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Mathematical modeling and optimization of the granulation process of biomass-based products with potential applications in the feed and food industries

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ABSTRACT

This study aimed to develop and validate a mathematical model for optimizing the granulation process of compound feed for cattle, with a focus on minimizing pellet crumbliness and specific energy consumption. A two-factor central composite design was used to evaluate the effects of feed mixture moisture, granulation temperature, steam pressure, and energy input. The crumbliness index was selected as the primary quality indicator. Experimental data were processed using Microsoft Excel 2010 and Statistica 10, and model adequacy was assessed using Fisher's criterion. The resulting second-degree polynomial models enabled the prediction of optimal granulation parameters: a moisture content of 18.9%, a steam pressure of 0.31 MPa, and an energy consumption of 8.3 kWh/t, corresponding to a pellet crumbliness of 22%. The application of mathematical modeling proved effective in enhancing product quality by enabling real-time control of key technological factors. These findings support the use of optimized granulation parameters in industrial feed production to improve efficiency and reduce material losses.

Keywords: modeling, steam pressure, granulation, feed, cattle

INTRODUCTION

The food industry, despite its evident importance for human sustenance, is a significant source of organic waste. According to the FAO, up to 1.3 billion tons of food are lost globally each year, a portion of which could be reused. Effective management of food processing waste is a crucial aspect of sustainable development. Food waste, particularly high-protein materials (such as meat trimmings and dairy residues) and carbohydrate-rich materials (like oilseed cakes, bran, and fruit pomace), can be successfully processed into a granular form after appropriate treatment. Granulation helps reduce waste volume, prevents environmental pollution, and lowers methane emissions from the decomposition of organic matter in landfills. Stabilized granules are less susceptible to microbiological degradation. Granules made from food waste can serve as raw materials for the production of: feed for livestock and fish; organo-mineral fertilizers; biofuel (pellets); and biopolymers and packaging (in the case of waste containing biopolymer components, such as starch) **[1]**.

Among the various methods for processing organic residues, granulation is given special attention as a universal technology that facilitates storage, transportation, and the potential reuse of granules as secondary resources, such as animal and fish feed, fertilizers, biofuels, and more.

The modern system of complete nutrition for farm animals involves the scientifically based balancing of feeding rations by nutrients, energy, macro- and microelements, and vitamins. Numerous studies have demonstrated that the productivity of farm animals, including cattle, is significantly enhanced when they are provided with complete feed. This is achieved through animals' balanced diets. The need for animal husbandry in compound feed is very high. To increase the efficiency of using feed resources in the Republic of Kazakhstan, it is advisable to replace concentrated feed with compound feed. An important source of various nutrients for cattle are secondary resources of the processing industries: corn feed, corn gluten, beet pulp, molasses, meals and cakes **[2]**, **[3]**, and **[4]**. Various by-products of oil crop processing are actively incorporated into feeding practices. They have become promising animal feeds and potential protein sources for use in the livestock industry to improve animal productivity **[5]**, and **[6]**. Technological solutions for the rational use of waste from processing and agricultural raw materials enable the extraction of additional profit **[7]**, and **[8]**.

The Kazakh Research Institute of Processing and Food Industry LLP is the only research institute in the Republic of Kazakhstan that develops compound feed for farm animals. In recent years, the institute's employees have been working on using waste from processing industries for compound feed. Scientists at the institute are creating new recipes and technologies for granulated and extruded compound feed for farm animals.

Granulated complete feed has several advantages over traditional feed products, including reduced feed losses, facilitated transportation and distribution, and improved physical and taste qualities **[9]**. Biologically active substances are also better preserved in granules **[10]**. When feed is granulated, biochemical changes occur under the influence of mechanical and hydrothermal processes, increasing its nutritional value and digestibility by 10% **[11]**.

The simultaneous action of moisture, heat, and mechanical pressure in the press chamber provides the necessary moistening and heating of the product, followed by the formation of granules in the spinnerets channel **[12]**, **[13]**, and **[14]**.

