Mathematical planning of a multi-factor experiment and optimization of the feed extrusion process

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Abstract. To increase the level of protein and fat in milk, it is necessary to increase the total amount of feed fed, the diet must be balanced in energy, protein, fiber, minerals and vitamins; the feed must be of high quality. Oilseed waste produced during post-harvest processing and industrial processing contains a sufficient amount of protein and raw fat that can be used in animal feeding diets to increase milk productivity, and when using advanced processing methods, such as extrusion, it becomes a source of environmentally friendly vegetable protein that can increase the nutritional value of the feed several times. In order to study the efficiency of the technological process, the dependencies of quality parameters were determined. Using mathematical methods of planning a multi-factor experiment, a mathematical model of the extrusion process of feed raw materials was developed. The obtained model is used to identify recommended modes of extrusion of feed raw materials from post-harvest waste.

Keywords: extruded feed additive, modes, raw materials, extrudate, flax cleaning waste.

1. Introduction

One of the problems of modern animal husbandry is to increase the productivity of animals due to higher efficiency of using feed nutrients. This can be achieved by increasing the metabolism of the animal's body and the metabolizable energy of feed, increasing the transformation of feed nutrients into products through the use of new technologies for preparing feed for feeding (Shvetsov et al., 2011. Shevchenko, 2012. Shvetsov and Ievlev, 2011. Yacko et al., 2013. Lyapchenko et al., 2014).

Unfortunately, the modern feed base does not allow to organize a full and balanced feeding of animals, which entails the use of the genetic potential of livestock productivity by only 40-60%. To increase the level of protein and fat in milk, the following main recommendations should be followed: increase the total number of feeds fed; provide the necessary variety of feeds; the diet should be balanced in energy, protein, fiber, minerals and vitamins; the feed should be of high quality. The production of mixed feeds is based on the use of raw materials, mainly crop products (Gaivoronsky and Ramazanov, 1998. Lanetsky, 2008).

To increase the nutritional value of feed in general and its structural components, special processing methods are used, the most common of which is thermal (Mishuro, 2006).
The object of research are waste from post-harvest processing of oilseed flax produced in Northern Kazakhstan, extruded feed based on waste from post-harvest processing of oilseed flax.

2.1 Methods of research

The objects of research are waste from post-harvest processing of oilseed flax produced in Northern Kazakhstan, extruded feed based on waste from post-harvest processing of oilseed flax.

2.2 Methods of conducting research on the extrusion of post-harvest processing waste of oilseeds

To study the quality indicators, well-known methods were used, including: GOST 11549-76 “Linen flax seeds. Industrial raw material. Specifications”; GOST 10582-76 “Oilseed flax seeds. Industrial raw material. Specifications”; GOST 10583-76 “Rapeseed for industrial processing. Specifications”; GOST 22391-89 “Sunflower. Industrial raw material. Specifications”; GOST 10854-2015 “Oilseeds. Methods of determining the weed, oilseed and specially considered impurities”; GOST 27988-88 “Oilseeds. Methods of determining the color and smell”; GOST 10856-96 “Oilseeds. Methods of determining the moisture content”; GOST 10857-64 “Oilseeds. Methods of determining the oil content”; GOST R 51410-99 “Oilseeds. Determination of the acidity of oils”; GOST 10852-86 “Oilseeds. Acceptance rules and sampling methods”; GOST 29142-91 “Oilseeds. Sampling”; GOST 13496.15-97 “Crude fat content”; GOST 13496.18-85 “Acid number of fat”; GOST 13496.2-91 “Crude fiber content”; GOST 26226-95 “Crude ash content”; GOST 26657-97 “Phosphorus content”; GOST 26593-85 “Peroxide number of fat”; NFES (nitrogen-free extractive substances) were determined by calculation; digestible protein was determined using the coefficients of digestibility; flowability – according to V.E. Pestov; hygroscopicity – by establishing the equilibrium moisture by statistical method; granulometric - determined according to GOST 13496.8-72.
Working out the extrusion modes of oilseed flax waste was carried out at the production site of the scientific and innovative complex “North Kazakhstan scientific research institute of agriculture” on the feed extrusion line, which consists of a crusher, mixer, hoppers for dewatering and an extruder “PE-150”. The line capacity is 150 kg/hour.

