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Received: 6 October 2025

Accepted: 12 March 2026

Published online: 19 March 2026

Cite this article as: Aliiev E., Malehin R., Aliieva O. *et al.* Development of a homogenizer-disperser of liquid fodder for pigs. *Sci Rep* (2026). <https://doi.org/10.1038/s41598-026-44547-9>

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Development of a Homogenizer-Disperser of Liquid Fodder for Pigs

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Abstract

During the experiment, dependencies were established as follows: changes in the content of particles sized 0-0.5 mm in the mixture (k_{fr} , %) as a function of rotor rotation frequency (n , rpm), stator inlet orifice diameter (D_{in} , m), and equipment operation time (t , s); changes in the mixture stratification index (i_d , %) as a function of rotor rotation frequency (n , rpm), stator inlet orifice diameter (D_{in} , m), and equipment operation time (t , s); changes in the mixture temperature (T , °C) as a function of rotor rotation frequency (n , rpm), stator inlet orifice diameter (D_{in} , m), and equipment operation time (t , s); changes in the power consumption of the motor (N , kW) as a function of rotor rotation frequency (n , rpm), stator inlet orifice diameter (D_{in} , m), and equipment operation time (t , s); and changes in energy consumption (E , MJ) for the process execution as a function of rotor rotation frequency (n , rpm), stator inlet orifice diameter (D_{in} , m), and equipment operation time (t , s). Under the condition where the parameter i_d is less than 5% and the efficiency E_Q needs to be minimized, the optimal value of equipment operation time t for different types of input material is observed within the range of 45.1–50.4 minutes. Additionally, there is a slight change in the specific energy consumption E_Q depending on the type of cereal crops used during the experiment. The lowest specific energy consumption is observed when using soybeans – 0.696 MJ/kg, wheat – 0.794 MJ/kg, and barley – 0.896 MJ/kg.

Keywords: liquid fodder, homogenization, dispreparation, swine breeding, parameters

Introduction

As noted in studies [1, 2], effective pig farming is impossible without providing animals with quality balanced feed at competitive prices and in the necessary quantities. The quality of feed is primarily determined by the technological operations involved in its preparation [3]. Firstly, feeds should be uniform in particle size distribution. That is, the grinding process should ensure uniform particle size distribution for each of the plant components that make up the feed [4]. Secondly, feeds should be uniform in the distribution of components within the mixture. This means that the mixing process should provide a high coefficient of variation in the

distribution of plant components throughout the volume (or mass) of the mixture [5]. Thirdly, feeds should preserve all nutrients and vitamin complexes, not contain harmful substances, and meet the requirements of waste-free transformation of plant raw materials along the food chain [6]. This means that feed preparation should involve technological processes that satisfy these conditions.

The aforementioned requirements correspond to the process of dispersing and homogenizing feed components using cavitation treatment. According to research [7, 8], dispersion is a technological process of finely grinding and distributing solid material, liquid, or gas in volume, resulting in dispersed systems: powders, suspensions, emulsions, aerosols. Homogenization, on the other hand, is a technological process that reduces the degree of heterogeneity in the distribution of components and phases within the volume of a heterogeneous system [9, 10]. Cavitation is a physical process of bubble formation (cavities) in liquid mediums, followed by their collapse and release of a large amount of energy (shock wave) resulting from external physical influences [11, 12]. Therefore, cavitation treatment of feed components allows for their comminution through the action of shock waves. Thus, the relevant task is to increase the efficiency of preparing high-quality liquid feeds by applying technological processes of dispersion and homogenization with cavitation treatment of feed components.

Currently, there are many dispersers and homogenizers that utilize cavitation effects [13, 14], including those for processing feed components into highly digestible feeds. Primarily, these hydrodynamic installations are designed to prepare liquid feed pastes from grains, oilseeds, and legumes, as well as feeds of animal origin for young and adult livestock, simultaneously disinfecting them and destroying toxic substances (mycotoxins and alkaloids) in the form of suspensions and emulsions [15].

The main elements of the most common designs of cavitation hydro-impact dispersers are the rotor and stator (Fig. 1) [16, 17]. Resonance chambers (resonators) are arranged around the circumference in the rotor. The stator contains openings - confusers. When the rotor rotates, the output openings of the resonators are periodically covered. The rotation frequency of the rotor typically ranges from 1000 to 3000 rpm. Comminution occurs due to the action of cavitation on the particle, as well as double (direct and reverse) hydraulic impact when interrupting the slurry flow at a specified frequency. The frequency is usually chosen equal to the natural frequency of the rotor. The hydraulic impact is pulsating in nature. The broken particles are subjected to hydraulic impact in the resonance chambers (resonators). Due to the coincidence of the resonator's natural frequency with the frequency of pressure pulse passage in the chambers, there is a multiple increase in pressure amplitude (10 times compared to rotary pulsation devices). Hydrodynamic processes in the installation are accompanied by developed turbulence. This contributes to a good degree of homogenization of the processed material.

The design of the cavitation disperser-homogenizer proposed in this study possesses engineering novelty [18], which consists in the substantiated constructive parameters (Fig. 1) of the working elements (rotor and stator). These parameters were not selected empirically but were determined based on previous theoretical investigations of the hydrodynamic and cavitation processes in rotor-stator systems and refined using numerical modeling of flow structure, pressure pulsations, and cavitation zones [19–20]. Such an approach ensured the purposeful formation of cavitation and hydro-impact effects in the working chamber.

However, despite the widespread use of cavitation dispersers, existing studies mainly focus on general design descriptions or qualitative assessments of cavitation intensity, without providing an integrated experimental justification of rational design and operating parameters for liquid feed preparation. In particular, the combined influence of rotor rotation frequency, stator inlet orifice diameter, and processing time on dispersion quality, mixture stratification stability, temperature rise, and energy efficiency remains insufficiently investigated. In this context, the novelty of the present work consists in the systematic experimental and statistical substantiation of rational design-technological parameters of a cavitation homogenizer-disperser for liquid feeds.

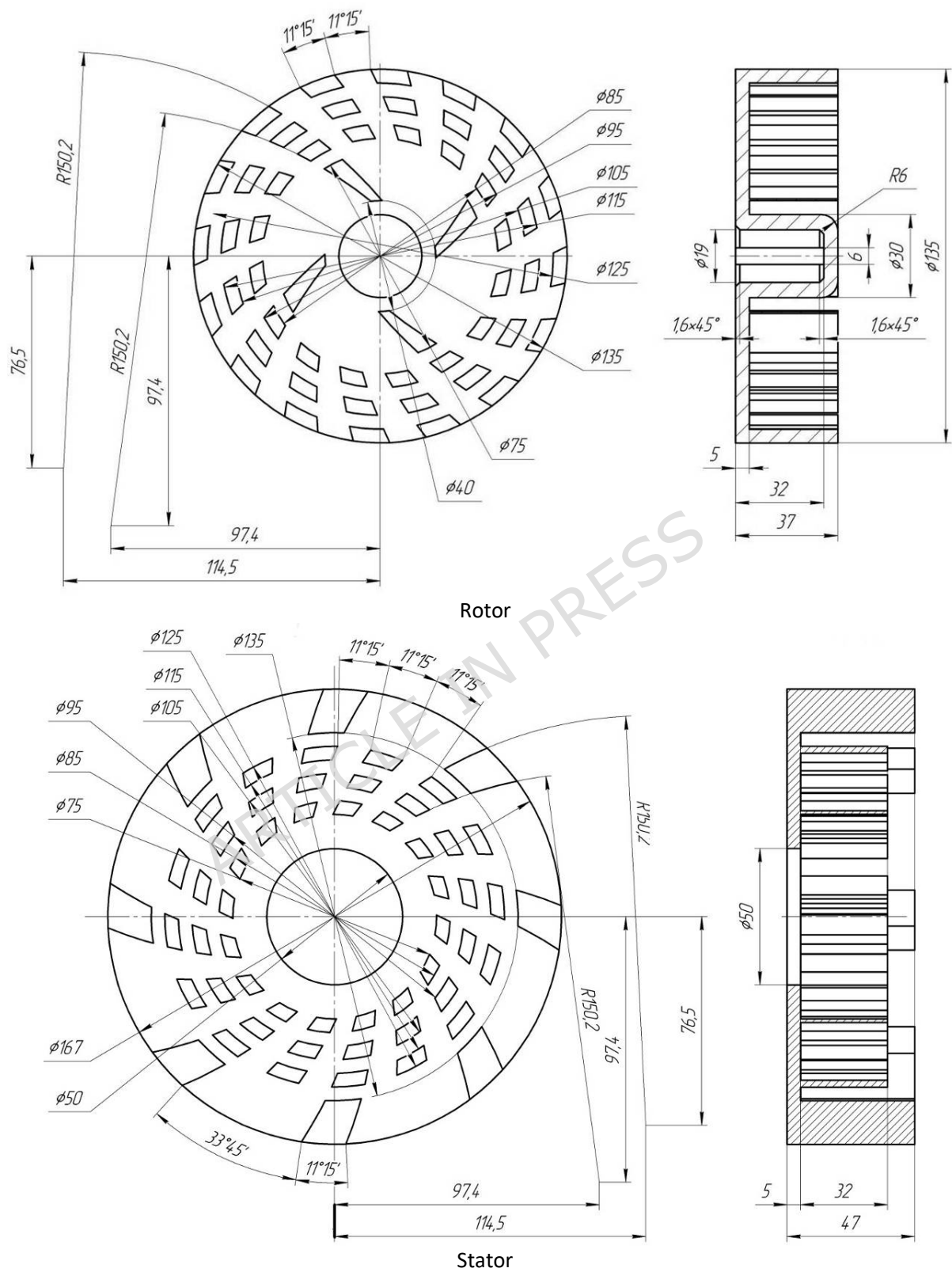


Figure 1. Geometric dimensions (mm) of the rotor and stator of the cavitation disperser-homogenizer [19–20]

Structural and technological scheme

To execute the aforementioned technological processes, a homogenizer-disperser for liquid feeds has been developed, the design process of which is illustrated in Fig. 2. In the first stage, as a result of patent and information analysis of similar equipment designs, a structural and technological scheme of the homogenizer-disperser for liquid feeds was developed and patented [18]. In the second stage, using the Siemens NX 2023 Build 2801 (CAD software) package (Siemens Digital Industries Software, Germany, <https://plm.sw.siemens.com/en-US/nx/>), a 3D model of the working elements – the stator and rotor - was created. In the third stage, numerical simulation of the interaction process of the working elements of the homogenizer-disperser with the components of the liquid feed was carried out using the Simcenter Star-CCM+ 2306.0001 (18.04.009) software package (Siemens Digital Industries Software, Germany, <https://plm.sw.siemens.com/en-US/simcenter/fluids-thermal-simulation/star-ccm/>) [21, 22]. In the fourth stage, the stator and rotor of the homogenizer-disperser were manufactured using the Siemens NX Build 2801 (CAM software) product (Siemens Digital Industries Software, Germany, <https://plm.sw.siemens.com/en-US/nx/manufacturing/cam-software/>) and a CNC milling machine. The fifth stage involves the production of an experimental sample and conducting corresponding experimental studies.

