Available online at www.ijournalse.org

Emerging Science Journal

(ISSN: 2610-9182)

Vol. 9, No. 3, June, 2025

Development of Rye-Wheat Bread Containing Flaxseed Flour and Rice Husk Dietary Fiber

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Abstract

The study aims to improve the nutritional and biological value of rye-wheat bread by incorporating defatted flaxseed flour and dietary fiber from rice husks. Conducted in two stages, the research first introduced defatted flaxseed flour into bread formulations at 5–20% of wheat flour weight. In the second stage, rice husk-derived dietary fibers were added in powdered form at 0.3–0.7% of the total rye-wheat flour mass. The effects of these additives on dough's physicochemical and rheological properties were analyzed. Results indicated that adding flaxseed flour and dietary fibers produced medium-strength dough, ensuring adequate bread volume. Optimal dosages were identified as 15% flaxseed flour (to wheat flour weight) and 0.5% dietary fiber (to rye-wheat flour mass). The study also proposed technological modes to enhance consumer properties of the bread. The research demonstrated increased nutritional value, with a 39.7% rise in protein content, a 2.8-fold fiber increase, higher levels of minerals, and significant vitamin boosts (C: +0.375 mg/100 g; E: +3.55 mg/100 g). A 15.4% reduction in carbohydrates was also noted. Additionally, the additives improved gas-holding capacity, crumb structure, and moisture retention, reducing staling and extending shelf life.

Keywords:

Bread, Dough;
Rye-Wheat Flour;
Flaxseed Flour;
Dietary Fiber;
Nutritional Value.

Article History:

Received:	22	November	2024
Revised:	24	April	2025
Accepted:	06	May	2025
Published:	01	June	2025

1- Introduction

Dietary fiber plays a critical role in maintaining human health, particularly in the prevention of various chronic diseases. A significant portion of dietary fiber is found in traditional raw materials commonly used in the food industry, such as second-grade durum wheat flour, oat flour, and others [1-3]. Dietary fiber is a complex of complex carbohydrates: cellulose, hemicellulose, pectin, gum, mucus, and non-carbohydrate lignin (a polymer of aromatic alcohols) [4, 5]. These fibers are known to improve intestinal motility and metabolism, and their consumption is associated with a lower risk of conditions such as colon cancer, hemorrhoids, constipation, polyps, ulcerative colitis, obesity, diabetes, cardiovascular diseases, and more [6, 7]. Given the extensive health benefits, it is essential to ensure adequate dietary fiber intake through the consumption of functional food products, including bakery items.

While various sources of dietary fiber are available, the use of non-traditional raw materials like rice husk and flaxseed flour in food production is gaining increasing attention. Rice husk, a by-product of rice milling, is rich in organic matter (70%-85%) and contains up to 78% dietary fiber, including cellulose, lignin, and mineral ash. The high content of silicon dioxide in rice husk provides additional health benefits, such as promoting toxin removal from the body, strengthening capillary walls, and enhancing immunity [8, 9]. Similarly, flaxseed flour, rich in polyunsaturated fatty acids, dietary fiber, protein, and essential vitamins and minerals, has been identified as a valuable ingredient for improving the nutritional profile and functional properties of bakery products [10, 11].

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DOI: http://dx.doi.org/10.28991/ESJ-2025-09-03-05

Flaxseed flour is rich in the following components:

1. Polyunsaturated fatty acids. α-linolenic and linoleic acids. They are necessary for the proper growth and functioning of the human body, are part of all cell membranes.
2. Dietary fiber. Presented in the form of plant cell membranes and consist of polysaccharides. Fiber accounts for about 28% of the dry mass of flaxseed flour.
3. Vegetable protein. Its share can reach 50%. Flaxseed flour proteins have high biological value.

Beneficial properties of flaxseed flour:

- Normalizes the gastrointestinal tract;
- Can act as a mild laxative;
- Prevents the development of cardiovascular diseases;
- Useful for people with type 1 and type 2 diabetes;
- Helps to avoid obesity and promotes weight normalization [12-14].

Despite the promising potential of these materials, gaps in existing literature remain regarding the optimal use of rice husk dietary fiber and flaxseed flour in bakery products, particularly rye-wheat bread. Previous studies have primarily focused on the individual effects of these ingredients in various food matrices, but few have explored their combined impact on the physicochemical and rheological properties of dough, as well as the nutritional and biological value of the final product. Furthermore, there is limited research on the methods for processing and integrating these ingredients into bakery formulations without compromising the bread's quality, texture, or safety.

This study aims to fill these gaps by evaluating the feasibility of incorporating flaxseed flour and rice husk dietary fiber as active biological additives in the production of rye-wheat bread. The research objectives include: (i) reviewing the literature on the use of rice husk in food production; (ii) evaluating the physicochemical and rheological properties of dough containing flaxseed flour and/or rice husk dietary fiber; (iii) determining the optimal recipe and dough preparation techniques based on these properties; and (iv) assessing the quality, safety, and biological value of the finished bread. Through this approach, the study seeks to contribute valuable insights into the effective use of non-traditional raw materials to enhance the nutritional value and functional properties of bakery products.

2- Material and Methods

This study used dietary fiber prepared from rice husk leaching (in powder form), a mixture of peeled rye and first-grade wheat flour, and flaxseed flour (TC 10.61.20-001-38744625-2016) that was produced locally from the Karabalyk district (bred at the Kazakh Research Institute of Agriculture and Plant Industry LLP). The research was conducted at the Department of Technology of Bakery Products and Processing Industries of Almaty Technological University. The experimental scheme is presented in Figure 1. The research was conducted in two stages. First, rye-wheat bread was generated with first-grade wheat flour and 5%, 10%, 15%, or 20% defatted flaxseed flour. Second, dietary fiber from rice husk without removal of amorphous silicon dioxide was added (0.3%, 0.5%, or 0.7%).

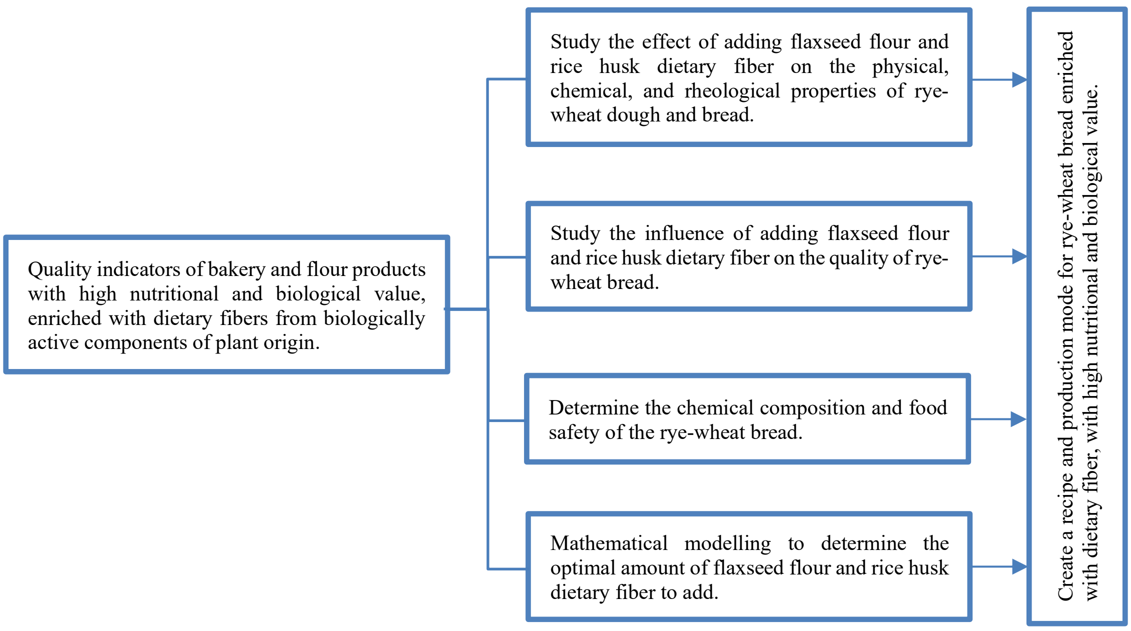


Figure 1. The experimental scheme

Defatted flaxseed flour is light grey or brown in colour; has a musty but not spoiled smell; a bitter but not sour taste; 7% moisture, 4% acidity, 1.25% ash; for coarseness, 2% of the sample is left in the sieve after using No. 27; and whiteness is 70 conventional units. Rice husk dietary fiber is grey-black in colour; smells musty but not spoiled; tastes bitter, but not sour, is not itchy; contains 10% moisture and 2.1% acidity; its heavy metal content meets food safety standards; and its microbiological quality meets the regulatory requirements. The dough was prepared from a sourdough starter comprising rye and first-grade wheat flour at a ratio of 60:40, salt, fermented rye malt, sugar, vegetable oil, and water until the dough moisture content reached 48.0%. The dough was cut, proofed, and baked as described previously [15]. Figure 2 shows the scheme to prepare fermented milk with flaxseed powder and flour.

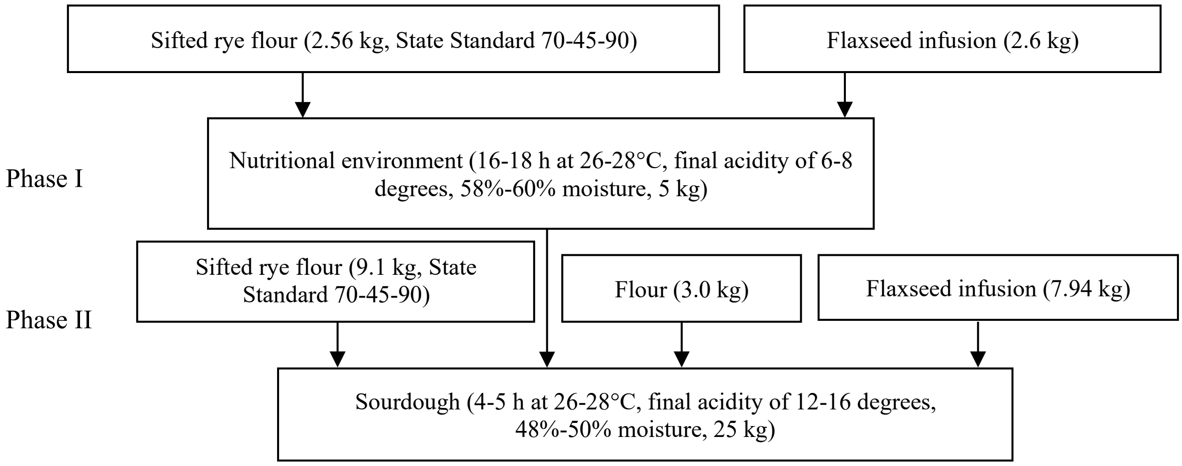


Figure 2. The scheme for the preparation of fermented milk with flaxseed powder and flour

Figure 3 shows the technological scheme of rye-wheat bread prepared from rye-wheat flour, yeast, flaxseed flour, and rice husk dietary fiber. Table 1 shows the recipe.

