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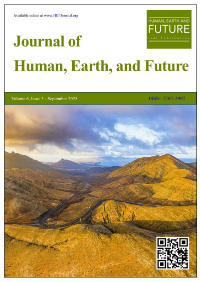

A Study on the Quality of Food Flakes Obtained from Triticale Sprouts

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Abstract

This article presents work on the development and implementation of a technology for obtaining food flakes from triticale sprouts bred in Kazakhstan in order to create a functional product with high nutritional and biological value. The methodology included the determination of optimal drying modes, an analysis of the chemical composition, an organoleptic evaluation, and testing of the properties of the product. The optimal drying parameters for the sprouts were found to be 6–8 min at 60–70°C, which ensures the preservation of up to 85% of their biologically active substances, including B vitamins, tocopherols, and natural antioxidants. Comparative analysis showed that triticale flakes contain 12-15% protein, have a high dietary fibre content (up to 6.8 g/100 g), and have a low glycemic index (≤55), which makes them especially valuable for dietary and preventive nutrition. The organoleptic investigation confirmed a high taste acceptability and attractiveness of the product for consumers. The novelty of the work lies in the use of triticale sprouts in the production of finished flakes with improved characteristics, which allows us to expand the range of domestic functional products and increase the share of local raw materials in the food industry.

Keywords: Triticale; Food Flakes; Sprouts; Production Technology; Quality; Nutritional Value.

1. Introduction

In the context of the growing consumer demand for products with high nutritional and biological value, researchers are paying special attention to the use of grain crops that have both agronomic advantages and nutritional potential. One of these crops is triticale, an interspecific hybrid of rye (*Secale cereale*) and wheat (*Triticum aestivum*), combining winter hardiness and disease resistance with a high protein content and improved technological properties [1, 2]. A number of studies have identified that triticale grain contains a more balanced amino acid profile than traditional cereals, especially with respect to lysine, and is also rich in dietary fibre, B vitamins and minerals [3, 4]. Of particular scientific interest is the use of sprouted triticale grain, which contains enzyme systems activated during germination and biologically active synthesised compounds, including antioxidants and vitamins [5]. Healthwise, studies have shown that sprouted cereals have a positive effect on the metabolism and immune function, and help in the prevention of chronic diseases [6]. Despite this, the use of triticale sprouts in the food industry remains limited. Previous works have mainly focused on the agronomic and breeding aspects of crop cultivation, while technological approaches to processing the

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sprouts into finished food products have barely been developed [7, 8]. In particular, the possibility of creating food flakes—a popular category of instant products—from triticale sprouts, while preserving their functional properties, remains poorly understood.

The development of a technology for producing food flakes from sprouted triticale grain is a promising area. Such a technology could not only expand the range of functional food products, but could also increase the degree of processing of raw domestic grain materials. This is especially relevant for Kazakhstan, where triticale is considered a promising crop for sustainable farming and import substitution. The creation of sprout-based products with high nutritional and biological value meets modern trends in healthy and preventive nutrition, including a reduction in glycemic load, an increase in the consumption of dietary fibre and vegetable protein [8, 9]. Sprouted grains have improved bioavailability of nutrients, high digestibility and a positive effect on the metabolism, which makes them especially valuable in therapeutic and functional diets.

It should also be noted that the flour-milling properties of triticale occupy an intermediate position between those of wheat and rye. According to a number of studies, the crude protein content of triticale grain varies from 12.8 to 14.5%, which exceeds similar indicators for other cereals, but the quality of the gluten is often inferior to that of wheat due to the high activity of proteolytic enzymes that destabilise its structure [10, 11]. Nevertheless, triticale flour, wholemeal and de-husked, is characterised by a high content of lysine, dietary fibre and minerals, underscoring its high nutritional value and its potential in the production of fortified products [12, 13].

Studies conducted in a number of countries, including Germany, Poland and Canada, have confirmed the promise of using triticale flour in baking, despite some technological limitations. In particular, although baked goods made from triticale flour are characterised by a smaller volume and reduced crumb porosity, which are associated with the characteristics of the protein complex, such products demonstrate improved nutritional properties, including a relatively high dietary fibre content (up to 4%), as well as a more balanced amino acid profile than in other flours, including an increase in the content of lysine and tryptophan [14, 15]. In the countries of the European Union, alternative uses of triticale are being actively studied, including the production of pasta, cereals, muesli and breakfast cereals. Sprouted triticale grain is considered a promising raw material for functional products due to its high content of γ-aminobutyric acid (GABA), B vitamins, as well as its pronounced antioxidant activity [16–18], and particular attention is being paid to the processing of sprouted triticale because the germination processes are accompanied by the activation of hydrolytic enzymes, the breakdown of complex carbohydrates, the synthesis of biologically active compounds and an increase in the bioavailability of nutrients. This allows the use of sprouted grain as a functional ingredient with potential physiological activity. Foreign studies, including from Japan and South Korea, have shown that the inclusion of sprouted triticale in breakfasts helps to reduce total cholesterol levels, improve antioxidant status and normalise metabolic parameters in people with metabolic disorders [19, 20].

Products based on sprouted triticale grain have a number of proven physiological benefits. Specifically, these include: a relatively high B vitamin (in particular B1, B2 and B6) content, plus vitamin E and β-carotene; an active antioxidant system due to the presence of polyphenolic compounds and tocopherols; a high concentration of dietary fibre (up to 7 g/100 g), which helps normalise lipid metabolism and intestinal functioning; a low glycemic index and moderate content of digestible carbohydrates, which makes them suitable for people with metabolic syndrome and diabetes; and the presence of GABA, which has a sedative and anti-stress effect [21, 22]. Considering the benefits of sprouted triticale, the development of a technology for obtaining food flakes from it has merit.

However, the technological aspects of its processing into food products, and flakes in particular, remain insufficiently studied. Previous studies have been limited to laboratory experiments and have not taken into account the regional characteristics of the raw material, the technical and economic parameters of the processing or the requirements for scaling to the level of industrial production [23, 24]. Thus, the purpose of this study was to develop a technology for the production of food flakes from Kazakhstani sprouted triticale grain with the maximum preservation of biologically active substances.

Here, for the first time, an approach to processing sprouted triticale into food flakes, while preserving their biologically active components, has been experimentally substantiated. The process is efficient, keeping the energy costs down, and ensures the preservation of the vitamins, essential amino acids and dietary fibre, as proved by a comprehensive assessment of the chemical composition of the product and its organoleptic and functional properties. Our findings help to address the existing scientific and technical deficit in the field of triticale processing, and further the goal of introducing new types of food products that are based on local raw materials.

2. Material and Methods

The study involved samples of winter triticale of the Asiyada variety, which has been approved for cultivation in the southern regions of Kazakhstan since 2013. The aim was to develop and substantiate technology for the production of food flakes from triticale seedlings. We approached this through physicochemical, technical and microstructural analyses aimed at assessing the quality of the raw materials, the parameters of the process and the characteristics of the resulting product.

Germination of the triticale grain was carried out in water at 10–14°C for 18–32 h, with periodic aeration of the grain mass every 8–10 h. The criterion for optimal completion of the germination process was the length of the sprout reaching 0.5–2.0 mm. The process of obtaining food flakes from these sprouted grains involved first drying them in a laboratory dryer using infrared (IR) radiation. Then, the grains were flattened on a QC-104 flattening machine to form cereal, following which the product was subjected to repeated IR drying to achieve an optimal humidity of 14%.

The experimental data were analysed mathematically, the statistical processing of the results carried out using Microsoft Excel and Statgraphics Plus 5.0 software.

3. Results and Discussion

The qualitative characteristics of the grain used in the experiments are shown in Table 1.

Table 1. Initial qualitative characteristics of the triticale prototypes

Sample no.	Bulk density of grain, g/l	Weight of 1000 grains, g	Density, g/cm^3	Grain volume, mm^3
1	791	39.9	1.42	29.4
2	665	38.1	1.32	31.2
3	640	38.1	1.10	32.4
4	661	25.8	1.24	27.8

Note. Samples 1 and 2 were grown in the Almaty region, Samples 3 and 4 in southern Kazakhstan.

From Table 1, it can be seen that the 1000-kernel weight of the triticale samples varied within 25.8–39.9 g. This is one of the key indicators of grain maturity and the potential productivity of the crop. A higher weight would indicate a fully formed, mature grain, which would be associated with a higher proportion of endosperm—the main part of the grain responsible for the accumulation of starch and protein. A positive correlation was established between the 1000-kernel weight and the grain processability. Grain with a higher weight was easier to flatten and dry, and formed uniform and intact flakes. This can be explained by the fact that increased grain weight, as a rule, is due to a smaller proportion of shell and a more pronounced starchy part, which improves the behaviour of the grain during mechanical processing. The grain bulk density ranged from 640 to 791 g/l. High natural weight values (more than 750 g/l) indicate grain fullness and density, which offer greater processing potential, the dense structure specifically increasing the grain's resistance to mechanical damage, reducing losses during processing and increasing the yield of the finished product. At the same time, a low natural weight (<670 g/l) could signal an increased content of germ and shell, which would complicate uniform thermal and mechanical processing and reduce the suitability of the material. The grain density, which varied from 1.10 to 1.42 g/cm^3, is an integral indicator reflecting the ratio of the internal components—endosperm to aleurone layer to shell to germ. Denser grain contains mainly endosperm, and is rich in starch and proteins and, to a lesser extent, lipid- and fibre-containing shell structures. This makes it more suitable for the production of food flakes, such grains being easier to flatten to produce a uniform structure. Grain with a low density, conversely, may indicate immaturity or unfavourable conditions for crop formation.

