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Baking and rheological properties of alternative flour types

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Abstract. The baking properties of green buckwheat, lentil, corn, coconut, amaranth, and brown rice flours as well their effect on the rheological properties of dough semifinished products made from wheat flour were investigated. For the study, high-grade wheat flour as well as mixtures of high-grade wheat flour and the flours under investigation (5; 10; 15; 20; and 25% replacement) were taken. The breadmaking properties of the flour types were tested at 5, 15, and 25% replacement. Rheological properties were determined using farinograph (Brabender), alveograph (Chopin), amylograph (Brabender), and falling number measurement device (Perten). It was found that amaranth flour had the greatest effect on the water absorption capacity of the flour mixture, with its increase by 13.3% when replacing wheat flour at a 25% ratio. To evaluate the baking properties of the studied flour types, an analysis on their influence on the volume of finished products, sensory characteristics of bread, and change of bread softness during storage was conducted with the use of a texture analyzer (TA.XTplus100C). When 10% coconut flour was added to the dough, its kneading stability increased significantly, reaching 48 minutes 49 seconds. Alveographic tests demonstrated a decrease in the baking power of the dough semifinished products in all samples, with the corn flour sample showing the smallest decrease of 35.2% and the lentil flour sample showing the largest decrease of 75.4%. Based on the studies conducted, the amylograms of the flour mixtures showed the highest increase of 486 units in the gelatinization maximum in the sample containing corn flour at 25% dosage. Replacing wheat flour with coconut flour, corn flour, and hydrothermally unprocessed buckwheat flour reduced the specific volume of bread. The most pronounced decrease in specific volume was observed when replacing with coconut flour, by 0.6 cm^3/g at 25% replacement. The optimum ratio of dough rheological properties and baking quality was achieved in the mixture of high-grade wheat flour with 25% amaranth flour.

Keywords: biotechnology; bakery products; rheological properties of the dough; gluten-free flour; breadmaking properties

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Исследование хлебопекарных и реологических свойств альтернативных видов муки

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Аннотация. Исследовали хлебопекарные свойства муки из зеленой гречихи, чечевицы, кукурузы, кокоса, амаранта, бурого риса и их влияние на реологические свойства тестовых полуфабрикатов на основе пшеничной муки. Объектами изучения стали: мука пшеничная высшего сорта и смеси пшеничной и исследуемых видов муки в дозировках 5; 10; 15; 20 и 25% от общей массы муки. Хлебопекарные свойства исследуемых видов муки проверяли в дозировках 5; 15 и 25%. Реологические свойства определяли с использованием приборов фаринограф (Brabender), альвеограф (Chopin), амилограф (Brabender) и прибора определения числа падения (Perten). Установлено, что амарантовая мука в наибольшей степени повлияла на водопоглотительную способность мучной смеси, увеличив данный показатель на 13,3% в дозировке 25% от общей массы муки. Для оценки хлебопекарных свойств изучаемых видов муки проводили анализ их влияния на объем готовых изделий, органолептические характеристики хлеба и изменение его мягкости при хранении с использованием анализатора текстуры (TA.XTplus100C). При добавлении 10% кокосовой муки в тесто, его устойчивость к замесу значительно увеличилась, достигнув 48:49 мин. Испытания на альвеографе показали снижение хлебопекарной силы тестовых полуфабрикатов во всех образцах, при этом образец с кукурузной мукой выявил наименьшее снижение (35,2%), а образец с чечевичной мукой – наибольшее (75,4%). На основе данных амилограмм, в образце с добавлением 25% кукурузной муки зарегистрировали прирост максимума клейстеризации на 486 единиц в сравнении с контрольным образцом, что стало наибольшим показателем. Замена пшеничной муки на кокосовую, кукурузную и муку из зеленой гречихи снижает удельный объем хлеба, где наиболее выражено это проявилось при замене на кокосовую муку – на 0,6 см³/г в дозировке 25%. Оптимальное соотношение реологических свойств теста и качества выпечки достигнуто в смеси пшеничной муки высшего сорта с 25% амарантовой муки.

Ключевые слова: биотехнология; хлебобулочные изделия; реологические свойства теста; безглютеновая мука; органолептические свойства

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Introduction

In recent years, the search for ways to improve nutritional properties and expand the range of bakery products has driven interest in the use of alternative flour types in the baking industry. In this context, the study aims to analyze the influence the flour of various alternative types (coconut, corn, amaranth, lentil, hydrothermally unprocessed common buckwheat, brown rice) has on rheological properties of dough and organoleptic properties of wheat-based bakery goods.

Previous research has shown that the dough samples made using the alternative flours have rheological properties that are significantly different compared to wheat dough [1, 2]; at the same time, mixtures of various flour types have unique and distinguished properties [3].

Previous research in the field has shown that the inclusion of coconut flour allows to increase plant fiber content in dough, while replacement of wheat flour with coconut flour in quantities up to 15% by total flour mass improves the aroma and water binding capacity [4, 5].