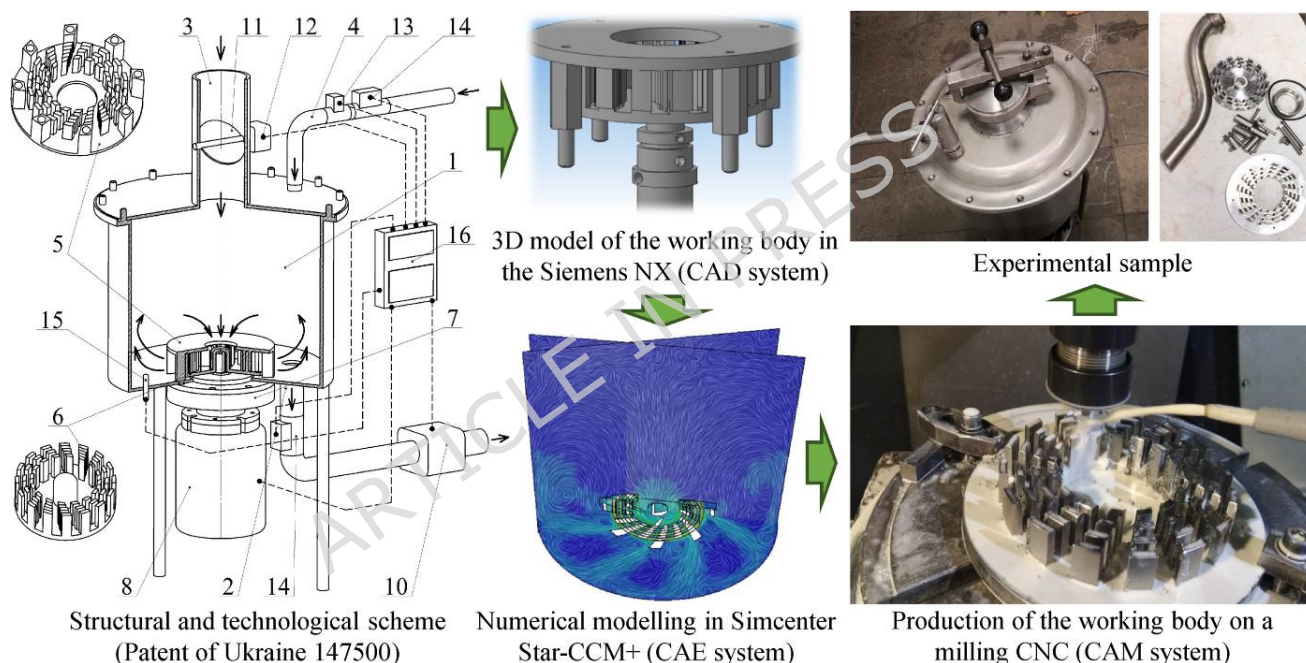


Figure 2. Stages of manufacturing an experimental sample of the homogenizer-disperser for liquid feeds
 1 – working vessel; 2 – discharge nozzle; 3 – nozzle for bulk components; 4 – nozzle for liquid components; 5 – stator; 6 – rotor; 7 – bearing unit; 8 – asynchronous motor; 9 – electrically operated valve; 10 – electric pump; 11 – valve; 12 – stepper motor; 13 – liquid flow sensor; 14 – electrically operated valve; 15 – temperature sensor; 16 – control unit

Drawn by the authors in Microsoft PowerPoint (Microsoft, USA, <https://www.microsoft.com/uk-ua/microsoft-365/powerpoint>) using screenshots from Siemens NX and Simcenter Star-CCM+ software packages

Purpose and program of research

The aim of the experimental research is to substantiate the rational design and technological parameters of operation for the cavitation homogenizer-disperser for liquid feeds. The research program includes the following tasks:

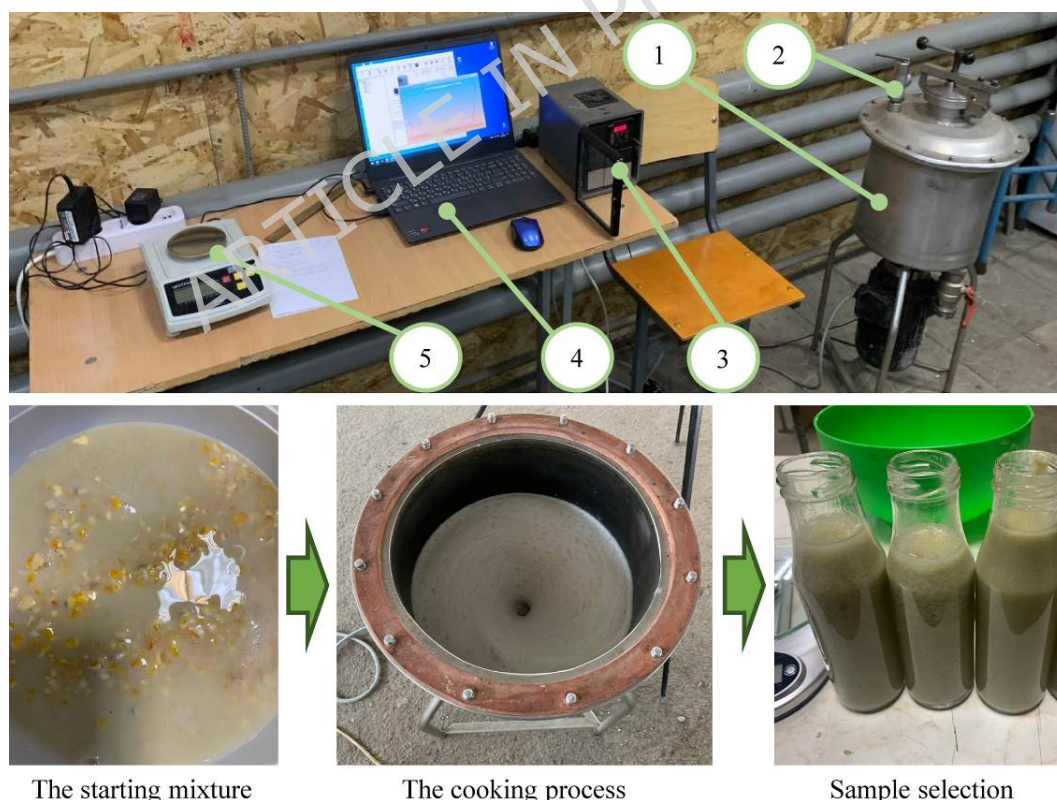
- Manufacture experimental samples of the homogenizer-disperser and equip the test bench for experiments;

- Develop a methodology for experimental research;
- Determine the influence of design and technological parameters of the homogenizer-disperser on the quality of the liquid feed, equipment productivity, and energy consumption;
- Conduct statistical analysis of the obtained data and compare the obtained dependencies with the results of computational modeling;
- Determine the rational design and technological parameters of operation for the homogenizer-disperser.

Stand for conducting research

The experimental studies were conducted on a test bench (Fig. 3), which consisted of an experimental sample of the homogenizer-disperser, equipment for changing the parameters of the working process of preparing liquid feeds (a control unit with a frequency controller N700E-022SF, Hyundai, South Korea), and control-measuring equipment, an electronic thermometer based on the DS18B20 digital temperature sensor (Dallas Semiconductor, USA) and a personal computer with installed software Hims N700 (Hyundai, South Korea) and TM32 (Ukrrele, Ukraine).

The design of the experimental sample of the homogenizer-disperser and the use of test bench equipment allowed for the possibility of changing design and technological parameters and measuring indicators of the working process: the diameter of the stator inlet orifice D_{in} from 0.04 ± 0.001 m to 0.07 ± 0.001 m by changing the flanges; rotor rotation frequency n from 0 rpm to 3000 ± 1 rpm using a frequency converter; volume of loaded components V up to 0.34 m³; dynamics of the mixture temperature in the homogenizer-disperser vessel using the electronic temperature sensor DS18B20 from 0°C to $100 \pm 0.1^\circ\text{C}$ with a reproducibility of 0.5 s; dynamics of the power of the homogenizer-disperser asynchronous motor using the H_{ims} N700 frequency converter from 0 kW to 2.00 ± 0.01 kW with a reproducibility of 0.5 s.



The starting mixture

The cooking process

Sample selection

Figure 3. Test bench and stages of experimental research

1 – experimental sample of the homogenizer-disperser for liquid feeds; 2 – DS18B20 temperature sensor; 3 – N700E-022SF frequency converter; 4 – personal computer; 5 – electronic scales VTE-Tsentroves-15-T3-DV.

Methodology of experimental research

As the starting material for the experimental studies, wheat, barley, and soybeans were chosen. According to research [23], the concentration of dry matter in the mixture should be 12%. Taking into account the grain moisture content (8%), the ratio of water mass to bulk component mass is 6.75:1. The mass of the initial mixture was 5 kg (0.65 kg of grain + 4.35 kg of water).

The mixture's initial apparent viscosity was measured at room temperature using a rotational viscometer to ensure reproducibility, and viscosity was controlled as a process parameter throughout the experiments.