The specific volume of the grain, in the range of 27.8–32.4 mm^3, has an inverse relationship with density, and also correlates with the morphological structure of the grain. A higher specific volume can be associated with a loose and porous structure, characteristic of grain with a high proportion of shell elements, which affects the hydration properties. Such grain absorbs moisture faster during soaking and germination, but its heterogeneous structure can complicate uniform processing and drying. Contrastingly, grain with a lower specific volume, as a rule, has a high density and a uniform structure, which is a desirable characteristic in the production of food flakes, ensuring the stability of the processing and a high quality of the final product. Thus, the morphological and physicotechnological characteristics of the triticale grain allowed us to establish that samples with a high 1000-grain weight, a natural weight of over 750 g/l, a density of about 1.35–1.42 g/cm^3 and a specific volume within 28–30 mm^3 were the most suitable for processing into food flakes.

The seed properties of grain, including its germination energy, germination and viability, are key indicators of its suitability for germination and further use in food production. High values of these parameters ensure uniform germination, which is important for obtaining high-quality raw materials with high biological value. The germination energy characterises the intensity of the initial growth phases and the rate of emergence of seedlings, which reflects the physiological activity of the grain. Germination determines the proportion of viable seeds capable of full germination, which directly affects the yield of the finished product. The viability of the grain determines its resistance to processing, including hydration, enzymatic activity, and subsequent drying, which directly affect its ability to germinate [25, 26]. In this regard, the evaluation of the seed properties of the grain made it possible to determine its biological potential and suitability for use in the production of processed food products based on it (Table 2).

Analysis of the data in Table 2 showed that the triticale grain samples had good seed characteristics, with high physiological maturity and the ability to germinate. Germination in the range of 86–88% indicates good reproductive potential, which is especially important in the production of products from sprouted grain because mass germination requires a stable and uniform initial growth in the majority of the grains. This allowed us to predict a high yield of sprouts and, accordingly, a few raw material losses in the early stages of production.

Table 2. Indicators of seed properties of triticale grain prototypes

Sample no.	Germination, %	Germination energy, %	Viability, %
1	86	92	94
2	88	94	98
3	86	90	96
4	86	92	94

A germination energy varying from 90 to 94% reflects a high speed and intensity of the onset of physiological processes in the grain. This value indicates that most grains not only germinate, but also do so in a short time, which is of practical importance—accelerated germination reduces the overall time of the production cycle and reduces the risks of developing unwanted microflora. This is especially important in an industrial context, where both the efficiency and biological safety of the product are important.

Grain viability (94–98%) is also a critically important parameter, reflecting the ability of the seed to maintain metabolic activity under adverse environmental conditions (changes in humidity, temperature, mechanical stress). High viability ensures resistance to physical stresses, such as soaking, germination, drying and flattening, resulting in the preservation of the nutrient composition and functional properties of the sprouts.

At the physiological level, germination is accompanied by the activation of enzyme systems, including α-amylase, protease and lipase, which promotes the hydrolysis of macromolecules (starch, proteins, lipids) to more accessible and easily digestible forms. This increases the nutritional and biological value of the product, makes it more easily digestible and enriches its amino acid and vitamin profile, especially B vitamins (B1, B2, B6), vitamin E, GABA and antioxidant compounds. In addition, the germination process reduces the content of anti-nutrients (e.g. phytates), which improves the absorption of micronutrients, such as iron, zinc and magnesium. Thus, the assessment of the seed properties of the triticale samples not only confirmed their high suitability for producing sprouts, but also indicated the optimal quality of the raw material for creating functional food products.

Experimental work was then carried out to determine the optimal germination parameters, including duration, temperature and humidity levels. These parameters play a decisive role in the biochemical composition of the sprouts and their suitability. In addition, optimisation of the germination mode allows for a balance between maximum activation of enzymatic processes and a minimisation of dry matter losses, which directly affects the profitability and industrial efficiency of the process. Also, considering that the efficiency of germination has a direct impact on the organoleptic characteristics, texture, digestibility and nutritional value of the finished product, the choice of germination modes was a key step in the development of the process.

From an economic point of view, the development of an optimal germination regime would make it possible to reduce production costs related to energy consumption, water use and time spent on raw material preparation. Excessive lengthening of the process can lead to increased resource consumption and a decrease in yield, while an insufficient degree of germination would decrease the quality of the raw material. The main criterion for choosing the germination parameters was the sprout length because this is directly related to the intensity of the biochemical processes occurring in the grain [27, 28].

Based on our results, the optimal length of the sprout was 0.5–2.0 mm. Upon reaching this value, enzymatic processes are activated, leading to the breakdown of the grain reserves (starch, proteins) into more digestible forms. This range ensures the maximum accumulation of biologically active compounds, including amino acids, B vitamins and antioxidants, which positively affects the nutritional and biological value of the finished product.

With an increase in the length of the germ to more than 2.0 mm, we recorded a decrease in the nutritional value of the grain, which can be explained by the intensive consumption of reserve substances for the development of the embryo and growth processes. This leads to a loss of dry matter, decreases in the starch and protein contents, and a change in the grain structure—it acquires a wrinkled surface, which can negatively affect its processing properties. If the length of the sprout is less than 0.5 mm, the process of enzymatic cleavage of the reserve substances is insufficient, which means a failure in the triggering of the necessary biochemical changes. As a result, the product would not achieve optimal biological values, reducing the bioavailability of the nutrient components, with the contents of easily digestible proteins, sugars and vitamins remaining low.

To produce sprouted triticale flakes, it is recommended to use a grain in which at least 85% of the seeds germinate. This guarantees uniformity of germination and the formation of the homogeneous biochemical changes necessary to increase the nutritional value of the final product. The optimal duration of germination was determined by taking into account the intensity of the enzymatic processes and the sprout length.

Based on our results (Table 3 and Figures 1 to 4), the germination regime was optimised to ensure the formation of high-quality raw materials for the production of food flakes.

Table 3. Dynamics of triticale grain germination depending on germination time

Time, h	Sample No. 1, %	Sample No. 2, %	Sample No. 3, %	Sample No. 4, %
14	0	0	0	0
15	18	0	16	54
16	54	34	54	66
17	80	54	78	84
18	86	62	86	88
19	88	68	86	88
20	88	68	86	92
21	90	74	88	94
22	90	86	88	94
23	92	90	88	94
24	92	94	92	94
25	96	94	92	94
26	96	96	94	94
27	96	96	94	94
28	0	96	0	0

Note. Samples 1 and 2 grown in the Almaty region, 3 and 4 in southern Kazakhstan.

Percentage of sprouted grains <85%
Sprout length = 0.5–2.0 mm and percentage of sprouted grains >85%
Sprout length >2.0 mm

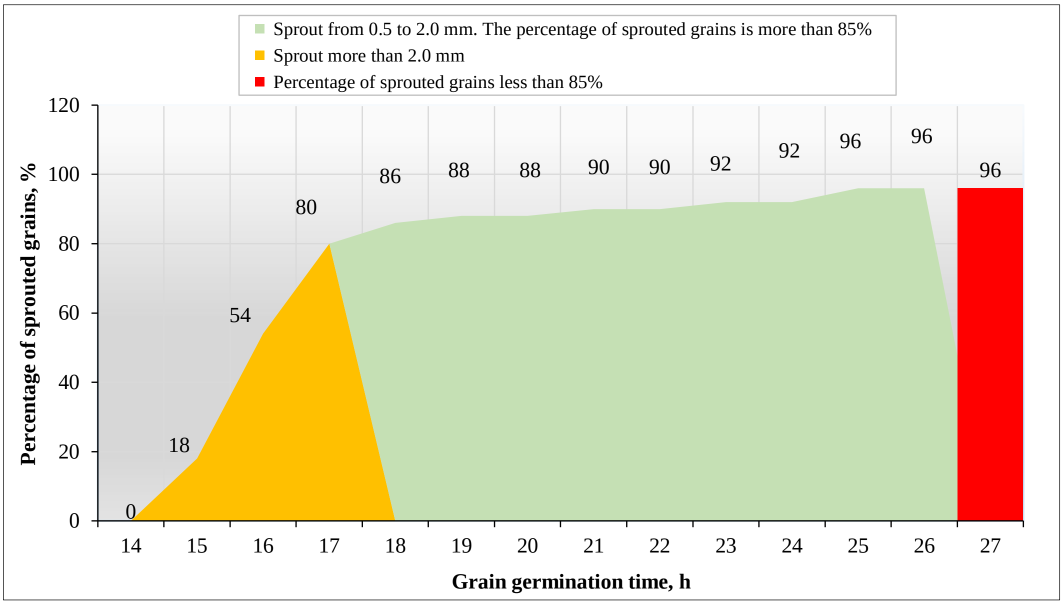

Figure 1. Change in the percentage of germinated grains in Sample 1 based on germination time