Addition of coconut flour in quantities higher than 15–20% of the total mass of flour leads to a sharp decline in technological and sensory characteristics: dough development time increases, water absorption capacity, specific volume and porosity, crumb elasticity decrease, appearance, aroma, taste and texture of the product deteriorate [6, 7].

Addition of corn flour allows to reduce the time of dough development, increase the resistance of bread to staling, and from the organoleptic side gives the product a golden hue and specific flavor highly appreciated by a wide group of consumers. In addition, corn flour has a high nutritional value due to its balanced amino acid composition (the only limiting amino acid is lysine), as well as a high content of flavonoids and other compounds [8, 9]. On the other hand, the introduction of corn flour significantly disrupts the structure of the gluten network, which reduces the stability, extensibility, and other rheological characteristics of the dough [9, 10]. Extrusion of cornmeal can slightly improve these parameters, but it loses the increased resistance of products to staling [10].

The addition of amaranth flour increases the water absorption capacity of the dough and increases the gelatinization temperature of starch, which can have a positive effect on the specific volume of products. Also, the addition of amaranth flour in amounts up to 20% of the total flour mass can increase the stability of the dough; extensibility, however, decreases, while development time increases [11]. In terms of nutritional value, amaranth flour is rich in proteins and minerals, and a number of amaranth varieties have a complete protein composition [12, 13].

Lentil flour in the amount of 10% has little effect on the consumer properties and rheological characteristics of the product – however, its addition in amounts of 15–20% and higher leads to a decrease in the volume of products and accelerated staling [14]. At the same time, preliminary germination of lentils before milling allows to obtain a flour mixture that positively affects a number of technological parameters of the product – so, the addition of 7.5% of flour from sprouted lentils allows to increase the specific volume, porosity and elasticity of products compared to products made entirely of wheat flour, but at the same time their stiffness also increases [15]. As for the nutritional value of lentil flour, it is known to be rich in antioxidants and have an amino acid composition that is close to complete – only sulfur-containing amino acids are deficient [16–19].

Hydrothermally unprocessed buckwheat and brown rice flours are also used to create gluten-free products, but their influence on rheological properties is less thoroughly studied. Buckwheat starch is known to have a higher water absorption capacity compared to wheat and corn starches, which may account for the higher water absorption capacity of flour mixtures with its use [20]. In addition, buckwheat contains a large amount of phenols, particularly proanthocyanidins, which can strengthen wheat gluten [21]. Regarding the nutritional value of hydrothermally unprocessed buckwheat flour, a high antioxidant content is also known to be present [16, 22, 23].

Brown rice flour is known to have a high nutritional value: unlike polished white rice, brown rice has a complete protein composition and contains a large amount of nicotinic acid, riboflavin, and thiamine [24, 25]. In addition, it is known that the addition of flour from sprouted brown rice in the amount of 30% increases the water absorption capacity of the flour mixture, but at the same time significantly increases the resistance of the dough to extension. The addition of phytase and hemicellulase allows the increase the volume of the obtained products [26].

Still, most of the reviewed works describe the characteristics of only certain types of flour, which does not allow for a full-fledged comparative analysis of their impact on the rheological properties of dough and the final quality of bakery products. At the moment, the issues of optimal proportions and combinations of different types of flour, which would improve the rheological properties of dough without deterioration of consumer properties of bakery products, are not sufficiently studied. A deeper understanding of the mechanisms for the interaction of components of the different types of flour with the gluten network of wheat flour is needed, which will allow to develop recommendations for their use in breadmaking.

The aim of this study is to conduct a comparative analysis of the effect of various alternative flours, including coconut, corn, amaranth, lentil, hydrothermally unprocessed buckwheat and brown rice flours, on the rheological properties of dough and the breadmaking properties of bakery products made with wheat flour. This study plays an important role in expanding the range of bakery products, increasing their nutritional value and improving their sensory characteristics, as well as for the development of new formulations using alternative flours.

Materials and methods

The following types of flour were used in the study: high-grade wheat flour (GOST 26574-2017, produced by Petersburg Milling Plant, Russia), coconut flour (produced by UFEELGOOD, Russia), corn flour, lentil flour, and brown rice flour (produced by Garnec, Russia), amaranth flour (produced by Russkaya Oliva, Russia) and hydrothermally unprocessed common buckwheat flour (produced by Garnec, Russia). The moisture content of each type of flour was evaluated using UniBloc MOC63u automatic moisture content meter (Shimadzu, Japan), and the obtained values were taken into consideration in subsequent studies. These types of flour were selected based on their nutritional properties, potential influence on the rheological properties of dough and organoleptic properties of baked products.

Rheological study

For rheological studies, the studied types of flour were added in dosages of 5, 10, 15, 20 and 25% instead of high-grade wheat flour (GOST 26574-2017), (Petersburg Milling Plant, Russia). A sample of high-grade wheat flour without additives served as control.

