



PRODUCTION ENGINEERING ARCHIVES

ISSN 2353-5156 (print)
ISSN 2353-7779 (online)

Exist since 4th quarter 2013
Available online at <https://pea-journal.eu>

Study of the operating process of a salt premix component mixer with a combined working unit and the influence of mixing degree on product quality

Bekbolat Moldakhanov^{1,2} , Yelibek Asangaliev² , Alina Kim^{3*} , Mikhail Doudkin^{1,2} ,
Bekzat Aukenova² , Ivan Yakovlev¹ , Dmitry Vasilkov¹ , Zhanna Starostina¹ 

¹ LLP Europlus Vostok, 26/4 Shosseyny Lane, Ust-Kamenogorsk, Republic of Kazakhstan; bekmoldahanov35@gmail.com (BM); mdudkin@ektu.kz (MD); ivanvladjak@gmail.com (IY); dima.1206.vasan@gmail.com (DV); janstarostina@gmail.com (ZS)

² D. Serikbayev East Kazakhstan Technical University, 19 Serikbayeva Street, Ust-Kamenogorsk, Republic of Kazakhstan; EAsangaliev@ektu.kz (YA); 7051760046b@gmail.com (BA)

³ Miras University, 3 Gani Ilyaeva Street, Shymkent, Republic of Kazakhstan; alinakim3107@gmail.com

*Correspondence: alinakim3107@gmail.com

Article history

Received 02.07.2024

Accepted 01.12.2025

Available online 16.03.2026

Keywords

mixer,
mixture homogeneity,
pressing,
hardness,
premix-licks.

Abstract

This article examines the effect of the mixing degree of feed mixture components on its homogeneity, mixing quality, and the uniform distribution of microcomponents and vitamins within the volume of the mixture. Additionally, the study evaluates the suitability of the mixture for the molding and pressing processes involved in the production of salt lick bricks (SLB). The research is conducted using a novel energy-efficient combined mixer. The study presents an analysis of the impact of mixing intensity on the quality of SLB under prolonged storage in various environmental conditions. The kinetics of the mixing process for salt premix components is investigated. A mechanical-mathematical model describing the mixing behavior of components in a combined mixer is developed. Based on experimental data, correlations are established between the physical characteristics of the final salt lick premixes – including shape, composition, and hardness – and the homogeneity of the initial mixture. Furthermore, the study assesses the stability of SLB premixes under adverse environmental conditions, including exposure to humidity and temperature fluctuations. A methodology for determining the optimal rotor rotation frequency in the combined mixer is developed, and its influence on mixture homogeneity is quantified.

The findings of experimental studies on a prototype combined mixer confirm the theoretical predictions. The results substantiate the efficiency and feasibility of thorough and intensive mixing of components in SLB production, which contributes to a reduction in material consumption for manufacturing equipment and a decrease in overall energy costs.

DOI: 10.30657/pea.2026.32.1

1. Introduction

The quality and homogeneity of any mixture depend on the degree of mixing and the design of the mixing machines. Food and animal feed products are no exception, as the mixing of ingredients, for instance, before pressing a loose salt mixture and turning it into a premix lick, significantly influences the structure and preservation of the salt lick brick (SLB). It should be noted that the fractional and phase composition of the SLB ingredients before mixing in the mixer varies significantly for certain components, making their uniform distribu-

tion throughout the SLB volume a rather complex task. In addition to the already used mixture components, it is necessary to ensure the uniform distribution of dried and ground fragments of Siberian fir needles, which contain a high concentration of vitamins and are practically cost-free for SLB production.

Agricultural mechanization is constantly evolving, and new mixer designs frequently enter the market, according to many websites.

High mixing quality is ensured by horizontal shaft mixers from the American company "Hayes & Stolz," which quickly



© 2026 Author(s). This is an open access article licensed under the Creative Commons Attribution (CC BY) License (<https://creativecommons.org/licenses/by/4.0/>).

and thoroughly mix the components throughout the mixing chamber while maintaining high productivity. Mixers also consume relatively little energy, remaining high-performance yet economical machines. These requirements - low energy consumption and short mixing time - were part of the initial design concept of these mixers. The requirements are interdependent, and reducing mixing time decreases energy consumption for each volume of the mixture (Hayes & Stolz, 2025).

The ready mixture is unloaded through a throw-away bottom or side doors as per the customer request (Apalihina, 2016; Apalihina, 2017).

The design and operation of the plowshare mixer, produced by the German company "Lödige," are also noteworthy (Lödige, 2025).

Mixers produced by the Swiss company "Bühler" operate on a similar principle, with the difference that "Bühler" mixers operate cyclically and are unloaded by forced pneumatic flow, ensuring the required homogeneity of the mixed components (Buehler, 2025).

In the English "Simon-Barron" horizontal shaft mixer, ingredients of feed briquette licks are mixed, loaded into the hopper after preliminary batch weighing (120L Simon Barron Conditioning Mixer, 2025).

The component mixing is complex, performed by the simultaneous rotation of the external spiral mixer and the screw located inside it. Components of the mixture adhered to the walls of the mixing chamber are scraped off by rotating special blades. The combined action of the spiral, screw, and blades during their rotation generates counter-flows of material components, quickly and effectively mixing them with sufficient homogeneity.

The mixer-extruder installation, patented in the Russian Federation No. 2347606 and No. 117698, has proven effective, where the mixed material streams move towards each other, allowing more complete mixing. However, such mixing required a bulky design with three sequential mixing chambers, each with different mixing devices, resulting in the final product as an extrudate. It is clear that salt mixtures cannot be mixed in such a mixer due to the final product form (Shevtsov et al., 2009; Apalihina, 2017).

The mixer body is made with three chambers, featuring loading nozzles and pipes through which the loose ingredients of the future mixture are loaded.

The sequential mixing of the mixture components by cone-shaped blades during their rotation is performed in all chambers, with additional mixing by swirling air flows generated on the outer edges of the blades. The design is highly productive but complex to manufacture, bulky, and overburdened with its own parts.

Drum horizontal mixers manufactured by the German company Amandus Kahl, featuring a three-minute vortex mixing process that ensures uniform distribution of mixture components, operate exclusively with homogeneous materials. However, when combining dry components, liquids, and salt within the mixture, achieving uniform ingredient distribution is not feasible (Dąbrowska et al., 2022; Bostanov et al., 2019).

An analysis of the presented data highlights the necessity for developing advanced technologies for the production of salt lick bricks (SLB) and efficient mixers capable of intensifying all stages of the production process while ensuring the rational use of energy potential and maintaining high quality and homogeneity of the final mixture. High-quality salt lick bricks should combine resistance to adverse weather conditions with sufficient plasticity (Asangaliev et al., 2021; Vavilov et al., 2020).