The occurrence of hydrodynamic cavitation in the rotor–stator system was confirmed using several additional methods: acoustic detection with a hydrophone to capture characteristic ultrasonic signals associated with cavitation events, and local temperature measurements using a DS18B20 digital sensor to detect heating in the cavitation zone. Pressure fluctuation monitoring in the working chamber, which allows registering rapid pulsations caused by bubble collapse, was carried out during numerical modeling described in the previous study [19].

All measurements were performed using calibrated instruments, including the DS18B20 digital temperature sensor and VTE-Tsentroves-15-T3-DV electronic scales, with known reproducibility limits (± 0.1 °C for temperature, ± 0.01 g for mass). Additionally, the mixture was prepared under identical conditions for each trial, and anomalous runs – e.g., with unexpected power fluctuations or temperature excursions—were excluded from the analysis. These measures ensured consistent hydrodynamic conditions, repeatable cavitation regimes, and reliable evaluation of the influence of design and operating parameters on the performance of the homogenizer-disperser.

Based on the conducted numerical modeling [21] and literature analysis [16, 17], three factors that have the most significant impact on the working process were selected for experimental research on the press, and their natural values at the zero level and levels of variation were chosen. The intervals and levels of variation of the factors in the conducted research are provided in Tab 1.

Table 1 Levels and intervals of variation of factors when conducting experimental studies of a liquid feed homogenizer-disperser

Levels and intervals of variation	Encoded value	Factors and their designations		
		Rotor rotation frequency n , rpm	The diameter of the stator inlet D_{in} , m	Working time t , min
Upper level	+ 1	3000	0.06	30
Basic level	0	2250	0.05	20
Lower level	– 1	1500	0.04	10
Variation interval	Δ	750	0.01	10

As optimization criteria, the following were adopted: the content of particles sized 0–0.5 mm in the mixture (k_{fr} , %); mixture stratification index (i_d , %); mixture temperature at the end of the process (T , °C); power consumption of the motor (N , kW); energy consumption (E , MJ); specific energy consumption (E_o , MJ/kg). The content of particles sized 0–0.5 mm in the mixture (k_{fr} , %) was determined by sieving the mixture into fractions on laboratory sieves and subsequent weighing on electronic scales VTE-Tsentroves-15-T3-DV (Centroves, Ukraine). The mixture stratification index (i_d , %) was determined by allowing the mixture sample to settle in a test tube for 5 hours, followed by calculating the ratio of the absolute value of the difference in the content of the filled upper and lower parts of the compacted component. When $i_d = 0\%$, there is no stratification, and when $i_d = 100\%$, there is complete stratification. Energy consumption (E , MJ) was calculated as the product of motor power consumption and equipment operation time. Specific energy consumption (E_o , MJ/kg) was determined as the ratio of consumed power to the productivity of the cavitation homogenizer-disperser, taking into account the content of particles sized 0–0.5 mm in the mixture. The productivity of the cavitation homogenizer-disperser (Q , kg/h) was determined as the ratio of the mass of the initial mixture to the operation time. To determine the influence of each factor on the optimization criteria of the liquid feed preparation process, research was

conducted using a second-order Box-Behnken D-optimal design matrix [24] for three factors with a total of 15 experiments. Each experiment was conducted in triplicate.

Particle size characterization in the experimental study was not limited to a single fraction. The complete particle size distribution of the processed mixture was determined by sieve analysis using a set of laboratory sieves covering the entire range of particle sizes present in the liquid feed. All size fractions were quantified by weighing after separation, which allowed evaluation of the overall dispersion pattern resulting from cavitation processing. At the same time, particular attention was given to the fraction of particles with a size of 0–0.5 mm, as this fraction is technologically the most important for liquid pig feed preparation. Maximizing the content of particles in this size range ensures high digestibility, prevents sedimentation, and promotes stable homogenization of the mixture. Fractions with larger particle sizes do not represent a critical limitation for practical application, since they can be effectively removed by filtration through standard sieves during the delivery of the liquid feed to the animals. Therefore, the fraction of 0–0.5 mm was selected as the primary optimization criterion, while the remaining fractions were treated as auxiliary indicators describing the overall grinding efficiency.

To ensure reproducibility of the experimental conditions and to confirm the occurrence of cavitation in the working chamber of the disperser-homogenizer, additional verification and control procedures were implemented. The presence of developed hydrodynamic cavitation was confirmed indirectly by a combination of characteristic physical indicators, including a rapid pressure pulsation regime, intensive acoustic noise in the ultrasonic frequency range, and a local temperature rise in the processing zone, which are widely accepted qualitative indicators of cavitation onset in rotor-stator systems. The operating ranges of rotor rotation frequency and stator inlet diameter were selected based on prior numerical simulations [21], which predicted stable cavitation zone formation under these conditions. Viscosity of the liquid feed mixture was treated as a controlled parameter throughout the experiments. The initial viscosity of the mixture was ensured by maintaining a constant dry matter concentration of 12% for all tested feedstocks, in accordance with recommendations reported in [23]. Before each experiment, the mixture was prepared under identical conditions, and its apparent viscosity was measured at room temperature using a rotational viscometer. During processing, viscosity changes were indirectly monitored through temperature measurements and power consumption trends, since viscosity reduction due to grinding and thermal effects directly influences hydraulic resistance and motor load. Experiments in which the mixture temperature exceeded admissible limits or demonstrated abnormal power fluctuations were excluded from further analysis to avoid distortion of cavitation and homogenization effects. These measures ensured stable hydrodynamic conditions, repeatable cavitation regimes, and comparable rheological properties of the processed mixtures, allowing reliable evaluation of the influence of design and operating parameters on the performance of the cavitation homogenizer-disperser.

Methodology of data processing

Experiments to determine the operating parameters of the press were conducted using the multifactorial design of experiments technique, which allowed to determine mathematical models of processes in the form of second-order regression equations (polynomials) [24] in compliance with all institutional, national and international recommendations and legislation. Processing the results of the conducted research using the factorial experiment planning method is performed using Microsoft Excel (Microsoft, USA, <https://www.microsoft.com/uk-ua/microsoft-365/excel>) and Wolfram Cloud (Wolfram Research, USA, <https://www.wolframcloud.com/>) software packages. The assumption of the homogeneity of the experiments implies approximately equal influence of errors at all points in the research plan. To verify the reproducibility of the experiments conducted in triplicate, the Cochran's criterion is used. The adequacy of the obtained models was checked using the Fisher's criterion. The significance of regression coefficients is verified by determining the confidence interval for the regression coefficients. A regression coefficient is considered significant if its absolute value exceeds the magnitude of the confidence interval, which is determined by the Student's t-test [25, 26].

Results

As a result of processing the data from the experimental studies, final regression equations of the second order were obtained (after rejecting insignificant coefficients according to the Student's criterion) for the content of particles sized 0–0.5 mm in the mixture:

- for wheat:

$$k_{fr} = -47.95 + 3126.39D_{in} - 32888.9D_{in}^2 - 1.22469 \cdot 10^{-6}n^2 + 0.0199444n - 0.00009tn + 0.860278t - 0.00572222t^2; \quad (1)$$

- for barley:

$$k_{fr} = -38.2833 + 3147.92D_{in} - 31479.2D_{in}^2 + 0.0134417n + 0.239375t; \quad (2)$$

- for soybeans:

$$k_{fr} = -30.6125 + 2957.92D_{in} - 33166.7D_{in}^2 + 0.0136778n - 0.000109444tn + 1.06688t - 0.00845833t^2. \quad (3)$$

where k_{fr} – content of particles sized 0–0.5 mm in the mixture, %; D_{in} – diameter of the stator inlet orifice, m; n – rotor rotation frequency, rpm; t – equipment operating (processing) time, min.

Data analysis performed using the Cochran's criterion shows that at a 95% confidence level, the dispersions are homogeneous: $G(1) = 0.0973$, $G(2) = 0.1318$, $G(3) = 0.1029$, which is less than the tabulated value $G(0.05, 2, 15) = 0.3346$. The Fisher's criterion values for each of the presented equations, $F(1) = 1.7033$, $F(2) = 1.4036$, $F(3) = 1.422$, are less than the tabulated value $F(0.05, 8, 30) = 2.27$. Therefore, it can be concluded that the calculated dependencies are adequate. The graphical interpretation of dependencies (1)–(3) is shown in Figure 4.

