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OPTIMIZING THE SEPARATION PROCESS OF DIFFICULT-TO-SEPARATE WHEAT AND BARLEY GRAIN MIXTURES USING VIBROFRICTION TECHNOLOGY

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Abstract: The study explores the feasibility of using a block-modular vibrofriction separator with non-perforated surfaces to efficiently separate challenging mixtures of wheat and barley grains. The research identifies key parameters influencing the separation process, including vibration amplitude, frequency, direction, and the inclination angles of the separating surfaces. Optimal settings-vibration amplitude of 0.9 mm, frequency of 95 Hz, vibration direction angle of 30°, and longitudinal inclination angle of 11°—were determined to achieve high separation efficiency.
The process enables the division of grain mixtures into fractions with varying wheat and barley content, suitable for different applications: seeds, bread flour, and polycomposite mixtures for bakery products. The proposed separation approach significantly enhances productivity and minimizes loss, offering practical recommendations for the food and grain processing industries.
Keywords: grain separation, wheat, barley, vibrofriction technology, food processing efficiency

1. INTRODUCTION

It is known that after harvesting and preliminary cleaning, the grain mixture contains a certain amount of damaged, defective, and small grains of the main crop, grains of other crops and weeds, as well as some organic and mineral impurities. The presence of these impurities, especially when moisture content is high, significantly deteriorates the quality

(Czajkowska et al., 2023) of the grain mixture and affects the quantitative and qualitative indicators during storage. Therefore, timely and high-quality cleaning of the grain mixture is one of the key factors ensuring high efficiency in the production of seeds and grain for industrial use in the processing and food industries (Derzhspozhyvstandart of Ukraine, 2003; Tyschenko et al., 2010, Bohomolov, 2013; Mykhailov, 2012; Nazarova and Shchennikova, 2011; Karaiev et al., 2021; Lezhenkin et al., 2021; Havrylenko et al., 2021). The primary goal of cleaning the grain mixture is to ensure the necessary quality for the use of grain in the production of groats and flour. In some cases, contamination with seeds of poisonous weeds can make the grain mixture unsuitable for industrial processing (Bohomolov, 2013; Mykhailov, 2012). Additionally, high-quality cleaning of the grain mixture improves storage conditions, reduces transportation costs, and minimizes pest infestation, creating more favorable conditions for drying. The economic relevance of utilizing difficult-to-separate grain mixtures of wheat and barley in the food industry cannot be overstated (Kotov et al., 2017; Uthayakumaran and Wrigley, 2010).

Agile management practices have been shown to improve operational efficiency in food processing enterprises, as demonstrated in Polish organic food production (Dziuba and Szczyrba, 2023). Additionally, implementing advanced risk management methods, such as the FMEA method integrated with the HACCP system, can significantly enhance the food industry’s ability to address potential hazards (Szczyrba and Ingaldi, 2024).

When evaluating raw material quality, such as dried herbs available on the European market, multidimensional approaches are critical for ensuring compliance with quality standards (Polańczyk et al., 2024). Safety considerations also remain central to agricultural systems, as studies on occupational hazards in agriculture underline the importance of effective prevention strategies (Pilarczyk and Ulewicz, 2023). Moreover, the use of computer simulations has proven effective in evaluating the efficiency of production line expansions, offering valuable insights for optimizing industrial processes (Poloczek and Oleksiak, 2024).

Given these considerations, improving the separation processes of difficult-to-separate mixtures like wheat and barley is an essential task. This study aims to substantiate the feasibility of using vibrofriction separators for efficient and loss-free separation, focusing on the physical and mechanical properties of the grains.