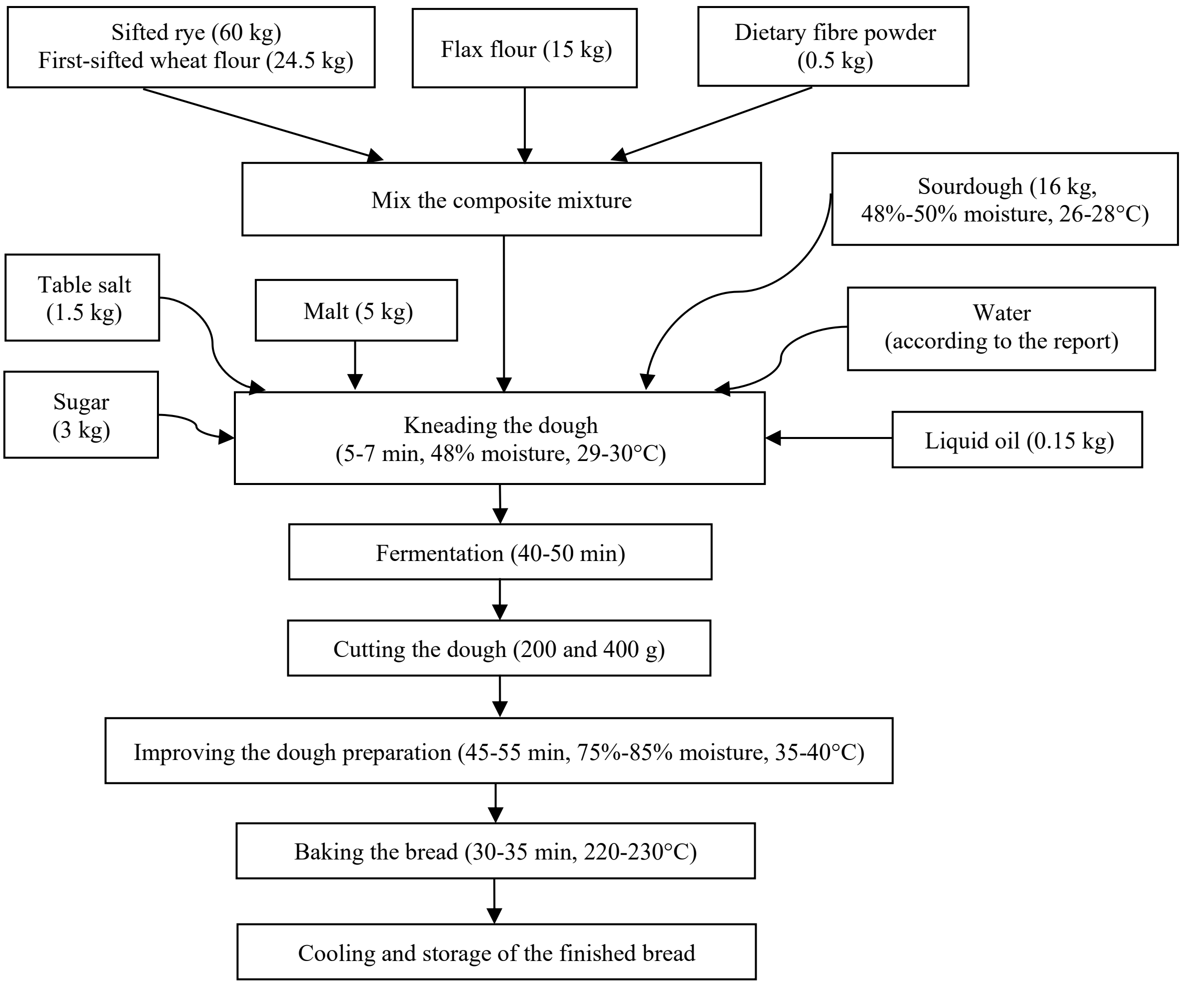


Figure 3. Scheme used to prepare rye-wheat bread with flaxseed flour and rice husk dietary fiber powder

Table 1. The recipe for rye-wheat bread from a sourdough starter with 15% flaxseed flour and 0.5% rice husk dietary fiber powder

Component	Amount of raw material (% by mass of flour)	
	Sourdough	Dough
First-sifted wheat flour, kg	-	24.5
Sifted rye, kg	11.37	60.0
Flax flour, kg	3.0	15
Dietary fiber powder, kg	-	0.5
Compressed yeast, kg	-	-
Sourdough, kg	8	16
Table salt, kg	-	1.5
Sugar, kg	-	3
Malt, kg	-	5
Liquid oil, ml	-	7
Water, ml	According to the report	
Initial temperature, °C	26-30	29-30
Opening duration, min	210-240	50-60
Humidity, %	48-50	48

The rye sourdough starter contained flaxseed infusion and flour. This starter increases the lactic acid bacteria biomass and accelerates the biochemical processes in the dough due to the accumulation of acidity in the starter, thus shortening the time required to prepare the dough. The dough was analysed in accordance with established methods for the organoleptic indicators (surface condition, consistency, degree of dryness, dough structure, and flavour) and physicochemical indicators (moisture [GOST 21094-75] and acidity) [16].

When evaluating the influence of new recipe components on the quality indicators of dough and bread, attention is placed on the structural and mechanical properties of the dough. It is clear that replacing part of the flour with other components alters the rheological properties of the dough and the finished products. Thus, while developing the recipe, the influence of various additives on the rheological properties of semi-finished products was examined with a Brabender farinograph. The method is based on the measurement of dough consistency during its formation from flour and water and during kneading [17]. The following parameters were determined from the farinogram: the water absorption capacity (WAC, %), the dough formation time (min), the dough resistance to kneading (min), the degree of dough liquefaction 10 min after the start, the degree of dough liquefaction 12 min after the maximum, and the farinograph quality index (mm).

A Chopin alveograph was also used to assess rheology [18]. The method is based on kneading a dough of constant moisture from flour and a sodium chloride solution under certain conditions, preparing samples from the dough to test a standard thickness after proofing, inflating them with air in the shape of a bubble, and plotting the differences in pressure inside the bubble over time. The properties of the dough are assessed based on the shape of the resulting diagrams. The following indicators were determined: the P parameter indicates the elasticity of the dough, that is, its ability to resist deformation; the L parameter indicates the maximum volume of air that the dough bubble can hold and indicates the extensibility of the dough; the I.e. parameter corresponds to the elasticity index; and the W parameter indicates the total deformation energy or the so-called baking strength of the flour.

A Structurometer ST-2 device was used to assess the elastic and plastic deformation of the dough (Figure 4), as described previously [19]. Briefly, the device was installed on a fixed table at 25 °C and < 80% relative humidity. It was preheated for 20 min prior to analysing the samples. The rheological property of the dough samples (10 g) was determined based on the ratio of its elastic tensile strain.

Figure 4. An image of the Structurometer ST-2 device

The effect of flaxseed flour on the rheological properties of dough was evaluated in samples in which wheat flour was replaced with 5%, 10%, 15%, or 20% defatted flaxseed flour. Table 2 provides the flour quality indicators. In addition, rice husk dietary fiber was added at 0.3%, 0.5%, or 0.7% of the total mass of flour. The control was rye-wheat flour with a ratio of 60:40.

The dough was kneaded well and then allowed to rise at 28-30°C for 150-180 min. Note that the initial temperature for the dough was 30-32°C for 60-90 min. After proofing, the dough was cut into 200-g pieces (to prepare round bread samples) or 400 g (when samples were placed in a mould), which were again allowed to rise at 35-40°C and 75%-80% relative humidity. The readiness of the dough pieces was determined based on visual inspection. The samples were baked in a laboratory oven at 220-230°C for 35-40 min (for the samples in a mould) or 25-30 min (for the round bread samples).

In the study, the acceptability of bread for consumers was assessed using sensory analysis, including tasting and questionnaires. The organoleptic indicators were determined based on the correctness of the sample's shape, appearance, crust colour, colour and elasticity of the inside, the porosity, taste, and aroma. The organoleptic index was determined according to State Standard 5667-2022. The humidity of the inside of the samples was determined according to State Standard 21094-2022. The acidity was determined according to State Standard 5670-96. Bread porosity was determined based on State Standard 5669-96 using Zhuravlev's device. The volume of the round bread samples was determined based on the ratio of its height to diameter. The volume of normal bread was determined on a special measuring device.

Table 2. The flour quality indicators

Quality indicator	Type of flour		
	First-grade wheat flour	**Sifted rye flour**	**Defatted flaxseed flour**
Organoleptic parameters			
Colour	White with a yellow tint	White with a grey tint	Light grey to brown
Odour	No extraneous odour	Characteristic extraneous odour	Peculiar, foreign, bruised
Taste	No extraneous flavour	No extraneous flavour	No extraneous bitter taste
Physicochemical parameters			
Humidity, %	13.5	15.0	7
Ash content, %	0.75	0.75	1.25
Acidity, degrees	3.2	5	4
Amount of gluten, %	34	-	-
By Gluten deformation meter (GSM), instrument units	68	-	-
Gas-forming capacity, ml	1450	-	-
Whiteness, conventional units	39	52	70
Density, % No. 35 remaining in the sieve	2	-	-
Density, % No. 27 remaining in the sieve	-	2	2
Number of falls, C	-	160	-
Autolytic activity,%	-	48	-

A mathematical model was developed to determine the optimal amount of flaxseed flour and rice husk dietary fiber powder. Specifically, a second-order rotatable plan (a Box plan) was employed to obtain the optimal set of input factors affecting the process of grain material milling at which the optimisation criterion takes the maximum value. The regression coefficients β_0, β_i, β_{ij}, β_{ii}, ..., are estimates of the theoretical coefficients and are used to calculate the optimisation criterion with Equation 1.

$$y = b_0 + \sum^{n} b_i\, x_i + \sum_{i<j}^{n} b_{ij}\, x_i x_j + \sum^{n} b_{ii} {x_i}^2 + \cdots, \tag{1}$$

These regression coefficients were determined from Equations 2 to 5:

$$b_0 = a_1 \sum_1^N y_u - a_2 \sum_1^k \sum_1^N x_{iu}^2\, y_u; \tag{2}$$

$$b_i = a_3 \sum_1^N x_{iu}\, y_u; \tag{3}$$

$$b_{ij} = a_4 \sum_1^{n_я} x_{iu}\, x_{ju} y_u; \tag{4}$$

$$b_{ij} = a_5 \sum_1^N x_{iu}^2 y_u + a_6 \sum_1^k \sum_1^N x_{iu}^2 y_u - a_7 \sum_1^N y_u, \tag{5}$$

In Equations 2 to 5, a_1, a_2, a_3, a_4, a_5, a_6, and a_7 are coefficients whose values are chosen based on the number of factors [20, 21].

