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Mathematical modelling and optimization of the granulation process of loose compound feed for broilers

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ABSTRACT

The article presents the results of studying the indicators of the crumbling of granules and the specific energy costs of experimental batches of granulated feed for broilers. The process of granulation of compound feed for broilers was studied using the statistical planning method of a multifactorial experiment using a granulation line, including a granulator press. The dependence of the crumbling of granules and the energy consumed on the selected factors has been established. The moisture content of the feed mixture W (%) and steam pressure P (MPa) were chosen to optimise the granulation process. A matrix plan of the experiment was compiled. With the optimal values of the factors obtained in the study using the experimental planning method, an experimental batch of granulated feed was developed. At the selected levels of factors, the calculated value of the crumbling of granules was 20.11%, which fits into the optimum according to the standard of the crumbling of granulated feed for poultry (no more than 22%). The specific electricity consumption was 9.23 kWh/ton. Experiments have shown that the discrepancies between the experimental and calculated data are insignificant and within these indicators' experimental error determination. Mathematical modelling of the granulation process of loose compound feed for broilers made it possible to solve an important practical problem – to optimize the granulation mode, which ensures the production of good quality granules with minimal energy consumption. The obtained optimal granulation parameters can serve as the basis for producing granulated feed for broilers.

Keywords: granulation, crumbability, granular feed, mathematical modeling, broiler

INTRODUCTION

Nature did not endow the bird with teeth; as a result, it is not able to hold and grifted taste, and the bird's actual intake stance left its mark on the nature of the choice and perception of the taste of the feed and on the actual intake of the bird. Moreover, birds are characterized by a more pronounced reaction of food intake to its physical and mechanical characteristics than mammals **[1]**.

For broiler chickens in the first seven days of their life, the physical structure of the feed is of particular importance. At this age, they are more willing to consume small granules, which contributes to the most intensive growth and development of the intestine: an increase in its length, mass, number of villi and microvilli, nutrient absorption surface, synthesis, and secretion of digestive enzymes. At an early age, the small intestine also grows intensively in chickens, in which the main absorption of nutrients and biologically active substances occurs. Subsequently, the growth of the gastrointestinal tract continues with less intensity **[2]**. It is believed that the physical form of the feed (loose, granules, or semolina) and size (particle or granule size) have a significant impact on broiler growth and feed intake **[3]**, **[4]**. In research Mingbin, feed form had a greater effect on broiler growth performance and the digestive tract than feed particle size.

Granular feed has several advantages over loose feed **[5]** since the separation of components **[6]** during transportation and distribution is excluded. At the same time, the bird does not have the opportunity to select individual particles, which eliminates the violation of the balance of feeding and reduces losses due to scattering and dust. Biologically active substances (especially carotene and vitamins) are better preserved in granules; during the granulation process, due to pressure and temperature, the availability of nutrients increases, and anti-nutritional factors are destroyed. The digestibility of organic substances of granulated feed is increased by 2.2-3.0%. As a result of granulation, the feed volume is reduced, which contributes to a more economical use of vehicles and storage facilities, provides a longer preservation of nutrients, and improves the sanitary condition of the feed **[7]**, **[8]**.

The quality of the granulation process can be assessed according to such criteria as energy costs for the formation of granules and their quality. Hydrothermal treatment has a significant influence on them. Under the influence of warm wet steam, loose mixed fodder undergoes, on the one hand, structural and mechanical changes, and on the other hand, biochemical changes, as a result of which a product of viscosity necessary for pressing is obtained. The component composition determines its colloidal porous structure. When moisture is absorbed, colloids swell and change. With an increase in temperature, the swelling is more intense, while the plastic properties of the product increase. The fat released from plant and animal cells uniformly envelops the warm and moist surface of the feed particles. When steaming grain components, starch gelatinizes and passes into a soluble form, more accessible to the action of enzymes. The dextrins and simple sugars formed as a result contribute to the adhesion of the feed particles to each other.

The most important negative of granulation is a very serious increase in energy consumption for its production compared to the production of loose feed. On average, this increase can lead to an increase in feed cost by 25-35% **[9]**.

Hancock **[10]** asserts that poor physical pellet quality (PPQ) produces more fine particles during feed transportation from feed mills to poultry house feed lines. Pellets are submitted to friction, impact, and pressure during storage, transport, and dispatch from the feed mill to the farms **[11]**, **[12]** and poor-quality pellets disintegrate, resulting in a feed consisting of a few pellets and fines. The geometric mean diameter (GMD) of fine particles is equal to or lower than that of mash diets, and these particles may cause a nutritional imbalance in feed chemical composition, which may negatively affect animal performance.

Some researchers **[13]**, **[14]**, **[15]** report that poor PPQ negatively changed the feed intake pattern of broilers.

Pellet quality is the ability to resist fragmentation and abrasion during handling without breaking up and reach feeders without generating high fines **[16]**. The pellet durability index (PDI) is one of the main parameters used to determine pellet quality, as it indicates the percentage of pellets that remain intact after being submitted to mechanical forces.

In the Republic of Kazakhstan, the crumbling of feed pellets is determined. The crumbling of granules is a qualitative indicator that characterizes the degree of cohesion of the particles that make up the granules. When transporting feed, especially over long distances, and if reloading from one mode of transport to another is forthcoming, or if transportation is carried out on roads of unsatisfactory condition, the granules can collapse, losing consumer qualities and decreasing volume.

The index of crumbling of compound feed for poultry affects the loss of feed nutrients and safety during transportation and distribution.

The crumbling of granules is usually determined according to GOST 28497-2014. The essence of the method lies in destroying the analysed product's granules, separating undestroyed granules from fines and crumbs by sifting, weighing them, and then calculating the crumbling **[17]**.