2. ANALYSIS OF LITERATURE SOURCES AND PROBLEM STATEMENT

It is known that the principles of separating grain mixtures are based on the differences in the physical and mechanical properties of the mixture particles (Bohomolov, 2013, Kotov et al., 2017, Shelest et al., 2017, Vereshchinsky and Vereshchinsky, 2018). The main physical and mechanical properties of grain include its length, width, thickness, shape, aerodynamic properties, elasticity, friction coefficient, roughness, specific weight, electrophysical properties, color, and moisture content. When choosing a method for separating the grain mixture, the primary consideration is the characteristics that ensure the most complete separation of the initial mixture into fractions with specified quality indicators (Mykhailov, 2012, Vereshchinsky and Vereshchinsky, 2018, Zhanfu and Tong, 2015, Bohomolov et al., 2019)

Cleaning impurities from seeds of cereals, legumes, and other agricultural plants has traditionally been carried out using grain cleaning machines with air-screen-trieur working bodies, which separate based on differences in the size and aerodynamic properties of seeds of cultivated plants, weeds, and impurities. Mixtures of weed seeds and impurities

that are similar in size and aerodynamic properties to the seeds of cultivated plants are considered difficult-to-separate.
Special machines are used to separate difficult-to-separate impurities, which divide grain mixtures based on other characteristics, such as frictional and elastic properties, shape, specific weight, color, or a combination of these characteristics. Such machines include pneumatic sorting tables, stone separators, and others (Shelest et al., 2017, Bredykhin et al., 2021, Bohomolov, 2004).
In wheat, difficult-to-separate weed impurities include smut balls, seeds of thick-fruited sophora, field bindweed, tartary buckwheat, darnel, hairy heliotrope, field madder, wild radish, and others. The use of new agricultural technologies and herbicides has practically eliminated weed seeds in newly harvested seeds. However, the reduction of crops in recent years to practically three in crop rotation—wheat, barley, sunflower, and sometimes corn—has led to an increase in the contamination of grain seeds with grain impurities, mainly affecting wheat and barley. Difficult-to-separate grain impurities in wheat include barley, and in barley, wheat (Bohomolov, 2013).
For separating such difficult-to-separate mixtures, it is advisable to use methods of separating bulk materials based on a combination of physical and mechanical properties, i.e., separating the bulk mixture based on several separation characteristics on a single working body, where separation is carried out based on differences in frictional, elastic properties, and particle shape simultaneously, which significantly improves the quality of separation. Therefore, many authors' research is aimed at solving this problem (Bohomolov et al., 2019, Bredykhin et al., 2021, Bredykhin et al., 2021, Bohomolov, 2004, Sawant, 2016, Bohomolov and Myradov, 2016).

3. PURPOSE AND OBJECTIVES OF THE RESEARCH

The purpose of this article is to investigate the efficiency of the separation process of a difficult-to-separate grain mixture consisting of wheat and barley using a block-modular separator with vibrating non-perforated surfaces. This includes determining the optimal structural and kinematic parameters of its operation and providing recommendations for the use of the obtained grain fractions after separation.
To achieve this goal, the following tasks have been identified:
1. Investigate the separation process of the wheat and barley mixture based on a combination of physical and mechanical properties on a vibrating non-perforated surface, establishing the parameters of the separation process.
2. Determine the optimal structural and kinematic parameters of the separation process of the wheat and barley mixture using a vibrofriction separator.
3. Conduct a quantitative and qualitative analysis of the separation products, studying the composition of the obtained fractions to determine the feasibility of their rational use.

4. JUSTIFICATION OF PARAMETERS FOR THE SEPARATION PROCESS OF WHEAT AND BARLEY GRAIN MIXTURE

4.1. INVESTIGATION OF SEPARATION PARAMETERS OF WHEAT AND BARLEY GRAIN MIXTURE

To determine the efficiency of separating a difficult-to-separate mixture of wheat and barley on a vibrating non-perforated surface, a device (Fig. 1) was used to measure the speed and direction of vibrational movement. This device was used to study the impact of vibration parameters and the angle of inclination of the vibrating surface on the speed of

seed vibrational movement, which, as is known, affects the separation process (Bohomolov, 2013, Bredykhin et al., 2021, Bredykhin et al., 2021, Sawant et al., 2016).
The device consists of a frictional non-perforated surface (6) mounted on a vibrating table (2) with adjustable longitudinal inclination angle (α), a vibration exciter (3) with adjustable vibration direction angle (ε), compression springs (4), upper (1) and lower (5) seed receivers, a feeding device (7), and a shutter (8).

