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Effect of extrusion process parameters on pellet crumbliness in fish feed production

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ABSTRACT

The article presents the results of studying the pellets crumbliness index of a pilot batch of extruded compound feed for pike-perch. The regimes of extruded pellets fish compound feed production with minimal crumbling were defined using a mathematical model. A 3-factorial central composite design was implemented to obtain a mathematical model of the process of extrudate resulting in the second-degree polynomial. The process influencing factors include the feed mixture moisture W (%), extrusion temperature T (°C) and steam pressure P (MPa). Experimental studies were conducted according to the experimental plan. The experimental data obtained were entered into the planning matrix. Experimental data was processed in a program prepared in Microsoft Excel. As a result, an adequate second-order mathematical model describing the dependence of the crumbliness index on the feed mixture moisture before extrusion, extrusion temperature and steam pressure was obtained. The mathematical model adequacy was tested based on Fisher's variance ratio. The Fisher criterion is an important statistical tool for verifying the adequacy of the model and analyzing the variance. The analysis of the obtained model and its graphical interpretation are presented. A good extrusion process mathematical model was developed. The fundamental principles of feed mixture processing on a single-screw extruder and the choice of its rational parameters ensure the production of extruded compound feed pellets for pike-perch with minimal crumbling were studied. A minimal crumbling is provided at the following values of the factors - feed mixture moisture before extrusion is 32%, extrusion temperature is 132 °C, and pressure is 0.4 MPa. In the selected levels of factors, the calculated value of extruded pellets crumbling was 1.02%.

Keywords: aquafeed, extrusion, crumbability, modelling, extrudate

INTRODUCTION

The theory of balanced nutrition has allowed a scientific justification of the need for human food in terms of energy and plastic components to overcome many diseases associated with a lack of vitamins, essential amino acids, trace elements, etc. Various diets have been created for all population groups, considering physical exertion, climatic, and other living conditions. Fish and seafood are widely recognized in terms of their role in nutrition, as they provide protein and a unique source of omega-3 fatty acids and bioavailable micronutrients **[1]**. Aquaculture, as a feature of agriculture, has to play a huge role in implementing the balanced nutrition concept of the population. Apparent advantages include the possibility of fish cultivation organization directly in the places of its consumption and in a wide range according to population demand – from traditional to delicatessen species. The specificity of aquaculture as a technological process guarantees production transparency and controllability, which is the basis for improving efficiency, safety, environmental performance and quality of the final product **[2]**. However, the aquaculture of the Republic of Kazakhstan is developing slowly enough and its growth opportunities have not yet been exhausted. The intensive development of industrial aquaculture is currently holding the limited range of fish feed proposed by domestic feed manufacturers **[3]**. Developing full fish feeding is the paramount consideration of scientists from many countries with a growing aquaculture. Different species and ages fish feed formulation changes all the time, new components and feed additives, reflecting the latest data on the study of fish physiology and metabolism, are introduced into their composition **[4]**.

Kazakh Research Institute of Processing and Food Industry LLP is actively working to find new raw materials for the mixed feed production to improve fish compound feed's technological and structural-mechanical properties. The production of compound feeds is a complex technological process that allows obtaining a final feed product with the required characteristics from several types of raw materials. Each type of compound feed is produced according to a specific recipe developed, taking into account the breed, direction of cultivation, age and type of animal, bird or fish for which it is intended. At the moment, scientists are working on developing formulation and technology for the domestic extruded feed production for several promising aquaculture facilities for breeding fish, such as pike-perch, sharp tooth catfish, jade perch, tilapia and pike in recirculating aquaculture systems (RAS).

Pike-perch export to Europe has increased over the last 15-20 years. In this regard, there is a depletion of biological resources in fisheries waters – rivers, lakes, and ponds, which today remain the main sources of fish production in the background of extremely poor development of culture-based fisheries in the republic **[5]**.

