and without the risk of collapse of the product dome.

Second, strict observance of proofing duration makes it possible to achieve optimal crumb elasticity. Deviation toward over-fermentation inevitably destroys the viscoelastic framework, which makes the texture brittle or excessively moist, depending on the characteristics of the recipe composition.

The third effect consists in a significant slowing of staling processes due to controlled acidification and proper initial hydration of the mixture. These factors directly inhibit the retrogradation of starch polymers, ensuring stable moisture distribution inside the system and significantly extending the period of freshness preservation of the finished product. Thus, fermentation acts not only as a biochemical, but also as a structural tool for managing final quality.

INFLUENCE OF FERMENTATION ON NUTRITIONAL VALUE

The fermentation stage has a systemic influence on the nutritional profile of gluten-free bread, going beyond purely technological tasks.

Due to the activation of the enzyme phytase during fermentation, there is a significant reduction in the concentration of antinutrients, in particular phytates, which directly correlates with an increased level of absorption of critically important microelements [5; 8].

In parallel, the microflora provides partial pre-hydrolysis of carbohydrate chains, transforming complex structures into forms that are easier for metabolism, which significantly improves the overall digestibility of the product and its tolerance.

Separate attention should be paid to the natural synthesis of organic acids and complex esters, which form the authentic organoleptic profile of the product without the use of any synthetic enhancers.

In flour compositions based on pseudocereals, where buckwheat dominates, the duration of the fermentation cycle is critical for correcting the glycemic response, since bacterial metabolism products slow down the rapid enzymatic attack on starch.

As a result, fermentation implements a double strategy: it simultaneously stabilizes the physicochemical parameters of the crumb and creates the basis for the formation of a functional product with high biological value.

TECHNOLOGICAL MODEL OF COMBINED FLOUR SYSTEMS

Based on the comparative analysis, a practical model is proposed for three typical compositions.

Table 2. Technological Fermentation Model for Gluten-Free Flour Compositions

Flour composition	Fermentation regime	Expected effect	Technological comment
Rice flour 70% + buckwheat flour 30%	30–40 min preliminary fermentation + 35 min proofing	Better porosity, softer crumb	Addition of psyllium is advisable for stabilization
Rice flour 50% + corn flour 50%	25–30 min preliminary fermentation + 30 min proofing	Light volume, pronounced taste	Moisture control is needed to reduce brittleness
Corn flour 60% + buckwheat flour 40%	35–45 min preliminary fermentation + 35–40 min proofing	Higher nutritional value, denser crumb	Effective for pan bread and savory products

Additionally, for production conditions, the following control points are recommended:

- Hydration control. For each batch of flour, the amount of water should be adjusted based on actual absorption.
- pH control. The pH should be recorded at the end of fermentation as a predictor of texture and aroma.
- Time control. Universal regimes should be avoided; fermentation time should be adapted to the composition.
- Cooling control. Insufficient cooling after baking worsens crumb stability.

COMPARISON OF TRADITIONAL AND CONTROLLED APPROACHES TO GLUTEN-FREE FERMENTATION

Table 3. Traditional Approach vs. Controlled Fermentation

Parameter	Traditional approach	Controlled approach
Recipe adjustment	Fixed mixture, minimal adaptation	Dynamic composition for the target product
Fermentation regime	One fixed time for all batches	The regime depends on composition, pH, and hydration
Quality stability	High variability between batches	Reproducibility through control points
Sensory profile	Often a “flat” taste and brittle crumb	Better aroma, with a balance of elasticity and porosity
Nutritional value	Depends mainly on the flour composition	Additionally improved through fermentation

IMPLEMENTATION MODEL FOR THE U.S. MARKET

To ensure commercial relevance in the U.S. market, a four-stage model of technology adaptation is introduced.

At the stage of R&D screening, the basic flour composition is selected for specific target formats, such as sandwich bread or artisan products. This makes it possible, already at the start, to coordinate the physicochemical properties of the mixture with the texture requirements of the final product.

The second stage involves adjusting time-temperature profiles during pilot fermentation. At this stage, critical limits of acidity are recorded, which is necessary for stabilizing the viscoelastic matrix of the dough.

The stability validation stage is aimed at assessing the variability of indicators between individual batches and determining the actual shelf life. At the same time, sensory acceptability testing is carried out to confirm the competitiveness of the product.

Final scaling includes the transition to industrial lines with correction of mixing energy and baking profiles. At this level, cooling and packaging protocols are standardized to minimize defects. Such a sequence of actions significantly increases the predictability of quality when entering the saturated American market.

LIMITATIONS OF THE STUDY

The work has an applied character and is based on the generalization of literature data and technological experience. The main limitations include:

- the absence of a single international protocol for assessing texture specifically for gluten-free bread;
- significant dependence of the results on batch variability of raw materials;
- the need for additional standardization of sensory scales for different categories of consumers.

Despite this, the proposed model demonstrates sufficient flexibility for adaptation to production scenarios of different scales.

CONCLUSIONS FROM THIS STUDY AND PROSPECTS FOR FURTHER RESEARCH IN THIS DIRECTION

1. The comparative analysis confirmed the absence of a universal alternative flour: rice, corn, and buckwheat flour have complementary technological and nutritional properties.
2. Controlled fermentation is a central factor in forming the quality of a gluten-free product, since it determines gas formation, structural stability, aromatic profile, and partly nutritional value.
3. The highest reproducibility of results is provided by the approach “composition + hydration control + pH control + adaptive fermentation time.”
4. For production practice, it is advisable to introduce multi-criteria quality maps, where texture, sensory properties, and nutritional indicators are assessed simultaneously.
5. Prospects for further research are connected with mathematical modeling of fermentation kinetics, optimization of starter culture consortia, and the creation of predictive models of freshness shelf life for different gluten-free flour compositions.

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