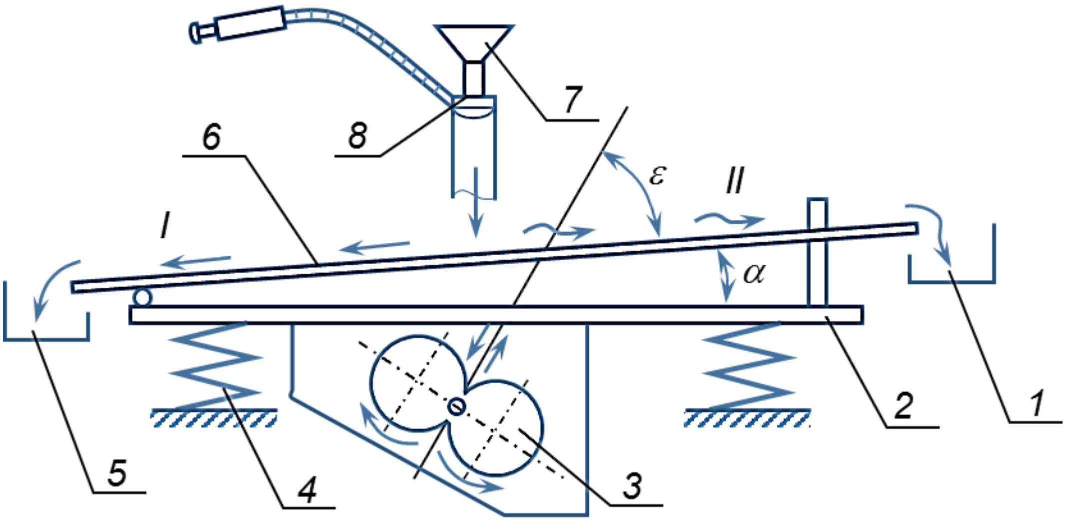

Fig. 1. Schematic diagram of the device for determining the speed and direction of vibrational movement: 1, 5 - Seed receivers; 2 - Vibrating table; 3 - Vibration exciter; 4 - Compression springs; 6 - Frictional non-perforated surface; 7 - Grain mixture feeding device; 8 – Shutter

The research was conducted in the following sequence. Seeds were placed in the feeding device (7), located in the middle part of the frictional non-perforated surface (6). After activating the directional vibration exciter (3), the grain was released onto the vibrating surface using the shutter (8). Depending on the physical and mechanical properties, the angle of inclination of the vibrating surface (α), the amplitude of vibrations (A), the frequency of vibrations of the vibrating surface (ω), and the angle of vibration direction (ε), the grain moved to the upper or lower receiver. The time the grain spent on the vibrating surface was recorded, and the speed of vibrational movement was calculated as the ratio of half the length of the separating surface to the time it took for the grain to reach the receiver.
The dependence of the vibrational movement speed of barley and wheat grains on vibration parameters was studied by varying the amplitude of vibrations of the vibrating surface (Fig. 2a) and the frequency of vibrations of the vibrating surface (Fig. 2b), as well as by varying the longitudinal angle of vibration direction (Fig. 3a) and the angle of inclination of the vibrating surface (Fig. 3b).
It was found (Fig. 2) that with an increase in the amplitude of vibrations (A) and the frequency of vibrations (ω), the speed of vibrational movement (V) of barley and wheat grains increases. Moreover, with an increase in (ω), the intensity of the increase in vibrational movement speed also increases. The vibrational movement speed of barley grains is slightly higher than that of wheat grains.