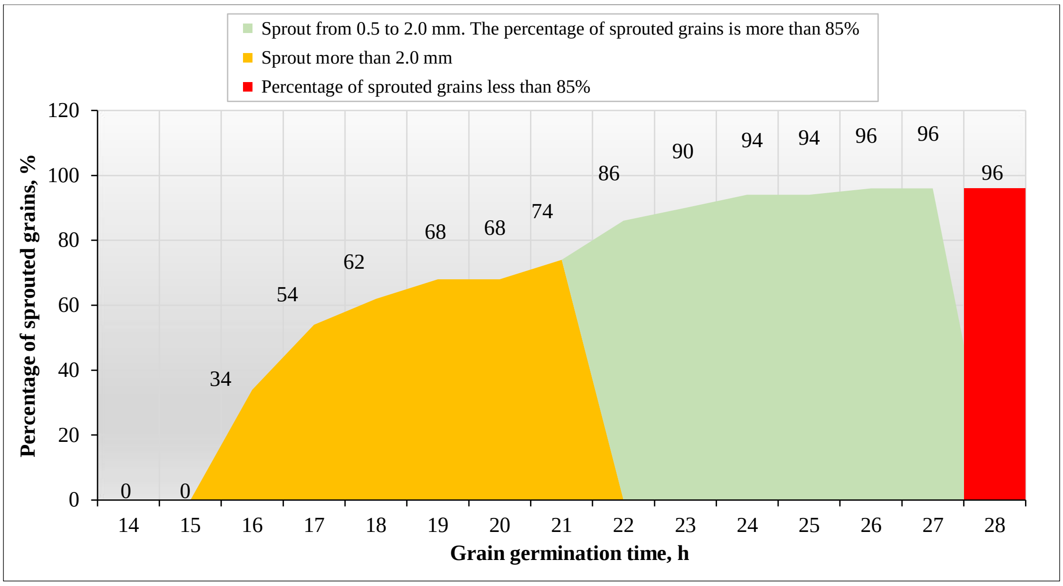

Figure 2. Change in the percentage of germinated grains in Sample 2 based on germination time

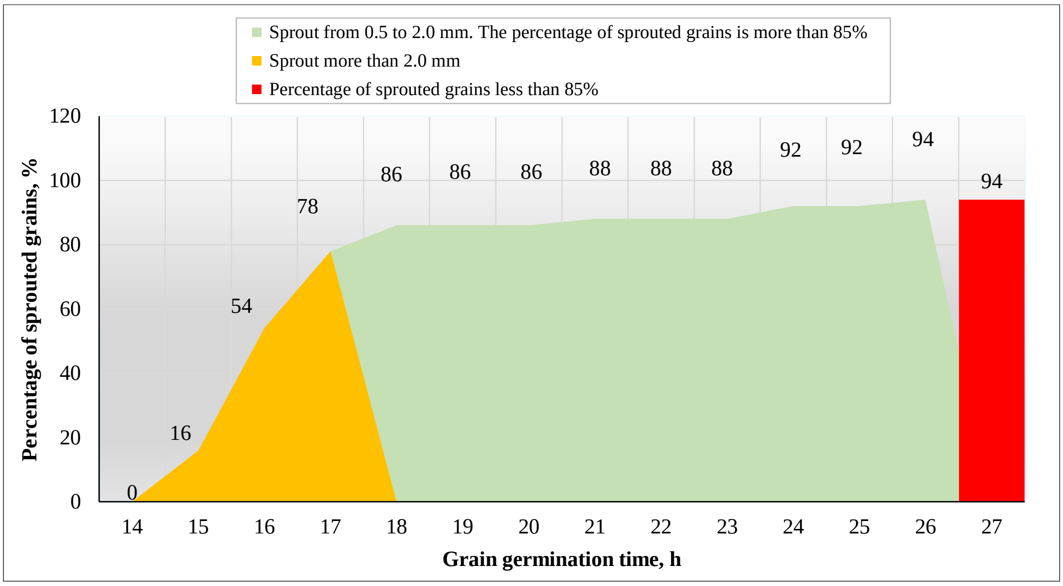

Figure 3. Change in the percentage of germinated grains in Sample 3 based on germination time

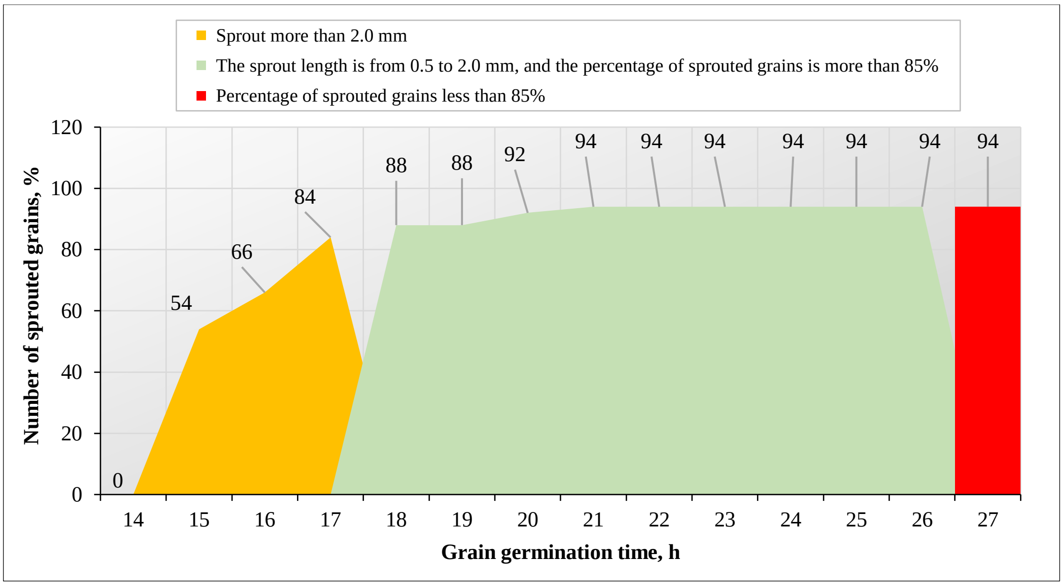

Figure 4. Change in the percentage of germinated grains in Sample 4 based on germination time

Table 3 shows that the intensity of germination of the Asiada variety triticale grain depends significantly on the duration of germination, as well as on the regional affiliation of the samples. These differences are of direct importance in the selection of the optimal time interval for germination, ensuring the maximum level of enzymatic activity with minimal resource costs.

The initial phase of germination (0–14 h) was characterised by a latency phase, during which metabolic processes are activated, albeit external morphological signs of germination are still absent. During this period, grain swelling, the restoration of cell metabolic activity and the activation of enzymes responsible for the mobilisation of reserve substances (starch, proteins and lipids) occur. In Samples 1 and 2 (Almaty region), the first signs of germination were absent until 15 h had passed, while Samples 3 and 4 (South Kazakhstan region) germinated earlier. This may indicate differences in the physiological maturity of the grain or in the activity of hormonal growth regulation due to differences in the growing conditions (e.g. temperature, humidity, insolation, mineral nutrition).

Between 16 and 22 h, active germination was observed, characterised by a sharp increase in the proportion of germinated grains. By Hour 18, the proportion of germinated seeds varied from 62% to 88%, indicating high physiological activity. This time interval represented a critical stage in which the peak metabolic activity occurred, when there are increases in the hydrolysis of macronutrients and synthesis of vitamins (especially group B), GABA, antioxidants and bioactive peptides. These biochemical processes directly affect the functional properties of the future product.

After 22 h, the rate of emergence of new sprouts stabilised, approximating the maximum potential germination. By Hour 24, 88–94% of the grains had sprouted, and by Hour 26, this value was 94–96%. This indicates that 22–26 h is the optimal amount of time for complete germination. Further germination did not lead to a significant increase in the percentage of sprouted grains and, in some samples, even a slight decrease in this indicator was noted, possibly due to overconsumption of the grains' energy reserves, a deterioration in their structural integrity, activation of autolysis processes and the possible development of undesirable microflora under high-humidity conditions. Thus, the following key interpretations can be identified:

To visually represent the dynamics of triticale grain germination, graphical dependencies were constructed (Figures 1 to 4). These plots illustrate the change in the percentage of germinated grains over time, highlighting the various stages (active growth, stabilisation, overgrowth) of the process using colour gradations.

Sample 2 had a more pronounced and prolonged active growth phase than the others, possibly due to the physiological characteristics of the variety, but also to factors related to its storage, such as humidity or temperature, and the degree of grain maturity at harvest. Such differences must be taken into account during industrial standardisation of the process because they affect the homogeneity of the resulting product and the stability of its quality. After 26–27 h, the intensity of growth of the sprout length slowed, and in some samples even decreased, indicating the beginning of the secondary metabolism phase, when the grain reserves begin to be depleted, the endosperm is destroyed, and the sprout biomass begins to consume nutrients. Excessive sprout growth is accompanied by an increase in humidity and changes in the texture and structure of the grain, which complicate processing and increase the risk of microbiological contamination. Mechanical processing becomes difficult because the grain becomes excessively soft and heterogeneous, the energy consumption of the drying process increases due to the excess moisture in the sprout structure and dry matter lost during heat treatment increases. This can also deleteriously affect the organoleptic characteristics of the finished flakes (e.g. the development of bitterness due to the activation of lipoxygenases).

