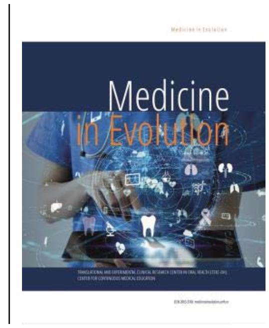
Hypoglycemic Bread as a Nutritional Strategy for the Management of Diabetes Mellitus



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Abstract

Diabetes mellitus represents a major global health challenge, requiring effective nutritional strategies to improve glycemic control and metabolic outcomes. The aim of this study was to evaluate the impact of bakery product reformulation on nutritional composition and sensory acceptability in the context of functional nutrition for patients with carbohydrate metabolism disorders. A comparative experimental design was applied to four bread formulations: white bread (control), rye bread, whole grain bread, and buckwheat bread with chia seeds. Nutritional composition was determined by indirect calculation methods, and sensory evaluation was performed using a hedonic scoring method with a semi-trained panel. The results showed a significant reduction in carbohydrate content from 41.13 g/100 g in white bread to 26.92 g/100 g in buckwheat bread with chia seeds ($p < 0.05$), along with a substantial increase in dietary fiber up to 10.10 g/100 g in rye bread. In addition, the energy value decreased from 247.09 kcal/100 g to 161.67 kcal/100 g. Sensory analysis indicated high acceptability for all formulations, with overall scores exceeding 4.0. In conclusion, the reformulation of bakery products using whole grains, pseudocereals, and functional ingredients represents an effective and practical strategy for improving dietary quality and supporting glycemic control in diabetes management without compromising consumer acceptability.

Keywords: diabetes mellitus; glycemic control; functional bakery products; dietary fiber; hypoglycemic bread; whole grains; pseudocereals; sensory analysis; clinical nutrition

INTRODUCTION

1.1 DIETARY MANAGEMENT IN DIABETES MELLITUS

Diabetes mellitus represents one of the most significant chronic metabolic diseases of the 21st century, characterized by persistent hyperglycemia resulting from defects in insulin secretion and/or action. This condition is associated with high morbidity and mortality rates, mainly due to its cardiovascular, neurological, and renal complications, constituting a major global public health challenge [1]. From an endocrinological perspective, diabetes involves a complex imbalance in energy homeostasis and carbohydrate metabolism, being closely associated with insulin resistance and pancreatic β-cell dysfunction.

In modern diabetes management, medical nutrition therapy plays a central role and is considered an essential and effective intervention for glycemic control and the reduction of complication risk [1]. Current evidence indicates that dietary interventions can achieve significant improvements in glycated hemoglobin (HbA1c), in some cases comparable to pharmacological treatments [2]. Therefore, optimizing dietary composition, particularly carbohydrate intake, represents a key strategy in the metabolic management of patients with diabetes mellitus.

Carbohydrates are the primary determinant of postprandial glycemic response, and their quality is considered more important than the total quantity consumed [3]. In this regard, current guidelines recommend the consumption of carbohydrates from whole-food sources, rich in dietary fiber and micronutrients, while limiting refined products such as white bread and other bakery items with a high glycemic index [3]. Products derived from refined cereals are rapidly digested, leading to sharp increases in blood glucose levels and an exaggerated insulin response, thereby promoting metabolic stress and disease progression [4].

Bakery products occupy a central place in human nutrition, representing a major source of energy and carbohydrates worldwide. However, frequent consumption of white bread has been associated with an increased risk of developing type 2 diabetes, mainly due to its high content of available carbohydrates and elevated glycemic index [4]. Epidemiological studies have shown that diets characterized by a high glycemic index and low dietary fiber intake are associated with a higher incidence of diabetes mellitus and metabolic syndrome [4].

In contrast, increased dietary fiber intake and consumption of whole grains are associated with significant metabolic benefits. Cohort studies have demonstrated a 20–30% reduction in diabetes risk among individuals with higher fiber intake, particularly when derived from whole grains [5]. Dietary fibers exert their effects through multiple physiological mechanisms, including slowing carbohydrate digestion and absorption, increasing intestinal viscosity, modulating incretin hormone secretion (GLP-1, PYY), and favorably influencing gut microbiota composition [6].

Recent meta-analyses confirm the beneficial effects of fiber supplementation on glycemic control, demonstrating significant reductions in HbA1c, fasting glucose levels, and insulin resistance in patients with type 2 diabetes [6]. Furthermore, diets rich in fiber and complex carbohydrates have been associated with improvements in lipid profile and a reduction in cardiovascular risk, which is particularly relevant given the frequent comorbidities associated with diabetes [7].

From a food technology perspective, reformulation of bakery products represents a key strategy for developing functional foods tailored to the needs of diabetic patients. The concept of “functional bread” involves the use of whole grain flours, pseudocereals (such as buckwheat), and fiber-rich ingredients (seeds, soluble fibers) to reduce glycemic index and improve the nutritional profile of the final product [8]. Experimental studies have shown that bread formulated with such ingredients leads to a significant reduction in postprandial glycemia compared to white bread, an effect correlated with increased fiber, protein, and lipid content [8].

Moreover, the physical structure of food plays an important role in determining glycemic response. Flour particle size, degree of processing, and the composition of the food matrix influence carbohydrate bioavailability and digestion rate [9]. Products made from less processed whole grains or coarser flours result in a lower glycemic response, highlighting the importance of processing technology in metabolic control [9].

Despite these nutritional benefits, the sensory acceptability of hypoglycemic bakery products remains a major challenge in the food industry. Organoleptic characteristics such as texture, taste, and appearance significantly influence consumer compliance, including among patients with diabetes mellitus. Therefore, the development of bakery products that combine metabolic benefits with desirable sensory properties represents a priority for both nutritional research and the food industry.

In this interdisciplinary context, at the intersection of endocrinology, clinical nutrition, and food technology, the present study aims to comparatively evaluate the nutritional and sensory profiles of different types of hypoglycemic bread, in order to assess their relevance as functional dietary interventions in the management of diabetes mellitus.

1.2 Clinical and metabolic relevance of hypoglycemic bakery products

The reformulation of staple foods such as bread represents an effective nutritional strategy for the management of metabolic disorders, particularly diabetes mellitus. The physiological impact of bakery products extends beyond macronutrient composition and is strongly influenced by structural, functional, and metabolic interactions within the food matrix and the gastrointestinal environment [11].

Current evidence indicates that several interconnected mechanisms contribute to the metabolic effects of hypoglycemic bakery products, including structural modifications of starch, dietary fiber functionality, appetite regulation, and sensory acceptability. These mechanisms act synergistically to modulate postprandial glycemic response, insulin sensitivity, and overall metabolic homeostasis [1].