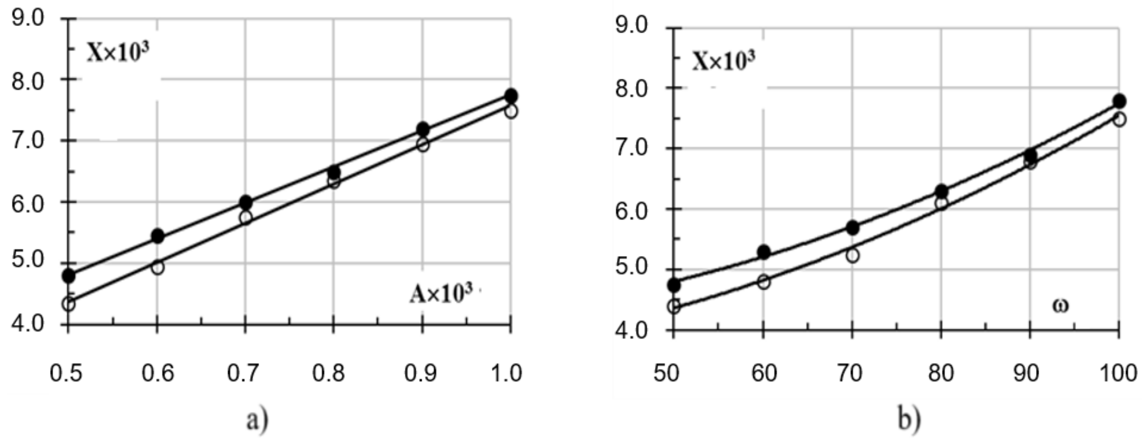

Fig. 2. Dependence of the vibrational movement speed of barley grain (1) and wheat grain (2) on vibration parameters: vibration amplitude (a) and vibration frequency (b) of the vibrating surface

It should be noted that the difference in the vibrational movement speeds of barley and wheat grains decreases with increasing amplitude (A) and frequency (ω). The convergence of the movement speeds of barley and wheat grains with increasing values of A and ω (Fig. 2a, b) can likely be explained by the specific shape of barley. In cross-section, the shape of barley can be approximated as an elongated oval. Under real conditions, it can be observed that during vibration, the oval rocks, and with increasing A and ω, this rocking increases, thus reducing the speed of barley in overcoming the inclination angle. This reduction may also be due to the greater micro-roughness of barley particles. The movement of barley particles at high A and ω resembles movement with tilting, sometimes even rotating in a plane perpendicular to the vibrating surface. It has been established that when the vibration frequency of the vibrating surface reaches $\omega = 95\ s^{-1}$ and the vibration amplitude for barley is A = 1 mm, and for wheat A = 0.9 mm, the particles detach from the vibrating plane, and in this case, the quality of separation, as is known, deteriorates [3]. Therefore, for the mixture, we accept A = 0.9 mm.

With an increase in the vibration direction angle within ε = 25…35°, the vibrational movement speeds of wheat and barley grains (Fig. 3) initially increase to values within $6.0…6.5×10^{-3}$ m/s, and then, with an increase in ε to 50°, decrease to values within $4.5…5.0×10^{-3}$ m/s and converge, which is explained by the reduction in the vibrational movement speed of barley due to the rocking of the oval. We accepted an angle of ε = 30° because, at this angle, the grain speed is the highest, and therefore the separation productivity is higher.

Changing the angle of inclination (α) of the vibrating non-perforated surface not only changes the magnitude of the vibrational movement speed but also changes the direction of movement of barley and wheat at different values of α, thus enabling their separation on the vibrating surface. It has been established that with an increase in the angle α, the vibrational movement speeds of wheat and barley decrease, with the intensity of speed reduction being higher. At smaller values of α, they change the direction of movement, in other words, they roll down. The reduction in speeds when moving down is explained by the fact that barley and wheat grains, due to vibrational movement, orient their longitudinal axis along the direction of movement of the separating surfaces. For wheat, this reduction is more pronounced due to its cross-sectional shape, which is closer to cylindrical.