The pressing process is as follows. The material absorbs mechanical energy (spends it on overcoming external and internal friction; transition of elastic deformations into plastic ones), heating the product by 5-10 ^{0}C. The best course of the granulation process for compound feed occurs at a component humidity of 14-16%. As a result of granulation, the shape and physical and mechanical properties of the original material change **[15]**. It acquires a large bulk density, good flowability, and becomes more transportable.

The obtained granules must comply with GOST 22834-87 in terms of quality indicators, which include water resistance, crumbliness, and density. The crumbliness of the finished granules was adopted as the primary criterion for the granulation process, as it affects their safety during storage and transportation.

Granule crumbliness is a qualitative indicator that characterizes the degree of coherence of the particles that make up the granules. When transporting feed, especially over long distances, and if transportation is carried out on roads in poor condition, granules can break down, losing their consumer qualities and decreasing in volume **[16]**, and **[17]**. In Kazakhstan, the crumbliness of granules is determined according to GOST 28497-2014 **[18]**.

Thus, when feeding high-quality granulated feed, higher productivity (milk yield, average daily weight gain) is observed than when using loose compound feed. Granulation increases feed consumption and live weight gain, while also improving feed conversion and digestibility. These advantages result from the impact on behavior, because the animal spends less energy to consume food. Granulation significantly reduces feed losses and prevents sorting. The intake of nutrients into the body during one meal becomes more uniform and balanced. In addition, granulation can minimize the impact of anti-nutritional factors in feed and simplify transportation and storage.

Considering that the crumbling of granules should not exceed 10%, in connection with which it restrains the increase in the productivity of the press, since with the growth of productivity, the crumbling also increases due to the reduction in the time of stay of the feed in the pressing channel with an increase in the frequency of rotation of the matrix and feed supply. In this regard, when developing recipes for compound feed for cattle, it is necessary to optimize the granulation process and reduce energy intensity and granule crumbling by developing a mathematical model. This will increase the profitability of compound feed.

Scientific Hypothesis

By changing the parameters of the granulation technological process, the physical properties of the resulting finished granulated compound feed for cattle can be influenced.

Creating an accurate mathematical model of the granular feed granulation process on a granulator press and determining its optimal parameters, such as steam pressure and humidity, will enable the production of feed pellets with minimal crumbling and low specific energy consumption.

Objectives

The objective of this study was to develop and validate a mathematical model that describes the granulation process of biomass-based materials used for granular product production. The model aimed to identify optimal operating parameters (steam pressure and moisture content) that minimize energy consumption and crumbliness of granules. Although the study focuses on cattle feed, the modeling approach and findings are potentially applicable to the granulation of biomass-derived food products.

MATERIAL AND METHODS

Samples

Granulation of compound feed for cattle.

Chemicals

No chemicals were used.

Instruments

Tabletop laboratory scales M WP-N, installation for determining the crumbliness of compound feed pellets U17-UKG, electric drying cabinet SESH-3M.

Laboratory Methods

The crumbliness of granules was determined following GOST 28497-2014 "Feed, compound feed. The method for determining the crumbliness of granules, moisture control, was carried out according to GOST 57059-2016, which states, "Compound feed, compound feed raw materials, express method for determining moisture.

Description of the Experiment

Number of samples analyzed: 13

Number of repeated analyses: 2

Number of experiment replication: 2

Description of the Experiment: replicates were analyzed.

Design of the experiment: Strictly according to the developed recipes, experimental compound feeds were developed at the plant of JSC "AsiaAgroFood" in the Almaty region, specifically in the village of Sahamalgan. Production technology modes for cattle using the granulation method have been worked out. The granulation line at the plant is equipped with a system from the Russian company TechnoAgroService.

The technological granulation process follows the following sequence: The ingredients are pre-crushed, then mixed to achieve homogeneity. Then, the mixture is fed to the mixer. Water regulates the humidity of the mixture. Humidity control was performed in accordance with GOST 57059-2016.