Currently, one of the priorities in developing grain processing technologies is to produce new types of grain products, including food flakes and dietary nutrition products. Cereal flakes are traditionally considered a healthy food that is available to a wide range of the population, including socially vulnerable groups. Triticale, being a hybrid of wheat and rye, combines the advantages of both crops. Triticale grains are usually longer than those of wheat and wider than those of rye [10, 29, 30]. Previous studies have suggested that triticale grain is superior to rye, but somewhat inferior to wheat (Table 1). In addition, triticale proteins contain more of the essential amino acid lysine than wheat proteins, which increases the nutritional value of triticale [31, 32] and makes it a promising raw material for the production of food flakes.

Among the key parameters that determine the structural, organoleptic and nutritional characteristics of flaked grain products are the grain germination time (intensity of biochemical processes and formation of nutrients), duration of drying before flattening (affects the moisture characteristics that affect mechanical processing), the roller gap (determines the degree of deformation of the grains during flattening and the formation of the structure of flakes) and the drying time after flattening (affects the final physicochemical properties of the product, including brittleness, moisture and the preservation of biologically active compounds).

When developing optimal processing modes, it is necessary to take into account not only the quality of the finished product but also its yield, which requires an integrated approach to maximise the processing efficiency of the raw material. The key technical step in the production of food flakes from sprouted triticale grain is flattening—a process that results in the grain product acquiring a characteristic lamellar shape and marketable appearance. This stage consists of rolling the grain through the gap between two smooth rollers, which compacts the structure, changing the morphology of the grain and forming the desired organoleptic characteristics of the product.

To determine the optimal flattening conditions, we studied the effect of roller gap size on the physicochemical properties of the flakes. We found that with an inter-roller gap of <0.4 mm, the grain was subjected to excessive mechanical stress, which led to excessive grinding, shape disruption and deterioration in the presentation of the flakes. By contrast, with an increase in the gap to >0.6 mm, the grain was unevenly flattened, which caused differences in the thickness of the flakes and reduced the uniformity of their subsequent drying during IR treatment.

To determine the optimal drying time for the sprouted grain before flattening, we analysed the dependence of flake yield on the duration of the pre-drying. The data are presented in Table 4 and Figures 5 and 6.

Table 4. Dependence of triticale flake yield on the drying time

Experiment number	Grain drying time before flattening, min	Flake output, %
1	0	80
2	1	85
3	2	96
4	3	83
5	4	81
6	5	85
7	6	80
8	7	78
9	8	79
10	9	75
11	10	72
12	11	60
13	12	58

Table 4 shows a pronounced dependence of flake yield on the drying time, which allowed us to determine the critical factors for achieving the maximum yield and quality of the finished product. Flake yield is one of the key indicators of processing efficiency, directly reflecting the degree of preservation of the grain mass, the physical suitability of the sprouts and the rationality for using that raw material.

At 0 min (no drying), the grain had a high moisture content, which limited its plasticity and reduced the efficiency of flattening. Nevertheless, the flake yield was about 80%, indicating minimal mechanical losses. However, the structure of the obtained flakes may not be sufficiently stable, with increased stickiness and a tendency to agglomeration. After drying for 1 min, the yield increased to 85%, indicating partial stabilisation of the moisture and an increase in grain plasticity, facilitating its more-complete flattening. The maximum flake yield (96%) was achieved after 2 min of drying. This indicates that the optimum level of residual grain moisture (~42–45%) had been reached, at which point the grain was plastic, but not easily destroyed during the flattening process, and did not crumble or stick. This represents the golden zone in which there is minimum mass loss during flattening, uniform flake thickness and structure, preservation of the integrity of the endosperm and germ, and reduced energy costs for subsequent flake drying.

Extending the drying time to 3–6 min led to a gradual decrease in the flake yield to 80–85%. This can be explained by overdrying of the outer layers of the grain, which lost elasticity and became brittle. As a result, the grain was crushed during flattening, forming small particles and waste, and the percentage of husks and cracks in the flakes increased. With critical overdrying (10–12 min), the yield decreased to 60–58%. This indicates a violation of the structural integrity of the grain, the internal tissues losing moisture, the grain losing plasticity, becoming hard and difficult to process. In addition, excessively dry grains are less effectively captured by the rollers, which increases yield losses.

The optimal state for flattening was achieved with a balanced moisture gradient between the centre and the shell of the grain. When drying for 2 min, the required moisture inside the grain was maintained, while the outer layer became dry enough to develop mechanical strength. In this way, there was uniform deformation of the grain during flattening and the formation of flakes of the correct shape. When the drying time is exceeded, the internal moisture-bound structure is lost, which leads to grain 'fragility', and also to a reduction in the thermal stability of the finished product (dried flakes become brittle and can be destroyed during transportation and packaging).

Control of residual grain moisture is a key parameter on which the stability of the entire production process depends. The optimal drying time for the triticale grains before flattening was identified as 2 min, which ensured maximum flake yield and high flake quality with minimal grain loss (formation of fines, husks, dust).

Figure 5 clearly illustrates the curve of flake yield dependence on time of preliminary drying of sprouted triticale grain. Analysis of the curve shape allowed us to identify the characteristic stages of change in the physical properties of the raw material under the influence of heat treatment, as well as clearly defining the efficiency limits and tolerances of the drying time. The interval of 0–2 min of drying (zone of physical instability) saw a moderate increase in flake yield (from 80 to 96%) with relatively little time expenditure. This can be explained by the fact that excess moisture in the sprouts in the initial stage (>40%) complicates the mechanical processing, the grain is easily deforming, but not breaking, or flattening evenly. Its internal structure remains excessively plastic, which leads to adhesion to the rollers, flakes sticking together and disruption of their shape. Thus, insufficient drying not only reduces the mechanical efficiency of the process, but also negatively affects the quality of the finished product, including its appearance, texture and suitability for subsequent thermal stabilisation. The 2–4 min interval (optimal technological balance zone) saw the grain reach the optimal level of residual moisture (28–37%). This corresponds to the critical point at which the grain retains its internal plasticity, but the outer shell becomes dry enough to withstand the efforts of the rollers. As a result, the flakes have a clear shape and an even thickness, there is reduced processing loss (crushing, sticking particles), the integrity of the endosperm is preserved, which is important for the nutritional value, and the appearance of the product, important for consumer appeal, is improved. The flake yield reached a maximum of 96%, which makes this mode the most economically and technologically advantageous.

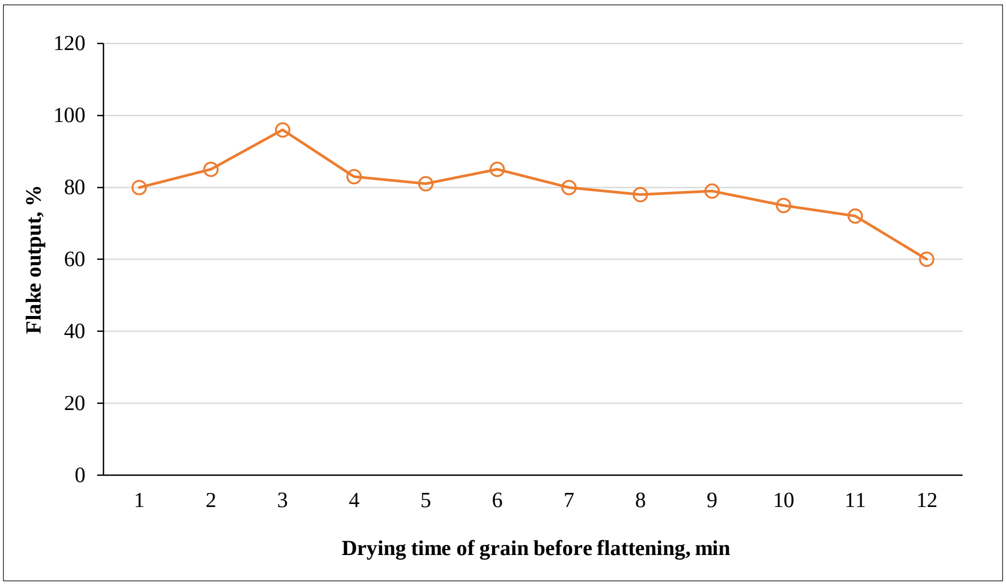

Figure 5. Effect of triticale grain drying time before flattening on flake yield

The 6–12 min interval (structure degradation zone) saw a rapid decrease in the flake yield (58–60%) caused by physical and mechanical changes in the grain. The main reasons being the grain shells losing elasticity and becoming brittle, the endosperm dehydrating and becoming hard, preventing flake flattening, and the flattening destroying the grain structure, accompanied by significant losses (formation of fines, husks, dust). Partial burnout of the enzymatic activity of the sprouts is also possible, which reduces the biological value of the flakes, especially if further heat treatment is not carried out using a gentle method.