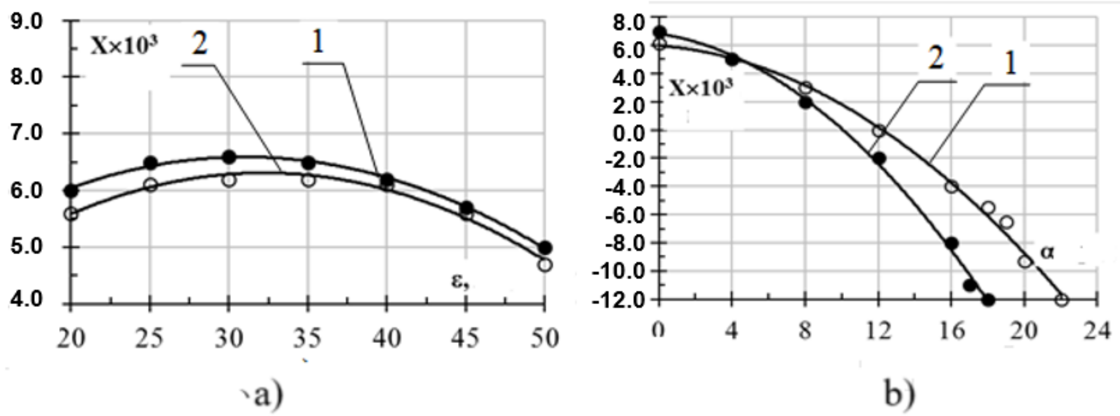

Fig. 3. Dependence of the vibrational movement speed of barley grain (1) and wheat grain (2) on vibration parameters: longitudinal angle of vibration direction (a) and angle of inclination of the vibrating surface (b)

From Fig. 3, it can be seen that when changing the longitudinal angle in the range of α = 10…12°, wheat and barley grains can move in different directions on the vibrating surface. At α = 10°, wheat grain stops on the vibrating surface (V = 0 m/s), while barley grain moves upward at a speed of V = 1.8×10^{-3} m/s. At α = 12°, barley grain stops on the vibrating surface (V = 0 m/s), while wheat grain rolls downward at a speed of V = -2×10^{-3} m/s. Therefore, an angle of α = 11° was chosen.

Considering that the components of difficult-to-separate mixtures have zero speed at certain longitudinal angles, it was decided to introduce another parameter—the transverse angle of inclination of the vibrating surface, β = 2° (Fig. 4), which ensures that grains with zero speed in the direction of vibration roll in the transverse direction (Bohomolov, 2013). To study the separation process of wheat and barley grains, a block-modular vibrofriction separator was developed (Fig. 4), with certain structural changes made to adjust the transverse inclination angle of the vibrating surface.

4.2. INVESTIGATION OF THE CAPABILITIES OF THE VIBROFRICTION SEPARATOR DESIGN FOR THE SEPARATION PROCESS OF WHEAT AND BARLEY MIXTURE

Since the specific productivity of a single vibrofriction separating surface is low, to increase the productivity of the vibrofriction separator, the separating surfaces were installed one above the other in a block module. The more separating surfaces installed in one block, the higher the productivity of the separator. Therefore, the structural scheme of the block-modular vibrofriction separator used for the research was assembled from four block modules, each with six separating surfaces with longitudinal-transverse inclination adjustment.

The research was conducted as follows. The grain mixture was fed using feeders (14) onto the working surfaces of the upper (1) and lower (2) block modules. Under the influence of directed vibrations created by the vibration exciters (4), the components of the mixture moved along different trajectories depending on their physical and mechanical properties. It was found that flat, rough, less elastic barley particles moved to the upper receivers of the separation products, while round, smooth, more elastic wheat particles rolled into the lower receivers (18). Intermediate fraction particles, which have vibrational movement speeds close to zero, moved into the side receivers (17). The separation process of the difficult-to-separate grain mixture was controlled by changing the values of the longitudinal inclination angle (α), the vibration exciter's direction angle (ε) (Fig. 1), the transverse inclination angle of the vibrating surface (Fig. 4), the amplitude (A), and the frequency of vibrations of the vibrating surface (ω) (Fig. 2).