The prepared mixture was supplied to the press unit. In the press unit, the matrix rotated, the mixture was drawn into the gap between the matrix and the rollers, and pressed into the holes in the matrix. As a result, granules were formed. The size of the holes in the matrix determines the diameter of the granules. The diameter of the holes in the granule press matrix is 5 mm. Then the resulting granules are passed through a cooling column, where the air flow reduces the humidity to 14-16%.

Combined feed for cattle is high in protein and energy. Accordingly, the components must be highly digestible. To increase the level of protein and fat in milk, spinnerets must be balanced in energy, protein, fiber, minerals, and vitamins; the feed must be of high quality. It is known that the lack of even 1% of feed protein in the cattle diet leads to an overspending of 2.0-3.5% of feed and an increase in production costs by 4.0-5.0%. When granulating, the fat content in the raw material should be no more than 6%, since a higher percentage negatively affects the density and strength of the granules.

The fat content of the raw material influences the process and results of feed pelleting. The pressure exerted on the raw material particles during pelleting causes fats and oils to migrate to their surface **[19]**. The surface lipid layer acts as a lubricant, reducing friction in spinnerets and thereby reducing the pelleting pressure and energy costs **[20]**. Fat reduces the contact of the raw material with the walls of the spinnerets channel, facilitating the passage of feed through it and thereby reducing compaction.

Therefore, granulated feed should contain 2 % to 8% fat. Such raw material for compound feed is the post-harvest waste of oil crops. Since post-harvest waste of oil crops contains mainly the substandard part of the main product, these waste of oil crops with a well-balanced amino acid composition of protein include a large amount of arginine (2 times more than in corn and wheat grain), histidine, lysine, and other essential amino acids.

The developed recipe is a complete feed for cattle, containing grain crops at up to 79%, post-harvest waste of oil crops at 18%, and mineral and other additives at 3%.

The crumbliness of granules was determined following GOST 28497-2014 "Feed, compound feed. Methods for determining the crumbliness of granules" on the U17-EKG device. To determine the crumbliness, two samples of finished granulated feed were taken and placed in separate chambers of the grinder. Set the time relay for 5 minutes, close the chamber lids, and turn on the unit. The chamber with granules rotates for 5 minutes at 50 rpm. After the time has elapsed, the grinder automatically switches off. Grinder chambers were open and pour its content onto the unit tray. The undestroyed granules were identified by sifting through small particles and crumbs. After sifting the granules, weigh with an error of ± 0.1 g.

The crumbling ability was calculated using the formula (1):

$$K = \frac{m_1 - m_2}{m_1} \times 100\% \qquad (1)$$

Where:

m_1 - mass of granules before testing, g;

m_2 - mass of granules after testing, g;

The final test result was the arithmetic mean of two parallel determinations.

Mathematical modeling is widely used to characterize various technological processes, including the production of compound feed. The process under study, described by various mathematical methods and formulas, ensures the protection of its energy efficiency. In the production of compound feed, the granulation process plays a crucial role. To achieve maximum efficiency, the feed granulation process must be set correctly. The output parameters are the pellet press's specific energy consumption and productivity.

The mathematical model was compiled using a multifactorial experiment. The following factors were selected: feed mixture moisture, granulation temperature, steam pressure, and energy costs. The crumbling index was adopted as the quality criterion. To develop a mathematical model of the granule production process in the form of a second-degree polynomial, a 2-factor central composite design was employed.

Statistical Analysis

The experimental data were statistically processed using Microsoft Excel 2010 (Microsoft Corporation, USA) and Statistica 10 (StatSoft Inc., Tulsa, USA).

The adequacy of the regression models was evaluated using Fisher's F-test, and the model was considered adequate when the calculated F-value was lower than the tabulated critical value at a 95% confidence level.