Work on pike-perch artificial reproduction for fish stocking of water reservoirs and cultivation of marketable products in the farms of Kazakhstan has recently begun. Therefore, studies are actively conducted toward increasing efficiency in pike-perch breeding within industrial conditions and developing the physiologically complete domestic starter and production extruded feed for them.

Currently, a significant part of plant and animal raw materials used in the production of feed for aquaculture is extruded **[6]**. The main advantage of this technological operation is the transformation of the raw material structure. For example, during the temperature treatment of the feed mixture under pressure, starch is broken down to dextrin and sugar, proteins are denatured, enzyme inhibitors are inactivated, some toxins are neutralized and their producers are destroyed. At the same time, nutrients become more available for fish to digest **[7]**. Extrusion makes it possible to change the properties of the finished feed over a wide range by varying the parameters of the technological process **[8]**. Many scientific publications outline the results of studies on the extrusion of one type of raw material, less often, a two-component mixture. However, the process of multicomponent mixtures extrusion, which are compound feeds for aquaculture, has not yet been studied sufficiently. At the same time, the established principles of the compound feed extrusion process need further clarification **[9]**. The composition of fish compound feed includes poorly pelletized components, namely: fish-flour, salt, chalk, whey, which affects the energy intensity of the extrusion process, as well as structural and mechanical properties of the pellets, such as hardness and crumbling. Compound feed pellets crumbling can be reduced by optimising the extrusion regimes without the formulation changing **[10]**.

The pellets crumbling is a quality factor which characterizes the degree of dependence of particles making up the pellets. During feed transportation, particularly over long distances, and in transshipping from one mode of transport to another, or in transportation under unsatisfactory conditions, the pellets can degrade, losing their consumer quality characteristics and reducing in volume. Fish compound feed crumbling index affects the depletion of feed nutrients in the water, the swelling characteristic, water resistance, safety during transportation and dispensing. During pneumatic transportation, collisions the pellets with the pipe walls can lead to damage to a particular part of the pellets, which is primarily a problem for large pellets (> 8 mm). As a rule, many different mechanisms are associated with the degradation of pellets. Abrasion of pellets or its surface leads to the formation of small particles. This is mainly because of the interaction of pellet with the pellet or pellet with the pipe wall.

The crushing of larger particles from the pellets is considered as shearing. In particular, ribs and corners are weak points and subject to shearing. As for the physical quality, during pneumatic transportation, the abrasion of pellets occurs in the feeder mechanism at various flight speeds (25, 30 and 35 m/s) and feed rates (9, 18 and 36 kg/min). The physical quality of the 12 mm feed pellets was measured as present quality, DORIS value, hardness coefficient and durability. Significant differences in fine particle formation between feeds were observed during pneumatic transportation. Increasing the air velocity (m/s) increased cracking (particle size 2.4-10 mm) and small particles (particle size < 2.4 mm). Increasing the feed rate (kg/min) had the opposite effect, causing the reduction of cracking and small particles **[11]**.

Thus, crumbled small feed particles generated during transportation and dispensing can lead to water pollution, and oxygen deficiency in water due to their bacterial decomposition. Suspended feed particles can settle inside the fish gills and cause tissue irritation with inflammatory processes.

Studies using special machinery and equipment for testing the strength of compound feed, where the mechanical impacts are made on the pellets, are carried out for evaluation of the pellets' strength with various methods and quality assessments **[12]**. In our country, the crumbling of feed pellets is usually determined according to GOST 28497-2014. The essence of the method lies in the degradation of the tested product pellets, the separation of nondegraded pellets from the fines and crumbs by their sieving and weighing, followed by the crumbling calculation **[13]**.

Scientific Hypothesis

By varying the parameters of the technological extrusion process, it is possible to affect the physical properties of the obtained finished pellets of fish compound feed. We expect that developing an adequate extrusion process mathematical model, the study of the fundamental principles of multicomponent mixtures processing on a single-screw extruder and the choice of its rational parameters will help obtain extruded compound feed pellets with minimal crumbling.