Thus, granulated complete feed has many advantages since it contains nutrients in its composition in a concentrated form, is easily distributed, and helps to maintain microbiological purity in the poultry house. With higher productivity rates, pelleting can significantly reduce unproductive feed losses and save on their total consumption per unit of product received. Granulation reduces the dispersion of compound feed in the poultry house, positively affecting its microclimate.

Given the above, using mathematical modeling, it is important to control the physical and mechanical characteristics of granulated feed and establish modes of compound feed production with the minimal crumbling of granules and specific energy costs. Therefore, it is advisable to optimize the granulation process when developing compound feed recipes by developing a mathematical model, considering its specific energy consumption, without losing the quality of the final product. This will reduce feed production costs and increase profitability **[18]**. Granulation of mixed fodder with optimal parameters will allow granules that meet the standard's requirements to be obtained.

Scientific Hypothesis

Drawing up a mathematical model of the granulation process based on experimental data will make it possible to determine optimal granulation modes that ensure minimum specific energy consumption with normalized granule crumbliness.

MATERIAL AND METHODOLOGY

Samples

Granulated feed for broiler chickens (13-28 days of growing). They are cylindrical granules of yellow-green color with a diameter of 3.5 mm and a length of 5 mm. The composition contains raw materials of plant origin (wheat, corn, corn germ, soybean meal, flaxseed cake, soybean oil), limestone flour, premix, and the mineral vermiculite.

Chemicals

No chemicals were used.

Instruments

CAS SW-2 bench scales (CAS Corporation, Seoul, South Korea), Model N: MW-113000, is used for weighing test samples. Model U17-EKG, (Zernotekhnika, Moscow, Russia) is installed to determine feed pellets crumbling. Round laboratory sieves with a stainless-steel shell with a cell size of – 3.0 mm and a diameter of – 300 mm (IP Sedov A. B., Moscow, Russia) are used to separate destroyed granules from unresolved ones.
Glass container for pouring the analyzed sample and weighing.

Laboratory Methods

The crumbling of granules was determined by GOST 28497-2014 "Feed, mixed feed.

The specific power consumption was determined using a wattmeter device.

Description of the Experiment

Sample preparation: 16 samples were analyzed, with two repeated analyses and two experiment replications for each sample.

Number of samples analyzed: 16.

Number of repeated analyses: 2.

Number of experiment replication: 2.

Design of the experiment: The development of experimental compound feed for broilers according to the developed recipes using optimal granulation modes was carried out at the Agrofit LLP plant in Konaev, Almaty region. Complete set of the granulation line at the plant from the Chinese company "HENAN RICHI MACHINERY CO.LTD". A press granulator with a vertical ring die was used for granulating the feed. The diameter of the holes in the matrix of the press granulator was 3.5 mm.

The technological process of granulation was carried out in the following sequence. The finished mixture was fed into the dispenser of the granulator press. It was the dosing of the amount of the mixture by changing the speed of the screw. Next, the mixture entered the mixer. Here, it is thermally treated with steam. The prepared mixture was fed into the press unit. In the press unit, the matrix rotated, and the press rollers rotated on their axis each. The mixture was drawn into the gap between the matrix and the rollers and pressed into the holes in the matrix. As a result, the formation of granules occurred. The size of the holes in the matrix determined the granule diameter. The length of the granules was adjustable. The granules were cut to the desired length with a shear knife. The process of granule formation took place at a temperature of 80 °C.

Data processing and all necessary calculations were done using the PLAN sequential regression analysis program developed at the Odesa National Technological University.

The essence of sequential regression analysis is that the least squares method, implemented in matrix form, calculates the regression coefficients, checks by Student's criterion t and x significance, the coefficient with the minimum ratio of its magnitude to the critical value is removed from the insignificant ones, and then the regression coefficients are recalculated. This cyclic procedure ends when only significant regression coefficients remain in the equation. Then, according to the Fisher criterion F, the adequacy of the obtained regression equation to the experimental data is checked **[19]**.

To determine the dispersion of reproducibility (experimental errors), 3 parallel experiments were carried out in the center of the experiment.

The calculations of the regression coefficients were carried out using matrices in natural dimensions; accordingly, the equations themselves were also obtained in natural dimensions. The adequacy of the mathematical model was tested based on the Fisher dispersion coefficient **[20]**. Fisher's test is an important statistical tool for model validation and analysis of variance.

Compound feeds for broilers are high in protein and high in energy and, therefore, must contain highly digestible components at a fat level of no more than 8%, with a higher percentage of the presence of fatty substances; granules with sufficient strength cannot be prepared.

The content of fats in raw materials influences the feed granulation process and results. The pressure exerted on the particles of plant materials during granulation leads to fats and oils moving to their surface **[21]**. The surface layer of lipids acts as a lubricant, reducing the friction in the spinneret and thereby reducing the pressure of granulation and energy costs **[22]**. Fat reduces the contact of raw materials with the walls of the die channel, facilitating the passage of feed through it and thereby reducing its compaction.

Therefore, pelleted feed should contain a certain amount of fat – at least 2% [**23]**. Such raw materials are meal, cake, wheat, and corn gluten.

The composition of the complete compound feed for broilers developed by us contains grain crops (up to 60%), linseed cake, meal, and oils (up to 35%), mineral raw materials (up to 5%), oils were applied to the granules by spraying after the granules left the granulator.

The crumbling of granules was determined by GOST 28497-2014 “Feed, mixed feed. Method for determining the crumbling of granules "on the device U17-EKG. The grinder is a two-chamber box with dividers that affect the feed sample during its rotation. To do this, two portions of 500.0 ±0.1 g of finished granular feed were placed in the installation chamber. After that, the device was turned on, and the camera was rotated.