The formulas determine the number of degrees of freedom for the adequacy and reproducibility variance.

$$f2 = N – [(k+2) \times (k+1)]/2 – (n0 - 1) = 13 – [(2+2) \times (2+1)]/2 – (5 - 1) = 3 \qquad (2)$$

$$f1 = n0 – 1 = 5 – 1 = 4 \qquad (3)$$

Where:

N is the number of experiments taken into account when estimating regression coefficients;

λ is the number of coefficients of the equation;

t0 is the number of repetitions of zero experience.

The tabular value of the Fischer criterion for f1 = 4 and f2 = 3 at α = 0.05 is Ftab = 9.12

As a result, an adequate mathematical model of the second order was obtained, describing the crumbling coefficient's dependence on the feed mixture's moisture content before granulation, the granulation temperature, and the steam pressure. Hypotheses about adequacy models were tested using Fisher's criteria.

Homoscedasticity is a property of the data used to build a linear regression model, which means that the variance along a straight regression line is constant.

The verification of the model residuals is conducted to assess the adequacy of the constructed multidimensional linear regression model.

The regression equation we have chosen is nonlinear.

RESULTS AND DISCUSSION

The results obtained from this study demonstrate a strong relationship between granulation parameters – specifically, steam pressure and feed moisture content – and key quality indicators, including crumbliness and specific energy consumption. The second-order polynomial models developed through multifactorial experimental design provided a high degree of predictive accuracy, as validated by the Fisher criterion.

These findings align with previous studies in the field of compound feed production **[7]**, which have emphasized the importance of optimizing physical processing parameters to enhance pellet durability and nutrient retention. Notably, this research introduces the potential to expand the applicability of such mathematical models beyond feed applications to food-grade granular products derived from biomass. Recent developments in sustainable food technology have sparked increased interest in utilizing plant-based by-products, such as oilseed processing waste, as ingredients for protein-rich functional foods.

The positive effect of moderate fat content in the biomass mixture, which acts as a iubricant and reduces friction during granulation, is also supported by earlier studies **[20]**. Excessive moisture, while beneficial for particle binding, can weaken granule structure, a balance that is crucial in both feed fnd food processing.

Our analysis of response surfaces (Figure 1 and Figure 2) suggests that optimal conditions (steam pressure of 0.31 MPa and moisture content of 18.9%) can achieve minimum crambliness (22%) and low specific energy consumption (8.3 kWh/t), enhancing production efficiency. These results support the notion that granulation technology can be fine-tuned for different biomass compositions, depending on the desired application.

The potential for extending this model to food granulation, particularly in the production of plant-based protein granules, snacks, or supplements, warrants further investigation. Such interdisciplinary adaptation could contribute to both sustainable feed and food production, reinforcing circular economy principles.

Future research should consider incorporating additional variables such as matrix die geometry, granulation speed, and thermal pre-treatment to expand the model's relevance to various biomass types and end-product quality requirements. The integration of sensory evaluation and nutritional profiling could also enhance the transition from feed-based to food-grade applications.

The variation intervals of the influencing factors and their levels are presented in Table 1.

Table 1 Intervals of variation of influencing factors and their levels.

Factors		Levels of variation			Interval
Natural	**Coded**	**-1**	**0**	**+1**	ε
Vapor pressure *P* (MPa)	x_1	0.2	0.3	0.4	0.1
Feed moisture content, *W*, %	x_2	15	18	21	3

According to the two-factor design B_2 the number of experiments is equal $N = 13$, the number of zero points is $n_0 = 5$.

The planning matrix and the experiment's results are presented in Table 2.

Table 2 Planning matrix and experimental results.

Experience number		Factors		Experimental results	
ordinal	random	X_1	X_2	y_1	y_2
1	1	-1	-1	*35.7*	*32.1*
2	13	0	0	*17.5*	*9*
3	10	0	0	*17.1*	*8*
4	5	-1.414	0	*33*	*27*
5	6	1.414	0	*30.9*	*21.9*
6	3	1	-1	*34.7*	*25.6*
7	9	0	0	*18.9*	*9*
8	7	0	-1.414	*40*	*32*
9	4	1	1	*24.4*	*17.8*
10	8	0	1.414	*30.2*	*19.6*
11	11	0	0	*18.8*	*10*
12	2	-1	1	*28.4*	*16.2*
13	12	0	0	*18.8*	*10*

The experimental data were processed using a program developed in the Microsoft Excel environment.