Feed analysis was performed on the device InfraXact FOSS in accordance with GOST 32040-2012 “Feed, mixed feed, feed raw materials. Method of determining the content of crude protein, crude fiber, crude fat, and moisture using near infrared reflectance spectroscopy”.

In order to determine the optimal mode of obtaining feed based on quality and economic indicators, experimental studies on the extrusion of flax cleaning waste were conducted. The results obtained were recorded in tables in text processor Microsoft Excel, then the data obtained was studied the influence dependence of die diameter ($D$, mm), moisture content of the feedstock ($W$ %), the feed rate of raw materials ($v$, $s^{-1}$) specific energy costs per unit of production ($W_P$, W/kg) and for a period of time ($W_T$, kW/h) and metabolizable energy ($q$, mJ/kg).

To obtain the mathematical model of technological process for receiving extruded feed material from flax cleaning waste, which represents the regression equation used rotatable plan of the second order (plan Box) when the number of factors $K=3$, the number of experiments plan more than 20, the number of experiments at the zero point was 6 and the number of coefficients is 10. The coded values for obtaining a mathematical model are shown in Table 1.

| Table 1 Coded values for obtaining a mathematical model |
|--------------------------------------------------------|
| **Coded values**                                        |
| $x_1$ | $x_2$ | $x_3$ |
| ------ | ------ | ------ |
| -     | -     | -     |
| -     | -     | +     |
| -     | +     | -     |
| -     | +     | +     |
| +     | -     | -     |
| +     | -     | +     |
| +     | +     | +     |
| -1.68 | 0     | 0     |
| +1.68 | 0     | 0     |
| 0     | -1.68 | 0     |
| 0     | +1.68 | 0     |
| 0     | 0     | -1.68 |
| 0     | 0     | +1.68 |
| 0     | 0     | 0     |

3. Results

A number of key components for the production of extruded feed additives from oilseeds were considered.

To investigate the interaction of various factors that affect the extrusion process, mathematical methods of experiment planning were used.

Coding of intervals and levels of variation of input parameters is shown in Table 2.

| Table 2 Coding of intervals and levels of variation of input factors |
|---------------------------------------------------------------------|
| **Factors** | **Variation levels** |
|dfsdfsa | natural | coded | -1.68 | -1 | 0 | +1 | +1.68 | Variation intervals |
|----------------------------------|------------------|--------|-------|-----|----|-----|-------|---------------------|
| $D$, mm | $x_1$ | 5.3 | 6 | 7 | 8 | 8.6 | 1 |

3
The upper and lower levels of factors are shown in Table 3.

**Table 3 Upper and lower levels of factors**

| Indicators         | Coded value | Planning,               |          |          |          |          |
|--------------------|-------------|-------------------------|----------|----------|----------|----------|
|                    |             | X₁ die diameter, mm     | X₂ moisture, % | X₃ frequency of rotation of the feed drive, s⁻¹ | X₄ size, mm |
| Upper level        | +           | 8                       | 10       | 8.2      | 3        |
| Zero level         | 0           | 7                       | 9        | 5.8      | 2.25     |
| Lower level        | -           | 6                       | 8        | 3.4      | 1.5      |

The rotatable planning matrix is presented in Table 1. Results of the experiments of two variants (with the particle size of the feed mixture – 3 mm and the particle size of the feed mixture – 1.5 mm) obtained on the basis of the planning matrix are presented in Table 4.

**Table 4 Results of experimental studies of extrudate production from flax cleaning waste 2 variants**

| Natural values | Experimental values |
|----------------|---------------------|
| D, mm          | W, %                |
|                | v, s⁻¹              |
|                | q₁, mJ/kg           |
|                | q₂, mJ/kg           |
| 6              | 8                   | 3.4       | 8.5      | 8.86     |
| 6              | 8                   | 8.2      | 8.96     | 8.8      |
| 6              | 10                  | 3.4       | 8.97     | 8.76     |
| 6              | 10                  | 8.2      | 8.9      | 8.63     |
| 8              | 8                   | 3.4       | 8.94     | 8.84     |
| 8              | 8                   | 8.2      | 8.8      | 8.71     |
| 8              | 10                  | 3.4       | 9.03     | 8.76     |
| 8              | 10                  | 8.2      | 8.8      | 8.72     |
| 5.3            | 9                   | 5.8       | 9.09     | 8.87     |
| 8.6            | 9                   | 5.8       | 8.59     | 8.68     |
| 7              | 7.3                 | 5.8       | 8.7      | 8.87     |
| 7              | 10.6                | 5.8       | 8.78     | 8.66     |
| 7              | 9                   | 1.7       | 8.64     | 8.49     |
| 7              | 9                   | 9.8       | 9.35     | 9.2      |
| 7              | 9                   | 5.8       | 8.97     | 8.94     |