3- Results and Discussion

3-1- Farinographic Parameters of the Dough

The following parameters were determined in the farinograph: water absorption capacity (WAC, %), dough formation time (min), dough resistance to kneading (min), the degree of dough dilution 10 minutes after the start, the degree of dough dilution 12 minutes after reaching the maximum value, as well as the farinograph quality index (mm).

The test dough samples were sent to the instrument in the form of wheat flour with 5, 10, 15, 20% addition of flax flour in the recipe of rye wheat bread with and without 0.3, 0.5, 0.7% dietary fiber.

Table 3 presents the farinographic parameters of the dough.

Table 3. The farinographic parameters of dough from a mixture of rye and wheat, flaxseed flour with the addition of dietary fiber

Flaxseed flour content, %	Water absorption capacity, %	Dough formation time, min	Test stability, min	Degree of liquefaction 10 min after the start, EF	Degree of liquefaction 12 min after the maximum, EF	Farinograph quality index, mm
Control	67.7	4.5	3.6	58	120	75
5%	68.2	4.7	2.0	91	141	63
10%	69.1	5.9	2.5	81	110	91
15%	68.4	5.5	3.4	63	95	80
20%	68.3	1.6	10.4	46	88	16
0.3% rice husk dietary fiber powder						
5%	67.9	4.7	2.1	105	156	59
10%	69.6	5.3	2.8	85	135	60
15%	67.2	6.4	7.7	48	91	87
20%	66.6	2.5	11.8	28	50	28
0.5% rice husk dietary fiber powder						
5%	68.4	4.7	2.2	107	150	60
10%	69.7	5.0	3.3	87	132	65
15%	68.2	6.7	6.1	35	101	76
20%	67.4	2.9	13.2	24	63	23
0.7% rice husk dietary fiber powder						
5%	68.7	4.8	2.7	87	142	61
10%	70	5.0	3.0	81	138	66
15%	68.2	7.2	6.8	37	98	90
20%	67.4	2.0	15.5	9	17	22

The initial stage of rheological evaluation of flour, conducted using a farinograph, involves determining the amount of water required to achieve a dough with the desired consistency (500 farinograph units). The results obtained from this process characterize the WAC of the flour and the impact of various additives on this parameter. The WAC of the flour is a primary factor influencing the consistency and rheological properties of the dough, as it directly affects the dough's consistency, yield, and crumb structure—ultimately influencing the final volume and sensory qualities of the baked products.

As shown in Table 3, the addition of 10% flaxseed flour resulted in a slight increase of WAC of the dough. However, further increasing the flaxseed flour content to 20% led to a decrease of WAC. A similar pattern of WAC alteration was observed when rice husk dietary fiber was incorporated into the dough formulation. It is important to note that the WAC is influenced by both the particle size and the biochemical properties of the flour. Coarser particles exhibit an 'additional swelling' property, which is directly associated with the content of biopolymers in the flour, such as proteins and non-starch polysaccharides.

One of the key technological distinctions between flaxseed flour and traditional cereal and legume flours is the composition of carbohydrates. Flaxseed flour contains high-molecular-weight polysaccharides (such as fiber and hemicellulose), which are insoluble in water. Additionally, flaxseed flour contains pentosans, which comprise 2.0%-6.5% of the seed weight. These pentosans are low-molecular-weight, water-soluble carbohydrates that easily form viscous gels (referred to as slugs) upon hydration. Compared to cereal seed flours, flaxseed has a significantly lower starch content (approximately 5.0%-7.0% of the seed composition). A noteworthy characteristic of pentosans is their ability to form gels when hydrated, which significantly impacts the rheological properties of the dough.

Flour obtained from flaxseed cake, which contains a higher proportion of sheath particles, also has an increased content of non-starch polysaccharides and hydrocolloids, which are known for their ability to absorb and retain moisture effectively. Therefore, it is expected that the inclusion of flaxseed flour in flour mixtures will lead to an increase in bread yield as the moisture content of the mixture rises.

Addition of up to 15% flaxseed flour increased the time required to form the dough (Table 1). Obviously, wheat proteins need more time for hydrophobic mutual orientation and gluten network formation. The observed pattern shows the interfering effect of flaxseed proteins on the gluten formation process. A similar effect of water-soluble proteins has been described with the addition of cereal and legume albumin [22-24].

The farinograms show a transition from the dough formation phase to the stabilisation phase. The stability of dough formation when flaxseed flour was included in the flour mixture was 2.0-10.4 min for the variants, with the control sample at 3.6 min.

Dough stability to kneading increased slightly (from 2.1 to 11.8 min) with the addition of 0.3% rice rusk dietary fiber to the flour mixture. This indicator increased from 2.2 to 13.2 min when adding 0.5% rice rusk dietary fiber, and from 2.7 to 15.5 min when adding 0.7% rice rusk dietary fiber. This phenomenon is due to the change in the properties of the gluten complex during dough formation. A small amount of flaxseed flour in the mixture promotes the formation of a stable gluten complex due to its better hydration. Adding dietary fiber increases the time of dough stability to kneading, with noticeable strong binding of dietary fiber to the flour components. Therefore, when adding dietary fiber to the dough, the gluten skeleton structure improves, a phenomenon that increases the stability of the dough and thus the bread.

The degree of dough liquefaction 10 min after the start of kneading was higher in the dough with up to 15% flaxseed flour compared with the control dough (only rye-wheat flour). Adding 20% flaxseed flour decreased the degree of dough liquefaction. The degree of dough liquefaction 12 min after reaching the maximum changed in the same way when flaxseed flour was added. The degree of dough liquefaction 10 min after the beginning of kneading was 28-105 EF when the addition of 0.3% rice husk dietary fiber, 24-107 EF with the addition of 0.5% rice husk dietary fiber, and 9-87 EF with the addition of 0.7% rice husk dietary fiber. For comparison, the control sample had a value of 58 EF. A decrease in the degree of dough liquefaction indicates an improvement in its rheological properties. Consequently, the introduction of flaxseed flour into the rye-wheat flour mixture improved the quality of the dough, with a higher dosage of flaxseed flour the quality of the dough deteriorates. Of note, the inclusion of rye-wheat flour, flaxseed flour, and rice husk dietary fiber had a positive effect on the degree of dough liquefaction, which improved the rheological properties of the dough.

The farinograph quality index is a complex value that provides information about the quality of the dough, including its characteristics in terms of formation time, kneading stability, and degree of liquefaction. The higher the farinograph quality index, the better the rheological properties of the dough [25, 26]. The addition of flaxseed flour and rice husk dietary fiber to the rye-wheat flour mixture increased the farinograph quality index. The sample containing 15% flaxseed flour and 0.3%-0.7% rice husk dietary fiber had the highest farinograph quality index. Of note, the farinograph quality index was rather low when adding 20% flaxseed flour.

Overall, the replacement of wheat flour with flaxseed flour led to significant changes in the properties of dough: an increase of WAC, dough formation time, and farinograph quality index. By adding up to 10% flaxseed flour to the mixture, the degree of dough liquefaction decreased and the dough kneading stability increased slightly; therefore, the rheological properties of the dough improved. A further increase in the proportion of flaxseed flour in the mixture increased the degree of dough liquefaction and decreased the dough resistance to kneading. The addition of rice husk dietary fiber to the flour mixture exerted a positive influence for all parameters.

3-2- Alveographic Parameters of the Dough

The volume, elasticity, and several other key characteristics of bread made from wheat and rye flour are primarily determined by the gluten content. It is evident that substituting a portion of the flour with alternative ingredients will inevitably alter the rheological properties of both the dough and the final baked products [27]. Dough prepared from a mixture of rye and wheat flour exhibits properties more similar to those of rye flour than to wheat flour, and as such, it is processed in a manner similar to rye flour.

The incorporation of flaxseed flour into the dough led to a reduction in its elasticity, as indicated by the P parameter. However, the addition of dietary fiber to the dough mixture resulted in an improvement in elasticity, which was contingent on the proportion of flaxseed flour used. The presence of flaxseed flour also enhanced the extensibility of the dough, as reflected by an increase in the L index compared with the control dough. Specifically, the L value ranged from 40-260 mm for the dough with added flaxseed flour, compared to just 73 mm for the control sample.

In terms of tensile strength, a slight reduction was observed in the dough made from the rye-wheat-flaxseed flour mixture when dietary fiber was incorporated. The tensile strength decreased as follows: with 0.3% dietary fiber, the strength ranged from 19-161 mm; with 0.5% dietary fiber, it ranged from 29-182 mm; and with 0.7% dietary fiber, it ranged from 19-202 mm. Based on these findings, it was concluded that replacing 10% of the wheat flour with flaxseed flour (without dietary fiber) and 15% of the wheat flour with flaxseed flour (when dietary fiber was added) provided optimal formulations, both of which demonstrated superior characteristics compared to the control.

3-3- Rheological Properties of the Dough

To determine the rheological properties of the dough, 10 g of research models prepared for the workplace of the above unit were removed and the elastic deformation was detected.

The effect of dietary fiber and flaxseed flour additives on the mechanical properties of flour dough depends on many factors such as temperature, humidity, the duration and intensity of mechanical action on the dough, the recipe, the method of preparation and duration of dough fermentation, the baking properties, and the strength of flour. The addition of flaxseed flour and rice husk dietary fiber to wheat and rye dough markedly changed its structural and mechanical characteristics (Figures 5 to 9). By adding 5%-20% flaxseed flour, there was plasticisation of the dough structure (i.e., a decrease in the relative elastic-plastic deformation of the dough).