Mathematical models of granule crumbling y_1 (%) from steam pressure P (MPa) and feed moisture content W (%):

In coded values:

$$y = 18.228 - 0.996x_1 - 3.932x_2 - 0.75x_1 x_2 + 6.125x_1^2 + 7.726x_2^2 \quad (4)$$

mathematical models of granule crumbliness in natural values

$$E = 364.82 - 334.06P - 31.47W - 2.5PW + 615.17P^2 + 0.86W^{2.} \quad (5)$$

The adequacy of mathematical models was tested using Fisher's criterion. The dispersion of reproducibility according to formula

$$S^2(\bar{y}) = \frac{2.908}{5-1} = 0.727 \quad (6)$$

Dispersion of adequacy according to formula

$$S_{ad}^2 = \frac{20.094-2.098}{13-6-(5-1)} = 5.729 \quad (7)$$

Calculated value of F-criterion

$$F_e = \frac{S_{ad}^2}{S^2(\bar{y})} = \frac{5.729}{0.727} = 7.882 < F_k = 9.12 \quad (8)$$

Mathematical models of specific energy consumption y_2 (kW h/t) from steam pressure P (MPa) and feed moisture content W (%):

in coded values

$$y = 9.206 - 1.514x_1 - 5.154x_2 + 2.025x_1 x_2 + 7.051x_1^2 + 7.726x_2^2 \quad (9)$$

natural values

$$E = 422.71 - 559.69P - 34.646W + 6.75PW + 705.09P^2 + 0.858W^{2.} \quad (10)$$

The adequacy of the mathematical models was tested using Fisher's criterion. The dispersion of reproducibility according to the formula

$$S^2(\bar{y}) = \frac{2.8}{5-1} = 0.7 \qquad (11)$$

Dispersion of adequacy according to the formula

$$S^{2}_{ad} = \frac{17.949-2.8}{13-6-(5-1)} = 5.05. \qquad (12)$$

Calculated value of F-criterion according to the formula

$$F = \frac{S^2_{ad}}{S^2(\bar{y})} = \frac{5.05}{0.7} = 7.21 < F_k = 9.12 \qquad (13)$$

The construction of response surfaces for mathematical models was carried out using the Golden Software Surfer program.

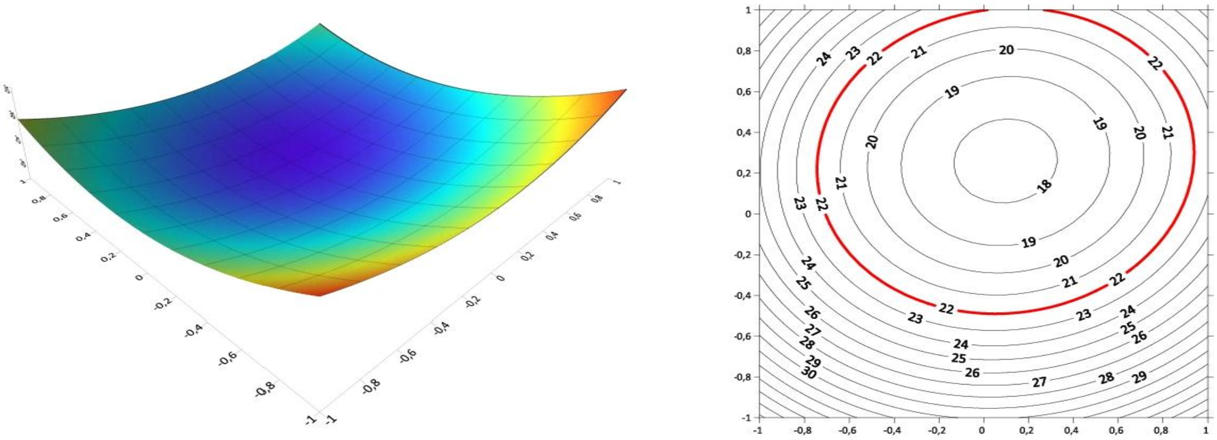

Figure 1 Dependence of granule crumbling y_1 on steam pressure x_1 and feed moisture x_2.