MATERIAL AND METHODOLOGY

Samples

Extruded pellets of compound feed for fish (compound feed for pike perch). They are cylindrical brown granules with a diameter of 6 mm and a length of 5 mm. The composition contains raw materials of animal origin (fish meal, meat and bone meal), vegetable origin (corn gluten, wheat, rapeseed meal, oil, betaine), feed yeast, mineral additives and oils.

Chemicals

No chemicals were used.

Instruments

CAS SW-2 bench scales (CAS Corporation, Seoul, South Korea), Model N: MW-113000, it 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 – 4.75 mm with a diameter of – 300 mm (IP Sedov A. B., Moscow, Russia) they are used to separate destroyed granules from unresolved ones. Glass container for pouring the analyzed sample and weighing.

Laboratory Methods

The pellets crumbling was determined following GOST 28497-2014 "Feed, compound feed. Method of crumbling properties granule determination" on the U17-EKG **[13]**. The essence of the method consists in destroying the extruded pellets, separating undisturbed pellets from the fines and crumbs by sieving, weighing them, and calculating the crumbliness index.

Description of the Experiment

A total of 24 samples were analyzed, with two repeated analyses and two experiment replications for each sample.

Design of the experiment: The production of experimental compound feed for pike-perch according to the developed formulations and testing of the production technology modes were carried out using feed components of domestic production by extrusion at the Golden Fish.kz LLP plant located in the Belbulak village, Almaty region. An extrusion line assembly of the plant is from the Chinese "HENAN RICHI MACHINERY CO.LTD". A single-screw extruder was used for the extrusion of feed. The working body is a screw rotating in the chamber, during its rotations, the crushed feed raw materials with a humidity of 12-16%, are heated to 120-150 °C, at a pressure of 2.8-3.8 MPa, plasticized and loomed through the holes of the circular cross-section matrix with a diameter of 5 mm, a soft knife fitting form to realize stepless speed change, which can cut the discharge arbitrarily into a product of the required length. Then the process quickly passes from the area of high pressure to the area of ambient pressure, the homogeneous mass expands, resulting in the formation of a product of a porous structure.

Compound feed for pike-perch is high-protein and high-energy. Respectively, raw materials for compound feed production had to be selected with a high protein content and digestibility.

From raw materials of animal origin, fish meal has a complete set of amino acids necessary and easily accessible for fish, but its use is limited due to its high cost and shortage in our region. As a result, it is necessary to use alternative sources of vegetable and animal protein to partially replace fishmeal. Meat and bone meal is also a good source of animal protein, it contains essential amino acids – arginine and histidine. The high content of saturated rapidly oxidizing fats limits its use to 10%. In the extrusion processing of the raw materials mixture, the fat content of it must be less than 6%, otherwise, the pellet will not form. Therefore, the raw material should be low in fat. It is established that such raw materials are various isolates and concentrates, protein meal and seed cake, and wheat and corn gluten. For example, soy meal can be used up to 40% as part of fish feed, it contains up to 40% protein and up to 1.5% fat. Soy isolate contains 86.6% protein and 0.5% fat. Wheat gluten contains up to 75% protein and 1.2% fat **[14]**.

The formulation of grower compound feed for pike-perch developed by us contains raw materials of animal origin – 40%, vegetable origin – 39%, microbiological origin (feeding yeast) – 15%, mineral and other additives – 2.75, oils – 3.25, which applied to the extrudates after the output of pellets from extruder by coating.

The pellets crumbling was determined following GOST 28497-2014 "Feed, compound feed. Method of crumbling properties granule determination" on the U17-EKG. The grinder is a two-chamber box, each chamber is 100 mm x 350 mm x 350 mm in size, on the side of the chambers there is a metal protruding plate (divider) that affect the compound feed sample during chamber rotation.