The total number of experiments for one size was 27: 8 experiments in the full-factor zone of the matrix, 2 variants of 6 experiments in the zone of star points and 7 experiments in the center of the plan.

Table 5 shows the values of the confidence intervals of the process optimization criteria for obtaining extrudate from the flax cleaning waste of 2 variants.

**Table 5 Values of confidence intervals of the optimization criterion**

| Variants | The process of obtaining extruded feed | Input parameter | Confidence intervals |
|----------|----------------------------------------|-----------------|----------------------|
| 1        | Exchange energy, q, mJ/kg              | y               | Δb₀, Δb₁, Δb₂, Δb₃   |
|          |                                        |                 | ±0.17, ±0.11, ±0.11, ±0.15 |
| 2        | Exchange energy, q, mJ/kg              | y               | ±0.12, ±0.08, ±0.08, ±0.11 |
The coefficient of the regression equation is significant if its absolute value is greater than the confidence interval \((b_i > \Delta b_i)\). Otherwise, it is considered insignificant and can be excluded from further consideration of the mathematical model. Comparing the values of confidence intervals from Table 5 with the corresponding regression coefficients in Table 6, it can be concluded that the interaction effects of input factors are insignificant, and they could be ignored.

### Table 6 Coefficients of regression equations for output parameters

| Optimization criterion | Coefficients | The process of obtaining extruded feed from flax cleaning waste | variant 1 | variant 2 |
|------------------------|--------------|-----------------------------------------------------------------|-----------|-----------|
|                        | For coded values of factors |                                                                  |           |           |
|                        | \(b_0\)      | 9.010637974                                                      | 8.888907786 |           |
|                        | \(b_1\)      | -0.0593652                                                       | -0.021929256 |           |
|                        | \(b_2\)      | -0.006986208                                                    | -0.000967704 |           |
|                        | \(b_3\)      | 0.105716904                                                     | 0.113768904 |           |
|                        | \(b_{12}\)   | 0.01375                                                          | 0.025     |           |
|                        | \(b_{13}\)   | -0.04125                                                         | 0.0025    |           |
|                        | \(b_{23}\)   | -0.02375                                                         | 0.0025    |           |
|                        | \(b_{11}\)   | -0.04780719                                                      | -0.047027785 |           |
|                        | \(b_{22}\)   | -0.08317124                                                     | -0.05056419 |           |
|                        | \(b_{33}\)   | 0.007007088                                                     | -0.02227295 |           |
|                        | For natural values of factors |                                                                  |           |           |
|                        | \(B_0\)      | -0.1530                                                          | 3.9177    |           |
|                        | \(B_1\)      | 0.585872958                                                      | 0.405418074 |           |
|                        | \(B_2\)      | 1.451241943                                                      | 0.728146058 |           |
|                        | \(B_3\)      | 0.239312214                                                      | 0.075592291 |           |
|                        | \(B_{12}\)   | 0.01375                                                          | 0.025     |           |
|                        | \(B_{13}\)   | -0.0171875                                                       | 0.001041667 |           |
|                        | \(B_{23}\)   | -0.00990                                                         | 0.00104    |           |
|                        | \(B_{11}\)   | -0.04780719                                                      | -0.047027785 |           |
|                        | \(B_{22}\)   | -0.08317124                                                     | -0.05056419 |           |
|                        | \(B_{33}\)   | 0.001216508                                                      | -0.003866832 |           |
|                        | \(F_p^*\)    | 1.004116599                                                      | 1.305505175 |           |

* - no more than the table value of the Fisher criterion \(F_{table}=5.05\)

Next, searched for the optimal response functions with the highest possible accuracy (solving a compromise problem), while taking into account insignificant coefficients for building a mathematical model, which will represent the regression equations (1):

\[
y_1 = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2,
\]  

(1)
Analysis of the presented graphs showed that on the three-dimensional model in space there are optimal regions of variable values of the magnitudes D (mm), W (W%), v (s⁻¹) at which the technological process of obtaining extrudate from the flax cleaning waste of 2 variants is carried out with the maximum values of the metabolizable energy content in the final product (q, mJ/kg).