A Brabender farinograph (Germany) was used to study the effect of non-traditional flours on the water absorption capacity of the flour mixture and dough stability in accordance with GOST ISO 5530-1-2013.

The change in the baking power of dough was determined using Chopin alveograph (US) in accordance with GOST P 51415-99.

Amylolytic activity of flour mixture was determined using Brabender amylograph (Germany) in accordance with GOST ISO 7973-2013 and Perten FN-1500 (Sweden) falling number measuring device in accordance with GOST 27676-88. The influence of different types of flour on the maximum gelatinization and falling number index was investigated.

The change in the mass fraction of crude gluten and the change in the gluten deformation index were evaluated using the ПЛАУН ИДК-3 М (PLAUN IDK-3 M) device (Russia) according to GOST 27839-2013. Gluten washing was carried out manually.

To analyze the effect of studied types of flour on the quality of baked products, they were added instead of wheat flour at dosages of 5%, 15% and 25%. Bread baked with 100% wheat flour served as a control. The dough recipes are presented in Table 1.

Laboratory baking

Evaluation of breadmaking properties of baked products was carried out by laboratory baking. All bread samples were prepared in a single stage without the use of sourdough.

Table 1. Dough recipes

Materials	Ingredients, kg/100kg flour			
	Control	5% replacement	15% replacement	25% replacement
High-grade wheat flour	100.0	95.0	85.0	75.0
Flour of s tudied type	–	5.0	15.0	25.0
Table salt	1.8	1.8	1.8	1.8
Compressed baker's yeast	2.5	2.5	2.5	2.5

An SP 24F dough mixer (Diosna, Germany) was used to knead the dough. Kneading was carried out for 4 minutes at slow speed and 5 minutes at fast speed. The dough temperature was 27–28°C, after which dough was left for 10 min at room conditions, then divided into 550 g pieces and placed in molds, proofing was carried out at 35°C and 75% relative humidity, baking was conducted using Miwe Condo oven (Miwe, Germany) at 220°C for 20 min with steam. The baked products were cooled down to 25°C and then packaged.

Quality assessment of baked products was determined by physicochemical and organoleptic parameters.

Specific volume was determined as the volume to mass ratio of baked products. The obtained value was expressed in cm^3/g [27].

The softness of the product during storage was evaluated on the third day of storage based on the hardness value. Crumb hardness of the finished products was measured using TA.XTplus100C texture analyzer (UK) according to the methods provided by the device manufacturer.

During the tests, the force required to press a 36 mm diameter cylinder into a 25 mm thick slice of bread to a depth of 6.25 mm was measured. Three slices of bread of the specified thickness were cut for each test sample. The cylinder was lowered in the center of the slice at a distance of ≥2 cm from the edge of the crust.

During the organoleptic analysis the crust color, crumb structure and color, aroma and taste of finished products were evaluated. Organoleptic parameters of bread samples were determined by sensory evaluation according to GOST 5667-2022.

Results and discussion

Water absorption capacity

The results of water absorption capacity tests in dough made with flour mixtures as per farinographic tests are presented in Table 2.

Table 2. Results of water absorption capacity measurements in high-grade wheat flour with addition of alternative flours

Proportion of tested flours added, %	Coconut flour	Corn flour	Lentil flour	Brown rice flour	Amaranth flour	Hydrothermally unprocessed buckwheat flour
	water absorption capacity, %					
0 (reference/wheat flour)	57.7	60.2	57.7	60.2	57.8	57.6
5	59.3	60	59.1	60.2	60	57.3
10	60.3	60.1	59	59.7	63	57.2
15	60.9	59.9	58.5	59.5	65.9	56.8
20	61.4	60	59	59.5	68.8	57.2
25	61.4	59.8	59.6	59.4	71.1	57.5

Reproducibility of water absorption capacity is 1.6% according to GOST ISO 5530–1–2013

Incorporation of corn flour, lentil flour, brown rice flour and hydrothermally unprocessed buckwheat flour had an effect on water absorption capacity within a ±2% difference, indicating a similar water absorption capacity to that of high-grade wheat flour. In similar studies, brown rice flour did not lead to any change in this indicator by more than 2% either [27]. There appears to be insufficient information on farinographic studies of wheat dough with corn, lentil or hydrothermally unprocessed buckwheat flour added. Adding coconut flour increased the water absorption capacity by 3.7% at the dosages of 20 and 25% by weight of wheat flour. An earlier study describes the negative effect of coconut flour on the water absorption capacity of flour mixture, which may be due to the different grind size of coconut flour [28]. The largest increase in water absorption capacity was registered in the sample containing 25% amaranth flour and constituted 13.3% relative to the reference sample, which is explained by the fact that amaranth flour has the highest content of dietary fiber [29].

The results of farinographic studies showed that the addition of various types of flour significantly affects the water absorption capacity of the dough. This factor is of great importance in the production of bread and other flour-based products, as it determines their texture, volume and quality.