In this regard 500.0 ±0.1 g double-finished extruded feed weight was taken and placed in the device's chambers. Then device was run, and the chamber began to rotate. The chamber with the extrudate is rotated for 10 minutes at a speed of 50 rpm. Then the device automatically shut off, the contents are poured, sifted through a sieve with a cell size equal to 0.75 of the diameter of the analyzed granules, the remaining granules on the sieve are weighed with an accuracy of ±0.1 g.

The crumbling was calculated using the following formula:

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

Where:
m1 – pellets weight before testing, g; m2 – pellets weight after testing, g.

The duplicate arithmetic mean was taken as the final test result. The mathematical model was carried out using a multifactorial experiment. The following factors were chosen: feed mixture moisture before extrusion, extrusion temperature, steam pressure. The crumbling index was taken as a quality criterion. A 3-factorial central composite design was implemented to obtain a mathematical model of the process of extrudate resulting in the second-degree polynomial **[15]**.

Statistical Analysis

In order to obtain a three-factor mathematical model, a Box-Behnken rotatable design B3 was implemented. Experimental studies were conducted according to the experimental plan. The experimental data obtained were entered into the planning matrix. Experimental data was processed in a program prepared in Microsoft Excel. Calculations of the coefficients of the mathematical model and verification of its adequacy were carried out according to the standard methodology for a Box-Behnken rotatable three-factor design. Calculations of the coefficients of the regression equation (mathematical model) in coded and natural values of the variance of reproducibility and adequacy, calculated values of Fisher's criterion to check the adequacy of the model were carried out in a Microsoft Excel spreadsheet according to the program prepared by the authors. As a result, an adequate second-order mathematical model describing the dependence of the crumbling coefficient on the feed mixture moisture before extrusion, extrusion temperature and steam pressure was obtained. The mathematical model adequacy was tested based on Fisher's variance ratio **[16]**. The Fisher's criterion is an important statistical tool for verifying the adequacy of the model and analyzing the variance. It compares the significance of factors and their interactions in the model and determines whether the model adequately describes the data.

RESULTS AND DISCUSSION

The variables changing the extrusion process and the properties of the finished extruded feed, are usually the following: raw material feed rate, extruder screw rotation speed, its dies diameter, extrusion temperature, and extruder output pressure **[17]**, **[18]**, **[19]**. In this study, the process influencing factors include the feed mixture moisture W (%), extrusion temperature T (°C) and steam pressure P (MPa). An experimental matrix design was prepared – Table 1.

Table 1 Matrix plan of the experiment in decoded form.

Experience option	**Parameters**			**$У_1$ crumbability,%**
	X_1 feed mixture humidity,%	**X_2 extrusion temperature, °C**	**X_3 pressure, MPa**	
1	28	128	0.3	1.48
2	28	132	0.3	1.34
3	28	138	0.3	1.11
4	28	140	0.3	1.08
5	32	128	0.3	1.33
6	32	132	0.3	1.08
7	32	138	0.3	0.98
8	32	140	0.3	0.95
9	36	128	0.3	1.08
10	36	132	0.3	1.05
11	36	138	0.3	0.99
12	36	140	0.3	0.83
13	28	128	0.4	1.11
14	28	132	0.4	1.08
15	28	138	0.4	1.05
16	28	140	0.4	1.01
17	32	128	0.4	1.01
18	32	132	0.4	0.96
19	32	138	0.4	0.93
20	32	140	0.4	0.72
21	36	128	0.4	0.82
22	36	132	0.4	0.79
23	36	138	0.4	0.75
24	36	140	0.4	0.69

The selected variability intervals of influencing factors and their levels are shown in Table 2.

Table 2 Variability intervals of influencing factors and their levels.