A detailed analysis of the moisture removal dynamics shown in Figure 6 confirms that the decrease in triticale grain moisture during drying occurred linearly throughout the entire time interval. This allowed the process to be modelled and the grain moisture parameters to be predicted with a high degree of accuracy when changing the drying time. The coefficient of determination, $R^2 = 0.956$, indicates the reliability of the mathematical description of the process, which is especially important for the design and adjustment of drying units under industrial production conditions.

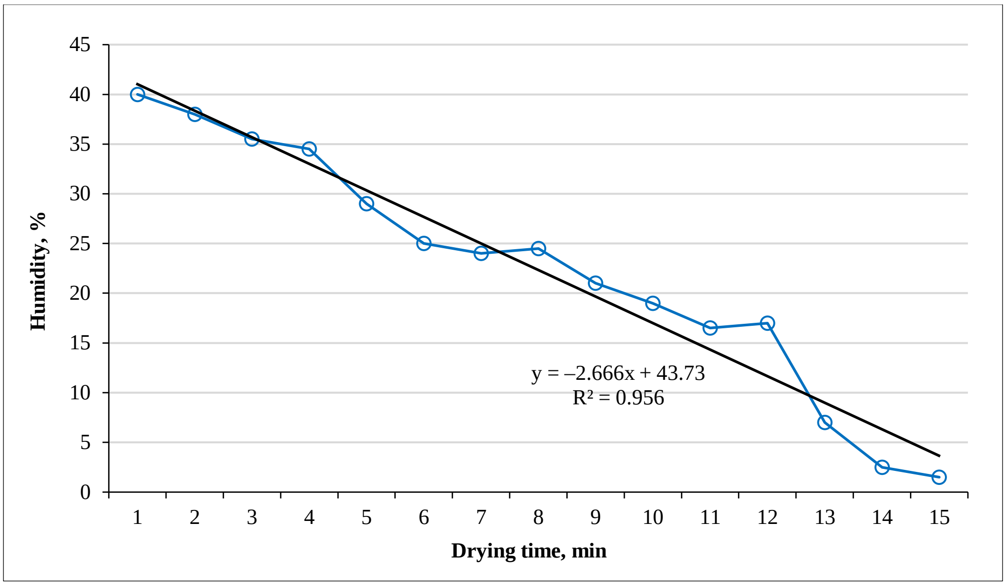

Figure 6. Monitoring of triticale grain drying

The upper moisture limit (37%) corresponds to the state of the grain still retaining plasticity and moisture, which contributes to a softening of the structure. However, excessive moisture reduces the mechanical strength of the shell and endosperm, causing sticking, shape loss and flake unevenness during flattening. Also, there is a risk of microbiological contamination with insufficient thermal stabilisation, which reduces the food safety of the product. The lower moisture limit (19%) is when the grain is excessively dry and brittle, leading to the structure being destroyed by mechanical action, forming crumbs and dust, sharply decreasing the flake yield. In addition, partial destruction of the enzyme systems activated during germination may occur, reducing the biological and nutrient value of the product.

Thus, the moisture content of the sprouted grain prior to mechanical flattening is a key parameter that determines the efficiency of the entire technological process. Its regulation allows for maximum flake yields, the formation of a uniform product structure with predictable organoleptic characteristics, minimisation of production losses, preservation of the functional activity of the enzymes, vitamins and antioxidants and adaptation of the heat treatment to the functional nutrition needs (including dietary and specialised products). The optimum humidity range (19–37%) should be accurately maintained, especially during the transition from drying to flattening. The use of real-time humidity sensors and automatic feedback systems can significantly improve process controllability and reduce process defects. Our data can be used to develop quality control regulations and algorithms at companies producing flakes from sprouted grain.

Table 5 summarises the studied factors and their effect on the flake yield. The experimental plan included a wide range of drying times and roller gap sizes and the results formed the basis for subsequent statistical modelling aimed at determining the optimal parameters for the production of triticale flakes.

Table 5. Summary of conditions for the production of triticale flakes

Experiment number	Drying time, min x_1	Inter-roller gap, mm x_2	Flake yield, % y_1
1	10	0.6	67
2	2	0.6	93
3	2	0.4	88
4	6	0.358579	68
5	10	0.4	54
6	11.6569	0.5	54
7	6	0.641421	78
8	0.343146	0.5	87
9	6	0.5	89
10	6	0.5	93

Analysis of the experimental conditions presented in Table 5 and the subsequent construction of a Pareto diagram (Figure 7) allowed us to move from the descriptive level to a quantitative assessment of the influence of physical factors on the flake yield from sprouted triticale grain. This approach was necessary to obtain a reasonable optimisation of the drying and flattening parameters and to eliminate subjective decisions when choosing processing modes.

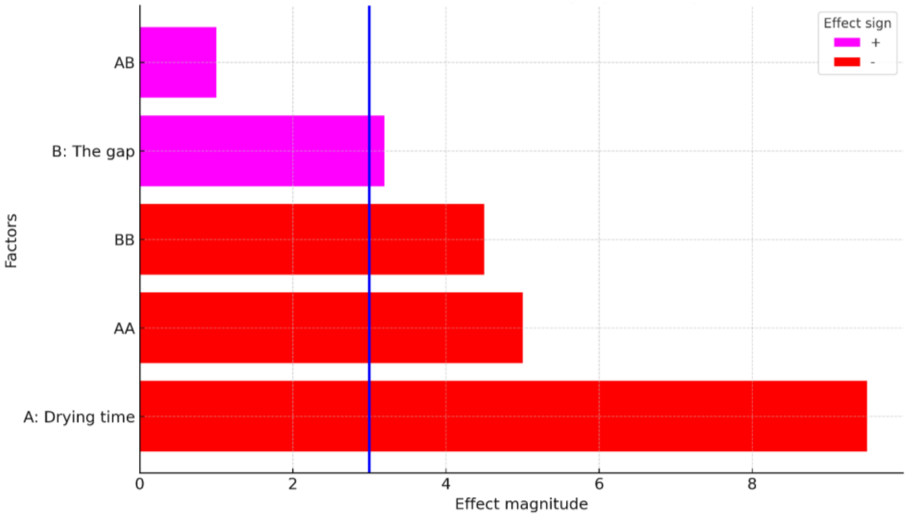

Figure 7. Pareto map for triticale flakes

Figure 7 was constructed based on the results of a factor analysis, and shows the influence of various factors on the triticale flake yield, with the size of the inter-roller gap being significant. The optimal gap of 0.5–0.6 mm allowed a balanced degree of flattening. At smaller gap values (<0.4 mm), the grain was subjected to excessive mechanical stress. If the gap was >0.6 mm, the grain was not flattened enough. However, the drying time had the greatest effect on the flake yield, with 2–6 min providing the optimal combination of moisture and mechanical properties.

These dependencies are clearly reflected in the Pareto diagram (Figure 7), which provides a visual assessment of the impact of each parameter and identifies the key factors requiring priority control in the production process.

In Figure 7, AA and BB are secondary factors that also significantly affected the outcome. Most likely, these are quadratic effects of the variables (e.g. the effect of drying time is not linear, but may increase or decrease at certain values). Meanwhile, AB is the interaction of the factors ‘Drying time’ and ‘Gap’. Its effect on the flake yield was the smallest among all the factors considered. The red columns in Figure 7 indicate the negative impact of the factors (reduction in flake yield), the magenta (positive) columns indicate that increasing these parameters had a positive effect on the flake yield. The vertical blue line represents the boundary of statistical significance. The factors represented by rows extending beyond this line had a significant impact on the process, whereas the factors whose rows do not extend beyond this boundary can be considered less significant.

To further refine the optimal conditions for obtaining triticale flakes and to visualise their dependence on the studied parameters, a mathematical approximation of the data was produced and a response surface was plotted (Figure 8). This provided a range of values for the factors at which the maximum flake yield was achieved.

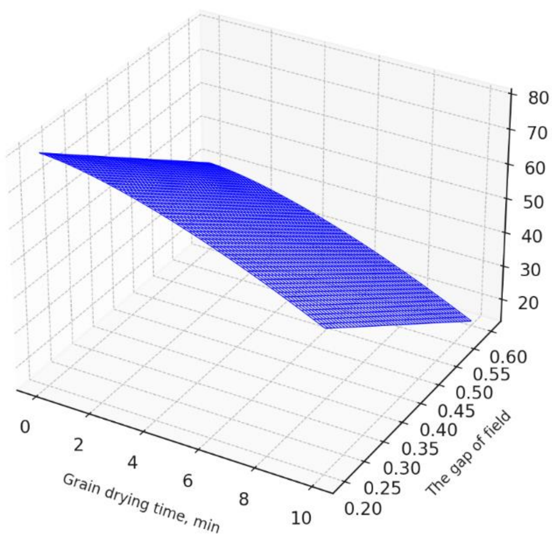

Figure 8. Response surface plot for triticale flakes

The response surface plot (Figure 8) shows the effect of grain drying time (x_1, min) and roller gap (x_2, mm) on flake yield (%). It can be seen that the maximum yield was achieved with a drying time of 3–4 min and a roller gap of 0.48–0.52 mm. This area is highlighted graphically where the blue colour is darkest, indicating the optimal process conditions.