Figure 1 synthesizes the multifactorial interactions underlying the metabolic effects of hypoglycemic bakery products, highlighting the integration of structural, physiological, and behavioral determinants. At the structural level, modifications of starch architecture—such as increased resistant starch content and reduced enzymatic accessibility—play a central role in attenuating glycemic excursions. In parallel, the incorporation of soluble and insoluble dietary fibers contributes to delayed gastric emptying, modulation of carbohydrate digestion, and enhanced fermentation in the colon, leading to the production of short-chain fatty acids with recognized metabolic benefits [12,13].

Furthermore, satiety regulation emerges as a critical pathway linking food formulation to energy intake control. The stimulation of gut-derived hormones involved in appetite regulation (e.g., GLP-1, PYY) may reduce subsequent caloric intake and improve long-term metabolic outcomes. Sensory acceptability, although often underestimated, represents an essential determinant of adherence, as the success of any reformulated product depends on its integration into habitual dietary patterns without compromising palatability [12,13].

Additionally, the figure emphasizes the role of food-based strategies within the broader context of metabolic disease management. By simultaneously targeting multiple physiological pathways, hypoglycemic bakery products may contribute to improved glycemic variability, enhanced insulin sensitivity, and reduced cardiometabolic risk. These effects extend beyond acute postprandial responses and may support long-term metabolic stability when such products are consistently included in the diet [14-16].

In addition to their direct metabolic effects, hypoglycemic bakery products have important practical implications for dietary interventions at the population level. As bread and similar products constitute staple foods in many dietary patterns, their reformulation offers a scalable and sustainable approach to improving nutritional quality without requiring major behavioral changes. This aspect is particularly relevant in the context of diabetes prevention programs, where long-term adherence to dietary recommendations often represents a major challenge [15,16].

Moreover, the integration of such products into daily nutrition aligns with current public health strategies aimed at reducing the burden of non-communicable diseases. By lowering the glycemic impact of widely consumed foods, these reformulated products may contribute to improved metabolic control not only in individuals with diagnosed diabetes, but also in those at risk of developing insulin resistance and metabolic syndrome [15,16].

Future research should focus on optimizing formulation strategies through the combined use of novel ingredients, processing techniques, and personalization approaches. Advances in food technology, together with insights from metabolomics and gut microbiota research, may further enhance the efficacy of hypoglycemic bakery products. In this context, the development of tailored functional foods adapted to individual metabolic profiles represents a promising direction within the field of precision nutrition [13].

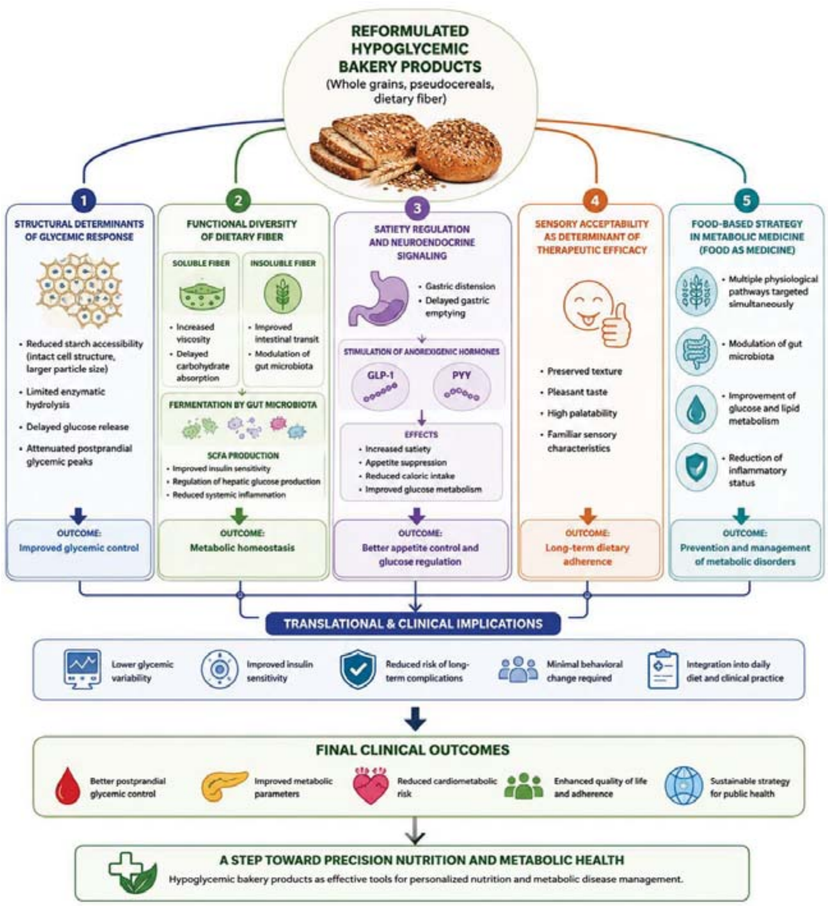

Figure 1. Conceptual framework of the clinical and metabolic effects of hypoglycemic bakery products (Figure created with ChatGPT-5 , OpenAI, San Francisco, CA, USA, accessed on 1 May 2026)

As illustrated in Figure 1, the metabolic impact of hypoglycemic bakery products arises from the interaction of multiple complementary mechanisms rather than a single isolated effect. Structural modifications that reduce starch accessibility contribute to slower digestion kinetics and attenuated postprandial glycemic responses [11]. In parallel, dietary fiber plays a central role in modulating gastrointestinal function and metabolic processes, including gut microbiota activity and short-chain fatty acid (SCFA) production [12,13].

The figure also highlights the importance of satiety-related and behavioral components. The stimulation of gut-derived hormones such as glucagon-like peptide-1 (GLP-1) and peptide YY (PYY) supports appetite regulation and long-term energy balance, while sensory acceptability ensures adherence to dietary interventions [14,16].

Taken together, these interconnected mechanisms reinforce the concept of "food as medicine," emphasizing the potential of reformulated bakery products as practical and effective tools in the dietary management and prevention of metabolic disorders [15].

Aim and objectives

The present study was designed as a comparative experimental investigation aimed at evaluating the applicability of reformulated bakery products within the framework of functional nutrition for patients with carbohydrate metabolism disorders. The methodological approach was based on the controlled analysis of how raw material composition influences the final nutritional characteristics of the products, with particular emphasis on parameters relevant to the modulation of glycemic response.