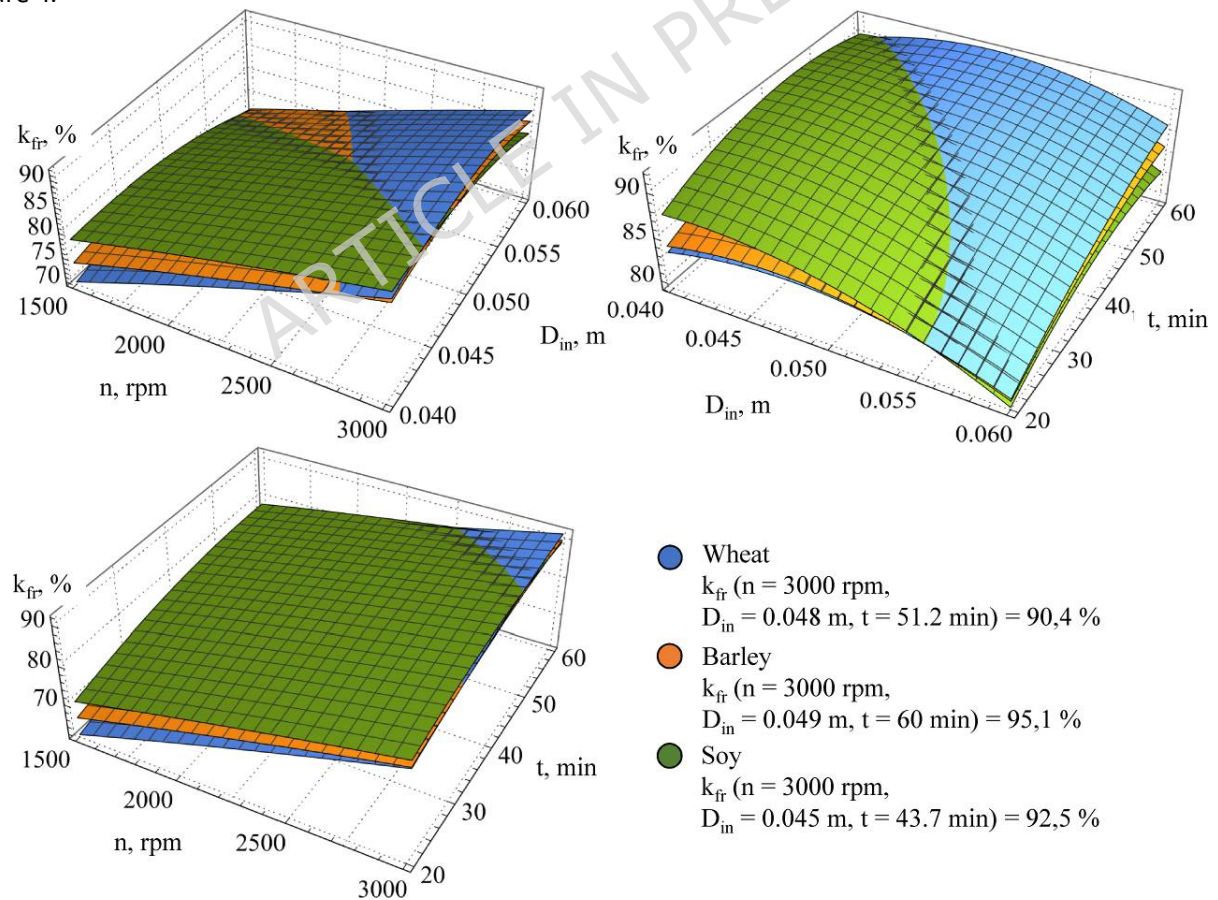


Figure 4. Dependencies of the change in the content of particles with a size of 0–0.5 mm in the mixture (k_{fr} , %) on the frequency of rotation of the rotor (n , rpm), the diameter of the stator inlet (D_{in} , m) and the time of operation of the equipment (t , min)

The maximization of the indicator of particles sized 0–0.5 mm content in the mixture k_{fr} occurs with an increase in the rotation frequency of the working elements n and a decrease in the diameter of the inlet opening D_{in} . During the comminution of different crops, the dependency differs. When grinding wheat, the k_{fr} index increases almost linearly with increasing rotation frequency of the working elements n . The maximum value of the k_{fr} indicator for grinding wheat, barley, and soybeans is achieved with a diameter of the opening of 0.048 m, 0.049 m, and 0.045 m, respectively. With all types of crops studied, the k_{fr} indicator reaches its maximum value with the highest rotation frequency n . The influence of the duration of equipment operation t is interesting. After reaching the maximum values of the k_{fr} indicator (at 51.2 min for wheat, 60 min for barley, and 44.7 min for soybeans), a leveling of the dependency curve is observed, and even a slight decrease. This is explained by reaching the critical value of the content of particles sized 0–0.5 mm in the mixture k_{fr} .

After analyzing the data from the experimental studies and discarding insignificant coefficients using the Student's criterion, final second-order regression equations for the mixture stratification indicator were formulated:

- for wheat:

$$i_d = 82.0292 - 0.0597667n + 0.0000125407n^2 - 0.116875t; \quad (4)$$

- for barley:

$$i_d = 80.1993 + 384.476D_{in} - 4894.76D_{in}^2 - 0.0610564n + 0.0000126557n^2 - 0.149375t; \quad (5)$$

- for soybeans:

$$i_d = 72.9792 + 753.472D_{in} - 9347.22D_{in}^2 - 0.0602667n + 0.000012279n^2 - 0.0807639t - 0.00117014t^2. \quad (6)$$

where i_d – mixture stratification index, %; D_{in} – diameter of the stator inlet orifice, m; n – rotor rotation frequency, rpm; t – equipment operating (processing) time, min.

The results of data analysis using the Cochran's criterion confirm the homogeneity of dispersions at a 95% confidence level: $G(4) = 0.1361$, $G(5) = 0.1513$, $G(6) = 0.1157$, which is less than the tabulated value $G(0.05, 2, 15) = 0.3346$. The Fisher's criterion values for each of the presented equations are also less than the tabulated value $F(0.05, 11, 30) = 2.13$, namely: $F(1) = 1.1050$, $F(2) = 2.0338$, $F(3) = 2.1135$. Therefore, it can be concluded that the obtained dependencies are adequate. The graphical representation of these dependencies (4)–(6) is shown in Figure 5.

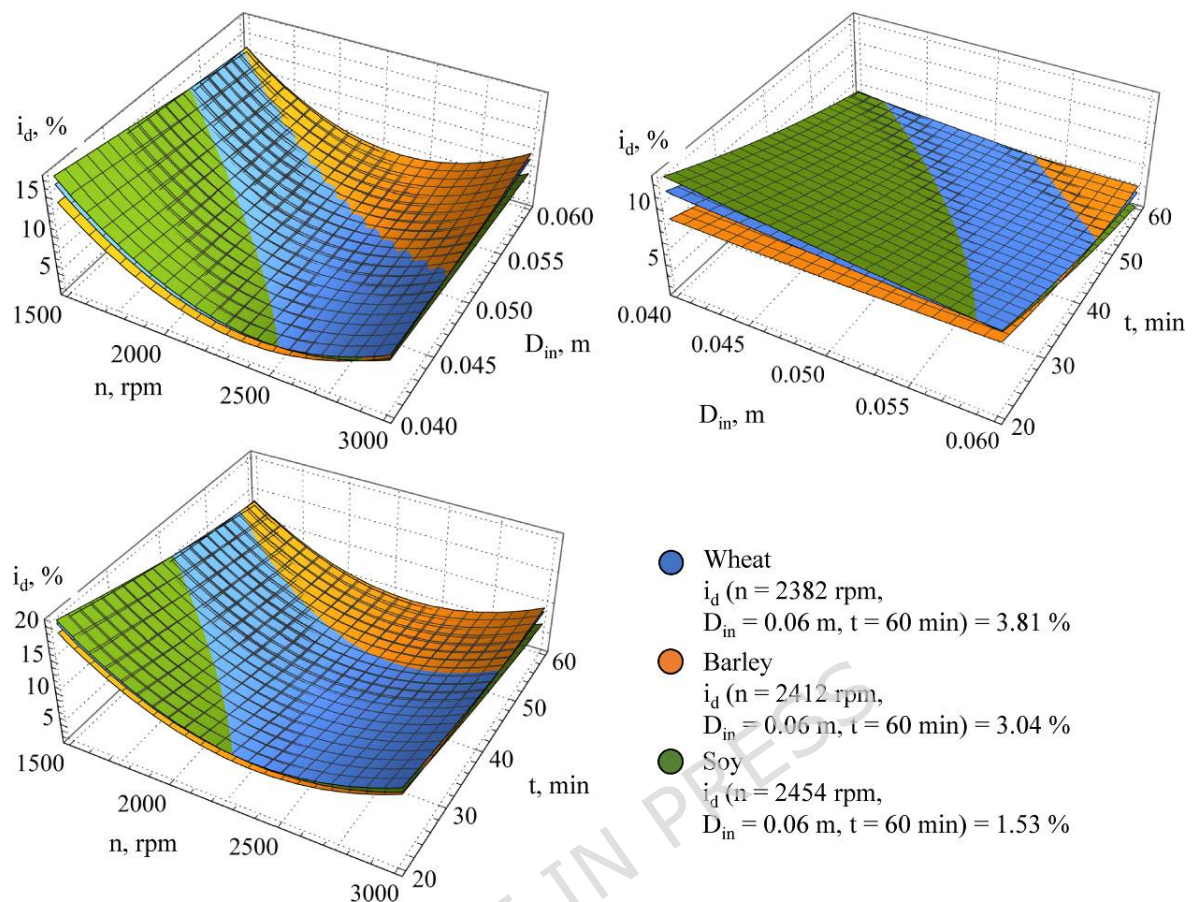


Figure 5. Dependencies of the change in the index of stratification of the mixture (i_d , %) on the frequency of rotation of the rotor (n , rpm), the diameter of the stator inlet (D_{in} , m) and the operating time of the equipment (t , min)

The mixture stratification indicator i_d obtained during the experiment significantly decreases with increasing rotation frequency n , reaching the lowest indicator at 2382 rpm (wheat), 2412 rpm (barley), 2454 rpm (soybeans). With further increase in the rotation frequency beyond these limits, a slight increase in the stratification indicator is observed. The mixture stratification i_d also depends on the duration of equipment operation t . The lowest stratification indicator is in the time range from 50 to 60 minutes, with a decrease in the mixing time, the stratification indicator increases

After processing the data from the experimental studies and discarding insignificant coefficients using the Student's criterion, final second-order regression equations for the mixture temperature at the end of the process were obtained:

- for wheat:

$$T = -6.57437 - 5.22333 \cdot 10^{-6} n^2 + 0.020433n + 0.0004829tn + 0.42018t - 0.01221t^2; \quad (7)$$

- for barley:

$$T = -19.4153 + 398.875D_{in} - 6.4208 \cdot 10^{-6} n^2 + 0.0211722n + 0.0005279tn + 0.339285t - 0.0130231t^2; \quad (8)$$

- for soybeans:

$$T = -15.914 + 271.375D_{in} - 4.71963 \cdot 10^{-6} n^2 + 0.0196833n + 0.00051958tn - 0.0758542t - 0.00713073t^2. \quad (9)$$

where T – mixture temperature at the end of processing, °C; D_{in} – diameter of the stator inlet orifice, m; n – rotor rotation frequency, rpm; t – equipment operating (processing) time, min.

The results of data analysis using the Cochran's criterion confirm the homogeneity of dispersions at a 95% confidence level: $G(7) = 0.1335$, $G(8) = 0.1337$, $G(9) = 0.1320$, which is less than the tabulated value $G(0.05, 2, 15) = 0.3346$. The Fisher's criterion values for each of the presented equations are also less than the tabulated value $F(0.05, 8, 30) = 2.27$, namely: $F(7) = 1.96$, $F(8) = 2.26$, $F(9) = 1.93$. This indicates the adequacy of the calculated dependencies. The graphical representation of these dependencies (7)-(9) is provided in Figure 6.