The three-dimensional response surface plot (Figure 8) shows the presence of a maximum flake yield area corresponding to 3.2 min for the drying time parameter and 0.52 mm for the roller gap parameter. To acquire further detail of this area, a contour plot was constructed (Figure 9), which provides an alternative visualisation of the response surface. The contour graph projects the flake output values onto a plane, displaying their gradient changes depending on the two key factors. The different colour zones make it possible to identify optimal process conditions and see the effect of the parameters on the output of the finished product. This graphical interpretation of the data makes it possible to identify the sensitivity of the flake yield to changes in drying time and roller gap, as well as predict the results for various combinations of parameters.

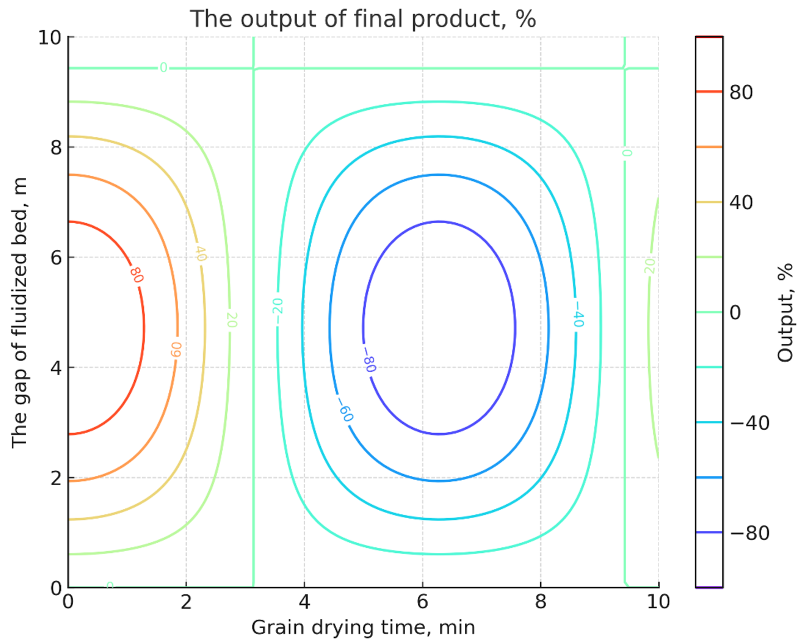

Figure 9. Contour graph for triticale flakes

On Figure 9, the maximum flake output zones (red and orange contours) correspond to the optimal process conditions, while a decrease in output (blue and green contours) indicates unfavourable processing modes. The gradient changes reflect the sensitivity of the flake yield to varying factors. Analysis of the plot shows that drying time (x_1) had a moderate effect—over 4 min, the flake yield decreased (excessive moisture loss deleteriously affects grain structure). Drying for <3 min is also not optimal (insufficient evaporation, deterioration in the flattening process). Roller gap size (x_2) played a significant role, confirmed by a pronounced change in the gradient on the contour plot. The contour map allows the boundaries of the optimal production conditions to be set and identifies critical areas where the flake yield is sharply reduced. This makes it possible to scientifically optimize the technological processes aimed at increasing product yield and improving its quality characteristics.

$$y_1 = -116.605 + 1.15091\, x_1 + 816.433\, x_2 - 0.582025\, x_1^2 + 5.0\, x_1x_2 - 806.255\, x_2^2 \quad (1)$$

Statistical processing of the experimental data allowed a regression equation to be obtained that quantifies the effect of the technological parameters on the yield of triticale flakes:

This regression equation indicates that the most significant factor determining flake yield is the roller gap (816.433 x2), the influence of grain drying time (1.15091 x1) being less pronounced. Positive coefficients for the linear variables indicate that increases in these parameters within technologically acceptable ranges contribute to increased output.

The significance of the quadratic terms (–0.582025 x12 and –806.255 x22) indicates the existence of an optimal range of factor values beyond which the yield of flakes decreases. This is because excessive drying of the grain leads to its fragility, which impairs the effectiveness of flattening, and an increase in the roller gap above the optimal range reduces the degree of pressing, impairing the formation of flakes. The factor interaction coefficient (5.0 x_1 x_2) reflects the relationship between the parameters, showing that their joint variation has a combined effect on the output of the finished product.

The results from Figures 8 and 9 confirm the validity of the regression model. The optimal parameters that ensure the maximum flake yield were confirmed as a grain drying time of 3–4 min and a roller gap of 0.48–0.52 (0.5) mm. To stabilise the structure and reduce the moisture content of the flakes after flattening, additional drying for 5 min is recommended.

Figures 10 and 11 show the microstructure of the central part of the endosperm of germinated triticale grains obtained by scanning electron microscopy. Studies have shown that, during germination, there is a significant transformation of starch granules in the endosperm and protein matrices due to the influence of enzymatic activity. As a result of the activation of previously inactive enzymes and the synthesis of new catalysts, the hydrolysis of biopolymers increases, accompanied by changes in the structure and chemical composition of the grain. These processes are clearly visible in microstructural images, demonstrating the destruction of protein–carbohydrate complexes and an increase in the availability of nutrients.

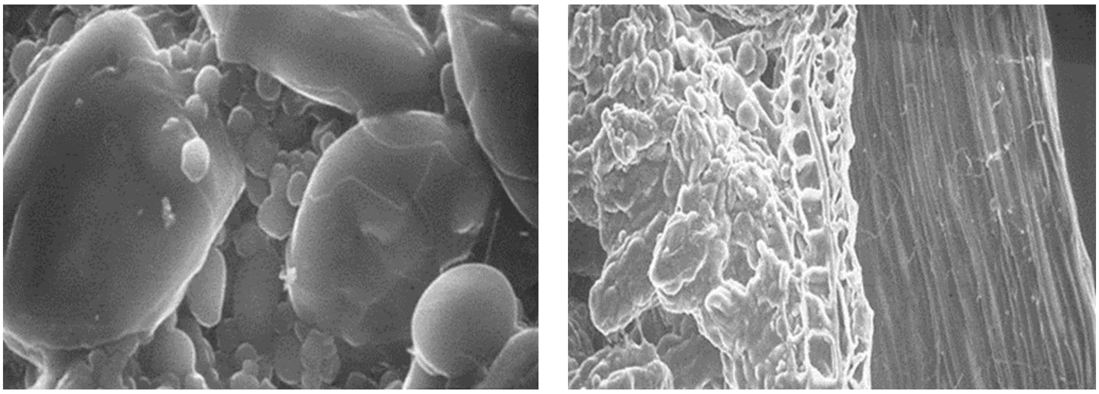

Figure 10. Microstructure of sprouted triticale grain

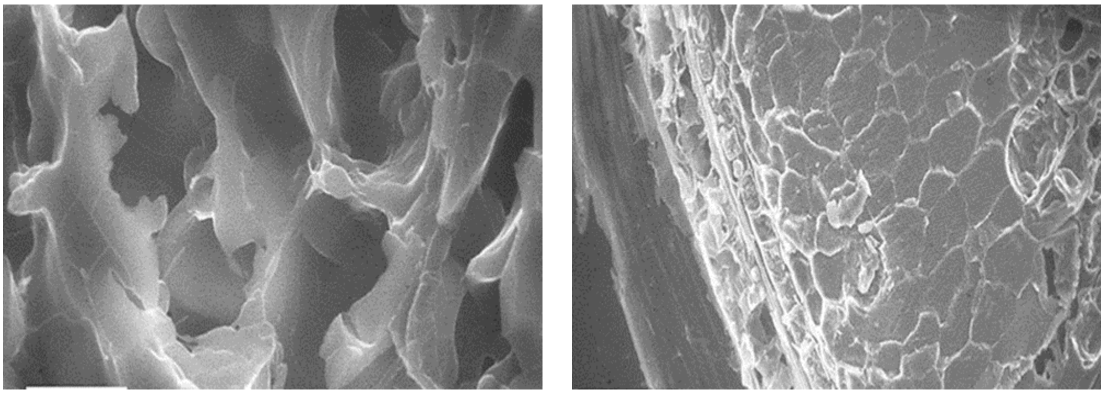

Figure 11. Microstructure of sprouted triticale grain dried using IR radiation

Structural and biochemical changes occur during the germination of triticale grains, affecting their protein matrices, starch granules and lipid components. Under the influence of activated enzyme systems, the hydrolysis of biopolymers, including proteins and starch, begins, which leads to their modification at the molecular level.

The protein matrices undergo partial denaturation, which reduces their structural density and increases the bioavailability of amino acids. This process improves the digestibility of the proteins and promotes the active breakdown of the starch, which, in turn, becomes more accessible to hydrolytic enzymes. As a result, the starch granules lose their original integrity, changing their degree of crystallinity and ability to swell, which ultimately affects the texture and physical properties of the flakes. In addition to the proteins and starch, these changes also affect the lipid complex. During germination, enzymatic modification of the fatty components occurs, which affects the taste characteristics, as well as the stability of the flakes during storage. These transformations comprehensively increase the biological value of the grain, ultimately improving the nutritional and functional properties of the final product.