The study design enabled a direct comparison between a conventional product, represented by white bread obtained from refined flour, and reformulated variants developed using alternative raw materials with enhanced nutritional value. Specifically, formulations based on rye flour, whole wheat flour, and buckwheat flour supplemented with chia seeds were selected, considering their distinct differences in dietary fiber content, carbohydrate structure, and nutrient bioavailability.

The experimental setup ensured strict standardization of technological parameters and processing conditions, allowing observed variations to be attributed exclusively to differences in raw material composition. Such standardization is essential, as the nutritional and metabolic properties of bakery products are influenced not only by their chemical composition but also by the interactions between macronutrients and the structure of the food matrix, which ultimately determine digestibility and postprandial glycemic response [8,9].

In addition, the study included an evaluation of the sensory characteristics of the developed products in order to determine their acceptability. This aspect is particularly important in a clinical context, as adherence to dietary interventions is strongly influenced by the sensory properties of foods. Reformulation strategies, especially those involving increased fiber content and the incorporation of pseudocereals, may affect texture, taste, and overall acceptability, thus requiring careful optimization to balance nutritional benefits with consumer acceptance.

Therefore, the main objective of the study was to comparatively evaluate the nutritional profile and sensory characteristics of reformulated bakery products, with the aim of identifying technologically and metabolically optimized formulations. At the same time, the study aimed to highlight the potential of these products to be integrated into modern clinical nutrition strategies, contributing to the development of effective and sustainable dietary interventions for the management of carbohydrate metabolism disorders.

MATERIAL AND METHODS

2.1 Raw and auxiliary materials used

The selection of raw materials used in the present study was carried out in accordance with the objective of developing bakery products with reduced glycemic impact and improved nutritional profile, suitable for integration into the diets of patients with diabetes mellitus. The choice of ingredients was based on both their chemical composition and their technological and functional properties, which influence the structure of the final product and nutrient bioavailability.

As a reference product, refined wheat flour type 650 was used, which is specific to conventional bakery products. This type of flour is characterized by a high content of easily digestible starch and a low dietary fiber content, resulting in a high glycemic index and a pronounced postprandial glycemic response [4]. For these reasons, white bread was used as the control sample in the comparative study.

For the hypoglycemic formulations, flours with superior nutritional value were selected. Whole wheat flour was included due to its high content of dietary fiber, vitamins, and bioactive compounds, resulting from the preservation of the entire grain (bran, germ, and endosperm). The consumption of whole grains has been associated with improved insulin sensitivity and reduced risk of diabetes mellitus, effects mainly attributed to their fiber content and the complex structure of the food matrix [5].

Rye flour was selected as another key raw material, being recognized for its high content of soluble dietary fibers, particularly arabinoxylans, which contribute to increased intestinal viscosity and slower glucose absorption. Studies have demonstrated that rye-based products lead to a lower glycemic response compared to those obtained from refined flour, making them suitable for individuals with metabolic disorders [8].

Buckwheat flour, used in combination with chia seeds, was selected due to its pseudocereal nature and distinct nutritional composition. Buckwheat is rich in high-quality proteins, dietary fiber, and phenolic compounds, and exhibits a lower glycemic index compared to conventional cereals. Furthermore, its structural characteristics contribute to reduced starch digestibility, positively influencing glycemic response [8].

Chia seeds were included as a functional ingredient due to their high content of soluble fiber and polyunsaturated fatty acids. Soluble fibers have the ability to form viscous gels in the digestive tract, thereby slowing carbohydrate absorption and reducing postprandial glycemic fluctuations [6]. In addition, their incorporation contributes to improved texture and increased nutritional value of the final products.

All formulations also included basic ingredients specific to the bread-making process, namely baker's yeast, table salt, and potable water. Yeast was used for dough fermentation, a process that influences not only the organoleptic properties of the final product but also its digestibility, through modifications in starch and protein structure. Fermentation can contribute to glycemic index reduction by promoting organic acid formation and altering the food matrix [8].

Therefore, the selection of raw materials was carried out strategically in order to obtain bakery products characterized by reduced available carbohydrate content and increased dietary fiber intake, both of which are essential factors in modulating glycemic response and supporting dietary management of diabetes mellitus.

2.2 Qualitative and quantitative acceptance of raw materials

The data presented in Table 1 reveal significant variability in the nutritional composition of the selected raw materials. Whole grain flours and rye flour exhibit substantially higher dietary fiber content compared to refined wheat flour, while buckwheat flour provides a balanced macronutrient profile. Chia seeds stand out due to their exceptionally high fiber and lipid content, contributing to improved metabolic properties. In contrast, refined flour and sugar are characterized by a high proportion of rapidly digestible carbohydrates and minimal fiber content, which are associated with an increased glycemic response.

Table 1. Comparative nutritional composition of selected raw materials used in bakery products (per 100 g)

Raw material	Carbohydrates (g)	Dietary fiber (g)	Protein (g)	Lipids (g)	Energy (kcal)	Reference
Refined wheat flour	72.0	2.7	10.3	1.7	340	[17]
Whole wheat flour	72.6	12.2	13.7	1.9	339	[18]
Rye flour	77.2	13.7	8.4	1.9	359	[19]
Buckwheat flour	75.0	10.4	8.9	2.5	358	[20]
Chia seeds	42.0	34.0	17.0	31.0	486	[21]
Wheat bran	64.5	42.0	16.0	4.3	216	[22]
Vital wheat gluten	13.0	0.6	75.0	1.9	370	[22]
Seeds mix (avg.)	27.0	12.0	20.0	45.0	560	[22]
Yeast (fresh)	41.0	26.0	40.0	7.0	325	[22]
Olive oil	0	0	0	100	884	[22]
Sugar (brown)	100	0	0	0	380	[22]
Salt	0	0	0	0	0	
Water	0	0	0	0	0	

Note: Values are expressed per 100 g of raw material and were obtained from literature sources [17–22]. Minor variations may occur depending on the origin and processing conditions of the raw materials.

In order to further evaluate the role of the main cereal and pseudocereal flours used in the formulation of bakery products, a comparative analysis was performed focusing on their nutritional and functional characteristics. The selected flours differ significantly in terms of carbohydrate composition, dietary fiber content, protein level, and technological behavior, all of which influence both the processing performance and the metabolic impact of the final products.

These differences are particularly relevant in the context of developing hypoglycemic bakery products, where the quality of carbohydrates and the fiber content play a key role in modulating postprandial glycemic response. The comparative nutritional and functional characteristics of the selected flours are summarized in Table 2.