The pellet chamber is rotated for 10 minutes at 50 rpm. Then, the device automatically turns off; the contents are poured and weighed with an error of ±0.1 g.

The crumbling was calculated using the formula:

$$K = \frac{m_1 - m_2}{m_1} \times 100\% \tag{1}$$

Where:
m_1 is the mass of granules before testing, g; m_2 – the mass of granules after testing, g.

The arithmetic mean of the results of two parallel determinations was taken as the final test result. The specific consumption was understood as the obtained value of the cost of electricity per unit of feed granulation, determined by the formula:

$$q = \frac{w}{\mathrm{M}} \tag{2}$$

Where:
w – the actual consumption of electricity for the production of granulated feed in the amount of M (tons per hour).

The mathematical model was compiled using a multifactorial experiment. As factors were chosen: the moisture content of the feed mixture and steam pressure. For the output criteria, the indicator of the quality of the granules (crumbiness) and the specific energy consumption for granulation were taken. To obtain a mathematical model of the process of getting granules in the form of a polynomial of the second degree, a 2-factor 4 c fh-level plan was implemented.

Statistical Analysis

The obtained experimental results were processed using methods for planning multivariate experiments based on the least squares method and subsequent regression analysis, which included calculating regression coefficients, assessing their significance, and checking the adequacy of the resulting regression equation. Based on the research, regression equations were obtained that adequately (according to the Fisher criterion) describe the dependences of the above indicators of the quality of granulated feed y1 and specific energy consumption y2 on the factors *W* and *P* that affect them.

RESULTS AND DISCUSSION

The granulation process is a complex technological process, the results of which depend on the influence of many mechanical, thermal, and technological factors. Its mathematical description is also complex.

The parametric diagram of the granulation process, performed in our research is shown in Figure 1. The input factors of the X group influence the granulation process, represented by the moisture content of loose feed *W* and steam pressure *P* **[24]**, **[25]**.

As the output criteria Y, normalized indicators of the quality of granules are taken – the crumbling of granules y_1 and specific electricity costs y_2. Disturbing factors, designated as Z (mixed feed recipe, granulation temperature, steam consumption, granule diameter, etc.) **[26]**, were the same (stable) in the experimental studies.

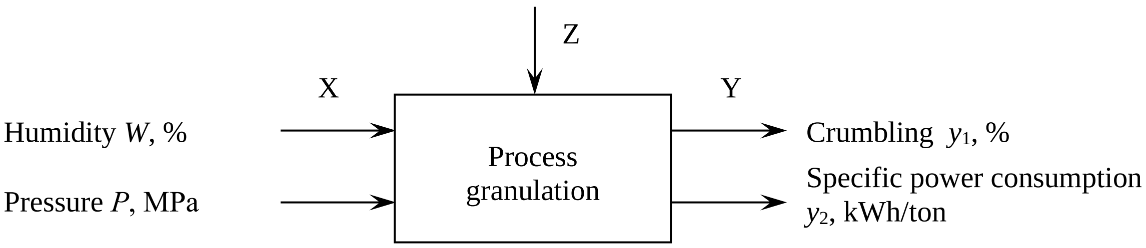

Figure 1 Parametric diagram of the granulation process.

At the first, experimental, research stage, the dependences of the main indicator of the quality of crumbling granules y_1 and the specific energy consumption for the granulation process y_2 on the granulation modes - the moisture content of loose feed *W* and steam pressure *P* were studied.

At the second, analytical, stage, based on the results of the experimental studies, regression equations were obtained that describe the change in the crumbling of granules and the specific energy consumption for the granulation process from the granulation modes.

At the third stage of research, based on the obtained mathematical models of the granulation process, an analysis was made of the influence of the studied factors *W* and *P* on the crumbling of the obtained granules (y_1) and the specific power consumption for granulating feed (y_2), and determined the optimal granulation modes that provide at minimum specific power consumption normative indicators of crumbling of granules.

Taking into account the complex dependence of the quality indicators of granules and the specific energy costs on the granulation modes, a four-level plan of experiments was drawn up, in which the moisture content of the loose feed was changed in the range of 13-19 % with a step of 2%, and the steam pressure in the range of 0.1 ... step 0.1 MPa. Such a multi-level plan will make it possible to obtain quadratic equations that describe complex nonlinear dependencies between the quality of granules and the specific energy consumption for their production, as well as to optimize granulation modes.

To reduce the influence of uncontrolled parameters on the results of experiments, the experiments were randomised using tables of random numbers **[27]**.

The general form of quadratic regression equations for 2 factors is as follows:

$$y_i = b_0 + b_1 W + b_2 P + b_{11} W^2 + b_{22} R^2 + b_{12} W P \quad (3)$$

Where:
y_i – *i* - th criteria of optimality: y_1 – crumbling, %; y_2 – specific electricity consumption for granulation, kW.h/t; b_0, …, b_{12} – regression coefficients determined by the least squares method based on experimental data; *W* – moisture content of loose feed, %; *P* – steam pressure, MPa.

The regression coefficients included in equation (2) characterize the influence of the first (W) and second (P) factors on the output criteria – granule crumbability y_1 and specific energy costs y_2. In this case, coefficients b_1 and b_2 reflect the linear nature of the influence of factors W and P, respectively, coefficients b_{11} and b_{22} are non-linear, and coefficient b_{12} is a joint pair interaction of the studied factors *W* and *P*. The "minus" signs in front of the coefficients indicate a decrease in the values of the output criteria y_1 and y_2 with an increase in the corresponding factors *W* or *P*, and the plus signs indicate, on the contrary, an increase in the criteria y_i with an increase in *W* or *P*. The detailed nature of the influence of factors is discussed further when analyzing the corresponding regression equations, and a clearer idea of the nature of the influence factors W and P is given in Figures 2-4.