Table 6 shows the quality indicators of triticale flakes obtained from sprouted grain. These parameters cover the proteins, fat and carbohydrate contents, as well as the physicochemical characteristics, which reflect the high nutritional value of the product. The germination process improves the nutritional composition of the grain, increasing its biological value and digestibility. As a result, flakes made from sprouted triticale have improved functional properties and are a promising product for a healthy diet.

Table 6. Qualitative characteristics of triticale flakes

Indicator	Characteristics and significance for flakes
Appearance	Oval and round flattened grains of various sizes with uneven edges
Colour, taste	Characteristic of a product made from the appropriate raw materials, from white to light yellow in colour, with various shades, having the taste of flakes with no bitter taste or any foreign flavour
Smell	Characteristic of this type of flake, with no musty, mouldy or other foreign odour
Humidity, %	6.2
Acidity, degree of acidity (°K)	6.0
Digestibility, min	3
Infestation, pest contamination of grain stocks	Not detected
Metallomagnetic impurities, mg per 1 kg	Not detected
Weed impurity, %	Not detected

The organoleptic evaluation of the sprouted triticale grain flakes presented in Table 6 was conducted in accordance with generally accepted methods, including the use of a point scale and the participation of a tasting committee. Several sensory parameters were evaluated. The taste was described as soft, slightly sweet, with a pronounced cereal profile. This reflects the enzymatic breakdown of starch during germination, which led to the accumulation of simple sugars that enhance the taste appeal of the product. The aroma was natural and bread-like, with no signs of rancidity, mould or chemical impurities, which indicates a good sanitary and hygienic condition of the raw materials and correct heat treatment. The colour was white to light yellow, which corresponds to the characteristics of minimally processed cereals and indicates gentle drying and flattening modes, during which no undesirable darkening reactions (e.g. melanoidin) occurred. The texture was evaluated after pouring boiling water on the flakes (simulating consumption as part of a quick breakfast). The flakes retained moderate elasticity, were not excessively boiled and did not form mucus, distinguishing these flakes from oatmeal and making them suitable for various culinary applications. The aftertaste was assessed as being neutral or slightly sweet, with no bitterness or sour notes, confirming the absence of oxidative or microbiological defects.

Overall, based on the total organoleptic assessment, sprouted triticale flakes scored 4.6 points out of a possible 5, which indicates the high consumer potential for this product. Despite the assessment being carried out under laboratory conditions with a limited sample, the data allow us to conclude that the flakes are highly sensorily acceptable and promising for use both in their pure form and as part of multi-component breakfasts, muesli and functional mixtures.

To further enhance the reliability and representativeness of the results, however, extensive consumer testing should be conducted on target populations, as well as a descriptive analysis involving a professional tasting panel and instrumental methods (e.g. texture analysis and an electronic nose) to quantify the sensory parameters.

The physicochemical characteristics of the product, such as its humidity (6.2%), acidity (6.0 °K) and digestibility (3 min) indicate it has balanced properties and ensure the convenience of its preparation. The sanitary and hygienic assessment showed the absence of pest infestation, weed and metallic/magnetic impurities, which confirms the effectiveness of cleaning and the strict control of the processing environment. Thus, triticale flakes have high nutritional value, are safe for consumption and meet the established requirements, which makes them a promising product for a healthy diet.

The next stage of production was to evaluate the appearance of the flakes, which is an important quality criterion. Figure 12 shows samples of flakes obtained from sprouted triticale grain, illustrating features of their structure and texture at various stages of processing.

Figure 12. Appearance of sprouted triticale flakes: (left) flakes after flattening, characterised by a pronounced lamellar structure; and (right) flakes after final processing, showing their uniform texture and shape

As shown in Figure 12, the flakes are characterised by oval and rounded shapes with uneven edges, which is due to the peculiarities of the processing. The particle size varies, giving the product a distinctive texture. The colour of the flakes ranges from white to light brown, which indicates minimal heat treatment and preservation of the biologically active components of the grain.

Based on our results, we developed a technological scheme for the production of triticale sprouted grain flakes, as shown in Figure 13.

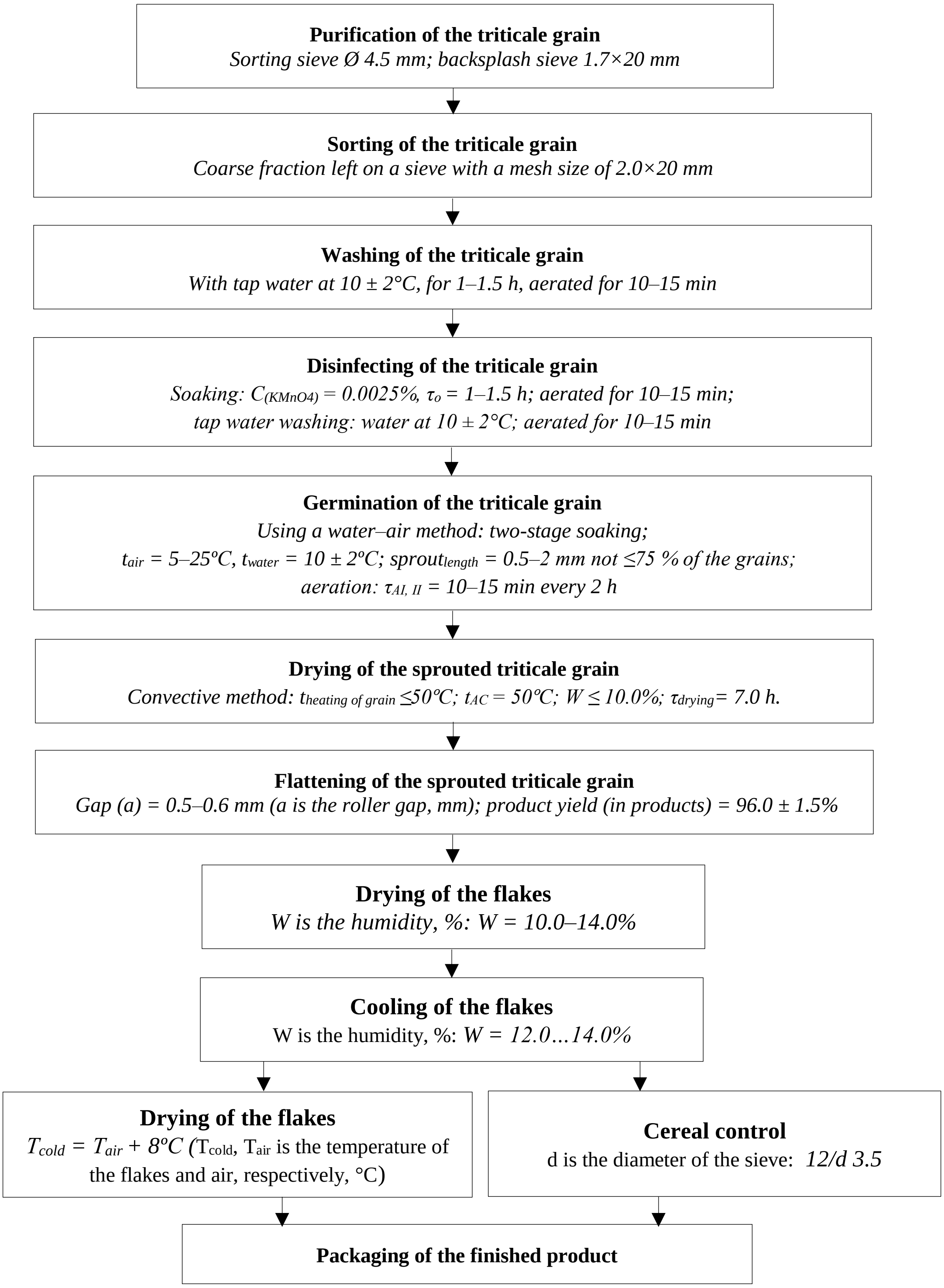

Figure 13. Scheme for the production of flakes from sprouted triticale grain

The value of the finished product is in its ability to meet the physiological needs of the consumer in terms of basic nutrients and energy to contribute to a balanced diet and maintain health. The chemical composition of food products plays an important role in the development and optimisation of production technologies aimed at creating healthy and safe nutrition. In this context, a detailed analysis of the chemical composition of the flakes was performed (Table 7).