Factors		**Levels of variation**				
Natural	**Encoded**	-1.68	-1	0	+1	+1.68
The humidity of compound feeds *W*, %	x_1	16	20	26	32	36
Extrusion temperature *T*, ^{0}C	x_2	116	120	126	132	136
Steam pressure *P*, MPa	x_3	0	0.1	0.25	0.4	0.5

According to B3 three-factor design, the number of experiments is $N = 24$, the number of zero points is $n^0 = 6$. Experimental data processing was carried out on a program developed in Microsoft Excel. Pellets crumbling mathematical models are in coded values.

$$y1=2.1964-0.2806_{x1}-0.3736_{x2}-0.3395_{x3}+0.30375_{x1x2}-0.16625_{x1x3}-0.07625_{x2x3}-0.076_{x1}^{2}-0.1907_{x2}^{2}-0.129_{x3}^{2} \quad (2)$$

Pellets crumbling mathematical models are in natural value:

$$Y1=-44.9464-0.9539W+1.032T-5.27P+0.0084WT-0.1847WP+0.0847TP-0.0021W^2-0.0053T^2-5.7312P^2 \quad (3)$$

The mathematical model adequacy was tested based on Fisher's variance ratio. Dispersion of reproducibility:

$$S^2(\bar{y}) = \frac{0.1442}{6-1} = 0.0288$$

Dispersion of adequacy:

$$S_{ad}^2 = \frac{0.8659 - 0.1442}{20 - 10 - (6 - 1)} = 0.1444$$

Calculated F-value:

$$F_{\text{p}} = \frac{S_{ad}^2}{S^2(\bar{y})} = \frac{0.1444}{0.0288} = 5.01 < \text{F}\text{т} = 5.05.$$

Degrees of dispersions freedom:

$$f_E = n_0 - 1 = 6 - 1 = 5$$

$$f_{ad} = N - \lambda - (n_0 - 1) = 20 - 10 - (6 - 1) = 5.$$

Tabular value of Fisher's variance ratio at $f_E = 5$ and $f_{ad} = 5$ is $F_т = 5{,}05$. Where, $F_p < F_т$ - a hypothesis for mathematical model adequacy.

Response surfaces and two-dimensional section contours *y=f(x, x₂), y=f(x₁, x₃)* and *y=f(x₂, x₃)* at *x₃=0, x₂=0* and *x₁=0* (Figures 1-3).

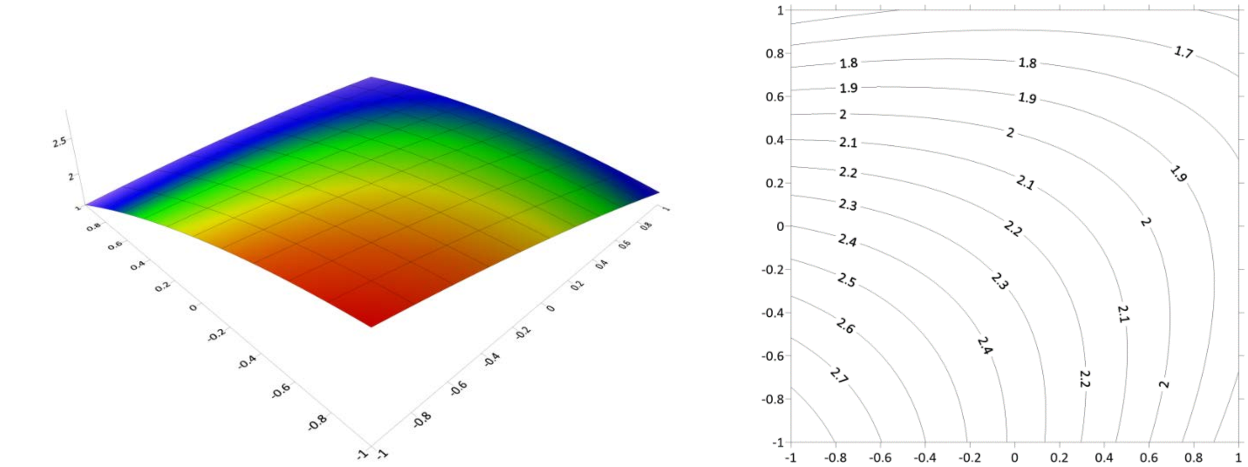

Figure 1 y_1 dependences of pellets crumbling on x_1 compound feed moisture and x_2 extrusion temperature at $x_3 = 0$.