Compiled for the studied criteria y_1 and y_2, the mathematical models allow predicting changes in feed crumbling and specific energy consumption depending on the values of the factors *W* and *P*.

W and *P* were formulated and solved, providing the minimum power consumption for the granulation process at a normalized value of the crumbling of granules – no more than 22%. At the same time, two-sided restrictions (limits of change) were imposed on the values of the factors *W* and *P*, equal to the conditions of the experiments in the matrix of experiments.

To visually illustrate the nature of the dependence of both optimization criteria on the factors influencing them, the resulting regression equations were presented in the form of surfaces and response isolines.

Matrix of the experiment plan with the conditions of the experiments and results of the experimental determination in each experiment of crumbling y_1 and specific energy costs for the granulation process y_2 are given in Table 1. The same table also shows the calculated values $\hat{y}_1$ and $\hat{y}_2$ obtained from adequate regression equations, which are given below in Tables 2 and Table 3.

Table 1 Conditions and results of experiments to study the dependence of the crumbling of granules and the specific energy consumption for the granulation process, depending on the modes of granulation.

Experience number	**Experience conditions**		**Experimental results**		**Calculation results**	
	***W*, %**	***P*, MPa**	**y_1, %**	**y_2, kW.h/t**	**$\hat{y}_1$, %**	**$\hat{y}_2$, kW.h/t**
1	13	0.1	26.42	14.41	27.03	14.67
2	15	0.1	23.89	13.68	22.16	13.00
3	17	0.1	20.63	12.84	20.68	12.23
4	19	0.1	21.49	13.02	22.59	12.35
5	13	0.2	25.80	13.86	25.99	14.23
6	15	0.2	23.08	13.17	21.12	12.56
7	17	0.2	18.45	10.46	19.64	11.79
8	19	0.2	21.08	11.75	21.54	11.91
9	13	0.3	23.56	12.91	24.94	13.50
10	15	0.3	22.33	12.74	20.07	11.84
11	17	0.3	15.70	9.35	18.59	11.06
12	19	0.3	22.36	11.08	20.50	11.18
13	13	0.4	23.19	12.57	23.90	12.48
14	15	0.4	21.73	12.03	19.03	10.82
15	17	0.4	13.03	9.08	17.55	10.05
16	19	0.4	22.04	10.89	19.45	10.17

A comparison of experimental and calculated values of granule crumbliness and specific energy consumption for their granulation shows some discrepancies (discrepancies) between them caused by the influence of some random and unaccounted factors, designated as Z in the parametric diagram (see Figure 1). However, these discrepancies are expressed by the average relative error (Mean Relation Percentage Error) is 2.51% for granule crushability and 5.67% for specific energy costs, which is quite acceptable for technical calculations.

As seen from Table 1 of the results of experimental studies, an increase in the humidity *W* of loose feed at a constant pressure *P* first leads to a decrease in granule crumbliness, and then to its increase. Thus, having a mathematical dependence of the crumbability of granules y_1 on the factors *W* and *P*, it is possible to calculate by calculation the values of *W* and *P* at which the crumbability will be minimal.

The humidity of bulk feed has a similar effect on the specific energy costs during granulation – increasing humidity at constant pressure first reduces energy costs y_2 then increases them. The presence of an equation that describes this pattern will make it possible to determine the values of *W* and *P* that provide the lowest specific energy consumption for the granulation process.

However, due to the likely presence of the effect of the mutual influence of factors *W* and *P* on both the crumbability of granules and specific energy consumption, it is possible to solve the optimization problem using the obtained mathematical models – to find such values of *W* and *P* at which there will be minimal energy consumption and the crumbability of granules will not exceed the normalized value meaning. This is an urgent task and is the goal of this work.

Using the PLAN sequential regression analysis program described above, the regression coefficients b_i , their confidence intervals ε_i, and some statistical characteristics of the equations for describing the dependence of the crumbling of granules y_1 and specific energy costs for granulation $\mathbf{y}_2$ on humidity *W* and steam pressure *P* during granulation of loose mixed fodder.

Summary data on characteristics of regression coefficients b_i and their confidence intervals ε_i are given in Table 2.

Table 2 Summary of characteristics of regression coefficients b_i and their confidence intervals ε_i.

Criteria	b_i / ε_i	0	1	2	11	22	12
y_1	**All coefficients b_i and their corresponding confidence intervals ε_i**						
	b_i	147.56	-14.618	-31.640	0.4234	0.3750	1.313
	ε_i	64.72	7.99	80.88	0.247	98.982	3.959
	Significant coefficients b_i and their confidence intervals ε_i						
	b_i	142.29	-14,290	-10.445	0.4234	-	-
	ε_i	62.56	7.931	8.853	0.2475	-	-
y_2	**All coefficients b_i and their corresponding confidence intervals ε_i**						
	b_i	47.50	- 3.847	- 10.80	0.1116	20.00	– 0.4390
	ε_i	28.84	3.56 2	36.04	0.110 3	44.11	1.7645
	Significant coefficients b_i and their confidence intervals ε_i						
	b_i	47.39	-3.956	-	0.1116	-14.55	-
	ε_i	27.87	3.534	-	0.1103	7.77	-

The confidence intervals ε_{bi} given in Table 2 were determined by the expression:

$$\varepsilon_{bi} = tS_e\sqrt{c_{ii}},$$

Where:
t – is the Student's test with a confidence level of p = 0.95; S_e – root mean square dispersion (error) of experiments; c_{ii} – diagonal elements of the dispersion matrix.

The significance of regression coefficients was assessed by observing the ratio $| b_i | \geq \varepsilon_{bi}$.