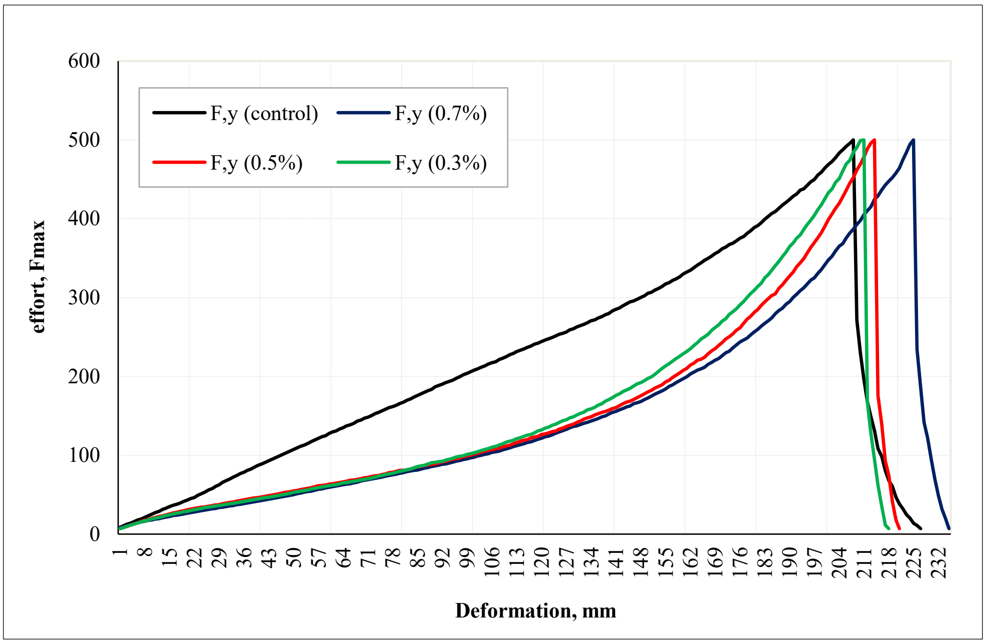


Figure 5. The effect of rice husk dietary fiber on elastic-plastic deformation of rye-wheat flour dough before fermentation

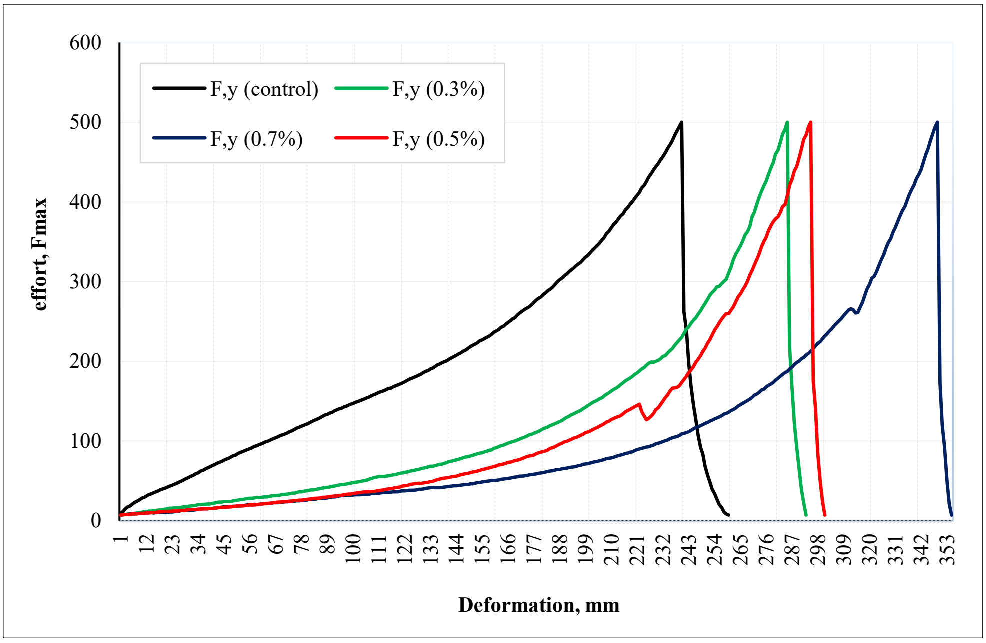


Figure 6. The effect of rice husk dietary fiber on elastic-plastic deformation of rye-wheat flour dough after fermentation

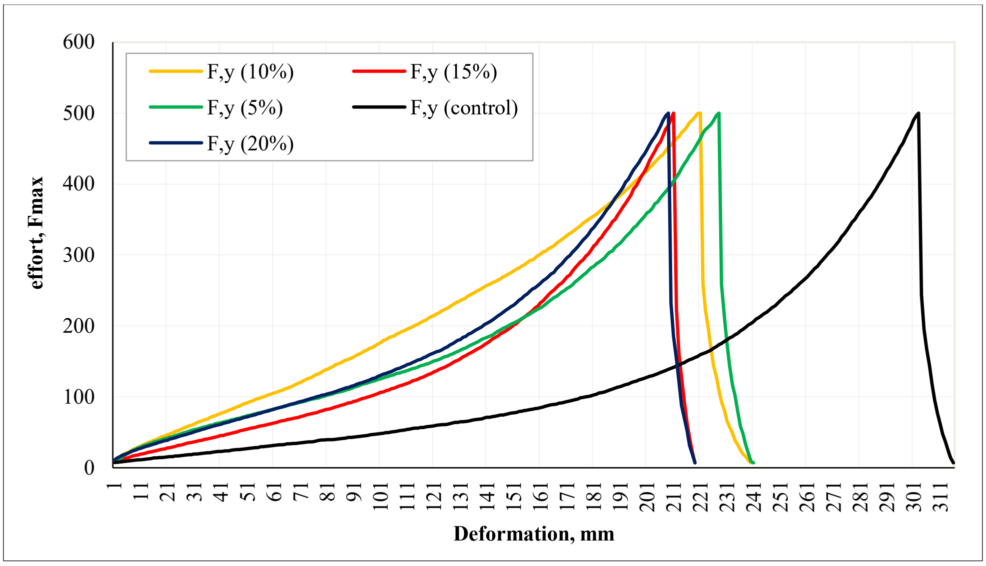


Figure 7. The effect of flaxseed flour on elastic-plastic deformation of rye-wheat flour dough before fermentation

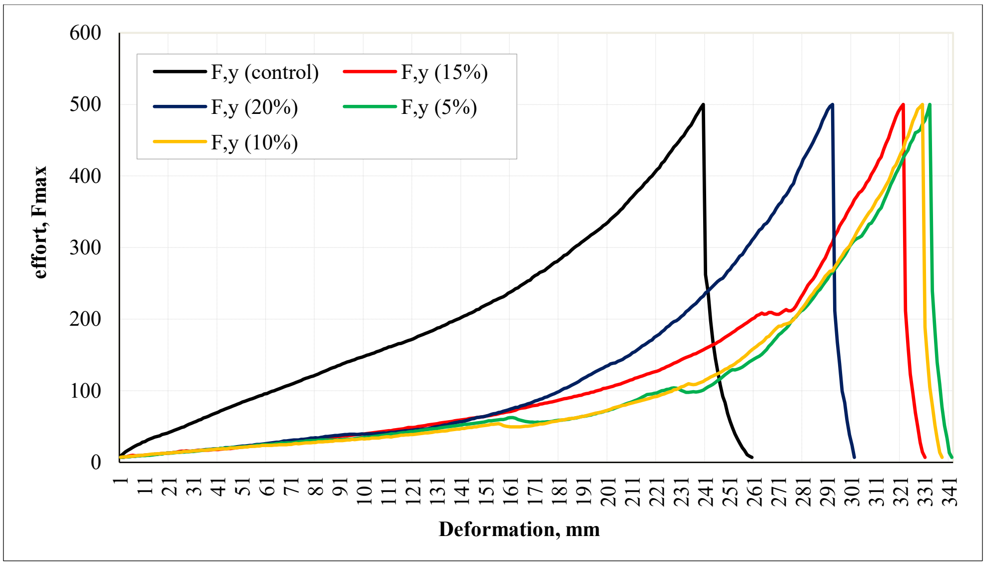


Figure 8. The effect of flaxseed flour and 0.5% rice husk dietary fiber on elastic-plastic deformation of rye-wheat flour dough before fermentation

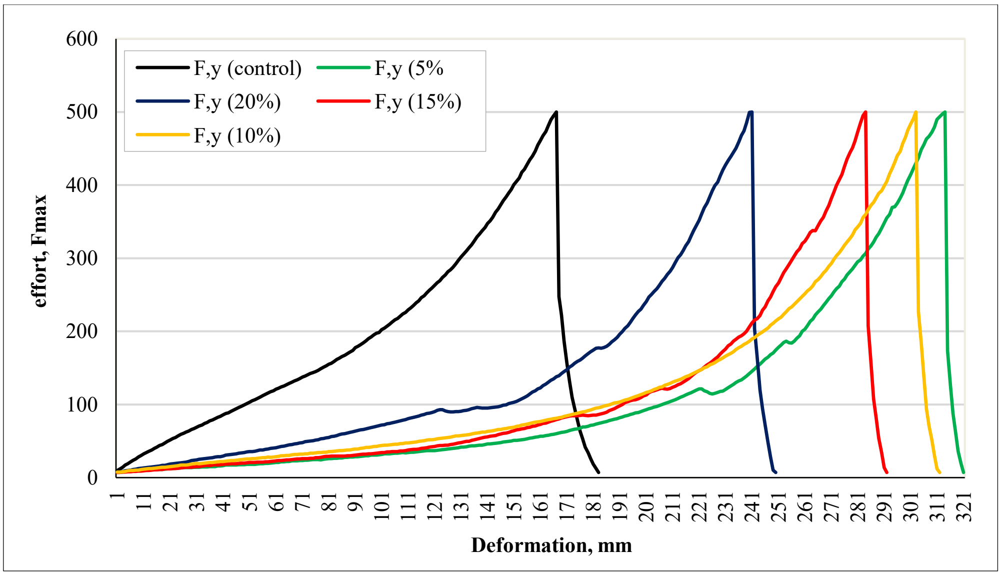


Figure 9. The effect of flaxseed flour and 0.5% dietary fiber on elastic-plastic deformation of rye-wheat flour dough after fermentation

Figures 5 and 6 show the effect of rice husk dietary fiber on the structural and mechanical properties of rye-wheat dough before and after fermentation. Dough made of rye-wheat flour without the addition of dietary fiber served as the control. The dough with 0.7% rice husk dietary fiber took more time to reach elastic tensile deformation compared with the control, whereas the dough with 0.3% or 0.5% rice husk dietary fiber were similar to the control dough. This difference can be explained by the fact that dietary fiber is good at improving the gluten framework that forms the structure of the dough. Moreover, when opening the dough there is enough time for proteins contained in the dough to swell during the colloidal process.

Based on Figure 7, the dough deformation with 5%, 10%, 15%, and 20% flaxseed flour was 208, 210, 221, 228 mm, respectively, at a force of 500 N. For comparison, the control dough had a value of 300 mm at the same force. As shown in Figure 8, this figure increased slightly due to the specificity of dough properties before and after opening. The addition of up to 15% flaxseed flour had a positive effect on the properties of rye-wheat flour dough. However, the addition of 20% flaxseed flour did not further improve the performance: that dough performed similarly to the control dough.

Figure 9 shows the elastic-plastic deformation of rye-wheat dough with the addition of flaxseed flour (5%-20%) and 0.5% rice husk dietary fiber. Similarly to the results from Figure 8, the addition of up to 15% flaxseed flour had positive results, whereas the dough with 20% flaxseed flour behaved similarly to the control dough. Dietary fibers enhance the glue quality and improve the structural and mechanical properties of the dough. In addition, the good WAC of flaxseed flour contributed to the improved performance.

The structure of non-fermented dough containing rye-wheat flour and no additives showed enhanced plasticity compared with the other samples, due to the water-soluble compounds present in rye flour. After fermentation, the dough had a low viscosity and a high relative elasticity. The addition of 0.3-0.7% rice husk dietary fiber to the dough significantly reduced its plasticity and increased its relative elasticity. The effect of flaxseed flour on the structure of unfermented dough, aged 1-2 h, was similar to the effect without ageing. The amount of added flaxseed flour influenced the dough properties. The addition of a large quantity of flaxseed flour was added to non-fermented and fermented dough worsened the dough's baking properties. The joint addition of rice husk dietary fiber and flaxseed flour slightly increased viscosity and elasticity. The addition of these additives was superior compared with some biologically active additives in terms of dough stability to deformation. This amended rye-wheat bread dough could hold its form, indicating the pastillability of the dough.