Stability time of dough

The results for stability of dough made with a mixture of flours as measured with farinograph are shown in Table 3.

Table 3. Results of kneading stability measurements in dough made with high-grade wheat flour with addition of alternative flours

Proportion of studied flours added, %	Coconut flour	Corn flour	Lentil flour	Brown rice flour	Amaranth flour	Hydrothermally unprocessed buckwheat flour
	stability time, min					
0 (reference/wheat flour)	9:31	14:38	9:31	14:38	10:55	07:34
5	20:09	14:11	12:28	13:28	8:35	15:32
10	48:49	7:10	6:59	16:15	5:27	17:14
15	–	7:01	5:53	12:14	4:03	8:44
20	32:45	4:16	4:53	12:03	3:05	7:49
25	25:32	4:14	4:13	15:52	2:25	6:23

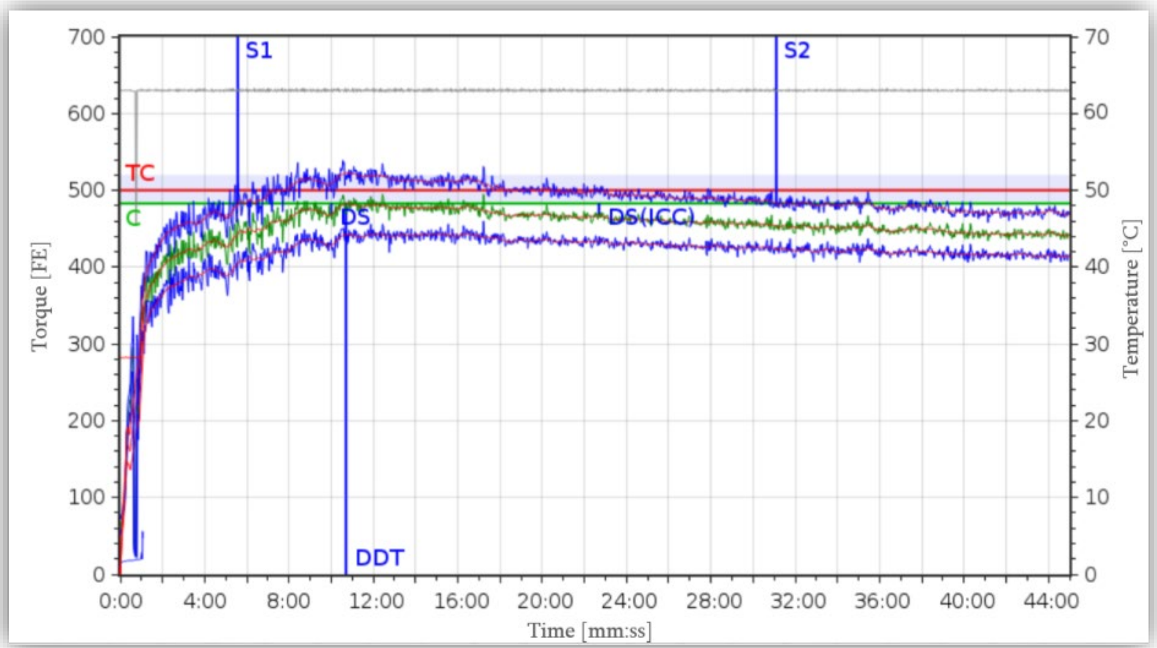

Figure 1. Farinogramm or the dough with 25% coconut flour replacement

When corn and amaranth flours were added, the stability time decreased as the dosage of the tested flours replacing wheat flour increased. This was due to a decrease in the gluten content of the flour mixture, which does not allow the dough to retain its consistency under mechanical action during kneading [30]. The most pronounced decrease in stability was registered with the introduction of amaranth flour, as the replacement of 25% led to a decrease in stability by 8 minutes 30 seconds. This can be explained by the most pronounced weakening of the gluten network, which is likely to be due to a higher fat content in the composition of flour [31]. The addition of brown rice flour resulted in a change in the stability time within ±3 min, indicating comparable degrees of liquefaction of brown rice flour and of wheat flour. When lentil flour was added at a dosage of 5% of wheat flour, the indicator was observed to increase. However, with a further increase in dosage, there was a decrease in dough kneading stability time compared to the reference, which results in an increase in dough stickiness due to the release of moisture from the gluten network [32]. The greatest increase in dough stability was registered in the mixture of wheat and coconut flours. The maximum stability was observed in the sample with 10% coconut flour, with the gain of 39:18 min relative to the reference sample. Meanwhile, in the test with 25% coconut flour, farinogram was remarkably unstable (Figure 1). These results may be related to the high content of dietary fiber in coconut flour, which may affect the dough formation time and consistency [33].

The analysis of test results shows that adding various types of flour has a significant effect on dough stability and its quality.

Dough deformation energy

The deformation energy of dough made with the use of flour mixtures, as measured using the alveograph are shown in Table 4.