The table shows two variants of the values of regression coefficients for crumbability y_1 and specific energy costs y_2, calculated using the PLAN program. The first option shows all 6 coefficients, including the insignificant ones, and the second option shows only the significant ones, obtained after sequentially eliminating the insignificant ones and recalculating the remaining regression coefficients in the equation. From Table 2 the exclusion of insignificant coefficients leads to a change in the numerical values of both the coefficients bi and their confidence intervals ε_{bi} remaining in the equation.

Thus, the use of sequential regression analysis made it possible to obtain simplified adequate quadratic models of the granulation process. The regression equations in natural variables obtained based on processing the results of the experiments are summarized in Table 3. The same table shows the mean square errors of the experiments S_e and inadequacy $S_{n.ad}$, as well as the calculated F_p and critical F_{kp} values of the Fisher criterion, indicating that both equations obtained adequately describe the experimental data at a confidence level $p = 0.05$ (i.e., 5%).

Table 3 Regression equations in natural variables describing the dependencies of granule crumbling and specific energy consumption on granulation modes.

Regression Equations in Natural Variables	Standard deviation		Fisher's criterion	
	Experimental, S_e	**Inadequacy, $S_{n.ad.}$**	**Settlement, Fp**	**Critical F_{kp}**
Crushability of granules, %				
y_1 =142.29–14.290 W –10.445P–0.4234 W^2	0.92	2.31	6.28	19.41
Specific electricity consumption, kW.h/t				
y_2 =47.39–3.956 W +0.1116 W^2–14.55P^2	0.41	0.94	5.31	19.41

Based on the obtained regression equations, the calculated crumbling values were determined, $\hat{y}_1$ and swelling $\hat{y}_2$ granules for each experience are given above in Table 3.

Analysis of the obtained regression equations shows the following. The crumbling of granules y_1 and the specific energy consumption y_2 depend on both studied factors W and P. However, in the equation for the crumbling of granules y_1, the quadratic coefficient b_{22} for the factor P and the coefficient b_{12} were statistically insignificant pairwise interactions of factors W and P.

A significant non-linear (quadratic) effect on the crumbling of granules at $p = 0.05$ is exerted by the moisture content of loose feed W (coefficients b_1 and b_{11}). The effect of pressure on the crumbling of granules is linear (coefficient b_2).

In the equation for the specific cost of electricity for granulation of loose mixed fodder y_2, the coefficient b_2 and the coefficient of pair interaction b_{12} turned out to be insignificant factors W and P.

The remaining coefficients in both equations are significant at $p = 0.05$.

Significant quadratic coefficients indicate that there are extrema – minima y_1 and y_2 for negative humidity coefficients (b_{11}) and maximum y_2 for a positive vapor pressure coefficient (b_{22}).

The non-linearity of the regression equations and the fact that they are obtained in natural variables make it difficult to unambiguously assess the degree of influence of each of the considered factors W and P on the crumbling of granules and the specific cost of electricity for granulation.

Getting a better understanding of the influence of factors W And P on the criteria y_1 and y_2 can be based on the response surfaces (Figures 2 and 3) and isolines (Figures 4 and 5) built based on the regression equations given in Table 3.

Analysis of the response surface in Figure 2 clearly shows that with an increase in the moisture content of loose feed from 13 to 19%, the crumbling of granules first decreases according to a parabolic law. Then, upon reaching a minimum (at W = 16.87%), it begins to increase.

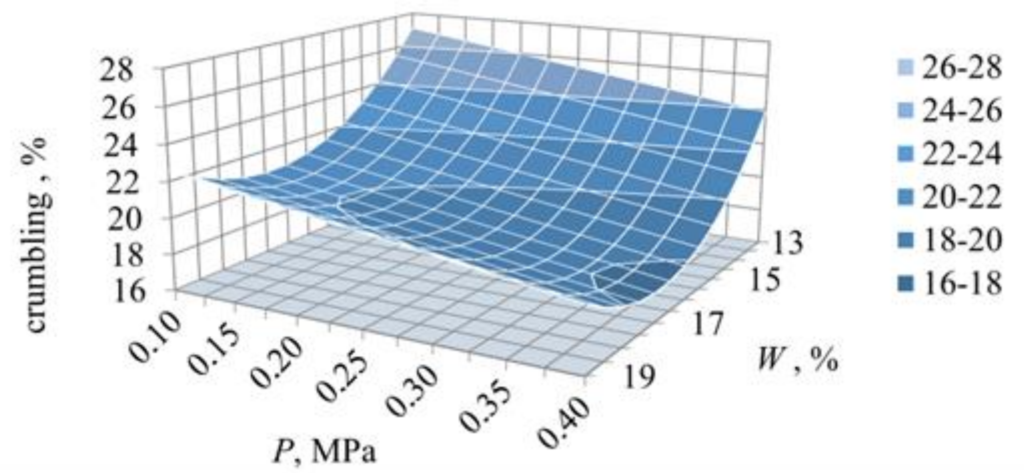

Figure 2 The response surface of the dependence of the crumbling of granules on the moisture content of loose feed and steam pressure during granulation.

It can also be seen that, regardless of the feed's moisture content, the granules' crumbling with increasing steam pressure gradually decreases according to a linear law and reaches the lowest value of 17.52% at W = 16.87% and P = 0.4 MPa.

The area of admissible values of the moisture content of loose compound feed and steam pressure during granulation, marked in green, is also clearly visible, in which the normalized crumbling of granules is ensured, not exceeding 22 %.

A clearer picture of the values of W and P, which provide the crumbling of granules up to 22%, can be seen in Figure 3, which shows the isolines of the dependence of the crumbling of granules on the indicated factors W and P. It is also clearly seen that at W = 19%, the permissible crumbling of granules can be ensured at P not less than 0.157 MPa. On the other hand, at P = 0.10 MPa, the permissible crumbling of granules can be ensured at W in the range of 15.11-18.94%.