The addition of 0.3%, 0.5%, and 0.7% rice husk dietary fiber after fermentation led to a dough deformation of 283, 293, and 345 mm, respectively, compared with 240 mm for the control sample. When rice husk dietary fiber was added at the same levels before fermentation, the dough deformation was 209, 212, and 223 mm, respectively, compared with 202 mm for the control sample. Thus, there was a more pronounced change in dough strains after fermentation compared with before fermentation of the dough. This is explained by the fact that the colloidal processes are good for kneading, and this effect is enhanced when the dough is chilled during fermentation. The addition of rice husk dietary fiber during kneading improves the dough's rheological properties because the rice husk powder forms a strong framework due to the convergence of hydrophobic methoxy groups in aqueous medium, and free carboxyl groups dissociate into ions. Indeed, rice husk contains surfactants that help improve the structural and mechanical properties of the dough [28, 29].

3-4- The Quality of the Dough and Finished Bread

The next stage of this study was the development of an appropriate technological mode to produce bread containing rye-wheat and flaxseed flour as well as rice husk dietary fiber. The selection of the appropriate mode involved evaluation of the moisture, temperature, and acidity of the dough (Table 4) [30].

Table 4. Technological mode of dough preparation from mixtures of rye-wheat and flaxseed flour and 0.5% rice husk dietary fiber

Name of process indicator	Control	Flaxseed flour content, %			
		5	10	15	20
Dough temperature, ºC	27-29	28-30	28-30	28-30	28-30
Dough moisture, %	48	48	48	47.5	47
Initial acidity, degrees	6-8	7-8	8-9	9-10	10-11
Final acidity, degrees	8-10	9-11	10-11	11-12	12-13
Fermentation duration, min	90-100	50-60	50-60	50-60	50-60

Compared with the control, the addition of flaxseed flour did not change the temperature of the dough, slightly decreased the moisture content (due to the high WAC of flaxseed flour and the water-binding capacity of dietary fiber), and increased the initial and final acidity by 2-3 degrees. The addition of flaxseed flour and rice husk dietary fiber markedly reduced the fermentation time by 40 min (to 50-60 min compared with 90-100 min for the control sample). The increased moisture content of the mixtures with flaxseed flour underscored the increased volume of water introduced during kneading. Of note, increased dough moisture can increase viscosity and stickiness, adversely affect the processes of division and rounding of dough pieces. Subsequently, during proofing, the products may show poor form stability. The baked bread may have a low specific volume and a compacted crumb. The introduction of 0.3%-0.7% rice husk dietary fiber improved the WAC but did not necessarily alter the dough moisture content [31]. The increased acidity of dough as the amount of flaxseed flour increased altered the dynamics of fermentation, with faster maturation of the dough and thus a shorter total duration of fermentation.

The organoleptic characteristics of the finished research models are determined according to GOST 5667-2022. The samples of bakery products were determined based on the results of the work of a research group of 10 people using a questionnaire. Taking into account all the studied parameters and the questionnaire data, it was found that the new types of bakery products meet the needs of different age groups and dietary preferences. Young consumers noted the soft texture and neutral taste, while older respondents emphasized its positive effect on digestion. Those following a diet rated the product as low-carbohydrate bread.

The quality of bread was evaluated 4-6 h after baking by organoleptic and physicochemical indicators [32]. Table 5 shows the effects of rice husk dietary fiber on the quality of the finished bread.

Table 5. The effect of rice husk dietary fiber on the quality of the baked rye-wheat bread

Quality indicator	Control	Amount of rice husk dietary fiber, %		
		0.3	0.5	0.7
Physicochemical parameters				
Humidity, %	49	48	47.5	47.0
Porosity, %	48	52	54	51
Acidity, degrees	7	7	7	7
Organoleptic parameters				
Shape and surface	Characteristic of bread, regular and convex			
Colour	Light brown	Grey-brown		Dark brown
Crumb condition	Baked, with no traces of unbaked bread	Baked, without traces of unbaked bread and well-formed porosity	Baked, without traces of unbaked bread and well-formed and uniform porosity	
Taste and flavour	Characteristic of bread with a pleasant taste and aroma			

The incorporation of up to 0.7% rice husk dietary fiber resulted in a reduction in the moisture content of the finished bread. The highest porosity was observed in the sample containing 0.5% rice husk dietary fiber. However, with the addition of 0.7% rice husk dietary fiber, porosity decreased, and the bread developed a noticeably darker color. Despite these changes, the introduction of rice husk dietary fiber did not significantly alter the odor or flavor of the bread compared to the control sample. Based on these findings, the optimal concentration of rice husk dietary fiber was determined to be 0.5%.

It is noteworthy that the inclusion of dietary fiber in dough made from a wheat-rye flour mixture enhances the absorption capacity of the final bread product. Additionally, dietary fiber plays a role in detoxification by binding to harmful substances, thereby reducing the exposure of the intestinal mucosa to toxins and mitigating the severity of inflammatory-dystrophic changes in the mucosal lining [33].

Following the determination of the optimal rice husk dietary fiber content, the optimal amount of flaxseed flour was established (Table 6). Based on the analysis of quality parameters, the ideal formulation for rye-wheat bread dough consists of 0.5% rice husk dietary fiber and 15% flaxseed flour.

Table 6. **The effect of flaxseed flour and 0.5% dietary fiber on the quality of the baked rye-wheat bread**

Quality indicator	Control	Amount of flaxseed flour, %			
		5	10	15	20
Crust colour	Light brown	Light brown	Brown	Brown	Grey-brown
The nature of the crust	Fat	Fat	Fat	Fat	Fat
Shape and surface	Straight, convex	Straight, convex	Straight, convex	Straight, convex	Straight, non-convex
Crumb condition	Fine, uniform	Fine, uniform	Medium, even	Fine, uniform	Very fine, uniform
Taste and flavour	Characteristic of bread, with a pleasant taste and aroma	Characteristic of bread, with a pleasant taste and aroma	Characteristic of bread, with a pleasant taste and aroma	Characteristic of bread, with a faint flavour and odour of flaxseed flour	Characteristic of bread, with a distinct flavour and odour of flaxseed flour
Moisture, %	49	48	48	47.5	47
Acidity, degrees	7	8	9	10.5	12
Porosity, %	48	46	44	42	40

The moisture content of the finished bread increased with the proportion of flaxseed flour added. The incorporation of free fatty acids and, to some extent, free amino acids from flaxseed flour likely contributed to the dynamic increase in the titratable acidity of the baked bread. The observed decrease in porosity and specific volume of the bread directly correlated with a reduction in the sugar- and gas-forming capacities as the amount of flaxseed flour increased. The reduction in porosity could also be partially attributed to the presence of polyunsaturated fatty acids in the flaxseed flour.

As the flaxseed flour content increased from 15% to 20%, a slight deterioration in the surface texture of the bread was noted, with the crust becoming marginally rougher. The higher moisture content in the dough with 15% flaxseed flour promoted more active microbiological and biochemical processes during dough fermentation. Consequently, the pores became larger, less uniform, and exhibited thicker walls. The crumb texture became denser, and elasticity was lost.

In a previous study, researchers utilized a sourdough starter from the homofermentative lactic acid bacterium *Lactobacillus plantarum*, with a moisture content of 50%. The introduction of 10% or 15% flaxseed flour into the sourdough starter significantly impacted the physicochemical and organoleptic properties of the bread made from a mixture of rye and first-grade wheat flour [34]. Flaxseed flour notably influenced the primary organoleptic attribute—color—and the flavor of the bread. As the amount of flaxseed flour increased, the bread crumb darkened to an almost grey hue, and it developed a mild flavor and aroma of flaxseed. At 20% flaxseed flour, the bread became bitter, which is a key reason for not recommending further increases in the flaxseed flour content in flour mixtures.

Between 15% and 20% flaxseed flour, the elasticity, porosity, and crust quality of the bread deteriorated when combined with rice husk dietary fiber; however, these parameters were still significantly better than in samples without dietary fiber. The highest-quality bread was achieved with a mixture of rye-wheat flour, 15% flaxseed flour, and 0.5% rice husk dietary fiber powder.

The challenge of incorporating flaxseed flour into conventional bakery products has been previously explored, primarily with wheat flour and wheat-rye flour mixtures [35, 36]. Flaxseed flour, like rye flour, contains substantial amounts of hydrocolloids, which contribute to the increased stickiness of the bread. As such, rye bread containing flaxseed flour presents a valuable product and lays the foundation for the development of a new technology for producing rye bread for mass consumption. In addressing national health concerns, it is essential not only to create functional food products but also to focus on food culture [37-39]. The inclusion of flaxseed flour in rye bread would result in a familiar product that could contribute to increasing the intake of protein, dietary fiber, and polyunsaturated fatty acids in the population's diet.

3-5- Mathematical Modelling

Table 7 shows the results of mathematical modelling with a two-factor rotatable (B3) Box plan.

Table 7. **Variable levels and intervals of the factors**

Factor		Variable levels			Intervals
Natural	Code	-1	0	+1	ε
Amount of flaxseed flour, %	x_1	10	15	20	5
Amount of dietary fiber powder, %	x_2	0.3	0.5	0.7	0.2

The amount of flaxseed flour (x_1) and rice husk dietary fiber (x_2) were 5% and 0.2%. The mathematical processing of experimental data resulted in the development of a mathematical model (6), which represents the response function for each factor and the response to the optimisation.

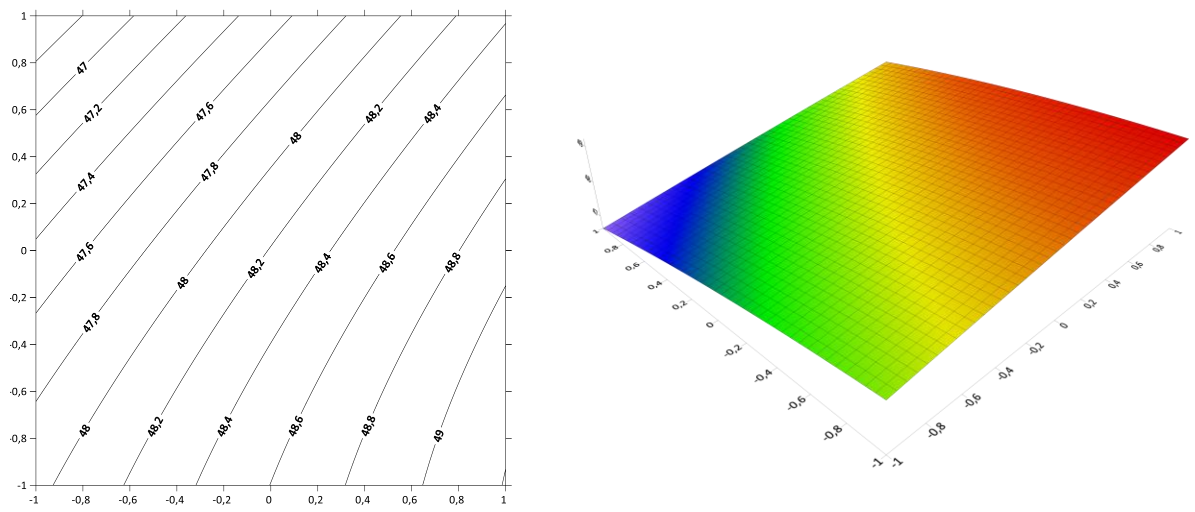
$$Y = F(X_1, X_2, ..., X_n) \tag{6}$$

The dependence of the quality indicators of the rye-wheat bread on the amount of flaxseed flour and rice husk dietary fiber is shown Table 8. The b_0 coefficient was by far the highest, so it was considered further. This peak corresponds to the moisture, porosity, and acidity of the finished bread.