Table 2. Comparative nutritional and functional characterization of selected flours (per 100 g)

Parameter	**Refined wheat flour**	**Whole wheat flour**	**Rye flour**	**Buckwheat flour**	**Reference**
Carbohydrates (g)	72.0	72.6	77.2	75.0	[17–20]
Dietary fiber (g)	2.7	12.2	13.7	10.4	[17–20]
Protein (g)	10.3	13.7	8.4	8.9	[17–20]
Lipids (g)	1.7	1.9	1.9	2.5	[17–20]
Energy (kcal)	340	339	359	358	[17–20]
Fiber classification	Very low	High	Very high	Moderate-high	[17–20]
Carbohydrate quality	Refined	Complex	Complex	Complex	[17–20]
Glycemic potential	High	Moderate	Reduced	Reduced	[17–20]
Functional properties	Low	Good	Very good	Good	[17–20]
Technological behavior	Excellent (gluten-rich)	Good	Dense structure	Gluten-free	[17–20]

Note: Values are expressed per 100 g of flour. Nutritional data were obtained from literature sources [17–20] and represent average values, which may vary depending on the botanical origin, processing method, and degree of milling of the flours

The comparative analysis presented in Table 2 highlights significant differences in dietary fiber content among the selected flours, which represents a key factor in modulating glycemic response. Refined wheat flour contains a very low amount of fiber (2.7 g/100 g), whereas whole wheat and rye flours provide substantially higher levels, reaching 12.2 g/100 g and 13.7 g/100 g, respectively

Rye flour exhibits the highest dietary fiber content, suggesting a stronger capacity to reduce carbohydrate digestibility and attenuate postprandial glycemic response. Whole wheat flour offers a balanced nutritional profile, combining elevated fiber and protein levels with good technological performance. Buckwheat flour, with a moderate to high fiber content (10.4 g/100 g), contributes additional functional benefits due to its pseudocereal nature and reduced gluten content.

These differences are directly reflected in the nutritional quality of the final bakery products and support the use of whole grain and alternative flours in the formulation of hypoglycemic foods for dietary management of diabetes mellitus.

2.3 Recipe Formulation and Standardization of the Technological Process

The formulation of the experimental recipes was carried out with the aim of obtaining bakery products with reduced carbohydrate content and increased dietary fiber, while maintaining acceptable technological and sensory properties.

White bread (WB) formulated with refined wheat flour was used as the control sample. Hypoglycemic variants were developed by partially or totally replacing refined flour with rye flour (RB), whole wheat flour (WGB), and buckwheat flour combined with chia seeds (BBCh). This substitution strategy was designed to reduce rapidly digestible carbohydrates and increase dietary fiber content, with expected beneficial effects on glycemic response.

The composition of each product was established based on technological and nutritional considerations, taking into account the different hydration capacity and gluten-forming potential of the selected raw materials.

The standardized formulations of the analyzed bakery products are presented in Table 3.

Table 3. Ingredient composition of bakery products used in the study

Ingredient	**Unit of measurement**	**WB**	**RB**	**WGB**	**BBCh**
Main flour	g	1000 refined wheat flour	220 rye flour + whole wheat flour	500 whole wheat flour	250 buckwheat
Water	ml	600	500	500	360
Yeast	g	25	25	25	8
Salt	g	20	7	20	7
Oil	ml	100	45	30	-
Bran	g	-	50	-	-
Seeds mix	g	-	30	100	-
Chia seeds	g	-	-	-	20
Sugar	g	-	7	-	-
Gluten	g	-	20	-	-

Note: Ingredient quantities are expressed per batch and were adapted to ensure optimal dough consistency and product quality

The formulations presented in Table 3 highlight the progressive substitution of refined wheat flour with whole grain and alternative ingredients characterized by higher dietary fiber content and reduced digestible carbohydrates.

The RB and WGB formulations include bran and mixed seeds, contributing to an increase in fiber and protein content, while the BBCh sample incorporates buckwheat flour and chia seeds, providing a distinct nutritional profile with functional properties. In contrast, the WB formulation is primarily based on refined flour, resulting in a higher proportion of rapidly available carbohydrates.

These compositional differences are essential for explaining the variations observed in the nutritional values and potential glycemic response of the final products.

2.4 Technological Process for the Production of Functional Bakery Products

The technological process applied for the production of the bakery products was standardized in order to ensure reproducibility and comparability between experimental variants. A classical bread-making process was used, adapted to the specific characteristics of the raw materials, while maintaining constant processing parameters.

The technological scheme of the process is presented in Figure 2 and includes the following stages: raw material preparation, dosing, mixing and kneading, fermentation, division and shaping, final proofing, baking, cooling, and storage.

Raw materials were weighed according to the established formulations and conditioned prior to processing. Mixing and kneading were carried out using a two-stage process, consisting of initial dough formation followed by final kneading, in order to achieve proper gluten network development. Kneading time ranged between 8–12 minutes, depending on flour type, with dough temperature maintained at 24–26°C.

Fermentation was conducted using baker's yeast at controlled conditions of 28–30°C for 60–90 minutes. In samples containing whole grain and pseudocereal flours, fermentation time was slightly extended to compensate for reduced gluten content and lower gas retention capacity.

After primary fermentation, the dough was divided, shaped, and subjected to final proofing at 30–32°C and relative humidity of 75–85% for 30–60 minutes, until optimal volume development was achieved.

Baking was performed at temperatures between 180 and 220°C for 25–35 minutes, ensuring proper starch gelatinization and formation of a porous crumb structure. These transformations are essential for determining the digestibility of carbohydrates and the glycemic response of the final product.

Following baking, the products were cooled at room temperature (20–22°C) for 2–3 hours to stabilize the structure and prevent moisture condensation. The final products were stored under controlled conditions until further analysis.

The application of standardized technological parameters allowed for the isolation of the effect of formulation on product characteristics, ensuring the reliability of the experimental results.

The technological flow diagram illustrating the processing stages of the bakery products is presented in Figure 2.