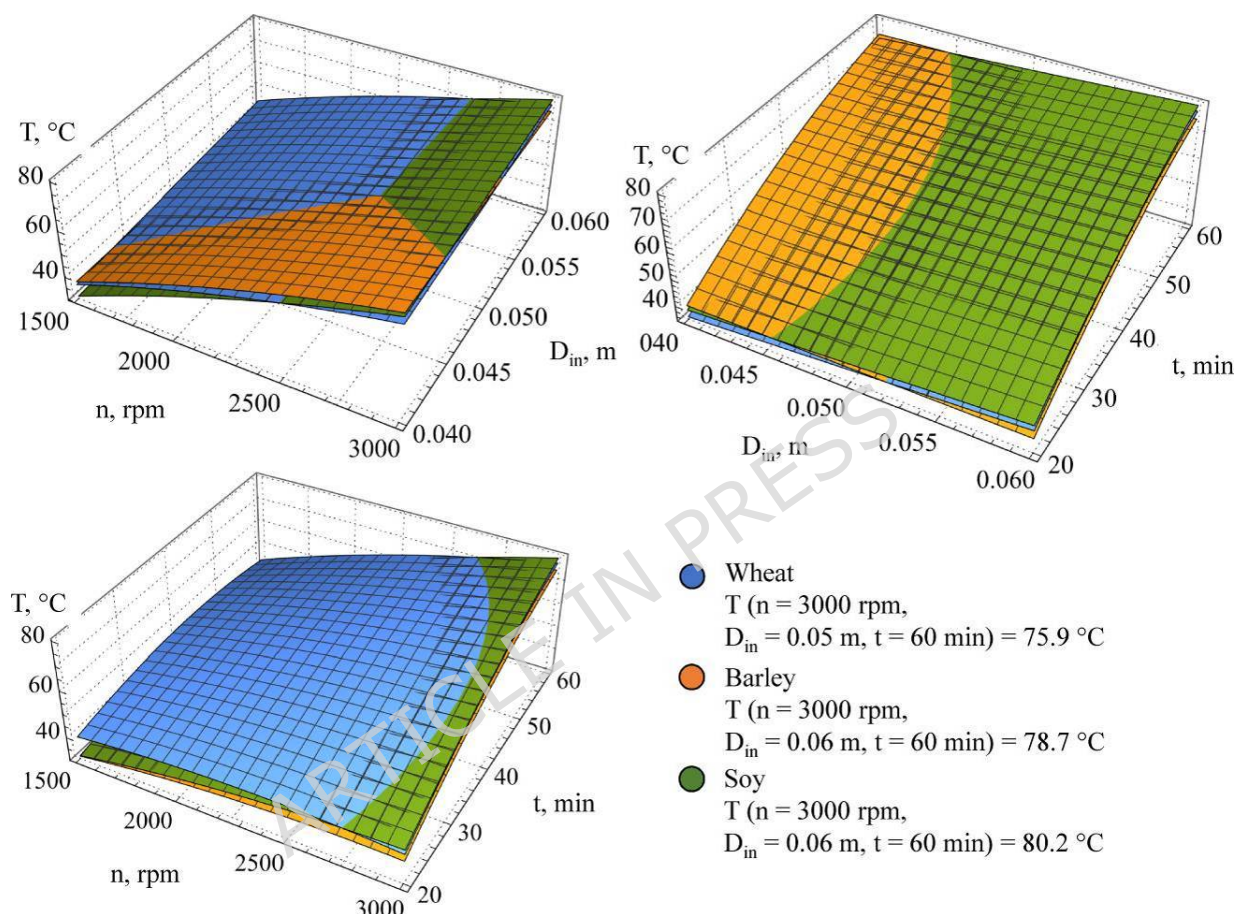


Figure 6. Dependences of the change in temperature of the mixture (T , °C) on the frequency of rotation of the rotor (n , rpm), the diameter of the stator inlet (D_{in} , m) and the operating time of the equipment (t , min)

The mixture temperature T during the preparation process of liquid feed exhibits a significant dependence on the equipment operating time t . Thus, with an increase in the process duration t from 40 minutes to 60 minutes, the temperature T rises from 40 °C to 80 °C. Predicting further changes in temperature T , we can assert its stabilization at a certain level (75.9 °C for wheat, 78.7 °C for barley, 80.2 °C for soybeans). Additionally, increasing the rotor rotation frequency n leads to an increase in temperature T , explained by the intensified process of grinding and cavitation. There is a minor difference in the mixture temperature T within the working chamber of the equipment for different materials. The diameter of the opening D_{in} practically does not affect the change in the mixture temperature T .

After discarding insignificant coefficients using the Student's criterion in the data processing of experimental studies, final second-order regression equations for the power consumption of the cavitation homogenizer motor were obtained:

- for wheat:

$$N = 1.86519 - 16.05D_{in} + 0.0122667nD_{in} + 1.50979 \cdot 10^{-7} n^2 - 0.0006754n - 3.93333 \cdot 10^{-6} tn - 0.0145227t + 0.000156065 t^2; \quad (10)$$

- for barley:

$$N = -1.00087 - 847.083D_{in}^2 + 1.0348 \cdot 10^{-7} n^2 + 74.5917D_{in} + 0.010156nD_{in} - 0.04833tD_{in} - 0.00033561n - 4.461 \cdot 10^{-6} tn + 0.0103438t - 0.000089479t^2; \quad (11)$$

- for soybeans:

$$N = 0.156708 + 11.6375D_{in} + 0.000478667n - 0.0452062t + 0.000428958t. \quad (12)$$

where N – electric motor power consumption, kW; D_{in} – diameter of the stator inlet orifice, m; n – rotor rotation frequency, rpm; t – equipment operating (processing) time, min.

The results of data analysis using the Cochran's criterion demonstrate the homogeneity of dispersions at a 95% confidence level: $G(10) = 0.1349$, $G(11) = 0.1160$, $G(12) = 0.1031$, which is less than the tabulated value $G(0.05, 2, 15) = 0.3346$. The Fisher's criterion values for each of the provided equations are also less than the tabulated value $F(0.05, 8, 30) = 2.27$, namely: $F(10) = 1.56$, $F(11) = 2.22$, $F(12) = 2.15$. This confirms the adequacy of the calculated dependencies. The graphical representation of these dependencies (10)–(12) is presented in Figure 7.

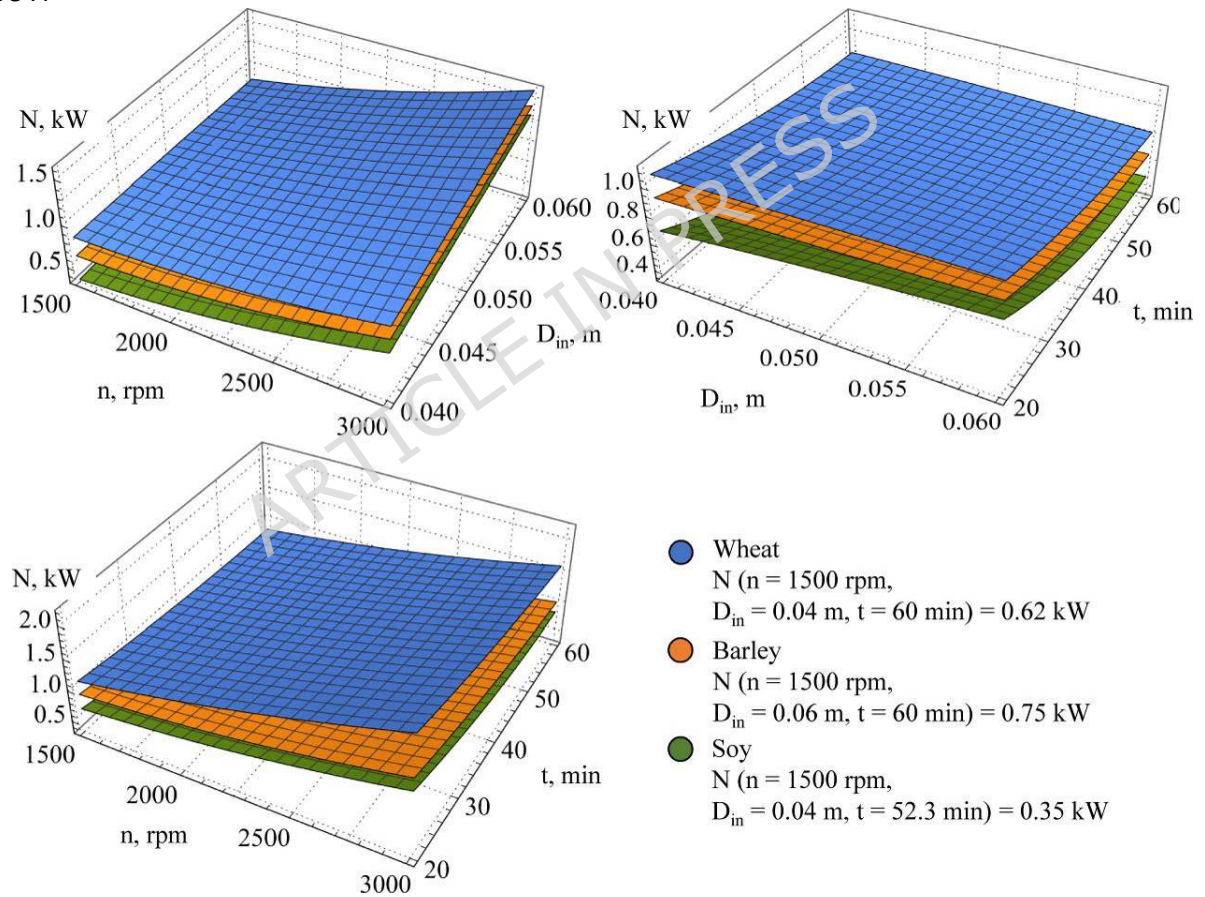


Figure 7. Dependencies of the change in the power consumption of the electric motor (N , kW) on the frequency of rotation of the rotor (n , rpm), the diameter of the stator inlet (D_{in} , m) and the operating time of the equipment (t , min)

Minimizing power consumption N is achieved by reducing the rotor rotation frequency to 1500 rpm, as well as by increasing the mixing time to 60 minutes. There is a dependence of power consumption N on the diameter of the inlet orifice in the stator of the disperser-homogenizer D_{in} . Thus, when using a stator with an

inlet orifice diameter of 0.040 m, the minimum value of power consumption N is observed. However, increasing the diameter of the inlet orifice in the stator from 0.040 m to 0.060 m results in an increase in power consumption by approximately 0.43–0.51 kW. Depending on the application of different crops: during wheat grinding, power consumption achieves the lowest value, while during soybean and barley grinding, power consumption increases by approximately 15.2–17.5 %. During wheat grinding, the power consumption by the equipment motor reaches the highest value among the listed values, ranging from 0.62 kW to 1.51 kW. This is due to the physical and mechanical properties of grains of different crops, such as density, size, and fracture strength.