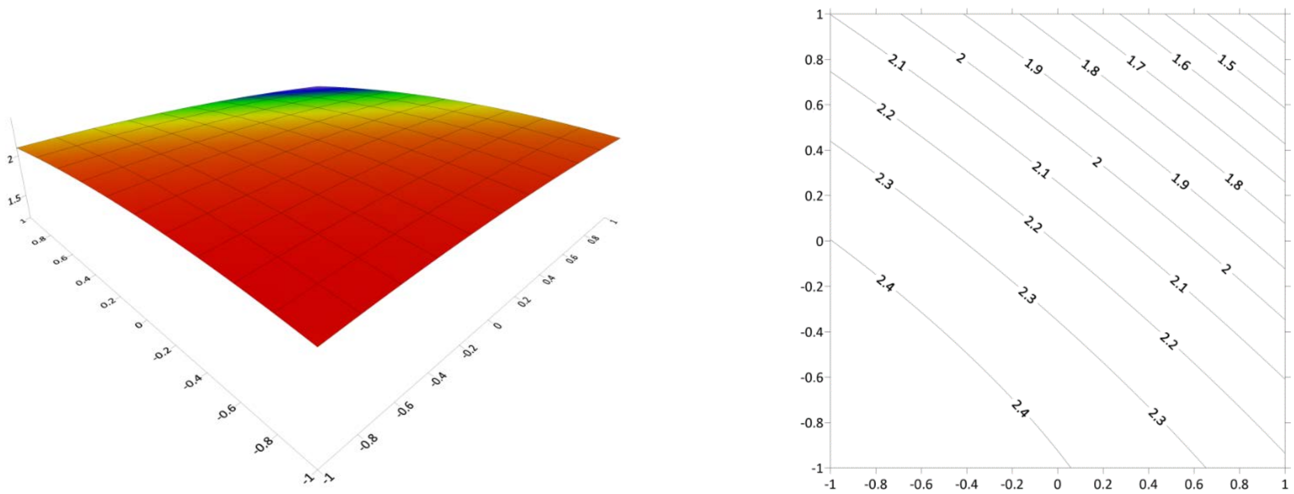

Figure 2 y_1 dependences of pellets crumbling on x_1 compound feed moisture and x_3 steam pressure at $x_2 = 0$.