Table 8. Dependence of the quality indicators of rye-wheat bread on the amount of flaxseed flour and rice husk dietary fiber

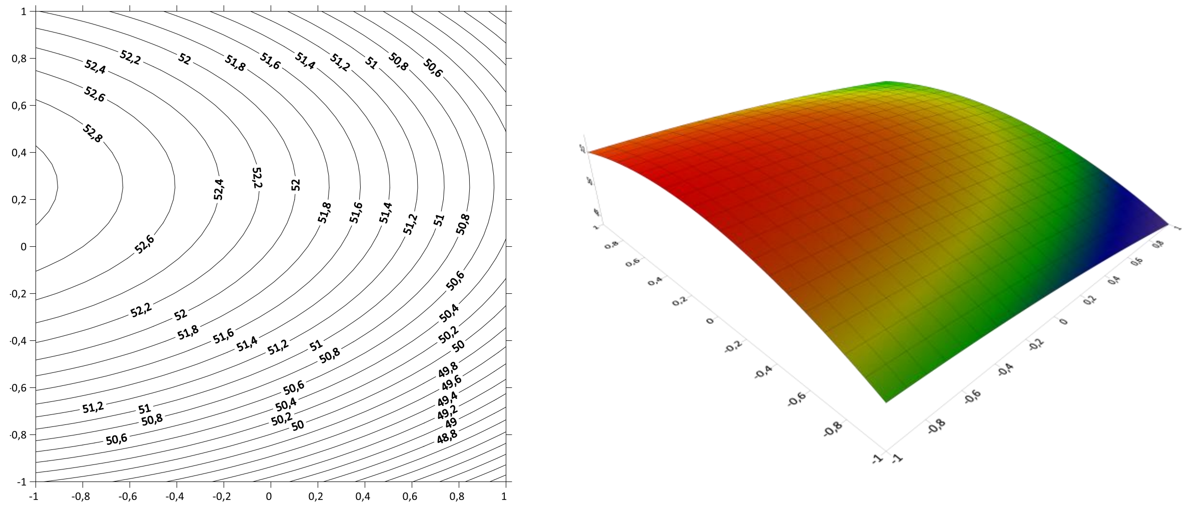
Coefficient	Moisture, %	Porosity, %	Acidity, degrees
b_0	48.21	52.01	9.1
b_1	0.754	-1.278	1.038
b_2	-0.541	0.995	-0.472
b_{12}	0.125	0	-0.05
b_{11}	-0.023	-0.362	-0.09
b_{22}	-0.148	-1.912	-0.065
B_0	47.11	38.15	5.58
B_1	0.116	0.179	0.341
B_2	-0.882	52.771	0.017
B_{12}	0.125	0	-0.05
B_{11}	-0.001	-0.014	-0.004
B_{22}	-3.698	-47.797	-1.629
F_p	1.45	1.62	8.83

Figures 10 to 12 depict the relationship between the moisture content (Figure 10), porosity (Figure 11), and acidity (Figure 12) of the finished rye-wheat bread and the proportion of flaxseed flour and rice husk dietary fiber, as determined by mathematical modeling. Each figure includes the corresponding equation. Based on the results of the modeling, the optimal moisture content was found to be 48.21%, the optimal porosity was 52.01%, and the optimal acidity was 9.1 degrees. There was either no significant change or a minimal variation in the limiting value of the flaxseed flour and rice husk dietary fiber amounts concerning the moisture content and acidity of the finished rye-wheat bread. However, when the proportion of flaxseed flour exceeded 15%, a decrease in porosity was observed. The maximum porosity was achieved with 15% flaxseed flour and 0.5% rice husk dietary fiber. Collectively, the mathematical modeling indicated that the combination of 20% flaxseed flour and 0.5% rice husk dietary fiber powder resulted in the highest values for moisture, acidity, and porosity in the rye-wheat bread.



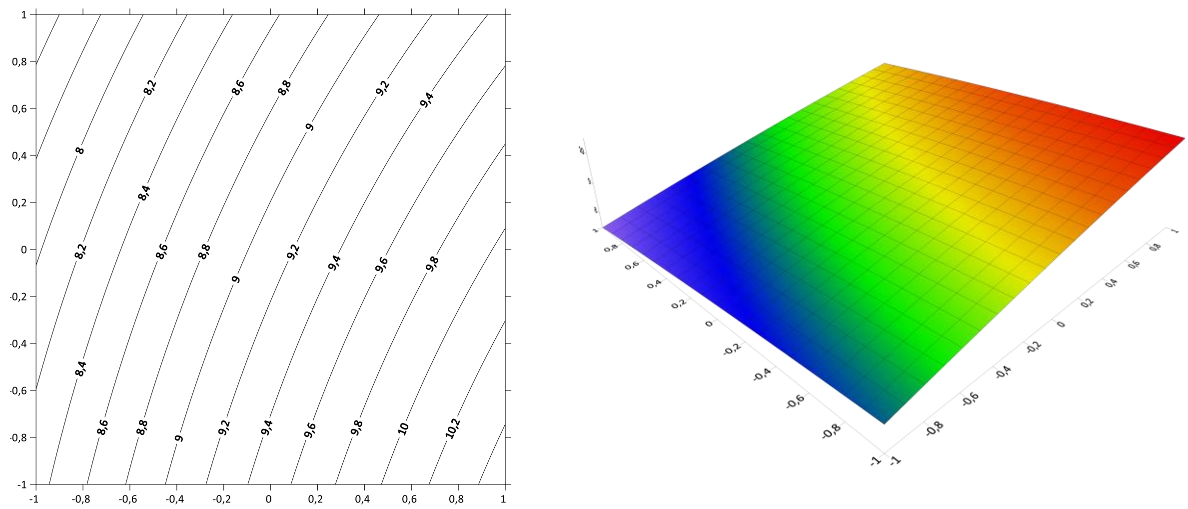
(a) (b)

Figure 10. The influence of the amount of flaxseed flour and rice husk dietary fiber on the moisture of rye-wheat bread: the (a) two-dimensional and (b) three-dimensional surfaces. The dependence of the moisture content on the two factors is given by the equation $Y = 48.21 + 0.754x_1 – 0.541x_2 + 0.125x_1x_2 – 0.023x_{12} – 0.148x_{22}$.



(a) (b)

Figure 11. **The influence of the amount of flaxseed flour and rice husk dietary fiber on the porosity of rye-wheat bread: the (a) two-dimensional and (b) three-dimensional surfaces. The dependence of the porosity on the two factors is given by the equation $Y = 52.01 - 1.278x_1 + 0.995x_2 - 0.362x_{12} - 1.912x_{12}$.**



(a) (b)

Figure 12. **The influence of the amount of flaxseed flour and rice husk dietary fiber on the acidity of rye-wheat bread: the (a) two-dimensional and (b) three-dimensional surfaces. The dependence of the acidity on the two factors is given by the equation $Y = 9.1 + 1.038x_1 - 0.472x_2 - 0.05x1x_2 - 0.09x_{12} - 0.065x_{12}$.**

The calculations and Figures 10 to 12 are based on mathematical modeling using regression analysis to determine the effect of two factors, flaxseed meal and rice hull dietary fiber, on the moisture, porosity, and acidity of rye-wheat bread. The equations provided represent the relationship between these factors and the resulting bread properties. A detailed breakdown of the analysis and calculations is provided below:

$$Y = 48.21 + 0.754x_1 - 0.541x_2 + 0.125x_1x_2 - 0.023x_1^2 - 0.148x_2^2 \quad (6)$$

Variables:

x_1: The amount of flaxseed flour added to the dough (in percentage).

x_2: The amount of rice husk dietary fiber added to the dough (in percentage).

Y: The moisture content of the finished bread.

Explanation:

x_1 and x_2: These are the independent variables representing the proportions of flaxseed flour and rice husk fiber, respectively.

Y: The dependent variable is the moisture content of the bread.

The coefficients in the equation indicate the influence of each factor on the moisture content. For example, a positive coefficient for x_1 (0.754) means that increasing flaxseed flour will increase the moisture content, while the negative coefficient for x_2 (-0.541) suggests that an increase in rice husk fiber will slightly reduce the moisture content.

Interaction term (x_1x_2): The coefficient for x_1x_2 (0.125) indicates that there is an interaction between the flaxseed flour and rice husk fiber. The effect of one component depends on the level of the other.

Quadratic terms (x_1^2, x_2^2): These terms account for the non-linear effects. Negative coefficients indicate diminishing returns when increasing the respective ingredient beyond a certain level.

Calculation: The equation helps predict the moisture content for any combination of flaxseed flour and rice husk fiber. For example, if 10% flaxseed flour (x_1=10) and 0.5% rice husk fiber (x_2=0.5) are added, the moisture content (Y) can be calculated by substituting these values into the equation.

$$Y = 52.01 - 1.278x_1 + 0.995x_2 - 0.362\,x_1^2 - 1.912\,x_2^2 \quad (7)$$

Variables:

x_1: The amount of flaxseed flour.

x_2: The amount of rice husk dietary fiber.

Y: The porosity of the finished bread.

Explanation:

The negative coefficient for x_1 (-1.278) indicates that increasing the amount of flaxseed flour reduces porosity.

The positive coefficient for x_2 (0.995) suggests that rice husk fiber helps increase porosity.

The quadratic terms show the non-linear impact on porosity, with more pronounced effects of flaxseed flour (due to the large negative coefficient for x_1^2).

Calculation: Similarly, porosity for a given combination of flaxseed flour and rice husk fiber can be estimated by substituting the values into the equation.

$$Y = 9.1 + 1.038x_1 - 0.472x_2 - 0.05x_1x_2 - 0.09023x_1^2 - 0.065x_2^2 \quad (8)$$

Variables:

x_1: The amount of flaxseed flour.

x_2: The amount of rice husk dietary fiber.