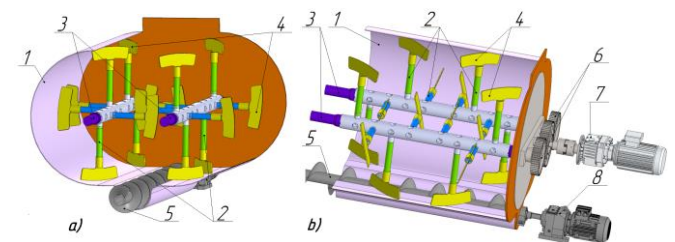
The primary objective of this study is to develop the design and scientifically substantiate the operational parameters of an energy-efficient component mixer and the production method for salt lick bricks, ensuring the uniform distribution of all mixture ingredients within the final product.

2. Development of a mixer with a combined working unit

Various mixers produced by well-known manufacturers are widely used in industry. Based on the analysis of experimental and theoretical data, this study proposes an original mixer design and investigates the operational process of a novel mixer equipped with a unique combined working unit for mixing various components, including highly viscous ones.

The process of mixing bulk materials is a complex mechanical phenomenon whose operational mechanism primarily depends on the mixer design. This process consists of the following fundamental mixing mechanisms: a) convective mixing – in which groups of adjacent particles are displaced from one location in the mixture to another through embedding, indentation, or layer sliding; b) diffusive mixing – where particles of different components gradually redistribute throughout the mixture via the newly formed interface boundary; c) segregation – where gravitational or inertial forces cause the concentration of mixture components with identical mass in specific zones of the mixer.

Figure 1 presents the structural schematic of the mixer, featuring two mixing shafts and a screw conveyor for discharging the final mixture.



1 – housing; 2 – radial rods; 3 – shafts; 4 – stirrer blades; 5 – screw conveyor for discharging the final mixture; 6 – stirrer shaft rotation mechanism; 7 – gear motor for the stirrer shaft drive; 8 – gear motor for the screw conveyor drive

Fig. 1. Design Diagram of the Mixer: a) left-side view of the design; b) main view of the design

In the oval-shaped housing (1), two mixing shafts (3) are located in its central part. Gears are installed at each end of the

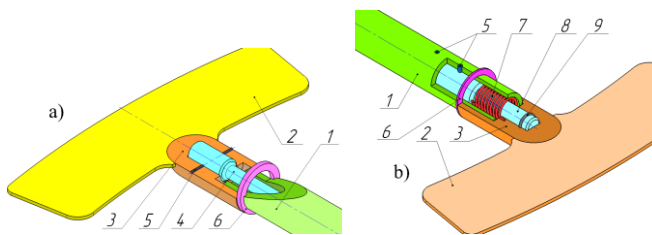
shaft, which engage with a gear fixed on the shaft of the motor-reducer (7). With such a drive 6, the rotation from the motor-reducer is transmitted so that the mixing shafts 3 rotate in opposite directions relative to each other at the same speed.

Along the entire length of shaft (3), there are special holes for installing radial rods (2), at the ends of which mixer blades (4) are mounted on elastic elements. Variants of mounting mixer blades (4) on the elastic elements of rods (2) are shown in Figure 4.

In Figure 2a, as an elastic element, the installation of the mixer blade (2) on a torsion bar (4) is shown, and in Figure 2b, the installation of the mixer blade (2) using a spring (7) is shown. The elastic elements allow the mixer blade (2) to be set at the optimal angle of entry into the mixed feed mixture by pre-twisting. The position of the mixer blades after installation is fixed.

The elastically movable stirrer blades prevent the formation of stagnant zones and, through convective and diffusive mixing, ensure uniform distribution of the components within the mixture, reducing ingredient segregation and enhancing mixture homogeneity.

For unloading the finished mixture, a screw (5) is installed in the lower part of housing (1) (see Figure 1), driven by the motor-reducer for driving the screw 8.



1 – radial rod; 2 – blade; 3 – bushing; 4 – torsion shaft;
5 – pin; 6 – seal; 7 – spring; 8 – finger; 9 – retaining ring

Fig. 2. Schematic diagram of the stirrer attachment mechanism in the mixer: a) Stirrer blade with a torsion shaft; b) Stirrer blade with a spring

The mixer operates as follows. Before starting, rods 2 with blades 4 are installed into the holes of shafts 3 so that the rods with the blades mounted on them do not touch each other with their working surfaces during shaft rotation. Then, by rotating around the rods 2, the final position of the blades 4 is adjusted, and the blade is fixed in this position.

This twin-shaft blade mixer implements the mixing process using mechanical fluidization of the blended components. The initial ingredients are loaded from the top into the housing (1), while the shafts (3) are already rotating, the stirrers are pre-set, and the screw conveyor (5) remains stationary or rotates in the opposite direction to discharge. Due to the counter-rotating movement of the stirrers, the feed mixture ingredients mix in the center of the housing, partially dispersing sideways, then falling downward, where they are picked up by the stirrer blades. This process of feeding and mixing ingredients repeats cyclically. Once the required homogeneity of the feed mixture

is achieved, the screw conveyor (5) begins to rotate in the opposite direction, gradually discharging the prepared feed mixture from the mixer.

The qualitative composition of SLB is verified by analyzing the content of essential ingredients in randomly selected briquettes from the produced batch. This analysis assesses both the presence of all components and their quantitative deviations from the original formulation. The same verification procedure is used to evaluate the efficiency and uniformity of component mixing in the mixer.

The allowable deviation in the content of SLB components must not exceed 4.5% of the formulation value; otherwise, the entire batch is deemed non-compliant with the recipe, and the mixer is considered ineffective.

A selective check of the uniform distribution of components in the SLB batch is conducted using a standard procedure, which includes spot sampling, combining samples into a composite sample, and deriving the actual test sample by mixing, reducing, and dividing the composite sample (Lytkina et al., 2016).

Potential variations in non-uniform mixing and component distribution may arise from random errors in quantitative chemical analysis methodologies for active ingredients within the blended mixture, as well as random errors in mass assessments of active substances during dosing into the mixer.

A theoretical assessment of the permissible deviation limits for uniform distribution and component content in the SLB batch, relative to the formulation data, can be conducted using established methods of mathematical statistics and probability theory (Kafarov et al., 2023).

3. Study of the kinetics of the mixing process of premix licks components

It is necessary to determine the influence of the rotation frequency of the combined mixer shafts on the homogeneity of the mixture. One of the important factors affecting the intensity of the mixing process is the speed of the mixer blades. The magnitude of this speed determines the intensity of particle movement, the nature of their motion, which ultimately affects the time required for the uniform distribution of components throughout the volume of the mixture (Doudkin et al., 2019a; Doudkin et al., 2019b; Doudkin et al., 2019c; Doudkin et al., 2019d).