Table 7. Chemical composition of the triticale flakes compared to oatmeal

Product	Protein, %	Fat, %	Sugar, %	Starch, %	Fibre, %
Sprouted triticale flakes	8.8	1.0	5.4	44.7	2.6
Oatmeal (control)	11.0	6.2	1.1	48.9	1.3

Table 7 shows a comparative analysis of the chemical composition of sprouted triticale flakes with oat flakes used as a control sample. The main indicators of nutritional value were determined. The triticale flakes contained 8.8% protein, which is slightly lower than the oat flakes (11.0%). However, the former still has a level of protein sufficient to maintain metabolic processes and body growth. The fat content in the triticale flakes was significantly lower (1.0%) than in the oatmeal (6.2%), which makes them more suitable for dietary purposes. The sugar content in the triticale flakes was 5.4%—much more than that in the oat flakes (1.1%). This is due to the enzymatic hydrolysis of complex carbohydrates during grain germination, which increases the proportion of simple sugars while also improving the taste of the product. The proportion of starch in the triticale flakes (44.7%) was slightly lower than in the oat flakes (48.9%) due to the peculiarities of the carbohydrate composition of triticale. At the same time, the fibre content in the triticale flakes (2.6%), which improves digestion and provides a beneficial effect on the intestinal microflora, exceeded that in the oatmeal (1.3%).

In addition to the data included in Table 7, it is necessary to consider the functional and biological significance of each component of the chemical composition and to examine what nutritional advantages and technological prospects certain deviations from the control sample (oat flakes) give to the sprouted triticale flakes. Despite the protein content in the triticale flakes (8.8%) being slightly lower than in the oat flakes (11.0%), it is important to consider not only the quantitative, but also the qualitative, composition of the proteins. During the triticale germination process, partial hydrolysis of the proteins occurs, forming peptides and free amino acids that increase the bioavailability of the proteins and facilitate their absorption by the body. Moreover, triticale proteins contain all the essential amino acids, including lysine, which is deficient in other cereals. This makes triticale flakes a valuable component of a balanced diet. The reduced fat content (six times less than in oat flakes) makes triticale flakes a particularly attractive product for people monitoring their calorie intake, as well as for nutrition in cases of cardiovascular disease and metabolic disorders. In addition, the smaller proportion of lipids helps to increase the product's resistance to oxidative spoilage, which improves its storage and technological stability.

The higher sugar content (5.4%) is the result of the natural enzymatic breakdown of starch during germination. This not only improves the taste and aroma of the flakes, but also helps to quickly replenish energy expended by the body, which makes the product especially valuable for athletes, children and people with increased mental or physical stress. Unlike added sugars in commercial products, natural sugars from sprouts do not have such a sharp effect on blood glucose levels. A slightly lower starch content (44.7% versus 48.9%) can be regarded as a positive factor, especially for people with carbohydrate metabolism disorders (e.g. prediabetes or insulin resistance), because some of the starch is converted into maltose and dextrins, which are more easily digested and stimulate enzymatic activity. The higher fibre content (twice as high as in oat flakes) significantly improves the functional properties of the product. It stimulates intestinal motility, promotes a long-lasting feeling of satiety, helps in the removal of toxins and lowers cholesterol levels. This feature makes triticale flakes an effective component of functional nutrition and preventive diets.

Thus, sprouted triticale flakes are not only a fully-fledged alternative to traditional cereal flakes, but also surpass them in a number of indicators, especially in terms of dietary focus and functionality. This makes them a promising component in the innovation of health food products.

4. Conclusion

The advantages of sprouted triticale flakes lie in their high digestibility, their increased sugar content, which improves its taste characteristics without the addition of sweeteners, their low fat content, making them suitable for dietary and sports nutrition, and their moderate fibre content, which makes them digestively well tolerated (compared to the coarse fibre of amaranth or quinoa), However, while sprouted triticale flakes are a balanced, technologically accessible and cost-effective product for mass functional nutrition [33, 34], convenient for use in the modern diet [35, 36], other grains have different, sometimes better, nutritional profiles. For instance, quinoa has a complete (all nine) amino acid profile, is gluten free, high in protein and mineral contents. However, it is costly and more difficult to process. Amaranth is high in protein and fibre and rich in lysine (an amino acid rare in cereals), but would be difficult to adapt to being processed into flakes. Green sprouted buckwheat is high digestibility, an excellent source of rutin (an antioxidant) and has a low glycemic index, and oats are rich in β-glucans, a valuable dietary fibre with proven cholesterol reduction, but are high in fat, which can limit its shelf life and product stability. However, triticale has the additional benefits of being easy to produce and being resistant to the climatic conditions of Kazakhstan.

The aim of this study was the development of a process for obtaining flakes from Kazakhstani sprouted triticale grain in order to expand the range of functional healthy food products. As part of the work, we examined the stages of biological activation of the grain, the parameters of its drying and flattening, as well as the chemical composition of the obtained product. To achieve this, we used the laboratory modelling of technological processes, mathematical processing of the experimental data, graphical analyses and comparative chemical analysis. From this, we established that the optimal time interval for germination is 18–26 hours, during which the sprout length reaches 0.5–2.0 mm, ensuring maximum enzymatic activity of the grain and its physical suitability. The parameters of preliminary drying before flattening were determined. The highest flake yield (up to 96%) was achieved by drying for 2 min, while the optimal grain moisture level was in the range of 19–37%. A relationship between the inter-roller gap and the flake yield was revealed, with the optimal result (up to 93%) being achieved with a gap of 0.5–0.6 mm. Based on analysis of a Pareto plot, it was proven that drying time had the most significant effect on the yield of the finished product, which allows us focusing control of the technological process on this parameter. It was found that when processing sprouted triticale grain, its chemical composition changes—protein content = 8.8%, fat = 1.0%, sugars = 5.4%, starch = 44.7%, fibre = 2.6%—reflecting an improvement in the digestibility and functionality of the product compared to the oat flake control. Due to the germination, there was an almost twofold increase in dietary fibre and an increase in the simple sugar content, which improved the taste characteristics and biological value of the flakes. Thus, we can confirm that sprouted triticale grain is a promising raw material for the creation of food flakes, with improved nutrient and functional properties, that the technological parameters (sprouting time, drying time, flattening) we determined ensure a high product yield (up to 96%) and stable quality, and that the developed technology can be adapted to industrial conditions, which opens up opportunities for producing a new type of healthy food product.

Further research could include a detailed study of the amino acid and vitamin compositions of the flakes, an evaluation of the organoleptic and sensory properties of the product in consumer tests, the development of an assortment of flaked products using natural additives (dried fruits, berries, spices), and integration of the technology into existing lines for the production of breakfast cereals. The findings from this study contribute to the development of scientific ways of processing sprouted grains and expand the possibilities of using domestic raw grain materials in the creation of functional products that meet the current requirements of nutrition and dietetics.

4.1. Limitations and Future Study

This study was aimed at developing the technology and assessing the quality characteristics of food flakes from Kazakh-bred triticale sprouts under laboratory conditions. The results have confirmed the potential of using sprouted grain as a basis for creating a functional product with high nutritional value and a balanced chemical composition. Considering that the germination process is accompanied by biochemical changes that affected the protein, antioxidant and other sensitive component contents, further research should look into optimising the processing stages (particularly, drying, flattening and packaging) in order to maximise preservation of the nutrients. We plan to examine options for gentler drying conditions, the use of antioxidant protection, and a modified gas environment during packaging, all of which will increase the stability and bioavailability of the nutrients. The issue of long-term product stability during storage also remains unresolved. We described the positive organoleptic and chemical characteristics of freshly prepared flakes, but for commercial implementation, it will be necessary to analyse their stability to determine their shelf life.

From a regulatory perspective, in order to introduce sprouted triticale flakes for major markets, it will be necessary to comply with national and international food safety standards, such as TR CU 021/2011 (for the Eurasian Economic Union countries), the Hazard Analysis Critical Control Point system and ISO 22000. Additionally, when planning to enter foreign markets, compliance with Codex Alimentarius standards will be required, as well as obtaining Halal, Kosher or Organic certifications, where necessary. Special attention should be paid to microbiological safety because sprouted grains are sensitive raw materials susceptible to microbial contamination. This requires strict adherence to sanitary and hygienic standards and the implementation of an effective critical point control system at all stages of production.

In the future, we also plan to conduct clinical and consumer studies to confirm the functional properties of the product and assess its effectiveness in the diets of various age and social groups. Not only will all this improve the technology, but it will also expand the possibilities of using sprouted triticale flakes as a component of functional and dietary nutrition.

5. Declarations

5.1. Author Contributions

Conceptualisation, A.K.; methodology, A.I.; software, T.K. and A.I.; validation, N.O.; formal analyses, N.O., A.O., and B.I.; investigation, A.O. and M.Y.; resources N.O. and A.O.; data curation N.O. and B.I.; writing—original draft preparation, N.O.; writing—review and editing, M.Y.; supervision, B.I. and A.I.; project administration, M.Y. and A.I.; funding acquisition, T.K. and A.I. All authors have read and agreed to 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 study was conducted within the framework of the scientific and technical programme of the Ministry of Agriculture of the Republic of Kazakhstan, No. BR22886613, 'Development of innovative technologies for the processing and storage of agricultural crop products and raw materials' (Project No. 9-2024/2026, 'Development of an innovative technology for the storage and processing of various varieties of triticale into highly efficient products of the grain processing industry').

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5.5. Institutional Review Board Statement

Not applicable.

5.6. Informed Consent Statement

Not applicable.

5.7. Declaration of Competing Interest

The authors declare that there are no conflicts of interest concerning the publication of this manuscript. Furthermore, all ethical considerations, 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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