Table 4. Results of dough deformation energy measurements in dough made with high-grade wheat flour with addition of alternative flours

Proportion of studied flours added, %	Coconut flour	Corn flour	Lentil flour	Brown rice flour	Amaranth flour	Hydrothermally unprocessed buckwheat flour
	W, *10⁻⁴ J (deformation energy)					
0 (reference/ wheat flour)	293	281	293	281	354	330
5	281	259	234	265	288	274
10	235	237	164	230	263	229
15	–	221	122	230	224	201
20	–	199	81	199	202	162
25	–	182	72	175	164	129

The reproducibility variation coefficient is: 8% for W and P according to GOST R 51415–99

The introduction of all tested types of flour leads to a decrease in energy deformation. The most pronounced decrease was observed in the dough with lentil flour added. The maximum decrease in the deformation energy of the dough was observed when 25% lentil flour was added instead of wheat flour – the decrease amounted to 75.4%. A similar result was obtained in the study of the effect of flour from sprouted lentil seeds on the deformation energy of dough [34]. The application of amaranth and corn flour at a dosage of 25% of the weight of the flour mixture resulted in a decrease in deformation energy by 53.7% and 35.2%, respectively. A decrease in the deformation energy of flour was also observed when coconut flour was added. Due to the significant decrease in dough elasticity with coconut flour added, it was not possible to investigate mixtures with dosage of 15% of wheat flour weight and above. The reason for this is the difference in the particle size (coarseness) of the flour, which has an adverse effect on the formation of a homogeneous dough. This also makes tests with mixtures at higher dosages unfeasible.

Incorporation of all the types of flour tested decreases the energy deformation. The strongest decrease is observed in the dough with lentil flour.

This decrease in deformation energy in all the samples studied can be attributed to the decrease in gluten content of the flour mixture. Similar data were also obtained in other studies [35].

Amylolytic activity of flour

Results of gelatinization maximum measurements for flour mixtures, as measured with amylograph are shown in Table 5.

Incorporation of coconut flour resulted in a decrease in the maximum gelatinization, with the highest decrease of 233 amylograph units observed in the sample with 25% of wheat flour replaced with coconut flour. These results may be due to a lower starch content in the chemical composition of coconut flour compared to wheat flour, which may result in less efficient gelatinization of coconut flour during heating. Addition of amaranth flour also led to a decrease in the maximum gelatinization as the dosage increased, which may be due to the size of the starch granules that are significantly smaller in amaranth flour compared to that of wheat [36].

On the other hand, adding corn flour, brown rice flour and hydrothermally unprocessed buckwheat flour led to an increase in gelatinization maximum. In the highest dosage of 25%, corn flour increased the maximum gelatinization by 69.6%, which can be explained by the higher gel-forming ability of corn starch in comparison with wheat starch [37]. Brown rice flour increased the gelatinization maximum by 62.0% and hydrothermally unprocessed buckwheat flour by 68.2%. When lentil flour was added, the maximum decrease was observed in the dosage of 15%, and amounted to 7.6%, which can be explained by the different grinding size of the studied types of flour, which entails changes in the size of starch granules.

Table 5. Results of amylolytic activity measurements in dough made with high-grade wheat flour with addition of alternative flour

Content of studied flours added, %	Coconut flour	Corn flour	Lentil flour	Brown rice flour	Amaranth flour	Hydrothermally unprocessed buckwheat flour
	gelatinization maximum, AU					
0 (reference/wheat flour)	946	698	946	698	916	606
5	925	758	969	777	858	670
10	849	900	898	877	787	721
15	787	1002	874	978	816	784
20	717	1114	890	1042	706	864
25	713	1184	917	1131	672	1019

Absolute error does not exceed 231 AU, which is in accordance with GOST ISO 7973–2013

Thus, the data obtained indicate the influence of all the studied flours on the amylolytic activity of the mixture.

Falling number

The results for the measurement of falling number in dough are listed in Table 6. The addition of coconut flour resulted in a decrease in the falling number of the mixture from 404 sec in the reference sample to 372 sec in that with 25% replacement. The data obtained may indicate that the viscosity of the suspension decreased during heating due to the low gelatinization capacity of coconut flour starch. The addition of lentil and amaranth flours also reduced this metric due to the lower starch content of these flours. Meanwhile, the addition of corn flour, brown rice flour and hydrothermally unprocessed buckwheat flour resulted in an increase in the falling number. The most pronounced increase was found in the samples of the mixture with hydrothermally unprocessed buckwheat.

Table 6. Results of falling number measurements in dough made with high-grade wheat flour with addition of alternative flours

Proportion of studied flours added, %	Coconut flour	Corn flour	Lentil flour	Brown rice flour	Amaranth flour	Hydrothermally unprocessed buckwheat flour
	falling number, s					
0 (reference/wheat flour)	404	335	404	335	377	274
5	403	345	380	353	372	291
10	395	354	387	354	370	320
15	381	358	360	357	370	335
20	370	357	364	372	365	349
25	372	363	335	380	350	370

At present, there does not seem to be sufficient research data investigating the effect of alternative flours on the falling number in flour mixtures. However, several studies have shown that amylolytic enzyme activity has a key influence on the metric and that it may vary depending on the activity of water required to activate alpha amylase in the flour [38].