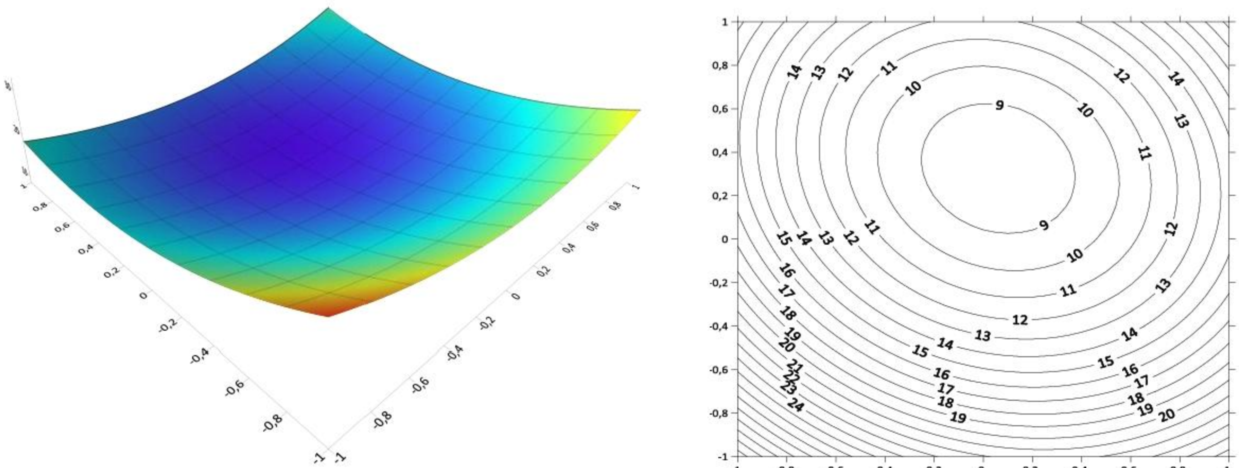

Figure 2 Dependence of specific energy consumption y_2 on steam pressure x_1 and feed humidity x_2.

The response surface analysis of the dependence of granule crumbliness y_1 on the vapor pressure x_1 and feed moisture x_2 (Figure 1) showed that in the range x_1 from -0.5 to 1 and x_2 from -0.7 to 0.9 the crumbling of granules has a value of less than 22%. With natural values, the desired range of factors lies at P = 0.25-0.4 MPa and W = 15.9-20.7 %.

Analysis of the response surface of the dependence of specific energy consumption y_2 on steam pressure x_1 and feed moisture x_2 (Fig. 2) showed that the minimum value of specific energy consumption y_2=8.3 kW is achieved at x_1 = 0.1 and x_2 = 0.3 %. For natural values, the factors are equal to P=0.31 MPa and W=18.9 %. Experiments have shown that the discrepancies between experimental and calculated data are insignificant and are within the limits of experimental error in determining these indicators.

Water contained in the raw material, added to the mixer during mixing, or introduced as steam during conditioning promotes particle binding during granulation **[21]**. Water's agglutinating ability is based on the capillary effect and surface tension. Thus, preliminary moistening of the plant material increases the strength of the resulting granules.

However, if excessively moistened, water can act as a lubricant, reducing friction in the spinnerets during the granulation process and negatively affecting the durability and strength of the granules.

R. Colovic studied this phenomenon in detail and found that increasing the moisture content of the raw material neutralizes the positive effect of increasing the matrix channel's length on the granules' strength **[22]**. In general, granules produced with insufficient moisture are dry and crumbly, while those with excess moisture are too weak.