After conducting data analysis of experimental studies and discarding insignificant coefficients using the Student's criterion, final second-order regression equations for energy consumption were obtained:

- for wheat:

$$E = 5.7478 + 4.70578 \cdot 10^{-7} n^2 - 0.0035578n + 0.00002478tn - 69.765D_{in} + 0.0328nD_{in} + 0.6375tD_{in} - 0.02985 t; \quad (13)$$

- for barley:

$$E = -0.916517 - 37.07D_{in} + 0.0294267nD_{in} - 0.00127713n + 0.0000250533tn + 0.0686008t - 0.000717917t^2; \quad (14)$$

- for soybeans:

$$E = -1.20842 + 35.51D_{in} + 0.000095n + 0.0000286467tn - 0.0175925t. \quad (15)$$

where E – energy consumption of the process, MJ; D_{in} – diameter of the stator inlet orifice, m; n – rotor rotation frequency, rpm; t – equipment operating (processing) time, min.

The results of the data analysis using the Cochran's criterion indicate the homogeneity of dispersions at a 95 % confidence level: $G(13) = 0.1559$, $G(14) = 0.1264$, $G(15) = 0.1217$, which is less than the tabulated value $G(0.05, 2, 15) = 0.3346$. The Fisher's criterion values for each of the provided equations are also less than the tabulated value $F(0.05, 7, 30) = 2.33$, namely: $F(13) = 2.21$, $F(14) = 2.12$, $F(15) = 1.76$. This indicates the adequacy of the obtained dependencies. The graphical representation of these dependencies (13)–(15) is shown in Fig. 8.

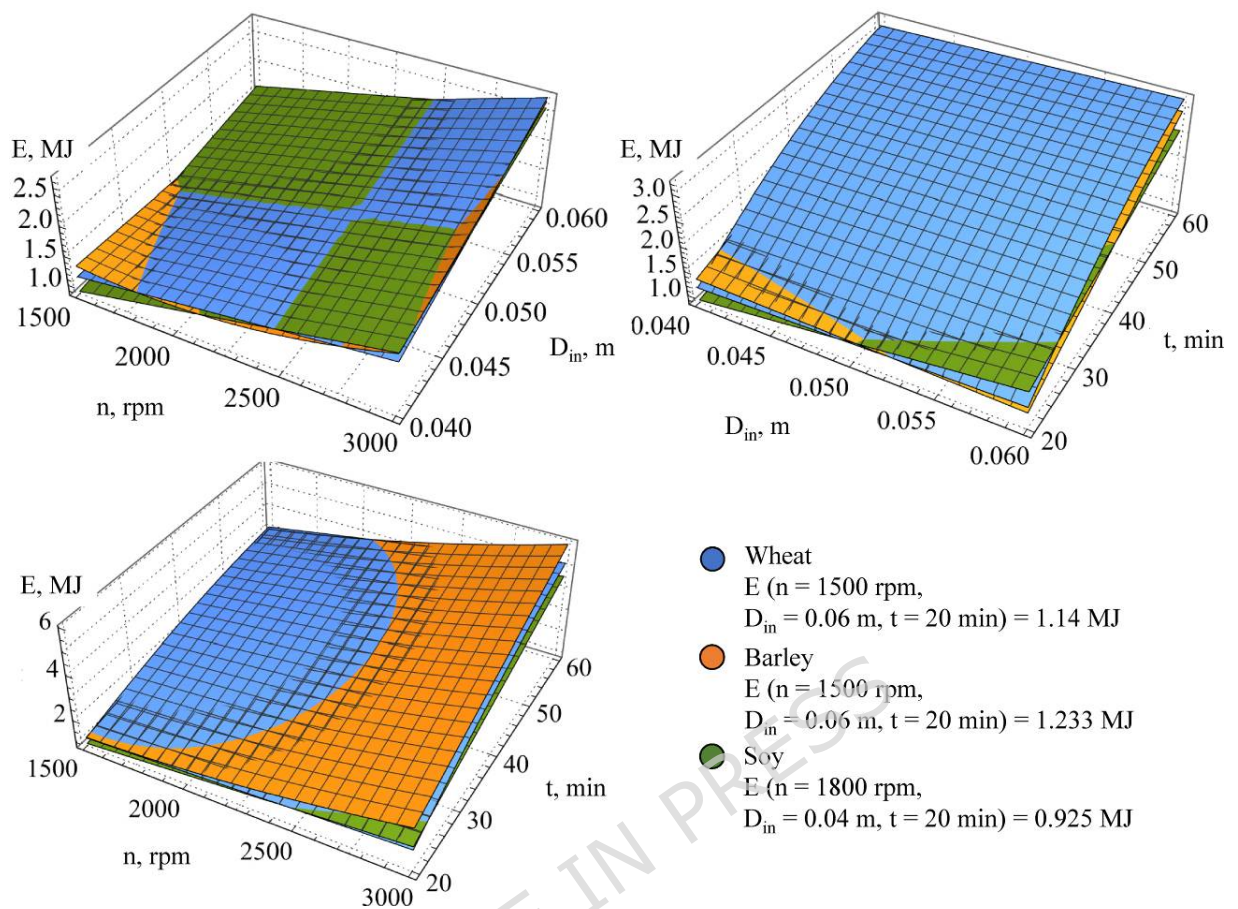


Figure 8. Dependence of the change in energy consumption (E, MJ) for the execution of the process on the frequency of rotation of the rotor (n, rpm), the diameter of the stator inlet (D_{in}, m) and the operating time of the equipment (t, min)

The energy consumption index E for the process depends on factors such as equipment operation time t, rotation frequency n, and the diameter of the inlet orifice in the stator D_{in} of the rotor disperser-homogenizer. A significant increase in energy consumption E from 0.9 MJ to 6.1 MJ is observed when the mixing time increases from 20 minutes to 60 minutes, with this increase being linear. Regarding this increase in energy consumption E, there is almost no observation of changes due to the variation of the diameter of the inlet orifice D_{in} in the stator. Additionally, there is a dependence of energy consumption E on the rotation frequency n of the equipment's rotor. When increasing the rotation frequency from 1500 rpm to 3000 rpm, there is an increase in energy consumption from 0.9 MJ to 1.8 MJ at 20 minutes of equipment operation. This is due to the increased circulation of the liquid in the dispersion process and, consequently, an increase in the load on the drive motor of the equipment.

To justify the rational design and technological parameters of the cavitation disperser-homogenizer, specific energy consumption values E_Q were calculated for each experiment. After processing the obtained data, a dependency in the form of a second-order regression equation of specific energy consumption E_Q on the research factors, taking into account rejected insignificant coefficients by the Student's criterion, was obtained:

- for wheat:

$$E_Q = 2.13427 + 380.642D_{in}^2 + 9.1278 \cdot 10^{-8}n^2 - 0.00073436n + 4.209 \cdot 10^{-6}tn - 50.9548D_{in} + 0.00678296nD_{in} + 0.134669tD_{in} - 0.00460813t; \quad (16)$$

- for barley:

$$E_Q = -0.745819 + 6.89807D_{in} + 0.00014967n + 0.0269918t - 0.000169362t^2; \quad (17)$$

- for soybeans:

$$E_Q = -0.267809 + 10.535D_{in} - 0.0000278195n + 5.7824 \cdot 10^{-6}tn - 0.003647t. \quad (18)$$

where E_Q – specific energy consumption, MJ/kg; D_{in} – diameter of the stator inlet orifice, m; n – rotor rotation frequency, rpm; t – equipment operating (processing) time, min.

The results of data analysis using the Cochran's criterion confirm the homogeneity of dispersions at a 95% confidence level: $G(16) = 0.2097$, $G(17) = 0.2412$, $G(18) = 0.3139$, which is less than the tabulated value $G(0.05, 2, 15) = 0.3346$. The Fisher's criterion values for each of the provided equations are also less than the tabulated value $F(0.05, 7, 30) = 2.33$, namely: $F(16) = 1.63$, $F(17) = 2.12$, $F(18) = 2.13$. This confirms the adequacy of the obtained dependencies.

By minimizing specific energy consumption E_Q while maintaining the mixture stratification index $i_d < 5\%$ (according to [16]), a graphical interpretation of the dependencies (16)–(17) taking into account (4)–(6) was constructed in Figure 9.

Minimizing specific energy consumption E_Q under the condition that the stratification index $i_d < 5\%$ occurs with a reduction in the diameter of the inlet orifice in the stator D_{in} of the disperser-homogenizer to the size of 0.056–0.057 m, which is due to the decrease in the fluid flow inside the equipment. In this case, a dependence of specific energy consumption E_Q on the rotor rotation frequency is observed, so that when increasing the rotor rotation frequency n from 1500 rpm to 3000 rpm, there is an increase in specific energy consumption E_Q within 0.5 MJ/kg. However, with $i_d < 5\%$, the rational rotation frequency n for different feedstock is within the range of 2267–2331 rpm. The time of equipment operation t has a more significant impact on specific energy consumption. Thus, when increasing the equipment operation time t from 20 minutes to 60 minutes, the specific energy consumption E_Q increases by approximately 0.8 MJ/kg at a constant rotation frequency n . Under the condition of $i_d < 5\%$, and E_Q to min, the rational value of the equipment operation time t for different feedstock is observed within the range of 45.1–50.4 minutes. There is a slight change in the specific power consumption index E_Q depending on the type of grain crops used during the experiment, thus the lowest specific energy consumption is observed when using soybeans – 0.696 MJ/kg, when using wheat – 0.794 MJ/kg, and when using barley – 0.896 MJ/kg.