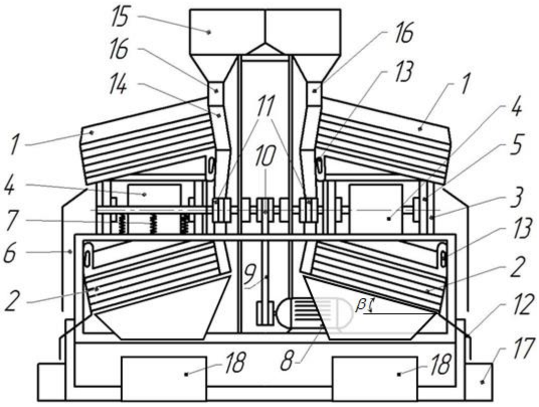

Fig. 4. Diagram of the block-modular vibrofriction separator: 1, 2 – Upper and lower blocks of separating surfaces; 3 – Vibrating table; 4 – Vibration exciter; 5 – Hinged suspension; 6 – Table; 7 – Springs; 8 – Electric motor; 9 – V-belt drive; 10 – Intermediate drive; 11 – Elastic couplings; 12, 13 – Mechanisms for adjusting the longitudinal and transverse inclination angles; 14 – Feeders; 15 – Hopper; 16 – Pipes; 17 – Side receivers; 18 – Lower receivers

5. RESULTS OF WHEAT AND BARLEY GRAIN SEPARATION AND THEIR ANALYSIS

When cleaning grain with a vibrofriction separator, the grain mixture is divided into fractions with different contents of wheat and barley, allowing the obtained fractions to be used differently, such as for seeds or the production of flour mixtures. In recent years, the use of flour from grain mixtures (Antonenko, 2015, Mansoor, 2022) in the production of flour confectionery products has been practiced. Therefore, we proposed combining the fractions into several streams depending on their use. The presence of barley grain impurities in wheat grain, if the flour is intended for flour confectionery products, can be not only appropriate but also desirable. The barley impurity in wheat grain usually ranges from 2% to 12%, and in flour mixtures for baking purposes, the barley component content can vary from 10% to 90% depending on the purpose. Therefore, the goal of separation can be not only to separate barley grain but also to divide the grain mass into fractions with different barley content. For the study, wheat grain of the second reproduction of the 2021 harvest, Smaglyavka variety, grown in the Kalyna farm of the Vovchansk district of the Kharkiv region with a barley grain impurity content of 9.8%, was used.

Experimental data on the results of separation and the content of fractions are presented in Table 1.

From the analysis of Table 1, it is evident that the obtained grain fractions can be combined into several streams depending on their subsequent use.

First Stream: Combining fractions 1 and 2 results in cleaned wheat grain, which constitutes 58% of the grain mass (with barley impurity not exceeding 2%). The germination and germination energy of wheat seeds in these fractions increase by 8% and 7%, respectively, compared to the initial mixture. Therefore, the grain from this stream is suitable for use as seed or for processing into bread wheat flour.

Second Stream: Fractions 3 and 4 can be combined, with a total yield of 30% (average barley content around 15%). The flour mixture obtained from milling this grain mass can be used in special types of bakery products.

Table 1
Quantitative and Qualitative Composition of Separation Products

Fraction Number	Fraction Yield (% of total mass)	Fraction Composition (%)		Wheat Grain	
		Barley Grain	Wheat Grain	Similarity of seeds	Germination Energy
1	30	1	99	96	93
2	28	3	97	96	93
3	18	10	90	93	90
4	12	25	75	88	84
5	7	42	58	82	78
6	3	70	30	76	72
7	2	92	8	62	58
Initial Mixture	-	9.8	90.2	88	86

Third Stream: Combining fractions 5 to 7 results in a total yield of 12% of the total grain mass fed into the separation process (average barley content of 68%). The milling product obtained from this stream is a mixture of barley and wheat flour in a 2:1 ratio. This mixture is recommended for use in the production of baked semi-finished products from shortcrust and biscuit dough, where the high quality is ensured by weak gluten or its low content in the flour.

The proposed recommendations for using the separated fractions in a single pass of the difficult-to-separate wheat and barley grain mixture through the vibrofriction separator will allow for the most appropriate, efficient (Muneer et al., 2023) and loss-free use of the separator.