To select the most rational mixing mode, experiments were conducted to study the effect of mixing duration on the mixing process at different rotation frequencies of the mixer blades. The main component (filler) used was crushed salt, and the indicator component was a metallic-magnetic impurity. The loading order into the mixer was first the main component, then the indicator component (Doudkin et al., 2019a; Doudkin et al., 2019b; Doudkin et al., 2019c; Doudkin et al., 2019d; Aduov et al., 2020; Doudkin et al., 2020; Doudkin et al., 2021a; Doudkin et al., 2021b; Doudkin et al., 2021c).

The change in mixture non-uniformity over time at different rotation frequencies of the mixer working bodies is shown in Fig. 3a. The analysis of the obtained dependencies shows that

the kinetics of the process is uneven: at all investigated frequencies, the mixing process initially proceeds quickly, then slows down, and finally, upon reaching equilibrium, the operation of the mixer does not affect the distribution of control components (Bostanov et al., 2019; Issabek et al., 2021; Kombayev et al., 2019; Kombayev et al., 2022; Doudkin et al., 2021b; Sakimov et al., 2018; Doudkin et al., 2020; Saveliev et al., 2019; Doudkin et al., 2022).

As a result of the conducted experiments, a dependency was identified: with an increase in the rotation frequency and consequently, the circumferential velocity of the mixer stirrers within the range of 12 to 13 s⁻¹, the mixing time required to reach the equilibrium state of the mixture, where the processes of mixing and segregation balance each other, is reduced. This phenomenon can be explained by the increased number of interactions between the mixer's working elements (stirrers) and the mixed components per unit of time, leading to more intense movement of the product particles relative to each other and the mixer housing (Temirbekov et al., 2019; Giel et al., 2021a; Giel et al., 2021b; Giel et al., 2022; Giel et al., 2023; Doudkin et al., 2021a; Doudkin et al., 2021b).

It should be noted that the change in the circumferential speed of the mixer blades was carried out taking into account not to disrupt the state of mechanical fluidization of the mixed bulk components (Giel et al., 2022).

Influence of component ratio on mixture quality. All known studies emphasize the significance of this factor in the distribution of components within a mixture; however, the reported effects vary across different research works. Compound feeds and premixes consist of components present in varying proportions. To determine the influence of component ratio on mixing homogeneity, experiments were conducted using different concentrations of the control component (sodium chloride): 0.1%, 0.2%, 0.3%, 0.4%, 0.6%, 0.8%, and 1.0%. The results are presented in Figure 3c. Parameters such as particle size, moisture content, and loading sequence were kept constant (Doudkin et al., 2021c).

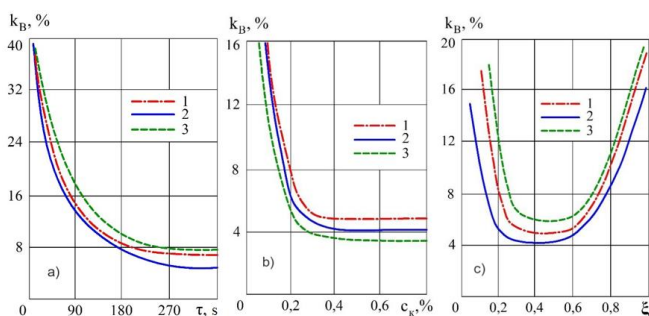


Fig. 3. Dependence of the Variation Coefficient on: (a) Mixing time at different circumferential velocity values; (b) Degree of mixer chamber filling; (c) Concentration of the key component: 1 – metallic-magnetic impurities; 2 – table salt (NaCl); 3 – manganese sulfate (MnSO₄).

The obtained dependency indicates that component concentration affects mixture quality up to a certain threshold. Specifically, when the component concentration in the mixture exceeds 0.1%, the mixtures exhibit greater homogeneity.

However, to achieve a uniform distribution of a component with a concentration below 0.1–0.2%, a two- or three-stage mixing process is required (Asangaliev et al., 2021; Aukenova et al., 2021; Kombayev et al., 2022).

4. Influence of moisture content on mixture quality

The natural sources of moisture in salt lick bricks (SLB) include air, raw materials used as fillers, and technological exposure to steam, water, and the surrounding environment. Moisture significantly affects not only the operation of the mixer and the mixing process but also the physicochemical properties of SLB. A particularly critical issue for water-soluble salts of microelements present in the mixture is hygroscopicity, as moisture absorption leads to a loss of flowability. Additionally, other technological properties deteriorate.

It is well known that as moisture content increases, particle mobility decreases, the coefficient of internal friction increases, and the angle of repose becomes steeper. Consequently, moisture content directly impacts mixing quality (Apalihina, 2017).

To establish the relationship between mixture quality and the moisture content of key components, the following control components were used: manganese sulfate with a moisture content of 5.28%, manganese carbonate with a moisture content of 2.82%, table salt (NaCl) with a moisture content of 0.4%.

For a more precise assessment of uniform mixing, Siberian fir needles were introduced into the mixture along with sunflower meal to increase the volume of components. The moisture content of the meal was varied from 7.8% to 27.0%, which resulted in: an increase in the angle of repose from 33° to 46°, a decrease in bulk density from 550 kg/m³ to 460 kg/m³ (Table 1).

Table 1. Physical and Mechanical Properties of Sunflower Meal

Moisture Content (%)	Bulk Density (kg/m ³)	Density	Angle of Repose (°)
7.8	550		33–34
10.2	520		37–38
14.5	490		42–43
20.0	460		44–45
27.0	460		46

To study the effect of the moisture content of the control component on mixture homogeneity, manganese sulfate with a moisture content ranging from 2.7% to 27.9% was used.

The dependence of the variation coefficient on the moisture content of the components is graphically represented in Fig. 4. The studies showed that with an increase in the moisture content of the main component, the distribution of table salt and manganese sulfate slightly improves. The opposite dependency was observed for manganese carbonate. The explanation for the identified dependencies is likely due to the formation of a liquid film on the surface of the particles as the moisture content of the product increases.