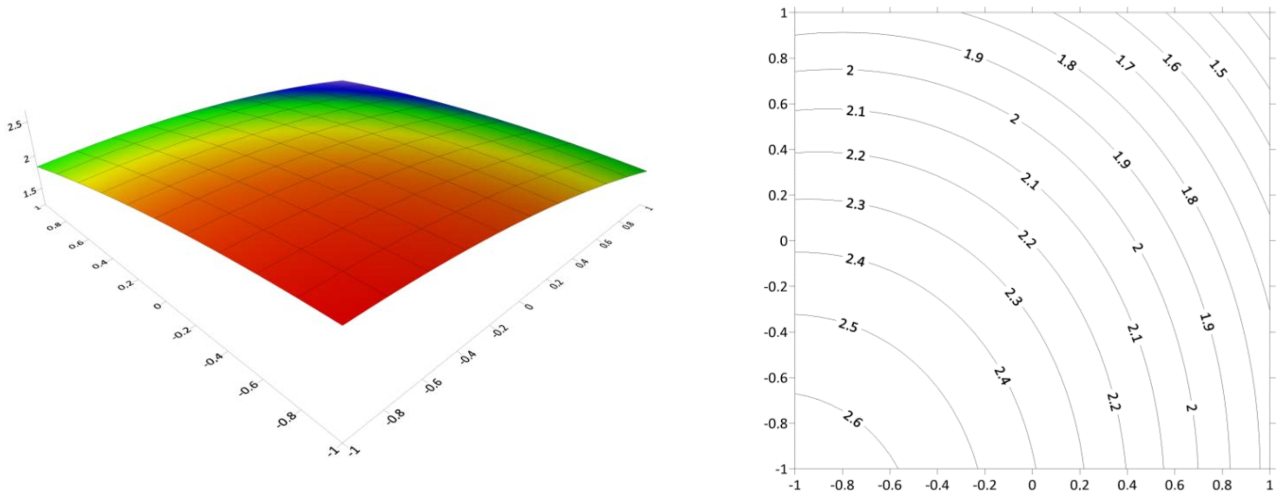

Figure 3 y_1 dependences of pellets crumbling on x_2 extrusion temperature and x_3 steam pressure at $x_1 = 0$.

Analysis of the two-dimensional section of the response surface showed the following:

- x1 and x2 influence study at x3 = 0, where the minimal pellets crumbling is provided at x1 = +1 and x2 = +1;
- x1 and x3 influence study at x2 = 0, where the minimal pellets crumbling is provided at x1 = +1 and x3 = +1;
- x2 and x3 influence study at x1 = 0, where the minimal pellets crumbling is provided at x2 = +1 and x3 = +1;

Summarizing the obtained results, it is possible to draw the following conclusion - a minimal pellets crumbling is provided at the following values of the factors:

- in coded values of the factors: x1 = +1, x2 = +1 and x3 = +1;
- in natural values of the factors: compound feed moisture is W=32%, extrusion temperature is T = 132 °C, and the steam pressure is P = 0.4 MPa.

In the selected levels of factors, the calculated value of extrudate pellets crumbling from equation (2), is y = 1.02%.

Calculations of the variation of these three technological parameters in the extrusion process made it possible to obtain an adequate mathematical model of processing a multicomponent mixture on a single-screw extruder.

Achieving the minimum crumble of granules is important, since dust and smaller particles formed as a result of high crumble have no nutritional value, lead to a loss of feed and, consequently, increase production costs. The interaction of feed with the aquatic environment creates problems that are not encountered when feeding terrestrial animals. This makes the physical properties of the feed more important for aquaculture than for terrestrial animal **[20]**. The presence of lost nutrients and uneaten feed in the wastewater of fish farms has been a major obstacle to the expansion of commercial aquaculture **[42]**.

The physical properties of the finished feed pellets by their characteristics directly depend on the conditions of extrusion processing, preparation and composition of the formulation. Process variables, such as temperature, humidity, screw rotation speed, raw material type, etc., cause different reactions depending on their interaction, where physical parameters make it possible to make decisions about optimal operating conditions, being a very useful tool when evaluating a new formulation. Calculating rational parameters will help to obtain pellets of extruded compound feed with minimal crumbling.

Factors such as moisture content and temperature profile used in the extrusion process affect the molten materials' viscosity and the finished product's characteristics **[43]**, **[44]**. The properties of raw materials such as particle size distribution and chemical composition (protein, lipids, carbohydrates content, etc.) are also important **[19]**.

Several authors have pointed out that adding a vegetable protein (soy and wheat) to fish-meal results in extrudates with sufficient porosity for maintaining a balance between the ability to absorb oil and enough durability making it possible to store, transport and feed product pneumatically **[21]**, **[22]**, **[23]**.

In the production of extruded feed products, it is important to provide the conditions of the lowest possible total stress in the process material of the extruder in order to prevent the mechanical destruction of the material. And also, at the same time, create the highest possible density of the processed material to obtain a finished product at the output of the extruder with a denser and more durable structure providing the required quality of the extruded feed product. This can be achieved by quickly changing the impact parameters on the processed material, depending on its structure **[24]**, **[25]**.