In variant 1, analysis of the behavior of resulting three-dimensional surface showed the presence of three distinct zones: the 1st with metabolizable energy of 9-9.5 mJ/kg; the 2nd with metabolizable energy of 8.5-9 mJ/kg; the 3rd is characterized by values of 8-8.5 mJ/kg (Figure 1).

Figure 1 shows a three-dimensional model that characterizes the dependence of die diameter and the moisture content of feedstock on the metabolizable energy of the extrudate of variant 1. Monitoring of obtained results showed that increasing the diameter of the die D from 5 to 9 mm leads to an increase in moisture W up to 9%, after which this indicator begins to decrease.
optimum zone and zone with metabolizable energy of 9-9.5 mJ/kg;
2 - reduction zone and zone with metabolizable energy of 8.5-9 mJ/kg;
3 - minimum zone and zone with metabolizable energy of 8-8.5 mJ/kg

Figure 1 Three-dimensional model in space that characterizes the dependence $y_n=f(D, \phi)$ of die diameter (D, mm) and the moisture content of feedstock (W,%) on the exchange energy (q, mJ/kg) of variant 1

In this case, the metabolizable energy $q$ decreases from 9.35 to 8.59 mJ/kg with an increase in the die diameter, and an increase in moisture to 9% leads to an increase in $q$ and with a further increase in $\phi$, the metabolizable energy begins to decrease.

For example, at D=5.3 mm and W=9%, the metabolizable energy is 9.09 mJ/kg, while the increase in the die diameter values led to a harmonic oscillation of the metabolizable energy values with the maximum value of studied indicator at the peak point: at D=6 mm, $q=8.85-8.97$ mJ/kg; D=7 mm, $q=8.64-8.74$ mJ/kg; D=8 mm, $q=8.8-9.03$ mJ/kg; D=8.6 mm, $q=8.59$ mJ/kg.

However, increasing the values of die diameter (D, mm) to 8.6 mm and increasing the moisture (W, %) of feedstock to 10.6 %, led to a decrease in the exchange energy (q, mJ/kg) to 8.59 mJ/kg.

The optimal technological mode, based on the consideration of the dependence of die diameter and raw material moisture on the metabolizable energy of extrudate, is D=6-7 mm and W=8-9%. The results of experimental studies indicate that the main indicator that affects the reduction of metabolizable energy is the diameter of die.

In variant 2, analysis of the obtained results showed the presence of two distinct zones: the 1st with a metabolizable energy content of 8.5-9 mJ/kg, in the range of values D=5-8 mm and W=7-10%; the 2nd is characterized by values of 8-8.5 mJ/kg in the range of values D=9 mm and W=7-10% (Figure 2).
The dynamics of changes in the metabolizable energy content (q, mJ/kg) is observed in a sinusoidal form at a fixed moisture with an increase in the die diameter, as well as at a fixed value of the die with an increase in moisture. The indicator at which the metabolizable energy content is the maximum q=8.88 mJ/kg and the rise of sinusoid goes into decline is the values of D=7 mm and W=9%.

Further, in order to determine the optimal content of metabolizable energy, conducted experimental studies to study the degree of influence of the die diameter and the rotation speed of the feed drive on the metabolizable energy (q, mJ/kg) in the obtained extrudate.

Figure 3 shows a three-dimensional model that characterizes the dependence of die diameter and rotation frequency of the feed drive on the metabolizable energy of the resulting extrudate of variant 1.