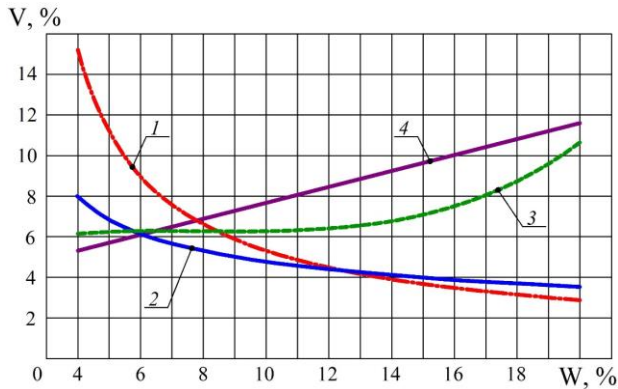


Fig. 4. Dependence of the variation coefficient on the moisture content of the main (1, 2, 3) and control (4) components: 1 – NaCl; 2 – $\text{MnSO}_4 \cdot 5\text{H}_2\text{O}$; 3 – $\text{MnCO}_3 \cdot \text{mH}_2\text{O}$

The increased moisture content leads to the adhesion of indicator components – table salt (NaCl) and manganese sulfate (MnSO_4) – and, in some cases, results in the partial dissolution of fine dust particles. Manganese carbonate (MnCO_3), on the other hand, is an insoluble compound. When manganese carbonate is mixed with high-moisture sunflower meal (20–27%), the liquid film does not wet it but instead promotes the formation of particle agglomerates, ultimately deteriorating the overall mixture quality.

Experimental studies have also established that an increase in the moisture content of the control component (manganese sulfate) reduces its dispersibility within the mixer due to inefficient distribution by the stirrer blades.

Thus, an increase in the moisture content of the primary component positively affects the distribution of water-soluble microcomponents but negatively impacts the distribution of water-insoluble microcomponents. The presence of moisture in microcomponents reduces the uniformity of their distribution within the mixture.

To identify the optimal range of mixing parameters, experimental design methods were employed. The selection of factor variation ranges was performed using central rotatable uniform planning, which enabled the derivation of regression equations that accurately describe the real mixing process based on 56 experiments, each conducted in triplicate (Kafarov, 2023).

5. Influence of plant component content on mixing quality with combined mixer shafts

It is particularly important to emphasize that, in order to achieve optimal animal growth, reproduction, or lactation, nutrients must be evenly distributed in the feed, the ingredients of which are mixed in the combined mixer developed by the authors (Apalihina, 2017; Asangaliev et al., 2021). However, there is a lack of empirical data confirming this assumption (Dąbrowska et al., 2022; Giel et al., 2021a; Giel et al., 2021b; Giel et al., 2022; Giel et al., 2023; Guryanov et al., 2024). As previously noted, during the mixing process in the mixer, both mixing and separation of the final mixture occur simultane-

ously. Therefore, enhancing process efficiency requires minimizing the separation of components (Doudkin et al., 2019c; Doudkin et al., 2021b; Moldakhanov et al., 2023).

One perspective suggests that to reduce segregation in the final dry mixture, it is advisable to introduce liquid additives, including plant-based components. Among these, oil-containing Siberian fir needles have been identified as a suitable addition (Apalihina, 2017).

The following experiments were conducted to investigate this. To test the mixer's performance with highly viscous materials, we examined the mixing of feed briquette components and added crushed molasses as one of the components, using crushed barley instead of salt as the main component (filler). Control components - manganese sulfate and table salt - were mixed with the main component, with molasses content varying from 15% to 47%.

The results showed an inverse proportional relationship between the mixture's heterogeneity coefficient and the molasses content in the main component (Fig. 5).

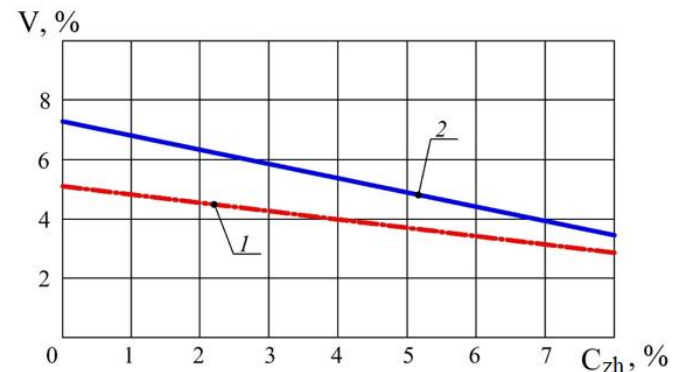


Fig. 5. Dependence of the variation coefficient of indicators (1 – NaCl; 2 – $\text{MnSO}_4 \cdot 5\text{H}_2\text{O}$) on molasses content in the main component

The analysis of the obtained results shows that the presence of fat improves the distribution of control components. The presence of fat in the main component reduces the intensity of the separation process due to particle adhesion (Lytkina et al., 2016). Thus, the molasses content positively influences the distribution of control components.

6. The influence of the nature of the main component on the uniform distribution of microcomponents after mixing in a mixer

It is necessary to test the operation of the mixer with a combined working body again by mixing the components of feed briquettes-licks. The following macronutrients were used as research objects: wheat bran, meat and bone meal, fish meal, feed yeast, crushed peas and barley, sunflower meal, dry milk, and chalk.

The particle size of the components corresponded to passing through a sieve with hole diameters of 1.5 mm. The moisture content and granulometric composition of the products are presented in Table 2. The control component was manganese sulfate ($\text{MnSO}_4 \cdot 5\text{H}_2\text{O}$).

The results of the mixing are shown in Fig. 6, and for comparison, the results for a spiral counterflow mixer are provided.

Table 2. Granulometric Composition of Feed Briquette Components

Component	Moisture Content (%)	Residue on sieves, %					
		1.00	0.63	0.50	0.40	0.20	Bottom
Wheat bran	9.3	19.0	15.0	14.5	20.5	24.5	6.5
Meat and bone meal	4.5	1.0	12.0	8.0	10.5	28.5	40.0
Chalk	0.4	2.0	22.0	28.0	20.5	7.0	20.5
Feed yeast	7.4	0.5	8.0	7.5	9.0	34.5	40.5
Crushed peas	10.0	5.0	41.5	12.0	11.5	17.0	13.0
Sunflower meal	7.8	4.5	48.0	14.0	12.0	16.5	5.0
Fish meal	7.0	1.0	10.0	6.5	15.0	36.5	31.0
Dry milk	8.3	0.5	9.0	7.0	9.5	34.0	40.0
Crushed barley	10.1						

Analysis of the results shows that in the combined mixer with the new working body (independent stirrers), the influence of the nature of the main component on the uniformity of microcomponent distribution is significantly less than in the spiral counterflow mixer. This is due to the progressive mixing method in a state of "mechanical weightlessness" or in a "fluidized" layer (Apalihina O.A., 2017).