All investigated types of flour affected the falling number, characterizing the activity of amylolytic enzymes. The greatest increase in the index was observed when hydrothermally unprocessed buckwheat flour was added to the mixture.

Gluten deformation index

The results for the gluten deformation index measurement are shown in Table 7. The gluten deformation index decreased in all samples with the addition of coconut flour instead of wheat flour. The maximum decrease in gluten deformation index was 18 units, observed in the sample on 15% replacement with coconut flour. When more than 20% coconut flour is added, the gluten becomes excessively loose and crumbly. Thus, it is not possible to wash the gluten in the sample with 25% coconut flour instead of wheat flour.

The addition of lentil flour also reduced the index, indicating the formation of stronger disulfide bonds in wheat flour.

Corn and amaranth flours as well as hydrothermally unprocessed buckwheat and brown rice flours had a less pronounced effect on gluten deformation index. The change in this index varied within the range of no more than ±7.4 gluten deformation index units. This indicates a less pronounced effect of wheat flour gluten compared to coconut and lentil flours.

Table 7. Results of gluten deformation index measurements in washed gluten of high-grade wheat flour with addition of alternative flours

Proportion of studied flours added, %	Coconut flour	Corn flour	Lentil flour	Brown rice flour	Amaranth flour	Hydrothermally unprocessed buckwheat flour
	gluten deformation index, GDI units					
0 (reference/wheat flour)	70.2	56	70.2	56	70.8	70.5
5	60.4	57	57.8	60	71.2	67.5
10	55.4	60.4	55.4	61	70.4	65.1
15	51.4	60.7	54.1	60.4	67.5	65.2
20	52.8	60.8	52.4	60.3	71.4	63.9
25	–	62	52.7	63.4	–	64.7

Absolute error between the results does not exceed 5 gluten deformation index units, which is in accordance with GOST 27839–2013

All investigated types of flour had an impact on the rheological properties of dough. There was a general tendency to decrease the deformation energy of dough due to a decrease in the mass fraction of gluten in the mixture. The change in the indicators is related to the properties of the studied types of flour, which, in their turn, affect the dough. These changes can be caused by moisture and coarseness of flour milling, as well as the differences in the quantity of protein and fiber.

Test baking

To support the data obtained through rheological tests and to study the influence of alternative flours on the baking properties of finished products, a number of laboratory baking tests were performed adding the investigated flours in the doses of 5, 15 and 25% of wheat flour weight. Bread made of 100% wheat flour served as a reference.

To determine the effect of various types of flour on the volume of baked products, the specific volume of bread, characterizing the gas-holding capacity of the dough, was measured (Table 8).

Table 8. Results of specific volume measurements in bread samples made with high-grade wheat flour with addition of alternative flours

Proportion of studied flours added, %	Coconut flour	Corn flour	Lentil flour	Brown rice flour	Amaranth flour	Hydrothermally unprocessed buckwheat flour
	specific volume, cm^3/g					
0 (reference/wheat flour)	2.3	2.3	2.3	2.3	2.3	2.3
5	2.2	2.3	2.3	2.4	2.3	2.4
15	2.0	2.2	2.4	2.3	2.4	2.2
25	1.7	2.1	2.3	2.2	2.5	1.9

Absolute error is ±0.1 cm^3/g

Laboratory baking showed a decrease in the specific volume of bread with coconut flour, corn flour and hydrothermally unprocessed buckwheat flour. The most pronounced decrease was 0.6 cm^3/g when 25% coconut flour was used. The incorporation of amaranth flour resulted in bread with greater volume relative to the reference sample. The influence of lentil and brown rice flour on the specific volume of bread was within a margin of error.

To assess the storability of baked products, the average hardness index was measured on a texture analyzer. The results can serve as indicators of freshness: the less effort is required to compress the crumb, the fresher the bread is. Due to the variability in the biochemical composition of the studied types of flour the process of bread staling had a varying intensity. The results obtained are summarized in Table 9.