Optimal moisture enhances the plasticity of the feed mass, facilitating molding and reducing mechanical resistance in the die. Moisture content between 14–18% achieves the best balance between energy consumption and pellet quality. Lower moisture levels increase energy demand, while excessive moisture reduces pellet strength and increases the risk of deformation **[23]**.

Samuelsson et al. confirmed that increasing moisture content while maintaining other parameters reduces die pressure, decreasing equipment wear and prolonging the service life of pelleting components. However, excess moisture may cause mass adhesion to internal die surfaces, leading to unstable machine operation, and emphasizing the importance of precise moisture control **[24]**.

Preconditioning of raw materials is essential for obtaining high-quality pellets, achieved through moisture absorption and structural modification of the feedstock **[25]**, and **[26]**. During conditioning, hot steam disrupts the starch structure, resulting in gelatinization, which facilitates the binding of feed particles and contributes to the formation of durable pellets **[27]**. Proper conditioning ensures high pellet strength, reduces energy consumption during production, and decreases die wear **[28]**.

Among scientific studies on this topic, M. Segerstrom's work confirmed that preheating plant raw materials reduces energy consumption by the pellet press **[29]**. If the material is not preheated before pelleting, the press requires more energy to produce durable pellets, resulting in increased wear on the die and rollers **[30]**. M.R. Abdollahi et al. evaluated the impact of conditioning temperature on the pellet quality of corn- and sorghum-based feeds, finding that increasing the temperature from 75°C to 90°C improved the PDI in both cases, with a more pronounced effect at 90°C **[31]**.

R. Kulig determined that the amount of steam and heat required during feed conditioning largely depends on the properties and composition of certain ingredients in plant raw materials **[32]**. Cereals and legumes with low fiber content readily absorb moisture and heat, whereas fiber-rich raw materials are less responsive to conditioning. In his experiments, Kulig found that alfalfa, rich in fiber, required the highest heat input during conditioning, while corn, with its low fiber content, required the least.

Pressure is an essential variable in the granulation process. The press rollers cause the resistance of the raw material as they push through the channels in the spinnerets **[33]**. Granulation pressure depends on the raw material, the type of granulator, and other process parameters and cannot be directly controlled.

In pellet presses, pressure is not measured directly, but is estimated based on the electrical power consumed during operation. S. Mani, investigated and described the process of granule formation from plant material in terms of applied pressure. According to him, the initial stage of granule formation, also known as particle rearrangement, occurs at low pressure, where the material particles move and rearrange, filling the voids. In the second stage, as the pressure increases, the density of the granules increases, causing the particles to adhere due to intermolecular forces. His studies on pelleting straw and stalks showed that increasing pressure from 30 to 160 MPa boosts pellet density, although this effect diminishes above 90 MPa, especially when inadequate thermal processing is used **[34]**. Hence, increasing pelleting pressure in the range of 20–150 MPa contributes to higher pellet density.

Pelleting pressure depends on feedstock characteristics, pellet press type, and other process parameters and cannot be directly controlled. For plant-based materials, pelleting pressure typically ranges from 20 to 200 MPa, with higher values used for the production of biofuel pellets **[35]**.

Pellet presses do not directly measure pressure; instead, it is inferred from the electric power consumption during operation **[36]**. W. Stelte et al., studying the pelleting of wood and straw for fuel pellets, found that pelleting pressure decreases significantly as feedstock temperature increases to 140°C, beyond which the rate of pressure reduction levels off **[37]**. C. Whittaker and I. Shield showed that higher pelleting pressures yield stronger pellets **[38]**. Increased pressure leads to higher pellet density—but only up to a certain point **[39]**. W. Stelte et al. also demonstrated that raising pressure above 200 MPa no longer improves pellet density **[37]**.

These findings align with earlier results by M.O. Faborode, who divided the compression process of fibrous agricultural materials into two phases: a dispersed phase, dominated by particle inertia, and a dense phase, where elastic forces prevail as the compacted material behaves like a solid body **[40]**.