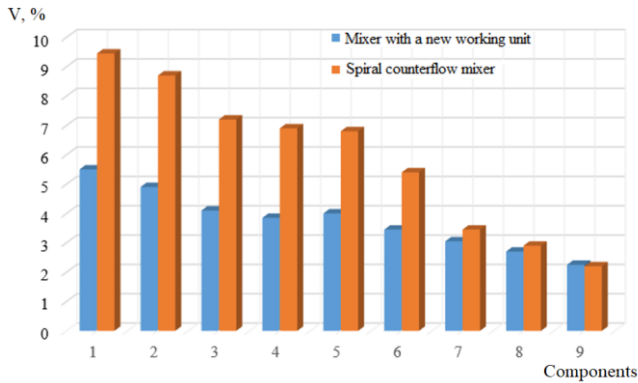


Fig. 6. Coefficients of heterogeneity of distribution of $MnSO_4 \cdot 5H_2O$ when mixing various components: 1 – wheat bran; 2 – meat and bone meal; 3 – chalk; 4 – yeast; 5 – chopped peas; 6 – sunflower meal; 7 – fish meal; 8 – milk powder; 9 – crushed barley

This method allows mixing components with significantly different bulk densities and other physical and mechanical properties. The results of studying the kinetics of the mixing process within optimal parameter ranges open up possibilities for modeling the mixing process based on the methodology proposed by Professor E.A. Asangaliyev (Asangaliyev et al., 2021).

7. Mechanics-mathematical model of component mixing in a mixer with a combined working body

The mechanics-mathematical model of homogeneous mixing of polydisperse components in premix licks in a combined mixer considers their stepwise distribution over time spent in the mixing chamber and its retention capacity, the volume size and dimensional length of the components (for example, needles of Siberian fir), spontaneous distribution of components with different thermal saturations throughout the working volume of the mixing chamber, the diversity of the physical and chemical properties of the components, complex chemical reactions between them, and other stochastic features.

The mechanics-mathematical model for mixing components for the production of briquetted premix licks in a three-shaft combined mixer was developed using an informal approach: transforming the mathematical representation of the mixing technology specifically for the mixer under consideration (Kafarov et al., 2023).

The mathematical analysis and representation of mixing binary ingredients in the combined mixer were based on the system of differential equations developed by Academician V.V. Kafarov:

$$\frac{d(c_A - m_A)}{dt} = -k(c_A - m_A)^2 + kD_A \quad (1)$$

$$\frac{d(c_B - m_B)}{dt} = -k(c_B - m_B)^2 + kD_B \quad (2)$$

where the coefficient $k = \mu \cdot (N_A a' + N_B b') / b'$; c_A, c_B – relative concentrations of components A and B; m_A, m_B – mathematical expectations of the concentrations of components A and B, corresponding to the prescription value of the concentration of the component in the mixture; μ – proportionality factor; N_A and N_B – number of associations of particles A and B; $a' = a\gamma_A V_A$; $b' = b\gamma_B V_B$; a and b – the number of particles included in associations A and B; V_A and V_B – volumes of particles of grade A and B; γ_A and γ_B – material densities of particles A and B; D_A and D_B – dispersions characterizing the incompleteness of the mixing process (Kafarov et al., 2023).

Equations (1) and (2) characterize the change in concentrations of components A and B within the working volume of the mixer. However, in industrial practice, the assessment of the mixture state is conducted based on a sample from a certain number of tests. Therefore, let us rewrite equation (1) for a sample of nl tests, taken from n randomly selected points within the mixer volume, with l parallel tests at each point, resulting in the following system of equations.

$$\frac{d(c_{ij} - m)}{dt} = -k(c_{ij} - m)^2 + kD_{c_{ij}} \quad \text{where} \quad (3)$$

$$i = 1, 2, \dots, n; \quad j = 1, 2, \dots, l$$

Summing this system of equations over n points and l tests, and then performing the corresponding transformations, we obtain

$$\frac{\sqrt{nl} d\sqrt{\sigma^2}}{nldt} = -k(\sigma^2 - \sigma_c^2) \quad (4)$$

where σ^2 - sample variance of component concentration in the mixture;

k - coefficient determining the mixing rate constant.

Figure 7 shows the kinetic dependence of the change in saturation variance σ^2 over the duration of the mixing process. The longer the mixing duration, the more homogeneous the mixture saturation σ_p^2 , at the maximum value of which dynamic equilibrium is reached. It is assumed that the classification process of the mixture will correspond to a different dependence, and there exists a linear relationship between the segregation variance and the breakdown (Apalihina, 2017):

$$\sigma_H^2 - \sigma^2 = \lambda(\sigma_c^2 - \sigma_{HC}^2) \quad (5)$$

where σ_H^2 - initial saturation variance of the ingredient at $t=0$; λ - uniformity coefficient; σ_{HC}^2 - initial segregation variance.

The operation of the combined mixer, which mixes a multi-component mixture, can be described by a known mathematical model:

$$\frac{1}{\sqrt{nl}} \cdot \frac{d\sqrt{\sigma_i^2}}{dt} = -k_i \frac{\lambda_i + 1}{\lambda_i} \cdot \sqrt{\sigma_i^2} \cdot \sum_{j=1, j \neq i}^S \sqrt{\sigma_j^2} + \frac{k_i}{\lambda_i} \quad (6)$$

where $\lambda_i = \frac{1 - \sigma_{pi}^2}{\sigma_{pi}^2}$ with initial conditions $t=0; \sigma_i^2=1; t=\infty; \sigma_i^2=\sigma_{pi}^2; i=1, 2, \dots, S$.

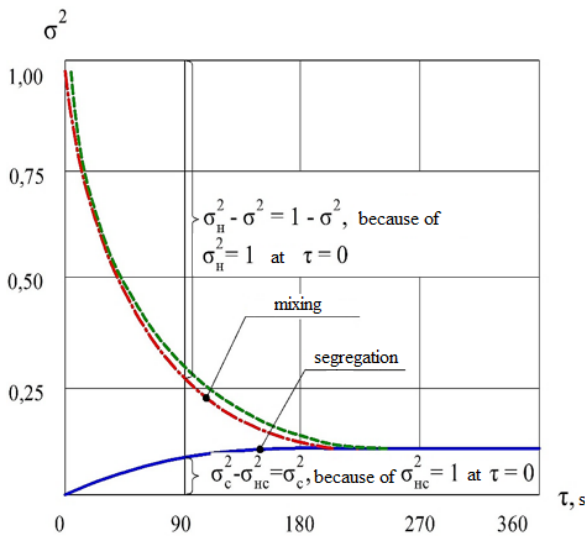


Fig. 7. Kinetic dependence of the change in saturation dispersion σ^2 over the duration of the mixing operation

Since the mixed mixture contains more than two ingredients, the indicators of the mixing process itself will be represented by separate kinetic dependencies for all the ingredients included in the mixture. After performing a series of transformations with respect to σ^2 , an almost complete model of the working process of the combined mixer is obtained:

$$\sigma^2 = \sigma_p^2 \cdot \left(\frac{\left(\left(\sqrt{\sigma_p^2 + 1} \right) - \left(\sqrt{\sigma_p^2 - 1} \right) \cdot \exp\left(-\frac{2k\sqrt{nl} \cdot \sqrt{\sigma_p^2}}{1 - \sigma_p^2} t \right) \right)}{\left(\left(\sqrt{\sigma_p^2 + 1} \right) + \left(\sqrt{\sigma_p^2 - 1} \right) \cdot \exp\left(-\frac{2k\sqrt{nl} \cdot \sqrt{\sigma_p^2}}{1 - \sigma_p^2} t \right) \right)} \right)^2 \quad (7)$$

where σ^2 - sample variance; σ_p^2 - equilibrium variance corresponding to maximum mixing; n - number of sample analysis points; l - number of analyses in each of the n points; t - mixing duration; k - mixing rate constant.