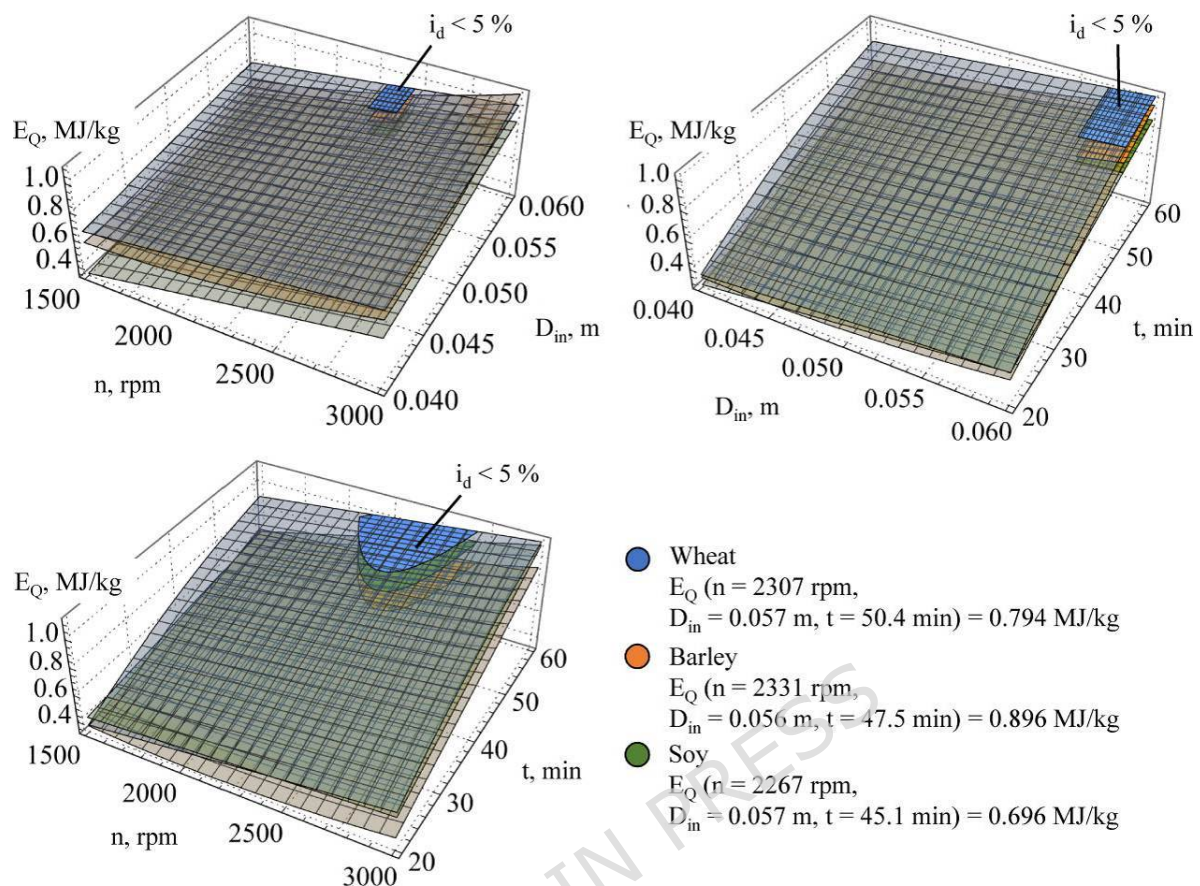


Figure 9. Dependence of the specific energy consumption (E_Q , MJ/kg) for the execution of the process on the frequency of rotation of the rotor (n , rpm), the diameter of the stator inlet (D_{in} , m) and the operating time of the equipment (t , min).

General summary numerical information for constructing a graphic interpretation of the figures is given in Appendix A.

The developed design-technological scheme of the liquid feed homogenizer-disperser [18] corresponded to the ideas laid down in the studies [16, 17]. Analysis of previous numerical modeling [19] confirmed the effectiveness of the adopted design. Conducted experimental studies allowed determining rational design-regime and technological parameters: diameter of the inlet orifice in the stator, rotor rotation frequency, and equipment operation time.

The derived second-order regression equations form a unified parametric model of the cavitation disperser-homogenizer, which can be directly implemented in an automatic control system of the equipment. In particular, the established relationships between rotor rotation frequency, stator inlet diameter, and processing time with dispersion quality, mixture stability, temperature, power, and energy consumption enable real-time adjustment of operating parameters to maintain the required technological indicators within specified limits.

From an engineering standpoint, the obtained models make it possible to design control algorithms that ensure stable homogenization of liquid feed ($i_d < 5\%$) while minimizing specific energy consumption, without exceeding admissible temperature levels. The regression equations can be used as a digital representation of the technological process (soft sensor), allowing predictive control of the equipment based on indirectly measurable parameters such as motor speed, power consumption, and processing time. This approach reduces operator intervention, prevents operation in energetically inefficient or technologically unstable regimes, and increases the overall reliability and efficiency of the cavitation disperser-homogenizer.

Thus, the presented dependencies should be interpreted as a practical tool for engineering design and automation of cavitation equipment rather than as isolated mathematical results, ensuring the transition from experimental research to industrial implementation of the proposed disperser-homogenizer.

The technical and economic efficiency of implementing a rotary cavitation disperser-homogenizer for liquid pig feed was evaluated in comparison with two reference installations: a rotary cavitation disperser RCD (ZNDCMT IMA AIP NAAS, Zaporizhzhia, Ukraine) and a flow-type homogenizer (STS Group, Dnipro, Ukraine). The comparison was carried out using the methodology of DSTU 4397:2005 [27]. The indicators and coefficients for calculating electricity costs, depreciation, maintenance and repair, and labor costs were adopted according to data reported in the literature sources [28,29].

The object of the study was a pig farm with a total livestock of 800 pigs, 25% of which (200 heads) were at the growing stage. Liquid feed produced using the cavitation rotary disperser-homogenizer was used as a milk replacer for growing piglets. As shown in Table 2, the first technology is the rotary cavitation disperser RCD (ZNDCMT IMA AIP NAAS), the second is an industrial flow-type homogenizer (STS Group), and the third is an experimental installation based on a rotary cavitation disperser-homogenizer. All three technologies operate in batch mode but differ in cycle duration, mixing volume, and design features.

Table 2 Indicators of economic efficiency of implementation

Indicator	RCD ZNDCMT IMA AIP NAAS (I)	Flow homogenizer STS Group (II)	Rotary cavitation disperser- homogenizer (III)
Number of pigs, heads	200	200	200
Daily requirement, kg	2	2	2
Annual requirement, kg	730	730	730
Total farm feed requirement, kg	146,000	146,000	146,000
Annual operating time, h	4,380	3,893.33	4,055.55
Batch mass, kg	20	30	18
Productivity, kg/h	33.33	37.5	36
Power consumption, kW	3.2	4.0	1.1
Operating time per batch, h	0.6	0.8	0.5
Annual electricity consumption, kWh	14,016	15,573.33	4,461.11
Personnel, persons	1	1	1
Machine cost, USD	2,258.82	2,823.53	3,294.12
Labor costs, USD	13,521.32	12,019.07	12,519.74
Electricity costs, USD	1,424.68	1,582.98	453.46
Depreciation costs, USD	406.59	508.24	592.94
Maintenance and repair costs, USD	67.76	84.71	98.82
Total costs, USD	15,420.35	14,194.80	13,664.49
Specific costs, USD/kg	0.105	0.097	0.093
Additional capital investment (compare III relative to I), USD	1,035.29	470.59	–
Economic effect (compare III relative to I), USD	1,754.21	529.91	–
Specific economic effect (compare III relative to I), USD/kg	0.012	0.004	–
Payback period of additional investment (compare III relative to I), years	0.58	0.88	–

The comparative assessment shows that the experimental rotary cavitation disperser-homogenizer demonstrates the highest economic efficiency among the analyzed technologies. Owing to significantly lower installed power (1.1 kW) and reduced electricity consumption, its total annual operating costs are the lowest, amounting to USD 13,664.49, compared to USD 15,420.35 for the RCD and USD 14,194.80 for the flow-type

homogenizer. As a result, the specific processing cost is reduced to USD 0.093/kg, which is 11.4% lower than for the RCD and 4.1% lower than for the industrial homogenizer.

Despite higher initial capital costs, the experimental installation provides a positive annual economic effect of USD 1,754.21 compared to the RCD and USD 529.91 compared to the flow homogenizer. The payback period of additional investments does not exceed one year (0.58–0.88 years), indicating high investment attractiveness. Overall, the results confirm that the proposed rotary cavitation disperser–homogenizer is economically justified and suitable for practical implementation in liquid pig feed production.

Discussion

The conducted research confirms the relevance and practical significance of improving technological processes for feed preparation through cavitation-based dispersion and homogenization. According to previous studies [7–12], cavitation processing enables simultaneous size reduction of particles and the uniform distribution of feed components in mixtures, which corresponds to modern requirements for the quality of livestock feed [3–6].

Our experimental results provide new data regarding the operational parameters of cavitation hydro-impact dispersers, particularly in relation to feed production for pigs. The obtained dependencies between the rotor rotation frequency, stator inlet orifice diameter, operation time, and the resulting technological effects allow for a comprehensive evaluation of process efficiency. The observed relationships between the parameters reflect both the physical principles of cavitation and the specifics of hydrodynamic processes in the resonance chambers, as highlighted in studies [13–17].