Y: The acidity of the finished bread.

Explanation:

The positive coefficient for x_1 (1.038) indicates that increasing flaxseed flour increases the acidity of the bread, while the negative coefficient for x_2 (-0.472) shows that rice husk fiber has the opposite effect, reducing acidity.

The interaction term (x_1x_2) and quadratic terms indicate that the effects of these additives on acidity are more complex and non-linear, with certain combinations of flaxseed flour and rice husk fiber leading to significantly higher or lower acidity levels.

Calculation: Like the previous equations, the acidity can be predicted by substituting the specific proportions of flaxseed flour and rice husk fiber into this equation.

3-6- Quality and Chemical Composition of the Finished Bread

Figure 13 illustrates images of the baked bread following the incorporation of flaxseed flour and/or rice husk dietary fiber. The most favorable outcomes were achieved with the addition of 5%-15% flaxseed flour and 0.5% rice husk dietary fiber powder (Figure 13c). Under these conditions, the bread maintained its proper shape and exhibited an even, smooth surface; the porosity was uniform, with no voids or compactions; and the crumb was elastic, non-dense, and not sticky. The inclusion of 0.7% rice husk dietary fiber powder resulted in an overly dark coloration. The effective utilization of dietary fiber facilitated the development of recipes and technological processes for the production of nutrient-dense rye-wheat bread incorporating flaxseed flour [40-42].

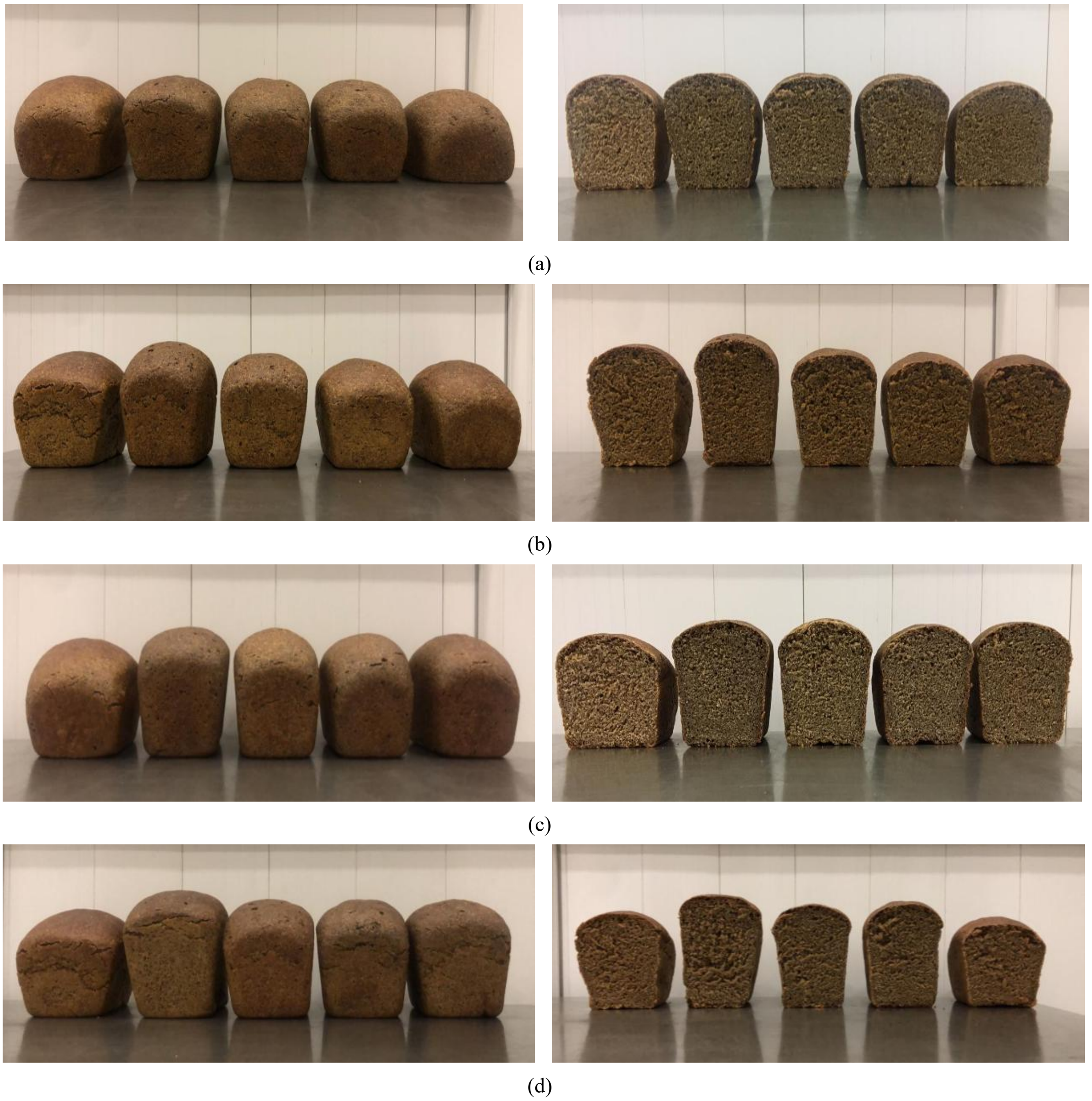


Figure 13. Images of the finished rye-wheat bread according to the amount of flaxseed flour and rice husk dietary fiber: (a) 5%-20% flaxseed flour without dietary fiber; (b) 5%-20% flaxseed flour and 0.3% dietary fiber; (c) 5%-20% flaxseed flour and 0.5% dietary fiber; (d) 5-20% flaxseed flour and 0.7% dietary fiber. In each panel, from left to right the bread contains 0%, 5%, 10%, 15%, and 20% flaxseed flour.

In a previous study, researchers incorporated flaxseed flour into a sourdough starter mixed with rye flour, as well as into a flaxseed flour-based starter and a mixture of flaxseed and rye flour, and also added it in dry form directly to the dough [43]. The organoleptic and physicochemical quality indicators of both semi-finished and finished products were evaluated. The addition of flaxseed flour to the sourdough starter resulted in minimal changes to the taste and aroma of the rye bread. Fermentation of flaxseed flour with rye flour did not reduce the flaxseed flavor or scent. Additionally, more water was required to prepare the starter with flaxseed flour compared to the preparation of the sourdough and dough with rye flour. The sourdough containing flaxseed flour developed acidity more rapidly. Bread produced with flaxseed flour incorporated into the sourdough was nearly identical to the control variant in terms of sensory characteristics. The crumb of this bread exhibited an acidity of 9.0 degrees, a moisture content of 49.9%, and porosity of 49%. Sensory evaluation indicated that the bread with added flaxseed flour scored the highest among the tested samples and was closest to the control variant [43].

Table 9 presents the chemical composition of bread made from rye-wheat flour with and without 15% flaxseed flour and 0.5% rice husk dietary fiber powder after a 14-hour storage period.

Table 9. Chemical composition of the finished rye-wheat bread

Quality indicator	Control rye-wheat bread	Rye-wheat bread with 0.5% rice husk dietary fiber	Rye-wheat bread with 15% flaxseed flour and 0.5% rice husk dietary fiber
Physicochemical parameters, %			
Mass fraction of protein	6.9	7.0	9.64
Mass fraction of fat	1.7	1.18	2.93
Mass fraction of fiber	0.71	3.07	3.53
Mass fraction of carbohydrates	43	31	36.57
Water-soluble vitamins, mg/100 g			
B_1	0.24	0.36	0.375
B_2	0.065	0.089	0.240
B_3	4.2	6.59	6.75
B_5	0.63	0.95	0.975
B_6	0.22	0.47	0.465
B_c	0.031	0.056	0.173
C	-	-	0.375
Vitamin E, mg/100 g	n/a	n/a	3.55
Minerals, mg/100 g			
Potassium	142.54	159.86	294.4
Magnesium	45	63.48	68.4
Sodium	30.2	28.77	433.1
Iron	2.35	2.51	22.5
Calcium	31.31	36.62	47.7
Copper	0.201	0.26	2.21
Selenium	0.028	0.029	0.071
Phosphorus	156.2	181.09	218.5
Zinc	1.07	1.56	2.18

Based on the results of the research identified in the laboratory "Quality and Safety assessment of Food Products" at the "Research Institute of Food Safety" of ATU, in general, the rye-wheat bread with flaxseed flour and/or rice husk dietary fiber showed higher nutrient levels compared with the control rye-wheat bread. For example, the protein content increased by 39.7% for the bread with flaxseed flour and rice husk dietary fiber compared with the control bread. The mass fraction of fiber also increased markedly – 2.4 and 2.8 times for the samples with flaxseed flour and flaxseed flour and rice husk dietary fiber – compared with the control bread. The addition of flaxseed flour and rice husk dietary fiber also substantially increased minerals such as potassium (2 times), iron (9.5 times), copper (10.9 times), and phosphorus (1.3 times) compared with the control bread. The addition of rice husk dietary fiber also introduced vitamins C and E into the bread (they were not found in the control bread or the bread with flaxseed flour but not rice husk dietary fiber). Figures 14 and 15 show the mass fraction of carbohydrates and the caloric content of the finished bread.