The derived mathematical model, in essence, coincides with previously known models and (7) confirms that the binary components of the mixture during mixing are influenced by the interaction of the two aforementioned variables - the mixing rate constant k and the stable saturation variance of the mixture components σ_p^2 (Apalihina, 2017).

Experimental and model-calculated kinetic curves for the considered model mixtures, of SLB based on σ_p^2 and k_{opt} , are presented in Figure 8.

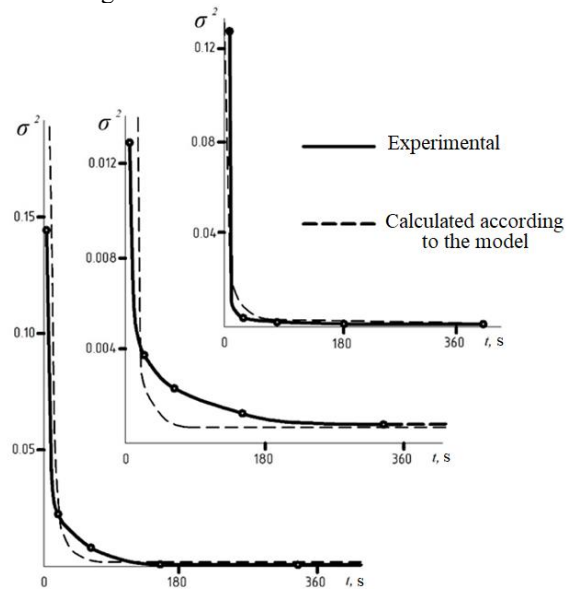


Fig. 8. Experimental (solid lines) and model-calculated (7) (dashed) kinetic curves for binary model mixtures obtained in the mixer with combined working elements: 1 - metallic magnetic impurities and crushed barley; 2 - table salt and crushed barley; 3 - feed molasses and crushed barley

8. Analysis of the quality of the obtained feed blocks

Forming is a crucial stage in the technological process of producing both salt and feed lick blocks. To determine the optimal cooling duration during their production, the dependence of the specific penetration force on the duration of treatment at various temperature regimes was studied. Figure 9 presents the results of the study of the structural-mechanical properties of feed lick blocks during the forming process.

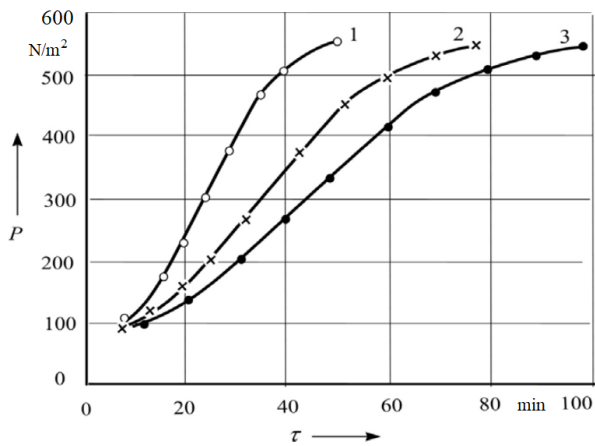


Fig. 9. Dependence of specific penetration force on processing duration at various temperature regimes: 1 – 15°C; 2 – 20°C; 3 – 25°C

The forming of the products was carried out in a special chamber. The obtained dependencies indicate that the strength of the structure of the SLB increases intensively in the initial period, then the process slows down. The second period is characterized by a sharp deceleration in the rate of increase in mechanical strength, which is associated with the onset of hardening. As a result of the analysis of the obtained data, the time parameters of the cooling process were determined. The required strength, corresponding to 400 N/m², is achieved at a temperature of 15°C in 30 minutes, at a temperature of 20°C in 46 minutes, and at a temperature of 25°C in 57 minutes.

Effect of the degree of mixing of mixture components on the change in quality of feed lick blocks during storage. Storage of experimental and control batches of feed lick blocks was carried out in floor-type warehouse conditions. The storage conditions were characterized by the following temperature and relative humidity indicators (Table 3).

Table 3. Storage Conditions

Month	Average monthly temperature, °C	Average monthly relative humidity, %
January	-2	64.5
February	-1	63.2
March	0	65.6
April	10.3	62.3
May	14.4	59
June	20.1	61
July	19.3	60
August	19.6	63
September	+19.8	63
October	+5.6	76
November	0	73
December	0	64

The most labile components in the studied product were the vitamins introduced during its production. Their preservation determined the quality of the feed lick blocks and allowed for the establishment of shelf life. Experiments were conducted

under production and laboratory conditions at a temperature of 30°C and relative humidity of 70%. The change in moisture content of the lick blocks during storage under production conditions is presented in Table 4.

Table 4. Change in moisture content of feed lick blocks during storage under production conditions (1 – experimental batch, 2 – control batch)

Variant	Storage duration, months						
	1	4	6	8	10	12	14
	Humidity, %						
1	10.1	10.2	10.6	11.3	11.4	12.7	13.1
2	10.3	10.6	10.8	11.2	11.6	12.8	13.3

The presented data indicate that the moisture content of the feed lick blocks during storage under production conditions increased slightly and reached 11.1–11.3% by the end of the 14th month in both the control and experimental variants. The moisture content of the lick blocks is greatly influenced by the moisture of the surrounding environment. The result of the development of vitamin activity or motility in the SLB, stored in natural conditions and an experimental laboratory environment, is illustrated in Figure 10. For storage durations of SLB exceeding 10 months, for example, 14 months, in the corresponding warehouse led to significant degradation of vitamin A. Losses ranged from 19.6% to 40.1% (Apalihina, 2017).