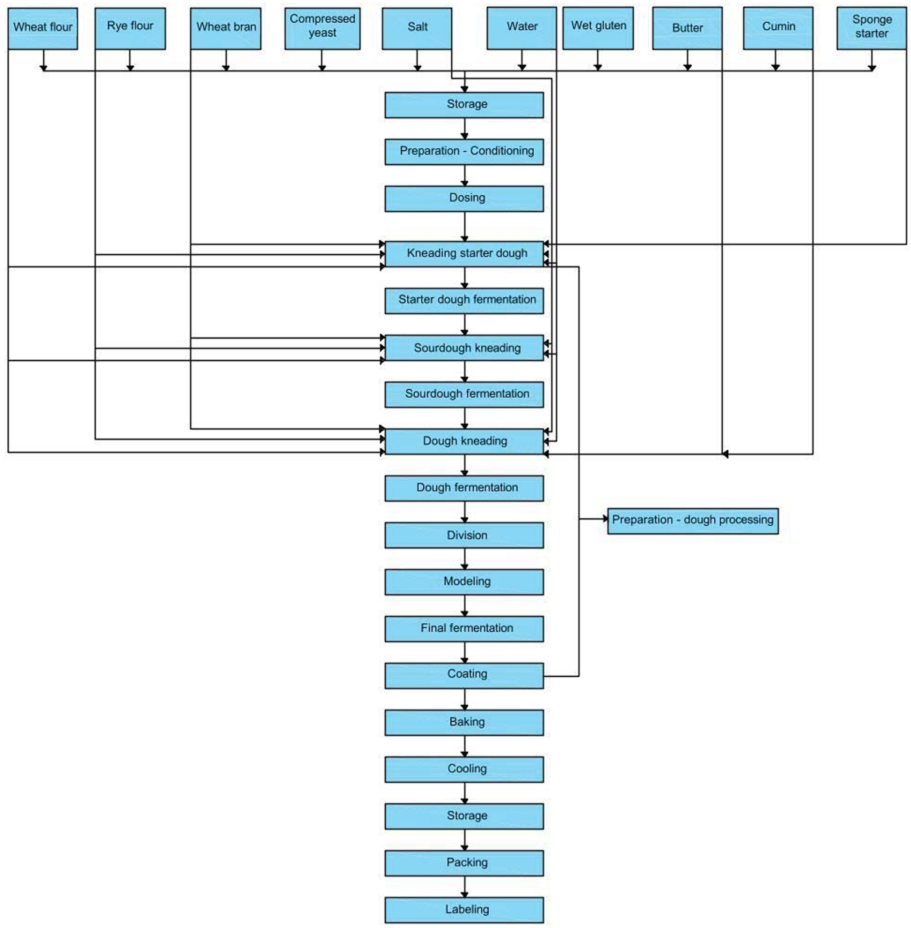

Figure 2. Technological flow diagram for the production of bakery products

The scheme highlights the sequence of technological operations and the integration of raw materials into the production process, ensuring process consistency and product quality.

2.5 Nutritional Analysis and Determination of Chemical Composition

The determination of macronutrient composition was performed according to standard analytical methods. Protein content was estimated using the Kjeldahl method (AOAC 920.87), while lipid content was determined by Soxhlet extraction (AOAC 922.06). Moisture content was evaluated according to AOAC 925.10 [10]

Carbohydrates were calculated by difference, by subtracting the sum of protein, lipid, ash, and moisture contents from 100%. Dietary fiber content was estimated based on the individual contribution of raw materials, considering their composition.

Nutritional values were calculated using the exact ingredient proportions for each recipe and expressed per 100 g of product. Energy value was determined using Atwater factors (4 kcal/g for proteins and carbohydrates, 9 kcal/g for lipids).

All analyses were performed in triplicate, and results were expressed as mean ± standard deviation. Statistical analysis was carried out using one-way ANOVA followed by Tukey's post-hoc test, with a significance level of $p < 0.05$.

2.6 Sensory Analysis of Functional Bakery Products

The sensory evaluation of the analyzed bakery products was performed in order to assess the impact of reformulation on organoleptic characteristics and overall consumer acceptability. This step is essential in validating functional food products, as compositional modifications—particularly increased dietary fiber content and the use of alternative ingredients—may significantly influence the sensory properties of the final product [8].

The sensory analysis was carried out using the hedonic scoring method, in accordance with the ISO 6658:2017 standard, which establishes general principles for the sensory evaluation of food products. This method is widely applied in both the food industry and research for determining product acceptability and comparing organoleptic characteristics across different variants [11].

The evaluation panel consisted of twenty semi-trained assessors familiar with the main sensory attributes of bakery products. The assessors received prior training to ensure consistent identification and evaluation of key characteristics such as texture, taste, and aroma, thereby enhancing the objectivity and reproducibility of the results.

The evaluation was conducted under controlled conditions, in rooms with uniform lighting and constant temperature, in order to minimize the influence of external factors on sensory perception. The samples were presented anonymously and in randomized order, and the assessors were not provided with information regarding product composition or type, in order to avoid subjective bias.

The sensory attributes analyzed included external appearance, color, aroma, texture, taste, and overall acceptability. Each attribute was evaluated using a scoring scale from 1 to 5, where 1 represented the lowest score and 5 represented the highest score. Overall acceptability was calculated as the mean of the scores assigned to the evaluated attributes, allowing for a comparative analysis between product variants.

The obtained results were summarized and expressed as mean values, which were used to assess the differences in sensory acceptability among the analyzed products. Products that achieved high scores were considered suitable for consumption, indicating that reformulation did not negatively affect their organoleptic characteristics.

The integration of sensory analysis into the study methodology enabled the correlation of nutritional modifications with their impact on consumer perception, thereby contributing to the validation of the developed products' applicability. This approach is particularly important in the context of clinical nutrition, where the acceptability of food products directly influences patient adherence to dietary interventions.

RESULTS AND DISCUSSIONS

3.1 Results on nutritional value and their interpretation

The nutritional values determined for the analyzed bakery products are presented in Table 4, expressed as mean ± standard deviation (SD), calculated based on three independent batches. The differences between variants were statistically evaluated, and values followed by different letters indicate statistically significant differences ($p < 0.05$).

These results reflect the direct impact of formulation on the nutritional composition of the products, particularly in terms of carbohydrate content, dietary fiber levels, and total energy value.

Table 4. Nutritional value of bakery products (per 100g product)

Nutritional parameter	Unit of measurement	WB	RB	WGB	BBCh
Energy (kcal)	Kcal	247.09 ± 2.15^a	223.73 ± 1.94^b	216.77 ± 1.82^c	161.67 ± 1.50^d
Protein	g	6.03 ± 0.21^a	7.77 ± 0.25^b	8.80 ± 0.28^c	6.91 ± 0.24^d
Carbohydrates	g	41.13 ± 0.52^a	35.48 ± 0.47^b	31.55 ± 0.43^c	26.92 ± 0.39^d
Lipids	g	6.30 ± 0.30^a	10.10 ± 0.33^b	7.50 ± 0.26^b	2.88 ± 0.20^c
Fiber	g	1.01 ± 0.09^a	10.10 ± 1.94^b	6.20 ± 0.28^c	4.95 ± 0.22^d

Note: Values are expressed as mean ± standard deviation (SD). Different letters on the same row indicate statistically significant differences ($p < 0.05$)

Legend:
WB – White Bread (refined wheat bread, control sample)
RB – Rye Bread (bread formulated with rye flour)
WGB – Whole Grain Bread (bread formulated with whole wheat flour)
BBCh – Buckwheat Bread with Chia (bread formulated with buckwheat flour and chia seeds)

The carbohydrate content differed significantly among all samples ($p < 0.05$), decreasing progressively from WB to BBCh. The WB sample exhibited the highest level of available carbohydrates (41.13 g/100 g), while the BBCh sample showed the lowest value (26.92 g/100 g).