Any intermediate values of the factors W or P at which the crumbling of the granules will not exceed 22 % can be determined from the above regression equation for y_1 by setting one of the factors and calculating the other. Less accurately, the same can be determined from Figure 3.

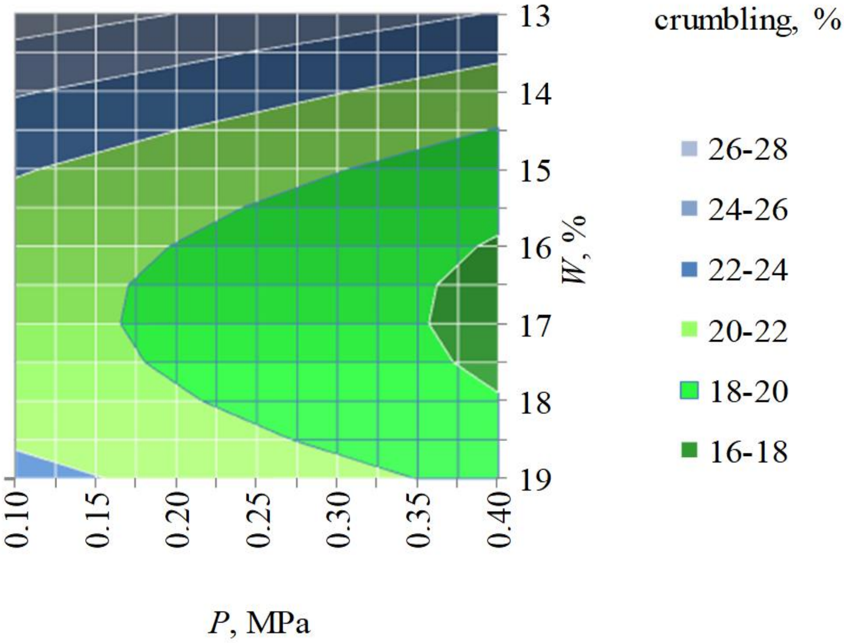

Figure 3 Isolines of the dependence of the crumbling of granules on the moisture content of loose mixed fodder and steam pressure during granulation.

Considering the response surface and isolines shown in Figure 4 and Figure 5 of the dependence of the specific energy costs for the granulation process on the moisture content of loose mixed fodder *W* and steam pressure during granulation *P*, their nonlinear (quadratic) nature is visible, determined by significant coefficients b_{11} and b_{22} in the equation for y_2.

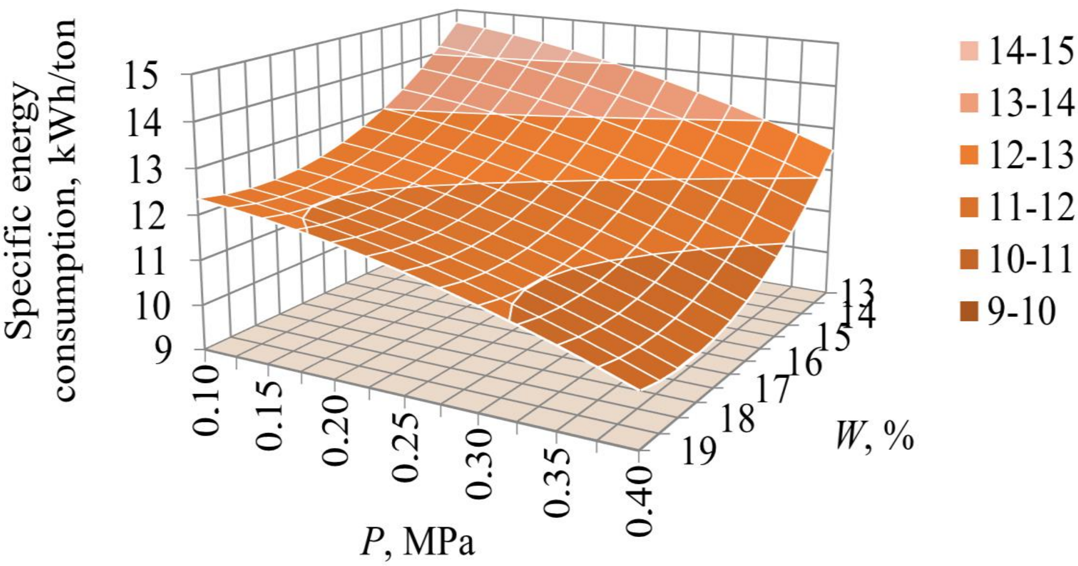

Figure 4 The response surface of the dependence of the specific energy consumption for the granulation process on the moisture content of loose feed and steam pressure during granulation.

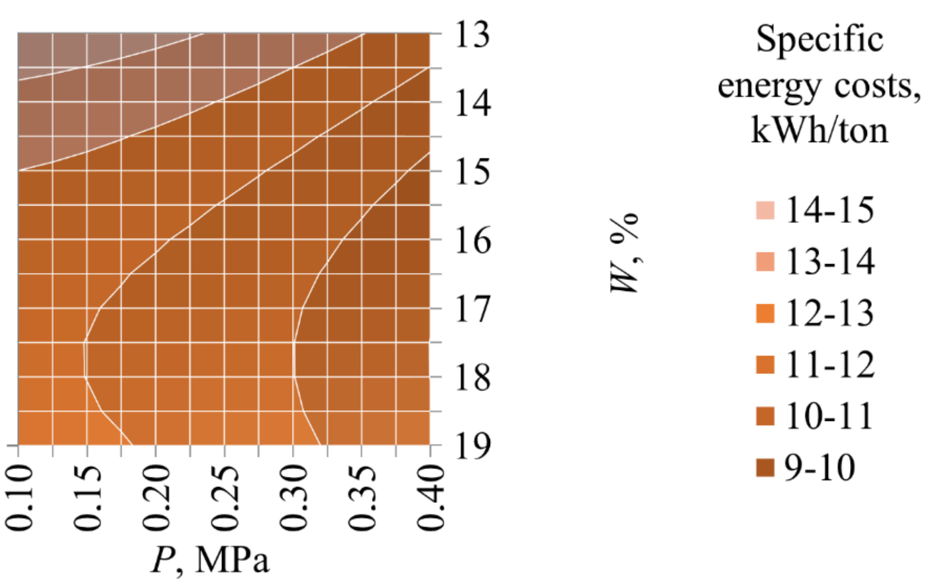

Figure 5 Isolines of the dependence of the specific energy consumption for the granulation process on the moisture content of loose feed and steam pressure during granulation.