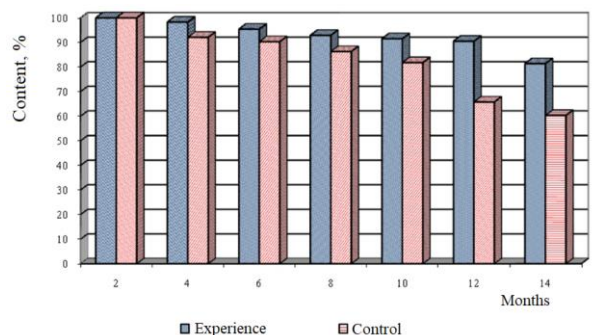


Fig.10. Change in vitamin A content in feed lick blocks during storage under production conditions

Storage of the product was carried out under production conditions for 10 months, where the average air temperature did not exceed 20.1°C, and the relative humidity was 76% (Table 5). These conditions did not lead to significant degradation of vitamin A in the experimental variant. Its content remained at 91.5% of the initial value. In the control, losses were higher and amounted to 19.2% after 10 months. Further storage led to further vitamin degradation, with losses exceeding acceptable values. The content of vitamins A, E, and D in the feed lick blocks at the end of the 10th month was 90.5%, 91.4%, and 90.7%, respectively, in the experimental variant, and 81.8%, 71.4%, and 70.3%, respectively, in the control.

With an increase in storage duration to 14 months, the vitamins began to degrade at an accelerated rate. In the control, the loss of activity by the end of the 14th month exceeded 40%, while in the experimental variant, it exceeded 20%.

Table 5. Change in moisture content of feed lick blocks during storage under laboratory conditions (1 – experimental batch, 2 – control batch)

Variant	Storage duration, months						
	1	2	3	4	5	6	7
	Humidity, %						
1	10.1	11.2	11.8	12.8	13.6	14.7	15.1
2	10.0	11.6	12.6	13.2	13.5	14.8	15.3



Fig. 11. SBL before measuring changes in shape (a), content (b), and hardness (c)

High-quality SLB (Fig. 11) must maintain resistance to adverse conditions. Storage at a temperature of 30°C and relative humidity of 70% resulted in a significant reduction in vitamin A content after 6 months. In the experimental variant, losses were 9.5% and 34.2% in the control. After 7 months, vitamin A losses exceeded 14.6% in the experimental variant and 39.7% in the control. It is proposed to limit the storage duration of feed lick blocks to 10 months under production conditions and to 6 months under adverse conditions.

9. Conclusion

1. The developed design of the combined mixer, equipped with independently rotating stirrers, demonstrated high mixing efficiency. Moreover, the operation of its independent stirrers did not have any adverse effects on the integrity and quality of the mixed components.
2. During the study of the mixing kinetics for salt lick brick (SLB) production, the most optimal mixing parameters were identified, ensuring high-quality SLB formation: mixing duration: 65–70 s; stirrer shaft rotation frequency: 12.0–13.0 s⁻¹; control ingredient concentration in SLB: ≥ 0.2%; mixer chamber fill ratio: 0.5–0.7; coefficient of variation for the control ingredient in SLB: 4.4–4.9%
3. Experimental results revealed that increasing the rotation frequency and consequently, the circumferential speed of the mixer's working elements within the range of 12.0 to 13.0 s⁻¹ reduces the mixing time required to reach equilibrium. This is due to a greater number of interactions between the mixer's working elements and the mixed products per unit of time, resulting in more intense movement of particles relative to one another and the mixer housing.
4. The developed mechanical-mathematical model of homogeneous mixing for polydisperse components in the combined mixer takes into account: stepwise distribution of components based on their residence time in the mixing chamber and its retention capacity; volume and particle

size distribution, including crushed Siberian fir needles; spontaneous distribution of mixture components with varying thermal saturation across the working volume of the mixing chamber; diversity of physicochemical properties of the mixture components, influenced by complex chemical interactions between them; other stochastic characteristics of the mixing process.

5. An exergy analysis was performed, yielding an exergetic efficiency of 8.2%, which is 2.5% higher than that of the standard technology, thereby confirming the validity of the selected design solutions.
6. The quality of the resulting SLB premixes was examined in relation to: the mixing efficiency and uniformity of components; the particle size and moisture content of both individual components and final SLB products; the plasticity of the ingredients; the presence of biologically active components before pressing, after pressing, and after a controlled storage period of 10 and 14 months; the optimal storage period was determined to be no more than 10 months.

Further research on crushers, mixers, and grinders will focus on modernizing mixing devices to ensure the required particle size distribution of mixture components; reducing energy and time consumption for component preparation and mixing; minimizing material consumption; eliminating exposed rotating components in the drive mechanisms of the developed machines; automating the mechanism for opening discharge port covers.

Acknowledgements

The research related to this publication is funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP26102017 “Justification of parameters and development of equipment for innovative high-performance technology for processing crop production waste”).

Reference

- 120L Simon Barron Conditioning Mixer. 2025. Available at: <https://www.rigal-bennett.com/Industry/Cosmetic/GetStockItem/11734>
- Aduov M., Nukusheva S., Kaspakov E., Isenov K., Volodya K., Tulegenov T. 2020. Seed drills with combined coulters in No-till technology in soil and climate zone conditions of Kazakhstan. *Acta Agriculturae Scandinavica, Section B: Soil & Plant Science*, 70(6), 525–531. DOI: 10.1080/09064710.2020.1784994
- Apalihina O.A. 2017. *Razrabotka i nauchnoe obespechenie energoeffektivnogo sposoba proizvodstva briketov-lizuntsov dlya podkormki krupnogo rogatogo skota* (Development and scientific support of energy-efficient production of briquetted licks for cattle). Dissertation, VGUIT, Voronezh, Russian Federation.
- Apalihina O.A., Pereverzeva S.A. 2016. *Smesitel s Z-obraznym organom* (Mixer with Z-shaped element). Russian Federation Patent No. 117698.
- Asangaliev Y., Kim V., Kim A., Doudkin M., Danilov M., Guriyanov G. 2021. Improvement of technology, machines, and recipes for the production of compound feed and feed additives for farm animals. *International Review of Mechanical Engineering*, 15(11), 598–608. DOI: 10.15866/ireme.v15i11.21291
- Bostanov B.O., Temirbekov E.S., Dudkin M.V., Kim A.I. 2019. Mechanics-mathematical model of conjugation of a part of a trajectory with conditions of continuity, touch and smoothness. *Communications in Computer*