This gradual reduction reflects the impact of reformulation strategies, where refined flour was replaced with whole grain and pseudocereal-based ingredients. The statistically distinct groups (different letters across all samples) confirm that each formulation significantly modifies the carbohydrate profile.

From a metabolic perspective, this reduction is particularly relevant, as lower carbohydrate availability is associated with a reduced postprandial glycemic response and improved glycemic control.

Dietary fiber content showed a significant increase in all reformulated samples compared to WB ($p < 0.05$). The RB sample presented the highest fiber content (10.10 g/100 g), followed by WGB and BBCh.

The WB sample, characterized by a very low fiber content (1.01 g/100 g), differed significantly from all other samples, confirming its limited functional value in metabolic nutrition.

The elevated fiber content in RB and WGB is associated with the use of whole grain flours and bran fractions, while BBCh benefits from the contribution of chia seeds and buckwheat flour. From a physiological standpoint, dietary fiber plays a critical role in delaying carbohydrate digestion and absorption, thereby contributing to improved glycemic stability.

The protein content varied significantly among samples, with WGB showing the highest value (8.80 g/100 g), followed by RB, BBCh, and WB. This distribution indicates the superior nutritional contribution of whole grain formulations in terms of protein intake.

Regarding lipids, RB and WGB exhibited similar values (no significant difference between them), while BBCh showed a significantly lower lipid content (2.88 g/100 g). The reduced lipid fraction in BBCh contributes to its lower energy density and enhances its suitability for hypocaloric diets.

The energy value showed statistically significant differences across all samples ($p < 0.05$), with a clear decreasing trend from WB (247.09 kcal/100 g) to BBCh (161.67 kcal/100 g).

To provide a clearer visualization of the nutritional changes induced by reformulation, the relative variation in carbohydrate and dietary fiber content compared to the control sample (WB) is presented in Figure 3 a)-b).

Figure 3. Relative variation (%) in carbohydrate content (a) and dietary fiber (b) of reformulated bakery products compared to the control sample (WB)

As illustrated in Figure 3 a), a consistent reduction in carbohydrate content was observed across all reformulated samples relative to the control. Compared to WB, carbohydrate levels decreased by approximately 13.7% in RB, 23.3% in WGB, and 34.5% in BBCh.

This progressive decrease reflects the impact of replacing refined flour with whole grain and pseudocereal-based ingredients, which contain lower proportions of rapidly digestible carbohydrates. From a metabolic perspective, this reduction is particularly significant, as it is directly associated with a lower postprandial glycemic response and improved glycemic control. The most pronounced reduction was observed in the BBCh sample, highlighting its potential as a hypoglycemic product.

In contrast, dietary fiber content showed a marked increase in all reformulated variants, as shown in Figure 3 b). The RB sample exhibited the highest increase, with an approximately nine-fold rise (+900%) compared to the control. Similarly, WGB and BBCh displayed substantial increases of approximately 514% and 390%, respectively.

This significant enhancement in fiber content is attributed to the use of whole grain flours, bran fractions, and functional ingredients such as chia seeds. From a physiological standpoint, increased dietary fiber intake is associated with delayed carbohydrate digestion, reduced glucose absorption rate, and improved glycemic stability.

Taken together, the graphical analysis demonstrates a clear and complementary trend: a reduction in carbohydrate availability alongside a substantial increase in dietary fiber content. This dual modification represents a major nutritional advantage of the reformulated products, as both factors contribute synergistically to improved metabolic outcomes.

Therefore, the results confirm that reformulation strategies significantly improve the nutritional quality of bakery products, supporting their use as effective dietary tools for glycemic control in diabetes management.

In order to further evaluate the nutritional impact of the analyzed bakery products, the contribution of 100 g of each sample to the recommended daily intake (RDI) of macronutrients was calculated. This parameter provides a practical perspective on the nutritional relevance of the products in the context of daily dietary requirements. The results are illustrated in Figure 4.

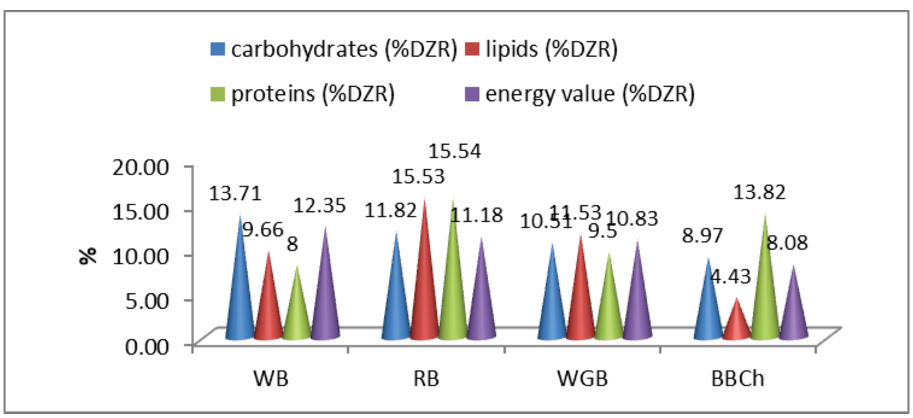

Figure 4. Contribution of 100 g of bakery products to recommended daily intake of macronutrients (%RDI)

As illustrated in Figure 4, the analyzed bakery products show distinct contributions to daily macronutrient intake, reflecting differences in formulation and raw material composition. The hypoglycemic variants demonstrate a reduced contribution to carbohydrate intake compared to white bread, along with a more balanced distribution of proteins and lipids. These modifications indicate an improved nutritional profile, supporting the role of reformulated bakery products in dietary strategies aimed at glycemic control and metabolic health.

The evaluation of the contribution of 100 g of bread products to the recommended daily intake (RDI) highlights important nutritional differences among the analyzed formulations, emphasizing the impact of flour type and functional ingredients on the nutritional profile of bakery products. The percentages were calculated considering the average adult daily requirements of 50 g proteins, 65 g lipids, and 300 g carbohydrates, corresponding to an energy intake of approximately 2000–2500 kcal/day [20]. These values are in agreement with European dietary reference frameworks proposed by EFSA for macronutrient intake in adults.