A critical factor in feed preparation is particle size distribution uniformity, which directly affects the digestibility and nutrient absorption by livestock [4]. Our results demonstrated that increasing the rotor speed improves particle dispersion, resulting in a higher content of fine particles (0–0.5 mm). However, this also leads to an increase in mixture temperature and energy consumption, as predicted by cavitation theory [11, 12]. Therefore, the selection of rotor speed must balance between sufficient comminution and acceptable energy costs.

The stratification index (i_d) was used as a quantitative measure of mixture homogeneity. When $i_d < 5\%$, the mixture can be considered sufficiently uniform for practical feed production. This condition was achieved in our experiments at specific operational settings, confirming the efficiency of the cavitation homogenization process. These findings correlate with previous reports on the intensification of mixing through turbulence and pulsating hydraulic impacts [15–17].

Energy consumption analysis revealed that the specific energy demand depends not only on machine parameters but also on the type of processed material. Soybeans required the least energy (0.696 MJ/kg), followed by wheat (0.794 MJ/kg) and barley (0.896 MJ/kg). This agrees with the physical properties of these grains—such as density, moisture content, and hardness—which influence their susceptibility to cavitation treatment.

When compared with similar studies, our results provide a more comprehensive parametric characterization of cavitation-based feed processing. For example, prior works [7, 9, 12] primarily reported single-factor effects, such as rotor speed or treatment time, on particle size or mixture homogeneity, without integrating multi-factorial optimization or energy consumption analysis. In contrast, this study simultaneously considers multiple operational parameters, their interactions, and their impact on both technological and energetic indicators, thereby offering a more holistic framework for process design and scale-up. Furthermore, while some previous studies [10, 11] highlighted potential improvements in particle dispersion, they did not provide quantitative guidance for optimizing operational duration or balancing energy costs, which are addressed in our experiments.

An important contribution of this study is the optimization of operational time. The identified optimal processing duration (45.1–50.4 minutes) minimizes specific energy consumption while ensuring high-quality

dispersion and homogenization. This optimization is particularly relevant for industrial applications, where minimizing costs while maintaining product quality is critical.

The statistical verification using Cochran and Fisher criteria confirms the adequacy of the obtained models. This strengthens the reliability of the regression equations for predicting system behavior under varying operational conditions. The use of these models can facilitate adaptive control of cavitation equipment in real-time feed production processes.

However, certain limitations should be noted. The experiments were conducted under controlled laboratory conditions, and scaling up to industrial production may introduce additional factors such as wear of structural elements, continuous feed flow management, and variations in raw material properties over time. These limitations also differentiate our work from pilot-scale studies [8, 12], emphasizing the need for further validation under industrial conditions to confirm the applicability of the optimized parameters.

In conclusion, the results of this study not only align with existing knowledge on cavitation processing in feed technology but also extend it by providing optimized parameters for producing high-quality liquid feeds. The data obtained contribute to the development of energy-efficient, waste-minimizing technologies in agricultural feed production systems.

The engineering novelty of the homogenizer-disperser for liquid feeds lies in the following:

- Unlike standard dispersers, in the developed device the resonator openings are formed using an annular cut of spiral-shaped blades, similar in shape to the impeller of a circulation pump rotor. This ensures high productivity through efficient suction of the mixture into the central opening and particle size reduction via impact cutting and cavitation phenomena.
- The design is optimized using second-order regression models, allowing simultaneous consideration of the effects of rotor speed, processing time, and stator diameter on key technological parameters (particle size, stratification index, energy consumption). This approach distinguishes the device from existing analogs, where optimization is mostly carried out based on a single parameter.
- Easily replaceable mechanical and hardware modules are provided, enabling rapid reconfiguration for different types of liquid feeds and easy scaling from laboratory to industrial level.
- An integrated energy consumption control system maintains optimal mixture processing modes, minimizing energy consumption while preserving homogeneity and dispersion. Such functionality is absent in standard cavitation dispersers.
- The new design reduces the temperature rise of the mixture, ensuring the preservation of the quality properties of the components during processing.

In contrast to existing studies, which are mainly limited to qualitative descriptions of cavitation intensity or isolated experimental observations, this work presents an integrated parametric representation of the process of producing high-quality liquid feed using a cavitation disperser–homogenizer. The proposed approach is based on a multifactorial experimental design and rigorous statistical validation of the results.

In particular, the scientific novelty of the study consists in the following:

- A unified set of statistically adequate second-order regression models has been developed, which simultaneously describe the influence of rotor rotational speed, stator inlet orifice diameter, and processing time on dispersion quality (particle size distribution), mixture stability (stratification index), temperature rise, power consumption, as well as total and specific energy consumption. Unlike previous studies, these models form an integrated parametric system rather than a collection of independent empirical relationships.
- A multi-criteria optimization framework for cavitation-based liquid feed preparation has been proposed, enabling the identification of rational operating regimes under simultaneous constraints on dispersion quality (maximization of the 0–0.5 mm fraction), mixture homogeneity ($id < 5\%$), thermal stability, and minimum specific energy consumption. This approach extends beyond the single-criterion optimization commonly reported in the literature.
- The interaction between hydrodynamic cavitation effects and process energy efficiency has been quantitatively characterized for different types of grain raw materials (wheat, barley, and soybeans). This

allowed the identification of material-specific optimal operating regimes and demonstrated that cavitation processes cannot be adequately described by universal parameter values.

– The obtained regression models serve as a preliminary digital representation (soft sensor) of the technological process, capturing statistically validated dependencies that can inform future development of automatic or predictive control systems. While they do not implement full real-time intelligent regulation, they provide a structured framework for potential integration into such systems.

– A combined experimental and economic validation of the proposed cavitation disperser–homogenizer has been carried out, demonstrating that the optimized operating regimes derived from the statistical models result not only in technological improvements but also in measurable economic benefits compared with existing industrial counterparts.

Thus, the scientific novelty of this research is interpreted as a systemic contribution to the theory and practice of cavitation-based feed processing, providing a validated parametric and optimization framework applicable to the design, control, and industrial implementation of rotary cavitation disperser–homogenizers for liquid feeds.

Conclusions

During the experiment, dependencies were established as follows: changes in the content of particles sized 0–0.5 mm in the mixture (k_{fr} , %) as a function of rotor rotation frequency (n , rpm), stator inlet orifice diameter (D_{in} , m), and equipment operation time (t , s); changes in the mixture stratification index (i_d , %) as a function of rotor rotation frequency (n , rpm), stator inlet orifice diameter (D_{in} , m), and equipment operation time (t , s); changes in the mixture temperature (T , °C) as a function of rotor rotation frequency (n , rpm), stator inlet orifice diameter (D_{in} , m), and equipment operation time (t , s); changes in the power consumption of the motor (N , kW) as a function of rotor rotation frequency (n , rpm), stator inlet orifice diameter (D_{in} , m), and equipment operation time (t , s); and changes in energy consumption (E , MJ) for the process execution as a function of rotor rotation frequency (n , rpm), stator inlet orifice diameter (D_{in} , m), and equipment operation time (t , s).

The dependencies of specific energy consumption (E_Q , MJ/kg) for the process execution as a function of rotor rotation frequency (n , rpm), stator inlet orifice diameter (D_{in} , m), and equipment operation time (t , s) were analyzed. The application of the Cochran and Fisher criteria confirmed the adequacy of the obtained regression equations. Specifically, the data analysis conducted using the Cochran criterion shows that at a 95% confidence level, the dispersions are homogeneous: $G(1) = 0.0973$, $G(2) = 0.1318$, $G(3) = 0.1029$, which is less than the tabulated value $G(0.05, 2, 15) = 0.3346$. The Fisher criterion values for each of the equations presented above, $F(1) = 1.7033$, $F(2) = 1.4036$, $F(3) = 1.422$, are less than the tabulated value $F(0.05, 8, 30) = 2.27$. Therefore, it can be asserted that the calculated dependencies are adequate.

Under the condition where the parameter i_d is less than 5% and the efficiency E_Q needs to be minimized, the optimal value of equipment operation time t for different types of input material is observed within the range of 45.1–50.4 minutes. Additionally, there is a slight change in the specific energy consumption E_Q depending on the type of cereal crops used during the experiment. The lowest specific energy consumption is observed when using soybeans – 0.696 MJ/kg, wheat – 0.794 MJ/kg, and barley – 0.896 MJ/kg.

Author Contributions:

Conceptualization, E.A., R.M. and T.H.; methodology, O.A., V.Y. and S.K.; validation, I.H. and P.K.; formal analysis P.K.; data curation, E.A., R.M.; software, I.H., V.P.; writing—original draft preparation, O.A. and V.Y.; writing—review and editing, T.H. and S.K.; project administration, E.A.; visualization, I.H., V.P.; funding acquisition, P.K.; supervisions, T.H. All authors have read and agreed to the published version of the manuscript.

Funding:

This project has received funding from the ministry of Education of Science Republic Poland for the Agricultural University in Krakow for the year 2026 and Ministry of Education, Science and Sports of the Republic of Lithuania and Research Council of Lithuania (LMTLT) under the Program 'University Excellence Initiative' Project 'Development of the Bioeconomy Research Center of Excellence' (BioTEC), agreement No S-A-UEI-23-14.

Data availability

The datasets used and analysed during the current study available from the corresponding author on reasonable request.

Acknowledgments:

We express our sincere gratitude to the anonymous reviewers for their constructive feedback, which significantly improved this manuscript, as well as to the Ukrainian University in Europe (<https://universityuue.com/>, access date: 09.09.2025).

Conflicts of Interest:

The authors declare no conflicts of interest.

Received:

Accepted:

Published online:

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Nomenclature

Symbol	Description	Unit
n	Rotor rotation frequency	rpm

D_{in}	Diameter of the stator inlet orifice	m
t	Equipment operating (processing) time	min
k_{fr}	Content of particles sized 0–0.5 mm in the mixture	%
i_d	Mixture stratification index	%
T	Mixture temperature at the end of processing	°C
N	Electric motor power consumption	kW
E	Energy consumption of the process	MJ
E_Q	Specific energy consumption	MJ/kg
Q	Productivity of the homogenizer–disperser	kg/h
V	Volume of loaded mixture	m ³
m	Mass of the mixture	kg