Due to the significant negative parabolic dependence of the specific energy consumption for the granulation process y_2 on the steam pressure *P*, its increase, regardless of the moisture content of the loose feed *W*, leads to a gradual decrease *in* y_2, reaching the minimum values of energy consumption at $P = 0.4$ MPa. The same nature of the dependence of y_2 on the factors *W* and *P* is more accurately seen in Figure 5. It can be seen that the minimum energy consumption for the granulation process is provided at a vapor pressure of $P = 0.4$ MPa in the moisture range of loose mixed fodder $W = 17.50\text{-}18.00\%$.

A joint analysis of the isolines in Figure 3, where green tints highlight the area of admissible values of crumbling granules $y_1 \leq 22\%$, and in Figure 5, which shows the isolines of changes in the specific energy consumption for the granulation process y_2, shows that at steam pressure $P = 0.4$ MPa and moisture content of loose feed $W = 17.50\text{-}18.00\%$, the crumbling of granules will be in the acceptable range equal to 20.84-21.21%.

Using the equations of dependencies y_1 and y_2 on the granulation modes (factors *W* and *P*) given in Table 3, the optimization problem was solved to determine the optimal granulation modes *W* and *P* that provide the minimum energy costs for granulation y_2 with a crumbling of granules of not more than 22%.

To determine the technological modes of granulation of loose mixed fodder, under which the minimum energy costs will be ensured, the following equation was taken as the objective function:

$$y_2 = 47.39 - 3.956\ W + 0.1116\ W^2 - 14.55 P^2 \rightarrow min \quad (4)$$

The equation of the dependence of the crumbling of granules on the modes of granulation was taken as a limitation on the normalization of the quality of the granules:

$$y_1 = 142.29 - 14.290\ W - 10.445 P - 0.4234\ W^2 \leq 22\% \quad (5)$$

Restrictions on the modes of granulation of loose feed were taken equal to the ranges of changes in the conditions of experiments in the matrix of experiments:

$$13\ \% \leq W \leq 19\%;\ 0.1\ \text{MPa} \leq P \leq 0.4\ \text{MPa} \quad (6)$$

Using the obtained system of equations and inequalities (4)-(6), the optimal technological modes of granulation of loose mixed fodder were determined by the method of nonlinear programming, subject to all restrictions:

– moisture content of loose mixed fodder $W^{opt} = 17.73\%$;

– steam pressure during granulation $P^{opt} = 0.4$ MPa.

These modes provide, when granulating loose mixed fodder, the minimum energy costs equal to $y_2^{opt} = 9.985$ kWh/ton, and the normalized value of the crumbling of granules, equal to $y_1^{opt} = 20.99\%$.

An experimental batch of granulated mixed fodder was developed with the optimal values of the factors, the moisture content of loose mixed fodder of 17.73%, and the steam pressure during granulation of 0.4 MPa. The experimental value of the crumbling of the granules was 20.11 %. The specific electricity consumption was 9.23 kWh/t. The experiments showed that the discrepancies between the experimental and calculated data are insignificant and are within the error of the experiments for determining these indicators.

Many researchers report that broilers fed pelleted feed had higher body weight and better feed conversion **[28]** than broilers fed loose feed **[29]**, **[30]**, **[31]**, **[32]**, **[33]**. Compared to a loose diet, a pelleted diet improves egg production, shell strength, and egg white quality **[34]**. When using granulated feed, the digestibility of protein (by 2.7%), fat (by 0.2%), and nitrogen-free extractive substances (by 5.3%) increased, as well as the use of nitrogen, calcium, and phosphorus **[35]**. Other benefits of granulation include reduced ingredient separation, ease of handling, improved feed flow in equipment, reduced formulation cost by incorporating alternative ingredients, and reduced caloric intake. Compared to mash, pellets improve bird performance by reducing feed wastage, facilitating selective feeding, eliminating pathogens, improving palatability, and increasing nutrient uptake. One of the disadvantages is that granulation costs about 10% more than the production of loose feed mixture **[36]**.

The positive effect of pelleting on broiler performance is partly due to improved nutrient digestibility **[37]**, increased feed consumption **[38]**, and increased broiler resting time, which favors lower energy expenditure in maintaining and increasing the availability of net energy for production **[39]**. However, this better performance can only be achieved if the pellets maintain their integrity until the birds ingest them.

Conditioning is the most critical step in manufacturing a quality pellet **[40]**. Steam conditioning represents a manipulable thermo-mechanical processing variable **[41]**. To obtain a good quality granulated feed, it is necessary to precondition the raw material, which is ensured by moisturizing it and changing its structure **[42]**. During conditioning, the hot steam breaks down the structure of the starch, causing it to gelatinize **[43]**, and allowing the feed particles to bind, resulting in strong granules. Applications of steam in animal feed manufacturing have long been recognized as a good way to produce high-quality pellets **[44]**.