Natural binders also play a key role. Starch, hemicellulose, and proteins act as natural adhesives when exposed to heat and moisture. Adding small amounts of wheat gluten to low-bonding materials such as sunflower husks or straw increases the PDI by 10–15%.

To obtain pellets with desired strength characteristics, it is essential to comprehensively consider the physicochemical properties of the raw materials, grinding conditions, conditioning parameters (temperature and moisture), and pressing regime. This integrated approach enhances yield, reduces energy consumption, and extends the service life of equipment.

The characteristics of plant feedstocks are fundamental to pellet formation, affecting energy usage, pellet strength, and the overall process efficiency. Different categories of plant materials—cereals, legumes, oilseeds, and coarse residues (straw, stems, husks, etc.)—vary significantly in their fiber, starch, protein, and natural binder content **[41]**.

Cereal crops (corn, wheat, barley) are traditionally used as feed bases. Their high starch content facilitates gelatinization during thermal treatment, resulting in strong pellet formation without the need for synthetic binders. Corn is particularly effective due to its low fiber content and high ability to absorb heat and moisture.

Legumes such as soybeans and peas are rich in protein and fiber. As shown by Lindberg (2005), their proteins partially denature upon heating and act as natural adhesives. However, excessive fiber content, especially in seed coats, negatively affects pellet quality, reducing strength and increasing energy demands.

Oilseed residues, including sunflower husks, rapeseed meal, and soybean meal, are challenging to pellet. Sunflower husks, for example, have low binder content and high fiber levels, necessitating higher temperatures and pressures to achieve sufficient pellet durability **[42]**. showed that adding starch-rich ingredients or natural binders greatly improves the formation and physical-mechanical properties of such pellets.

Straw, cereal stalks, and wood residues belong to hard-to-pellet categories. They are rigid, high in lignin, and exhibit low plasticity. Pelleting them requires high temperatures, pressures, and often the addition of binder additives **[43]**. Mani et al. confirmed that increasing pressure from 30 to 160 MPa raises straw pellet density, although efficiency declines above 90 MPa, particularly without sufficient heat treatment **[44]**.

Composite mixtures of cereals, oilseeds, and protein components enable the tailoring of final pellet properties by optimizing ingredient ratios. Such blends strike a balance between energy content, pellet density, and process parameters **[34]**.

Thus, the type of raw material directly influences pelleting regimes, equipment requirements, and the need for additives. Proper selection and preparation of raw materials significantly increase production efficiency.

Several factors can jointly influence the granulation process of plant raw materials and the quality of the resulting granules. Therefore, when developing compound feed recipes, it is necessary to take into account the optimal content of fats and oils in the composition, both from the point of view of the compound feed's exchange energy, nutritional value, and digestibility and from the point of view of the specific energy intensity of the granulation process.

Thus, oilseed waste in compound feed can positively affect the granulation process, improving its properties. However, specific physical and mechanical properties must be considered when optimizing the technological process of compound feed production. Studies conducted on granulated compound feed found that the resulting compound feeds, according to physical and chemical indicators, met the requirements for compound feed for cattle.

CONCLUSION

The obtained mathematical models of the process of granulation of compound feed for cattle, establishing the dependence of granule crumbliness and energy consumption on the selected factors. With the optimal values of the factors obtained in the experimental planning studies, pilot batches of granulated compound feed for cattle were produced. It was found that the granules were of good quality due to granulating a loose compound feed under optimal conditions. At the selected levels of factors, the calculated value of the specific power consumption was - 8.3 kW, the steam pressure at granulation 0.31 MPa, humidity - 18.9%. The obtained granules had good indicators of granule crumbling - 22%. Experiments have shown that the discrepancies between the experimental and calculated data are insignificant and are within the limits of experimental error in determining these indicators. Granulated compound feeds, produced using optimal granulation parameters obtained through mathematical modeling, can serve as the basis for granulated compound feeds for cattle.

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