- and Information Science, 998, 71–81. DOI: 10.1007/978-3-030-12203-4_8
- Buehler. 2025. Solutions for Materials Preparation, Testing & Analysis. <https://www.buehler.com/>
- Dąbrowska A., Giel R., Winiarska K. 2022. Sequencing and planning of packaging lines with reliability and Digital Twin concept considerations – a case study of a sugar production plant. *LogForum*, 18(3), 321–334. DOI: 10.17270/J.LOG.2022.762
- Doudkin M., Apshikur B., Kim A.I., Ipalakov T.T., Asangaliyev E.A., Mlynczak M. 2019a. Development of an installation for shear ground testing in railway track construction. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, 6(438), 22–35. DOI: 10.32014/2019.2518-170X.152
- Doudkin M., Apshikur B., Kim A.I., Ipalakov T.T., Asangaliyev E.A., Mlynczak M., Tungushbayeva Z.K. 2019b. Development of mathematical models describing the processes occurring in railway track construction. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, 5(437), 6–15. DOI: 10.32014/2019.2518-170X.120
- Doudkin M., Kim A., Mlynczak M., Kustarev G., Kim V. 2019c. Development and parameter justification of vibroscreen feed elements. In: *Mining Machines and Earth-Moving Equipment: Problems of Design, Research and Maintenance*, 203–226. DOI: 10.1007/978-3-030-25478-0_10
- Doudkin M., Kim A., Sakimov M. 2019d. Mathematical and experimental study of deformations of a steel roll of a road roller with variable geometry of contact surface. *Production Engineering Archives*, 25(25), 1–7. DOI: 10.30657/pea.2019.25.01
- Doudkin M., Sakimov M., Kim A., Mlynczak M., Doudkina Y. 2020. Mathematical and experimental study of deformations of steel roll road roller with variable geometry of contact surface. *International Journal of Mechanical and Production Engineering Research and Development*, 10(1), 559–572. DOI: 10.24247/ijmperdfeb202048
- Doudkin M., Kim A., Aukenova B., Radenkov R., Saveliev A., Andryukhov N. 2021a. Experimental studies on the interaction process with the environment of an adaptable bulldozer blade with variable geometry. *International Review of Mechanical Engineering*, 15(11), 554–565. DOI: 10.15866/ireme.v15i11.21756
- Doudkin M., Kim A., Moldakhanov B., Kustarev G., Andryukhov N., Rogovsky V., Doudkina Y. 2021b. Experimental studies of the physical model of the milling-rotary snow cleaner. *International Review of Mechanical Engineering*, 15(9), 453–463. DOI: 10.15866/ireme.v15i9.20952
- Doudkin M., Kim A., Moldakhanov B. 2021c. Determination of forces in the working unit of the milling-rotary snow cleaner. *International Review of Mechanical Engineering*, 15(2), 96–105. DOI: 10.15866/ireme.v15i2.20859
- Doudkin M., Kim A., Aukenova B., Saveliev A., Andryukhov N. 2022. Theoretical investigations of the process of interaction with the environment of a bulldozer blade with variable geometry. *Journal of Applied Engineering Science*, 20(3), 798–807. DOI: 10.5937/jaes0-37210
- Giel R., Dąbrowska A. 2021a. Estimating time spent at the waste collection point by a garbage truck with a multiple regression model. *Sustainability*, 13(8), 4272. DOI: 10.3390/su13084272
- Giel R., Dąbrowska A., Werbińska-Wojciechowska S. 2021b. Active learning for automatic classification of complaints about municipal waste management. *Environment Protection Engineering*, 47(4), 53–66. DOI: 10.37190/epe210404
- Giel R., Kierzkowski A. 2022. A fuzzy multi-criteria model for municipal waste treatment systems evaluation including energy recovery. *Energies*, 15(1), 31. DOI: 10.3390/en15010031
- Giel R., Dąbrowska A. 2023. Fuzzy evaluation method for environmental factors affecting a mobile robot's sensor system in view of Design for Logistics. *LogForum*, 19(2), 169–182. DOI: 10.17270/J.LOG.2023.823
- Guryanov G., Doudkin M., Kim A., Vavilov A., Asangaliyev Ye., Yakovlev V., Vasilyeva O., Vavilov O. 2024. Operating parameters of vibration disc-working engines of seeding units to improve energy-technological indicators. *International Review of Mechanical Engineering*, 18(3), 153–162. DOI: 10.15866/ireme.v18i3.24457
- Hayes & Stolz. 2025. Double Ribbon Mixer Demonstration. <https://www.hayes-stolz.com/>
- Issabek Z., Kadyrov Z., Kim A. 2021. Automatic control system of asphalt concrete milling process based on road milling machines. *International Review of Mechanical Engineering*, 15(8), 394–405. DOI: 10.15866/ireme.v15i8.20961
- Kafarov V.V., Dorohov I.N., Arutyunov S.Yu. 2023. *Sistemnyj analiz processov khimicheskoy tekhnologii: izmelchenie i smeshenie* (System analysis of chemical technology processes: grinding and mixing). Yurait, Moscow, Russian Federation.
- Kombayev K.K., Doudkin M.V., Kim A.I., Mlynczak M., Rakhadilov B.K. 2019. Surface hardening of aluminum alloy AL3 by electrolytic-plasma treatment. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, 4(436), 222–229. DOI: 10.32014/2019.2518-170X.117
- Kombayev K., Kim A., Yelemanov D., Sypainova G. 2022. Strengthening of low-carbon alloy steel by electrolytic-plasma hardening. *International Review of Mechanical Engineering*, 16(2), 84–91. DOI: 10.15866/ireme.v16i2.21712
- Lödige. 2025. Ringlayer Mixer Corimix for Continuous Operation. <https://www.loedige.de/en/industries/food/>
- Lytkina L.I., Shevtsov A.A., Shentsova E.S., Apalikhina O.A. 2016. The probabilistic model of the process mixing of animal feed ingredients into a continuous mixer-reactor. *Proceedings of VSUET*, 2, 16–21.
- Moldakhanov B., Doudkin M., Kim A., Rogovsky V., Andryukhov N. 2023. Experimental study of the snow removal process by helical blade of the milling feeder. *Journal of Applied Engineering Science*, 21(1), 157–166. DOI: 10.5937/jaes0-39760
- Sakimov M.A., Ozhikhenova A.K., Abdeyev B.M., Ozhiken A.K., Azamatkyzy S. 2018. Finding allowable deformation of the road roller shell with variable curvature. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, 3(429), 197–207.
- Saveliev A., Zhileykin M., Mikhailovskaya V., Kustarev G., Grib V. 2019. Increasing the reliability of the autograder metal construction by modeling and re-assembling of the working equipment. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, 6(438), 276–286. DOI: 10.32014/2019.2518-170X.179
- Shevtsov A.A., Lytkina L.I., Chaikin I.B., Ostrikova E.A. 2009. Mixer-Extruder. Russian Federation Patent No. 2347606, IPC7 B01F 7/02, Publ. 27.02.2009, Bull. No. 6.
- Temirbekov E.S., Bostanov B.O., Kaimov S.T., Kaimov A.T. 2019. Combined trajectory of continuous curvature. *Mechanisms and Machine Science*, 68, 12–19.
- Vavilov A., Kim A., Guryanov G., Likunov A. 2020. New technology of the steel fiber manufacturing from technogenic waste. *International Journal of Mechanical and Production Engineering Research and Development*, 10(3), 611–622. DOI: 10.24247/ijmperdjun202056