During conditioning, steam enhances particle adhesion, improving pellet **[45]** quality, as documented by Buchanan and Moritz **[46]**. With the right conditioning process, the granules have high strength, the consumption of energy used for their production is reduced, and the wear of the dies is also reduced **[47]**. Heat applied during conditioning may aid in the destruction of pathogens (i.e., Salmonella) and anti-nutritive factors found in certain ingredients (i.e., trypsin inhibitor in soybean meal) **[48]**.

High dietary fat content may result in less durable pellets **[49]**. Fat reduces the contact of the meal with die-hole walls, facilitating feed passage through the die and thereby reducing feed compaction inside the die holes **[50]**. The addition of fat before conditioning causes partial encapsulation of feed particles and hinders the penetration of steam, which thus reduces starch gelatinization and weakens capillary adhesion forces **[51]**.

Understanding how to optimize pellet quality through precision thermo-mechanical processing may impact broiler performance, nutrient availability, and, thus, the cost of production **[52]**. Choosing proper conditioning process parameters could save electrical energy consumption in the pelleting process and achieve targeted pellet quality **[53]**.

If the granulation technology is violated, the feed granules can be of high humidity and temperature and easily break down. The right moisture content value will maximize the quality of the pellets and increase the value of the Pellet Durability Index (PDI). Many factors affect the moisture content in the feed, such as changing the steam pressure configuration, adding moisture to the mixing process, changing the retention time configuration, and other methods **[54]**.

The ratio of the individual feed components in terms of their ability to interact with each other is also important. Hydrophobic and gyrophilic components are poorly retained among themselves in the composition of the granules. Often, the strength of the granules is sought to be increased by using very high granulation temperatures (above 85 °C) and high steam pressure. The performance of a feed mill is often attempted to be increased by rapidly cooling the pellets **[55]**.

It should be understood that such methods of increasing productivity and increasing the strength of granules are fraught with a sharp deterioration in their quality. The granules become very dense with sharp edges. Feeding such feed leads to trauma to the bird's oral cavity and damage to the cuticle of the muscular stomach **[56]**. Such granules, as well as fine grinding of loose compound feed, sharply increase the viscosity of the feed in the intestinal contents, which leads to a decrease in digestibility and assimilation of the feed, as noted above when characterizing loose compound feed.

Koshak and Koshak **[57]** studied in detail the effect of the composition of compound feed for poultry on the specific energy intensity of the granulation process. They found that an increase in the grain content in the feed by 35.16% leads to an increase in the specific energy intensity of the process by 60.13%. An increase in the content of meals and oils in feed by 7.2% causes a decrease in specific energy consumption by 18.1%.

The formulation of a pelleted diet has always been considered to be one of the most important factors that influence pellet durability. It is also highly influential in energy consumption as many ingredients are known to improve or diminish production capacity dramatically. This can be due to the presence, or lack thereof, of lubricating factors, the ability of ingredients to scour or “polish” the pellet dies, or because the bulk density of an ingredient requires the mill to exert an excess amount of energy to compress the material before it can be extruded through the die **[58]**.

Therefore, when developing compound feed formulas, it is necessary to consider the optimal content of meals and oils, both in terms of the exchange energy of the compound feed, its nutritional value, digestibility, and in terms of the specific energy intensity of the granulation process.

With a decrease in palatability, one should first study the physical and mechanical properties of the feed and evaluate them from the point of view of optimality **[59]**. Unsatisfactory physical and mechanical characteristics of the feed mixture or compound feed can drastically reduce the rate and degree of nutrient intake **[60].** Heterogeneous grinding of food makes the bird choose first particles of food 0.5-1.4 mm in diameter, then larger ones. The bird almost does not consume flour and grain dust, finely ground to 0.2 mm feed components. Pulverity and heterogeneity of feed reduces nutrient intake in chickens by 15-19% and in adult hens by 10-14% **[61]**. Sorting the feed by the bird during its consumption negates the computer's accuracy in calculating the feed ratio **[62]**.

As a result of solving the optimization problem, the optimal values of the input parameters were obtained, which made it possible to obtain high-quality mixed fodders. As a result of a comprehensive assessment of the quality of complete granulated feed, it was found that the resulting feed met the requirements for feed for poultry.

CONCLUSION

Mathematical modeling of the granulation process of loose compound feed for broilers made it possible to solve an important practical problem of optimizing the granulation modes, which ensures the production of granules of the required quality with minimal energy consumption. With the optimal values of the factors obtained in the study using the experimental planning method, an experimental batch of granulated feed was developed. At the selected levels of factors, the calculated value of the crumbling of the granules was 20.11%. The specific electricity consumption was 9.23 kWh/ton. The experiments showed that the discrepancies between the experimental and calculated data, respectively, the crumbling of 20.99% and the specific power consumption of 9.985 kWh/ton, are insignificant and are within the error of the experiments for determining these indicators. The conducted studies and modeling of the granulation process of loose compound feed made it possible to find out the nature of its moisture content's influence on granules' quality, as well as to determine the optimal granulation modes that provide normalized crumbling of granules. Granulation of mixed fodder using the optimal granulation parameters obtained using mathematical modeling is recommended: moisten loose mixed fodder up to 17.73% and maintain steam pressure during granulation at 0.4 MPa. The obtained optimal granulation parameters, established using mathematical modeling, can serve as the basis for producing granulated feed for broilers. Numerous studies have reported that the physical form of feed significantly impacts broiler growth and feed intake. Unsatisfactory physical and mechanical characteristics of compound feed can drastically reduce the rate and degree of nutrient intake. The first and most distinct reaction to a change in the physical and mechanical properties of the feed is the reaction to a change in the rate and volume of feed eaten by birds.

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The authors declare no conflict of interest.

Ethical Statement:

This article does not contain any studies that would require an ethical statement.

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