Among the analyzed samples, White Bread (WB) exhibited the highest contribution to carbohydrate intake, providing 13.71% of the daily carbohydrate requirement per 100 g product. This observation is consistent with the high proportion of refined wheat flour, characterized by increased starch availability and lower dietary fiber content. In contrast, the lipid contribution remained relatively low (9.66% DZR), while the protein contribution reached 8.70% DZR. The energetic contribution of WB represented 12.35% of the daily energy requirement, indicating a predominantly carbohydrate-based nutritional profile [21-23].

Rye Bread (RB) demonstrated the most balanced nutritional distribution and the highest overall nutritional density among the investigated products. The protein contribution reached 15.54% DZR, representing the highest value recorded among all samples, while lipid contribution increased to 15.53% DZR. In parallel, RB provided 11.82% of the recommended carbohydrate intake and 11.18% of the daily energy requirement. The elevated protein and lipid contributions may be associated with the higher nutritional complexity of rye flour, which contains increased levels of bioactive compounds, dietary fiber, and structurally complex carbohydrates. Rye-based products are frequently associated with improved satiety and attenuated glycemic responses due to slower starch digestion kinetics and enhanced matrix viscosity [11,12].

Whole Grain Bread (WGB) showed intermediate nutritional characteristics, with carbohydrate contribution values of 10.11% DZR and lipid contribution of 9.53% DZR. However, the protein contribution remained relatively high (10.80% DZR), reflecting the preservation of bran and germ fractions in whole wheat flour. The energetic contribution reached 10.83% DZR. Whole grain products are recognized for their higher dietary fiber, mineral, and phytochemical content compared to refined products, contributing to improved metabolic regulation and reduced postprandial glycemic variability [13]. Moreover, the structural integrity of whole grain matrices may limit enzymatic starch hydrolysis and delay glucose release during digestion [24,25]

Buckwheat Bread with Chia (BBCh) presented the lowest carbohydrate contribution among all formulations (8.97% DZR), while simultaneously exhibiting the highest energetic contribution (13.82% DZR). The lipid contribution remained comparatively low (4.43% DZR), whereas protein intake accounted for 8.08% DZR. The reduced carbohydrate contribution may be attributed to the replacement of refined cereal flour with buckwheat and chia ingredients, both characterized by higher dietary fiber content and lower digestible starch fractions. Chia seeds additionally contribute functional lipids rich in polyunsaturated fatty acids and bioactive compounds associated with metabolic health benefits. Such formulations are particularly relevant in the context of low-glycemic dietary strategies and functional food development [26-27].

Overall, the results demonstrate that the reformulation of bread products through the incorporation of whole grains, rye flour, buckwheat, and chia seeds significantly modifies the nutritional contribution of bakery products to daily dietary requirements. These changes may contribute to improved nutritional quality, enhanced satiety potential, and better metabolic control, supporting the growing interest in functional bakery products designed for the prevention and dietary management of metabolic disorders. Similar observations regarding the metabolic advantages of whole grain and fiber-enriched bakery products have been extensively reported in recent nutritional and clinical studies.

3.2 Results of sensory analysis and their interpretation

The results of the sensory analysis for each type of bakery product are presented in Table 5. The scores were obtained based on the evaluation performed by a panel of semitrained assessors, under controlled conditions, using the hedonic scoring method.

Table 5. Sensory evaluation scores of bakery products

Sensory Feature	WB	RB	WGB	BBCh
External appearance	4.5 ± 0.2^{a}	4.2 ± 0.2^{b}	4.3 ± 0.2^{b}	4.4 ± 0.3^{a}
Color	4.6 ± 0.2^{a}	4.1 ± 0.3^{b}	4.2 ± 0.2^{b}	4.3 ± 0.3^{b}
Smell/Aroma	4.4 ± 0.3^{a}	4.2 ± 0.2^{b}	4.3 ± 0.2^{ab}	4.2 ± 0.3^{b}
Texture/Consistency	4.6 ± 0.2^{a}	4.1 ± 0.3^{b}	4.3 ± 0.2^{c}	4.0 ± 0.3^{d}
Taste	4.5 ± 0.2^{a}	4.2 ± 0.3^{b}	4.3 ± 0.2^{b}	4.1 ± 0.3^{c}
Overall acceptability	4.52 ± 0.18^{a}	4.16 ± 0.21^{b}	4.28 ± 0.17^{ab}	4.20 ± 0.22^{b}

Note: Values are expressed as mean ± standard deviation (SD). Different letters on the same row indicate statistically significant differences ($p < 0.05$)

Legend:
WB – White Bread (refined wheat bread, control sample)
RB – Rye Bread (bread formulated with rye flour)
WGB – Whole Grain Bread (bread formulated with whole wheat flour)
BBCh – Buckwheat Bread with Chia (bread formulated with buckwheat flour and chia seeds

The data presented in Table 5 reveal statistically significant differences between the analyzed samples, indicating that the formulation of bakery products influences sensory perception across multiple attributes.

The WB sample achieved the highest scores for most parameters, particularly for color, texture, and taste, reflecting the well-established sensory properties of refined wheat-based products. These characteristics are mainly attributed to the optimal gluten structure and high consumer familiarity with white bread.

However, despite its superior sensory profile, WB does not represent a nutritionally optimal choice, as previously demonstrated by its high carbohydrate content and low fiber level.

The reformulated products (RB, WGB, and BBCh) exhibited high sensory acceptability, with all overall acceptability scores exceeding 4.0, indicating good consumer acceptance despite modifications in formulation.

The WGB sample demonstrated a balanced sensory profile, with consistently high scores across all attributes and no significant differences compared to WB in certain characteristics such as aroma and overall acceptability. This suggests that whole grain incorporation can preserve desirable sensory properties while improving nutritional value.

The RB sample, characterized by the highest fiber content, showed slightly lower scores for texture and color. These differences may be attributed to the denser structure and darker appearance typical of rye-based products. Nevertheless, its overall acceptability remained high, indicating that these differences do not significantly impair consumer acceptance.

The BBCh sample presented lower scores for texture and taste compared to WB and WGB, with statistically significant differences ($p < 0.05$). This effect is primarily related to the absence of gluten in buckwheat and the inclusion of chia seeds, which alter the structure and mouthfeel of the product.

Despite these differences, the overall acceptability score remained above 4.0, confirming that the product is still well accepted. Considering that BBCh also exhibited the most favorable nutritional profile, this result highlights its potential as a functional food suitable for dietary interventions.