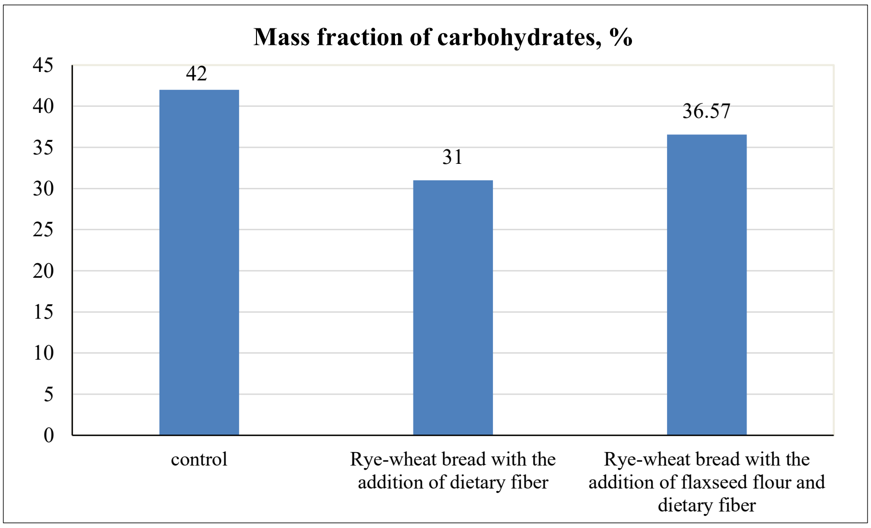


Figure 14. The carbohydrate content of the finished rye-wheat bread

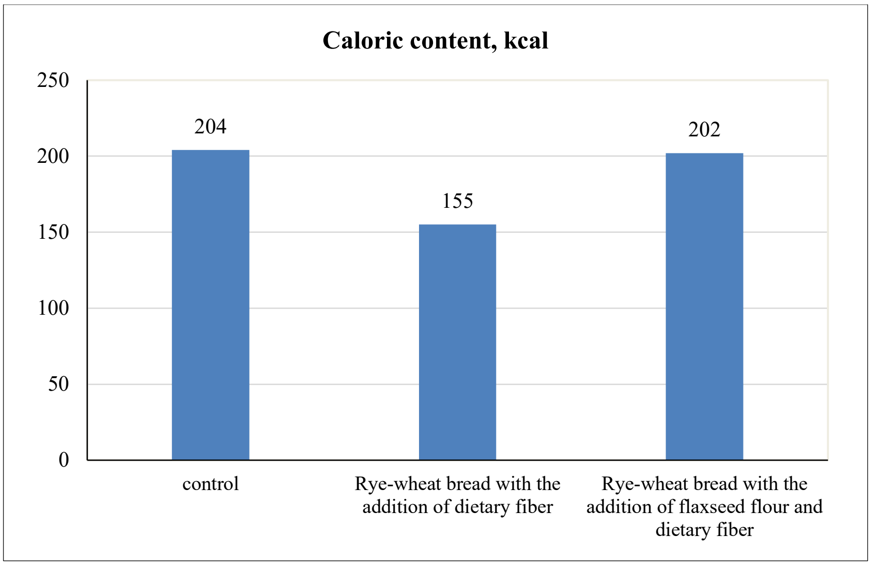
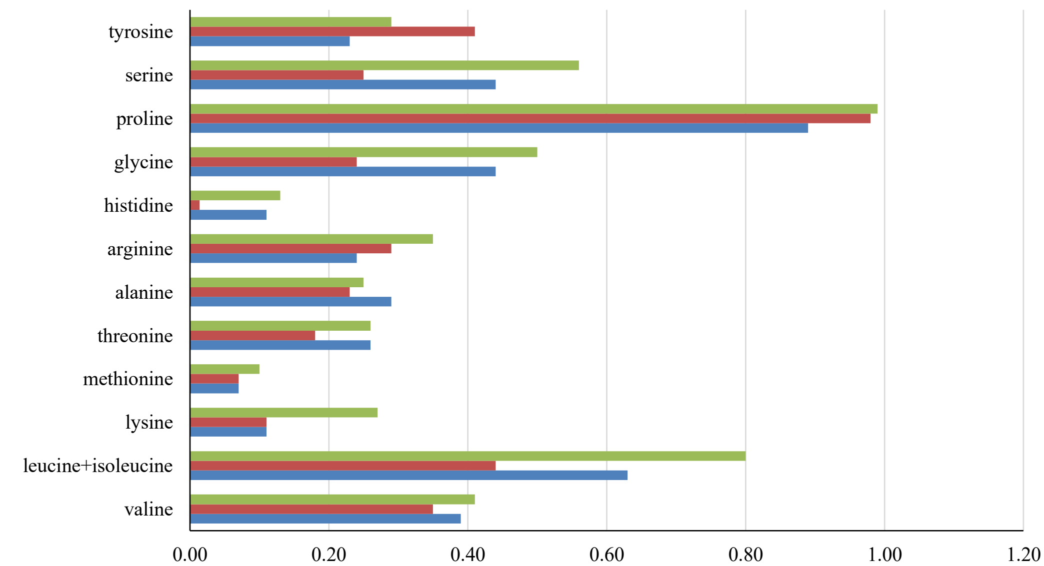


Figure 15. The caloric content of the finished rye-wheat bread

Figure 16 presents the amino acid composition of the finished rye-wheat bread. It is important to note that the amino acid profile of the bread is influenced by various factors, including the chemical composition, type, and quality of the flour used in its preparation, the composition of other ingredients in the recipe, and any potential losses that occur during the bread-making process. These factors collectively contribute to the final amino acid content.

The incorporation of flaxseed flour and rice husk dietary fiber into the bread formulation resulted in a significant impact on the amino acid content, particularly in terms of lysine. The lysine content in the bread was found to be 2.4 times higher compared to the control sample, indicating a notable improvement in the nutritional profile of the bread. This increase in lysine content is in line with the known nutritional properties of flaxseed meal, which is rich in proteins, including essential amino acids. The elevated levels of amino acids in the bread, therefore, reflect the contribution of flaxseed flour, which is a high-protein ingredient, enhancing the overall amino acid composition of the finished product.

In summary, the addition of flaxseed flour and rice husk dietary fiber not only affects the structural and texture properties of the bread but also provides a significant nutritional benefit by increasing the amino acid content, particularly the essential amino acid lysine, which is vital for human health.



	valine	leucine+isoleucine	lysine	methionine	threonine	alanine	arginine	histidine	glycine	proline	serine	tyrosine
Rye-wheat bread with the addition of flax flour and DF	0.41	0.80	0.27	0.10	0.26	0.25	0.35	0.13	0.50	0.99	0.56	0.29
Rye-wheat bread DF	0.35	0.44	0.11	0.07	0.18	0.23	0.29	0.01	0.24	0.98	0.25	0.41
Rye-wheat bread (control)	0.39	0.63	0.11	0.07	0.26	0.29	0.24	0.11	0.44	0.89	0.44	0.23

Figure 16. The amino acid composition (mg/100 g) of the rye-wheat bread with and without flaxseed flour and rice husk dietary fiber

Mould contamination is a primary cause of spoilage in bakery products, leading to degradation of their quality and safety. The most common bread moulds include *Aspergillus flavus*, *Aspergillus fumigatus*, *Aspergillus niger*, *Aspergillus ochraceus*, *Mucor mucedo*, *Mucor pusillus*, *Mucor spinosus*, *Penicillium crustosum*, *Penicillium expansum*, *Rhizopus nigricans*, and *Geotrichum candidum*. These mould species thrive in a temperature range of 5-50°C, which provides optimal conditions for their growth and development.

The microbiological quality of the finished rye-wheat bread, which included flaxseed flour and rice husk dietary fiber, was evaluated according to the standards outlined in GOST [44, 45]. The incorporation of flaxseed flour and rice husk dietary fiber into the bread formulation did not negatively influence the microbiological indicators of the bread. Specifically, the results demonstrated that the presence of these ingredients did not promote the growth of moulds, yeasts, or pathogenic microorganisms that could compromise the bread's safety.

As shown in Table 10, the bread samples met the microbiological requirements specified in TR CU 021/2011 of the Technical Regulations of the Customs Union, which outlines food product safety standards. The microbiological assessment involved the measurement of mesophilic aerobic and facultative anaerobic microorganisms, moulds, and yeasts at various intervals—specifically after 3, 7, 9, and 11 days of storage.

Based on the collected data, the safe storage period of rye-wheat bread containing flaxseed flour and rice husk dietary fiber was determined to comply with the established norms for food safety. The bread's microbiological stability indicated that these ingredients did not alter the product's shelf life or introduce any risks related to spoilage.

In conclusion, the addition of flaxseed flour and rice husk dietary fiber in the rye-wheat bread formulation did not have an adverse effect on the bread’s microbiological quality or its safe storage period. The bread maintained compliance with food safety standards, indicating its suitability for consumption over the specified shelf life.

Table 10. Microbiological indicators of the rye-wheat bread with and without flaxseed flour and rice husk dietary fiber

Indicator	Content in 100 g of product (bread)		
	Rye-wheat bread (control)	Rye-wheat bread with 0.5% rice husk dietary fiber	Rye-wheat bread with 15% flaxseed flour and 0.5% rice husk dietary fiber
After day 3			
Mesophilic aerobic and facultative anaerobic microorganisms, CFU/g (cm^3), max	Not determined	Not determined	Not determined
Moulds, CFU/g, max	Not determined	Not determined	Not determined
Yeast, CFU/g, not more than	32	Not determined	Not determined
After day 7			
Mesophilic aerobic and facultative anaerobic microorganisms, CFU/g (cm^3), max	1×10^3	Not determined	Not determined
Moulds, CFU/g, max	Not determined	Not determined	1×10^3
Yeast, CFU/g, not more than	Full growth	Not determined	Not determined
After day 9			
Mesophilic aerobic and facultative anaerobic microorganisms, CFU/g (cm^3), max	1.5×10^3	Not determined	3×10^3
Moulds, CFU/g, max	Not determined	Not determined	1.5×10^3
Yeast, CFU/g, not more than	Full growth	Not determined	Not determined
After day 11			
Mesophilic aerobic and facultative anaerobic microorganisms, CFU/g (cm^3), max	Full growth	6×10^3	4×10^3
Moulds, CFU/g, max	Not determined	Full growth	Full growth
Yeast, CFU/g, not more than	Full growth	11	Not determined

4- Conclusion

The results of this study confirm that the incorporation of defatted flaxseed flour into the rye-wheat bread formulation has a minimal impact on its consumer properties, particularly its appearance. To enhance both the visual appeal and nutritional value of the product, dietary fiber derived from rice husks was additionally introduced. Experimental data demonstrated that the inclusion of this component not only improved the organoleptic characteristics of the bread but also significantly increased its nutritional value. The scientific validity of using rice husks as a functional filler is supported by its positive effects on the structural and mechanical properties of the dough, increased yield of the final product, and enhanced organoleptic parameters. Key correlations were established between the physicochemical and rheological properties of the dough when combining flaxseed flour and dietary fiber from rice husks. The addition of up to 0.5% rice husk fiber and up to 15% flaxseed flour (relative to the weight of wheat flour) significantly enhanced the nutritional and biological value of the bread without negatively affecting the dough's rheological properties or the organoleptic characteristics of the final product. The optimal formulation for enriched rye-wheat bread was identified as a combination of 20% flaxseed flour and 0.5% dietary fiber powder, which resulted in the highest moisture retention, acidity, and crumb porosity. Mathematical modeling of the bread's quality characteristics confirmed that the inclusion of biologically active plant-based additives has a positive effect on the physicochemical and rheological properties of the dough, ultimately improving the overall quality of the final product. The findings of this study provide a foundation for the development of innovative bakery products incorporating flaxseed flour and rice husk dietary fiber, offering both functional and nutraceutical benefits.

5- Declarations

5-1- Author Contributions

Conceptualisation, A.I. and G.B.; methodology, Z.M.; software, A.I.; validation, A.I. and E.A.; formal analysis, Z.I.; investigation, N.B.; resources, A.I.; data curation, G.B.; writing–original draft preparation, G.I.; writing–review and editing, M.B.; visualisation, A.I.; supervision, Z.M.; project administration, M.B.; funding acquisition, A.I. and Z.I. All authors have read and agree with the published version of the manuscript.

5-2- Data Availability Statement

The data presented in this study are available in the article.

5-3- Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5-4- Acknowledgements

The authors express their gratitude to the leadership of the Almaty Technological University.

5-5- Institutional Review Board Statement

Not applicable.

5-6- Informed Consent Statement

Not applicable.

5-7- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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