6. DISCUSSION OF THE RESEARCH RESULTS ON THE SEPARATION PROCESS OF WHEAT AND BARLEY GRAIN MIXTURE

The influence of vibration parameters, namely amplitude, frequency, and vibration direction angle of the vibrating non-perforated surface, as well as its inclination angle, on the efficiency of the separation process of the difficult-to-separate wheat and barley grain mixture has been established (Bredykhin et al., 2021, Bredykhin et al., 2021, Bohomolov, 2004, Bohomolov and Myradov, 2016, Bredykhin et al., 2024).

The research was conducted using a specially designed device that allowed for the adjustment of these parameters to determine the range of structural and kinematic parameters for the vibrational separation of the mixture.

It was found that, for the effective operation of the vibrofriction separator, the best results in separating the difficult-to-separate wheat and barley grain mixture can be achieved with higher values of amplitude and frequency of vibrations of the non-perforated surfaces and a vibration direction angle in the range of 30…35°.

The best separation quality was achieved with an inclination angle of the vibrating non-perforated surfaces in the range of 10…12°, because at these angles, wheat and barley grains move in different directions, thereby improving the quality of separation of the difficult-to-separate wheat and barley mixture (Bohomolov, 2013). The structural and kinematic parameters for the separation process on the developed block-modular vibrating separator for dividing the wheat and barley grain mixture into fractions were set as follows: vibration amplitude A = 0.9 mm, vibration frequency of the separating surfaces

ω = 95 s^{-1}, vibration direction angle ε = 30°, longitudinal inclination angle α = 11°, and transverse inclination angle of the separating surfaces β = 2°.
The quantitative and qualitative analysis of the composition of the separation products of the obtained fractions allows for the conclusion that they can be combined into separate streams and used for different purposes. The grain from the first and second fractions, whose germination and germination energy increase compared to the initial mixture, is recommended for use as seed or for the production of polycomposite flour mixtures, as proven in (Ahmed et al., 2021, Antonenko, 2015, Mansoor et al., 2022, Bredykhin et al., 2024). The content of the third and fourth fractions is suitable for the production of flour mixtures for baking special types of bakery products (Ahmed et al., 2021, Antonenko, 2015, Mansoor et al., 2022, Bredykhin et al., 2024). The combined content of the other fractions is recommended for the production of flour mixtures for baking semi-finished products from shortcrust and biscuit dough (Ahmed et al., 2021, Antonenko, 2015, Mansoor et al., 2022, Bredykhin et al., 2024).

7. CONCLUSIONS

It has been proven that for the separation of difficult-to-separate grain mixtures of wheat and barley based on their physical and mechanical properties, the use of a block-modular separator with vibrating non-perforated surfaces, which allows for efficient and loss-free separation of these mixtures into fractions, is appropriate. It has been established that the separation of the mixture in such a separator is achieved due to the difference in the directions and magnitudes of the vibrational movement speeds of wheat and barley grains along the working separating surfaces of the separator.
For the effective separation of the difficult-to-separate wheat and barley grain mixture, the optimal values of vibration parameters and inclination angles of the separating surfaces are as follows: vibration amplitude A = 0.9 mm, vibration frequency ω = 95 s^{-1}, vibration direction angle ε = 30°, longitudinal inclination angle of the separating surfaces α= 11°, and transverse inclination angle of the separating surfaces β=2°.
The obtained fractions after separation are proposed to be combined into several streams, depending on the quantitative composition of wheat and barley grains. The cleaned wheat grain from the first stream, which may contain no more than 2% barley impurity, is recommended for use as seed or for the production of bread wheat flour. The second stream, a mixture of wheat and barley grains with about 15% barley content, is recommended for use in polycomposite flour mixtures for the production of special types of bakery products. The third stream, with a barley grain content of 68% in a mixture with wheat, will yield a milling product in a 2:1 ratio of barley to wheat flour, which is recommended for use in the production of baked semi-finished products from shortcrust and biscuit dough and other food products.

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