The radar (spider) chart (Figure 5) provides a visual representation of the sensory profiles of the analyzed samples, allowing simultaneous comparison of all evaluated attributes. The graphical representation clearly shows that WB occupies the largest area, confirming its superior overall sensory performance. WGB presents a relatively large and well-balanced area, indicating a consistent sensory profile across all evaluated attributes.

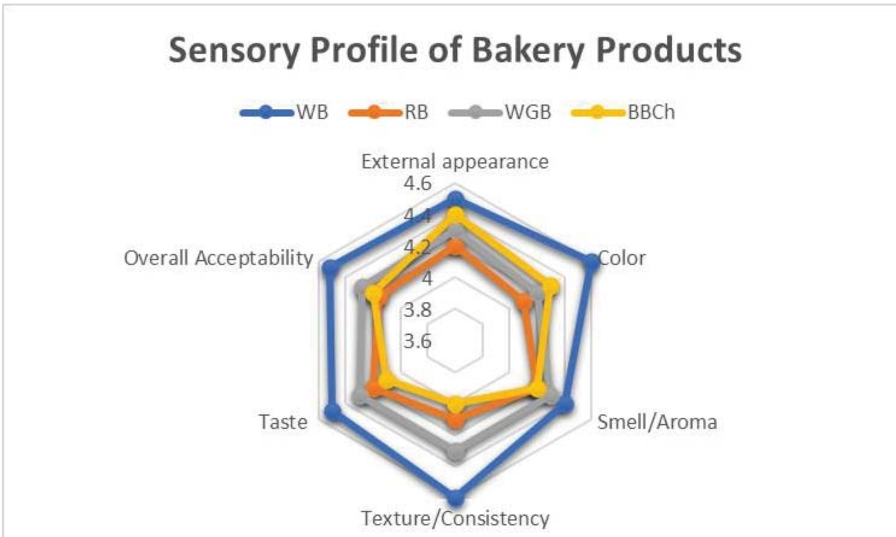

Figure 5. Radar chart representation of the sensory profile of bakery products (WB, RB, WGB, BBCh)

In contrast, RB exhibits a slightly reduced profile, particularly in terms of color and texture, while BBCh displays the smallest area, mainly due to lower scores recorded for texture and taste. However, the differences between samples remain relatively small, and all products maintain a compact radar profile, indicating good overall sensory quality.

This visual representation (Figure 5) confirms that reformulated bakery products retain acceptable sensory characteristics despite compositional modifications, supporting their potential application in dietary interventions targeting metabolic disorders.

From a clinical perspective, the sensory acceptability of functional foods is critical for long-term dietary adherence, especially in the management of chronic conditions such as diabetes mellitus.

The visual appearance of the analyzed bakery products is presented in Figure 7. a)-d), highlighting the differences in color, structure, and morphological characteristics between the samples. The WB sample exhibits a typical light color and uniform crumb structure, characteristic of refined wheat bread. In contrast, the RB and WGB variants show a darker color and a denser crumb, reflecting the presence of whole grain components and higher fiber content. The BBCh sample presents the most compact structure and darker appearance, associated with the absence of gluten and the incorporation of buckwheat flour and chia seeds. These visual differences are consistent with the compositional variations of the raw materials and support the results obtained in the sensory and nutritional analyses.

a) WB b) RB c) WGB d) BBCh

Figure 6. a)-d) Visual appearance of bakery products illustrating differences in color, structure, and surface characteristics: (a) WB, (b) RB, (c) WGB, and (d) BBCh.

The results demonstrate that all reformulated samples maintain high acceptability scores, suggesting that nutritional improvements (e.g., increased fiber and reduced carbohydrate content) do not compromise palatability.

This aspect is particularly important in medical nutrition therapy, where patient compliance is directly influenced by the sensory properties of recommended foods. The ability to develop

The combined analysis of sensory and nutritional results indicates that:

- WB provides the highest sensory quality but the least favorable metabolic profile
- WGB offers the best balance between sensory performance and nutritional improvement
- RB provides superior fiber content with acceptable sensory characteristics
- BBCh presents the most advantageous metabolic profile with slightly reduced, but still acceptable, sensory scores

Overall, the results support the feasibility of developing hypoglycemic bakery products that maintain consumer acceptability, highlighting the importance of integrating sensory evaluation into the design of functional foods for clinical nutrition.

products that combine metabolic benefits with acceptable taste and texture represents a key factor in the success of dietary interventions.

CONCLUSIONS

In conclusion, the findings of the present study demonstrate that the reformulation of bakery products represents a viable and clinically relevant strategy for improving dietary quality in patients with carbohydrate metabolism disorders, particularly diabetes mellitus. The observed reduction in available carbohydrates, combined with the substantial increase in dietary fiber content, provides a metabolic profile that is closely aligned with current nutritional recommendations for glycemic control.

The analysis of the contribution of the investigated bread formulations to the recommended daily intake values demonstrated that the incorporation of rye flour, whole grains, buckwheat flour, and chia seeds significantly influenced the nutritional profile of the bakery products. Reformulated breads exhibited improved nutritional density through enhanced protein contribution, moderated carbohydrate availability, and more balanced energy distribution compared to conventional white bread formulations.

Among the analyzed samples, rye bread presented the highest protein and lipid contributions, suggesting an increased nutritional complexity and potential satiety-enhancing effect. Whole grain bread provided a balanced macronutrient profile associated with the preservation of fiber-rich cereal fractions, while buckwheat bread with chia seeds showed the lowest carbohydrate contribution, supporting its potential suitability for low-glycemic dietary strategies. In contrast, white bread remained predominantly carbohydrate-oriented, reflecting the typical nutritional characteristics of refined cereal products.

These findings support the growing evidence that reformulation of staple bakery products using functional and whole-grain ingredients may improve their nutritional and metabolic relevance. Such products may contribute to better glycemic management, enhanced dietary quality, and increased alignment with contemporary recommendations for the prevention and nutritional management of metabolic disorders.

Importantly, the maintained sensory acceptability of the reformulated products supports their practical applicability in medical nutrition therapy, where long-term adherence remains a critical determinant of therapeutic success. This dual achievement—metabolic improvement without compromise in palatability—highlights the potential of functional bakery products as effective dietary tools in clinical settings.

From a translational perspective, these results support the integration of reformulated staple foods into evidence-based nutritional strategies for diabetes management, contributing to the development of sustainable, patient-centered interventions. The present study is therefore highly relevant for clinical nutrition practice and supports the growing paradigm of "food as medicine" in metabolic disease management, aligning with the scope and objectives of journals focused on endocrinology, diabetes, and nutritional sciences.

Patents

No patents resulted from the work reported in this manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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