Table 9. Results of hardness measurements in bread samples made with high-grade wheat flour with additional alternative flour

Proportion of studied flours added, %	Coconut flour	Corn flour	Lentil flour	Brown rice flour	Amaranth flour	Hydrothermally unprocessed buckwheat flour
	average hardness, g					
0 (reference/wheat flour)	1152	1152	1152	1152	1152	1152
5	1104	1297	1392	1294	1070	1280
15	1070	1428	1420	1336	920	1450
25	1113	1641	1617	1370	754	1702

Brown rice and hydrothermally unprocessed buckwheat flours as well as corn and lentil flours caused an increase in the average crumb hardness of baked products on the third day of storage, which is an adverse effect. This indicates a more pronounced retrogradation of starch in bread samples with these types of flour added. This also complements the results of previous studies on hydrothermally unprocessed buckwheat flour [39]. The hardest crumb was observed in the bread samples with hydrothermally unprocessed buckwheat flour in the dosage of 25% of wheat flour weight. When coconut flour was added, the change in the crumb softness was less pronounced and was within ±7.1% of the reference. The introduction of amaranth flour decreased the hardness of bread crumb compared to the control sample: the crumb of the bread with 25% of amaranth flour is 498 g less hard relative to the reference sample, which indicates an improvement in the consumer qualities of the finished product.

In previous studies it was noted that the use of coconut flour and amaranth flour had an adverse effect on this indicator of bread quality. However, it should be noted that in our study, the amount of water used in mixing was adjusted according to the water absorption capacity of the flour mixture investigated in our study. This may have a positive effect on this indicator [5, 40, 41].

Sensory evaluation of final products

Organoleptic parameters of all baked samples were evaluated at 16 hours after baking. Bread samples made with coconut flour had a denser, more finely porous and creased crumb and had a lighter color than the reference sample. Meanwhile, the volume of the product was lower. There was a pronounced sweet flavor and odor of coconut flour. On the third day of storage the crumb became more granular. The data obtained is in accordance with those from earlier studies [5].

Corn flour introduced into the mixture instead of wheat flour, allowed to obtain bread with a denser and drier crumb. The crumb color was darker, on the yellow side. There was a slight increase in the pore size compared to the reference. The flavor and odor of corn flour is less pronounced and only recognized in the samples with 25% corn flour replacement.

The data collected in the current study are comparable to that from the previous studies [42].

The addition of lentil flour also had a pronounced effect on organoleptic properties of bread. The crumb is more coarse-pored, slightly dry. The crumb and the crust colors are darker, with the crumb having a reddish hue. The flavor and odor are typical for lentil flour, with a light bitterness.

The data is in agreement with the results of other authors [43].

Brown rice flour had a lower effect on the quality of baked products. The volume of bread is slightly lower. The crumb color and the porosity structure remain without any pronounced changes compared to the reference. The crumb is slightly denser. The flavor and the odor do not differ significantly from the reference sample.

The addition of amaranth flour had a positive effect on the volume of baked products. The crumb structure did not manifest noticeable changes. The color of the crumb and the crust is darker compared to the reference. The crumb is softer and more elastic. The flavor and odor are typical for amaranth flour. Similar results were obtained in earlier studies [44].

Bread made with hydrothermally unprocessed buckwheat flour has a darker, denser and coarser crumb. The color of the crust was also darker. The volume of the products was lower compared to the control sample. The flavor and odor were highly pronounced. The results are summarized in Figure 2 and Table 10.

By comparatively testing six alternative flours in one experiment, it is possible to evaluate them relative to each other.

Figure 2. Baked bread samples made with 25% addition of: coconut flour (1), corn flour (2), lentil flour (3), brown rice flour (4), amaranth flour (5), and hydrothermally unprocessed buckwheat flour (6) compared to the reference sample (K)

Table 10. Organoleptic properties of bread with the addition of 25% alternative types of flour

Sensory evaluation indicators	Appearance	Color	Smell and taste	Crumb structure
Reference wheat flour	Volume satisfactory, surface uniform	Crumb and crust color light golden	Neutral taste and aroma, typical of wheat bread	Porous structure, satisfactory
Coconut flour	Low-volume bread, uniform surface	Crumb and crust color light	Sweet taste, pronounced coconut aroma	Dense structure
Corn flour	Volume satisfactory, smooth surface	Crumb color yellowish; crust light	Mild corn flavor and aroma	Large-pore structure
Lentil flour		Crumb and crust color dark with reddish tint	Characteristic lentil taste and aroma, with a slight bitterness	
Brown rice flour		Crumb and crust color light	Mild, neutral taste and aroma	Porous structure, satisfactory
Amaranth flour	Low-volume bread, uniform surface	Crumb and crust color dark	Moderate amaranth taste and aroma	Porous structure, satisfactory
Hydrothermally unprocessed buckwheat flour		Crumb and crust color dark	Distinct buckwheat flavor and aroma	Large-pore structure

The addition of the studied types of flour to wheat flour resulted in a significant change in the quality of baked products. The baked samples differed in the specific volume and softness retention during storage after three days.

To determine the optimal dosage of water for dough mixing, we considered the water absorption capacity of the tested flours. The ability of flour to absorb moisture plays a key role in the efficient commercial production of bread. The yield of finished products from 100 kg of flour depends on this ability, as when working with the flour of low water absorbing capacity it is necessary to reduce the amount of water added to achieve the desired consistency. This entails a reduction in the volume of the finished products and, consequently, in the profit of the enterprise. The results are summarized in Table 11. This information has not been given before by other researchers, but it has undoubted practical and economic significance and should be taken into account in the development of new products.