In addition to processing the feed mixture in the extruder, the pellets crumbling index is influenced by the components included in the formulation, and the fineness modulus of grinding the compound feed before extrusion (limit 0.2-1 mm) **[26]**. During the extrusion process, every powdered protein ingredient can be considered as a single phase, requiring a different moisture content and temperature conditions for plasticization into dough during the extrusion process **[27]**. Achieving these conditions for all ingredients in the feed mixture is essential for obtaining new intermolecular binding networks and an acceptable physical quality of the product **[28]**. Studies by Oterhals et al. **[44]** show that the critical moisture level for plasticizing soy protein concentrate was 233-306 g/kg. The same study determined a critical moisture level of 138 g/kg for fishmeal. The moisture content used in this study (235 g/kg) is at the lowest level for plasticizing soy protein concentrate. Pellets of pure mixture of soy protein concentrate had significantly lower hardness and durability compared to pure mixture of fishmeal and may result from incomplete plasticization of the soy protein concentrate mixture at this stage. This is in line with other studies conducted on extruded food foams and fish feeds **[10]**, **[29]**, **[30]**, **[31]**.

It is known that premoistening significantly stabilizes the extrusion process. Therefore, special attention was paid to the preliminary moisture-heat treatment of grain in the studies of the extrusion process. It was found that heat treatment significantly affects the carbohydrate complex of grain. Heating it at high temperatures causes starch degradation, followed by the creation of easily soluble carbohydrates, which has a positive effect on feed digestibility **[32]**, **[33]**, **[34]**. It was established that starch dextrinization and digestibility increased intensively with an increase in grain moisture content up to 18%. For example, in extruded corn, the degree of starch dextrinization and digestibility at this moisture value reached 65% and 140 mg/g, in grain mixtures – 45% and 108 mg/g, in wheat – 2% and 90 mg/g, respectively. The grain moisture content above 18 % does not have a noticeable effect on the growth of grain starch degradation. Starch degradation in it increases at the same value of grain moisture content (18%) with an increase in the heating temperature of the extruded grain **[35]**.

The pressure generated by the screw significantly influences the extrusion process. This indicator affects the mixture treatment temperature and the quality of obtained extrudate. Chevanan N. reports a significant decrease in pressure at the output of the extruder (from 13.5 to 3.7 MPa) with increasing temperature from 90 to 160 °C **[36]**. Similarly, as moisture content of the raw material increased from 15 to 25%, the pressure decreased from 12.8 to 5.4 MPa. To calculate the mixture treatment temperature during extrusion, it is necessary to deduce the mathematical dependencies of pressure changes along the length of the screw. Mathematical dependencies will allow at the designing stage of the extruder to set the design parameters thereof under which the pressure necessary for obtaining high-quality extrudate should be provided **[37]**, **[38]**.

Many studies have found that the pressure of the raw materials processed in the pre-matrix zone of the extruder can be controlled by its supply in the loading area, rate speed of the applied screw, and the diameter of the moulding channel **[39]**. It should be noted that these factors concerning the pressure are interdependent. Therefore, correct results in studies can only be obtained by considering this fact **[40]**, **[41]**.

CONCLUSION

The regime of extrudate production with minimal fish compound feed pellets crumbling was established using a mathematical model. This mode is provided with the following natural factors values - feed mixture moisture before extrusion is 32%, extrusion temperature is 132 °C and pressure is 0.4 MPa. In the selected levels of factors, the calculated value of extrudate pellets crumbling was 1.02%. This is a good achievement since, according to GOST 10385-2014, the crumbling of extruded feed should not exceed 3%. The obtained rational extrusion parameters, established using the mathematical, experimental design method, could serve as a basis for the fish feed production. Physical properties according to its characteristics are directly dependent on extrusion and compound feed formulation conditions. Process variables such as temperature, moisture, screw speed, as well as the type of raw material used in the formulation cause different reactions depending on their interaction, so analysis of physical properties in industrial processes should be carried out regularly, mainly when new ingredients are added or if processing conditions change.

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