Table 11. *Measured dough yield obtained with high-grade wheat flour with addition of alternative flours*

Proportion of studied flours added, %	Coconut flour	Corn flour	Lentil flour	Brown rice flour	Amaranth flour	Hydrothermally unprocessed buckwheat flour
	dough yield, kg per 100 kg flour					
0 (reference/wheat flour)	160.3	160.3	160.3	160.3	160.3	160.3
5	163.3	161.3	161.3	160.3	163.3	161.3
15	167.3	163.3	161.3	160.3	164.3	162.3
25	169.3	164.3	161.3	159.3	165.3	163.3

The data obtained demonstrates that the introduction of coconut flour in a dosage of 25% of the total flour mass allows to increase the dough yield by 9 kg from 100 kg of flour. Replacing wheat flour with corn and amaranth flours in the same dosage increases dough yields by 4 and 5 kg, respectively. Lentil flour and hydrothermally unprocessed buckwheat flour had a less pronounced effect on dough yield: at a dosage of 25% the introduction of thermally unprocessed buckwheat flour increased the dough yield by 3 kg, that of lentil flour by 1 kg. The addition of brown rice flour reduced water absorption capacity, which caused the dough yield to decrease by 1 kg relative to the control sample.

Conclusions

The results of this study confirmed and expanded upon the data of previous works concerning the effect of different types of alternative flours on the rheological properties of dough and the organoleptic properties of bread made from a mixture of different types of flours.

It was found for the first time that replacing 25% of wheat flour (produced by Petersburg milling plant JSC) with coconut flour (produced by UFEELGOOD JSC) increased the stability of the dough to 48 minutes and 49 seconds, which is 5 times greater than control, but reduced the specific volume of bread by 0.6 cm^3/g. At the same time, the results obtained complement previous studies that also showed an increase in the water absorption capacity of a similar flour mixture [6, 7]. It is recommended to limit the coconut flour content to 10% to maintain the volumetric characteristics of the bread.

For the first time, it was shown that replacing 25% of wheat flour with corn flour (produced by Garnec JSC) reduces the dough deformation energy by 35.2%, which significantly affects the dough structure. However, these findings confirm previous studies that reported the negative effect of corn flour on gluten network structure and dough rheological characteristics [45]. According to these findings, it is recommended to limit the corn flour content in the mixture to 5% to improve the texture of bread.

It was also discovered for the first time that replacing 25% of wheat flour with amaranth flour (produced by Russkaya Oliva JSC) reduces the hardness of bread by 34.6%, which makes it a preferred ingredient for improving the texture of bread. It was also found that such replacement increases the water absorption capacity of the dough by 13.3%, which is in agreement with previous findings [12, 13]. Amaranth flour had a positive impact on bread quality metrics in all studied formulations, suggesting that a replacement ratio of no less than 25% could be warranted.

The study found that lentil flour (produced by Garnec JSC) added at 25% total reduces dough deformation energy by 75.4%, which significantly affects its texture. This complements the previously known data, according to which the addition of lentil flour in the amount of 10% improves crumb quality [46]. It is recommended to adhere to a dosage of no more than 10% when using lentil flour in bread formulations.

The study has also shown that the addition of hydrothermally unprocessed buckwheat flour (produced by Garnec JSC) reduces the specific volume of bread and increases its hardness, which complements the existing body of knowledge on the water binding capacity of buckwheat flour [20]. Intense absorption of water by starch reduces its availability for gluten network formation, which reduces the ability to retain carbon dioxide and thereby directly affects the volume and texture of bread. For this reason, it is recommended to limit the addition of this type of flour to 15%.

It is identified for the first time that brown rice flour (produced by Garnec JSC) increases the hardness of bread. The effect of brown rice flour on increasing the water absorption capacity of dough was confirmed, as shown in the studies of Morita N. [26]. As a result of the study, it is recommended to add brown rice flour in quantities of up to 20%.

This research work demonstrates a comprehensive comparison of six alternative flour types and reveals quantitative changes in dough rheological properties and breadmaking properties of bread. The practical significance of the research is determined by the possibility of optimizing bakery product formulations using these flours to improve nutritional and sensory characteristics. Amaranth flour, added in the quantities of up to 25%, has shown itself as the most promising option, as it reduces the hardness of bread and increases the water absorption capacity, which makes it preferable for improving the texture, retaining softness during storage and increasing the yield of finished products from 100 kg of flour. For the successful use of other types of flour, it is recommended to take into account the results obtained in this study and further adjust the properties of dough semi-finished products by adding additional ingredients. Also, the results obtained for other types of flour help to take into account the identified peculiarities at the stage of bread recipe planning and correct them by adding additional ingredients. Further research is planned to focus on the combined use of several alternative types of flour to achieve optimal rheological and quality parameters of bread, as well as adjusting the quality characteristics of finished products through the use of specially selected baking sourdough starters.

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