Figure 2. Three-dimensional model in space that characterizes the dependence $y_n=f(D, \phi)$ of die diameter (D, mm) and the moisture content of feedstock (W, %) on the metabolizable energy (q, mJ/kg) of 2 variants

Figure 3. Three-dimensional model in space that characterizes the dependence $y_n=f(D, \varphi)$ of die diameter (D, mm) and the rotation speed of the feed drive (W, %) on the metabolizable energy (q, mJ/kg) of variant 1

1 - zone with a metabolizable energy content of 8.5-9 mJ/kg
2 - zone with a metabolizable energy content of 8-8.5 mJ/kg

1-2 - optimum zone; 3-4 - decrease zone; 5-6 - minimum zone
1 - zone with metabolizable energy of 8.4-8.6 mJ/kg;
2 - zone with metabolizable energy of 8.6-8.8 mJ/kg;
3 - zone with metabolizable energy of 8.8-9 mJ/kg;
4 - zone with metabolizable energy of 9-9.2 mJ/kg;
5 - zone with metabolizable energy of 9.2-9.4 mJ/kg;
6 - zone with metabolizable energy of 9.4-9.6 mJ/kg
Analysis of the behavior of the resulting three-dimensional surface (Figure 3) also showed the presence of six distinct zones: the 1st with metabolizable energy of 8.4 - 8.6 mJ/kg; the 2nd with metabolizable energy of 8.6 - 8.8 mJ/kg; the 3rd corresponded to 8.8 - 9 mJ/kg; the 4th zone, characterized by values of 9 - 9.2 mJ/kg; the 5th zone with metabolizable energy of 9.2 - 9.4 mJ/kg, and the 6th zone, respectively, 9.4 - 9.6 mJ/kg.

Analysis of the obtained results showed that the increase in die diameter D from 5 to 8.5 mm and rotation speed of the feed drive v from 1.7 s\(^{-1}\) to 9.8 s\(^{-1}\) leads to lower values of the metabolizable energy content in the extrudate, while q varies from 9.35 mJ/kg to 8.59 mJ/kg. For example, when v=9.8 s\(^{-1}\) and D=7 mm metabolizable energy obtained extrudate amounted to q=9.35 mJ/kg, with a further increase in the values of the die diameter D (mm) led to the decrease of the values of metabolizable energy at D=6 mm, q=of 8.96 mJ/kg; D=8 mm, q=8.8 mJ/kg; at D=8.6 mm, q=8.59 mJ/kg. A decrease in the rotation frequency of the feed drive (v, s\(^{-1}\)) in a constant value of the die diameter (D, mm) led to a decrease in the values of metabolizable energy (q, mJ/kg).

The optimal technological mode, based on the consideration of the dependence of die diameter and the feed rate of feedstock on the metabolizable energy of extrudate, is D=5-6 mm and v=9.8 s\(^{-1}\). The obtained results of experimental studies indicate that the factors that affect the reduction of metabolizable energy equally are the die diameter and the feed rate of the raw material.

In variant 2, analysis of the behavior of resulting three-dimensional surface (Figure 4) also showed the presence of six distinct zones:

1 - zone with a metabolizable energy content of 9-9.2 mJ/kg
2 - zone with a metabolizable energy content of 8.8-9 mJ/kg
3 - zone with a metabolizable energy content of 8.6-8.8 mJ/kg
4 - zone with a metabolizable energy content of 8.4-8.6 mJ/kg
5 - zone with a metabolizable energy content of 8.2-8.4 mJ/kg
6 -zone with a metabolizable energy content of 8-8.2 mJ/kg

Figure 4. Three-dimensional model in space that characterizes the dependence \(y_n=f(D,v)\) of die diameter (D, mm) and the rotation speed of the feed drive (v, s\(^{-1}\)) on the metabolizable energy (q, mJ/kg) of variant 2

-1st with a metabolizable energy content of 9-9.2 mJ/kg, in the range of values D=6-7 mm and v=8.2-9.8 s\(^{-1}\);
- 2nd is characterized by values of 8.8-9 mJ/kg in the range located on the periphery of the 1st zone, values of D=5-8 mm and v=3.4-9.8 s\(^{-1}\);
- 3rd, respectively, 8.6-8.8 mJ/kg in the range located on the periphery of the 2nd zone, values of D=5-9 mm and v=5.8-9.8 s\(^{-1}\);
- 4th is determined by the values of 8.4-8.6 mJ/kg in the range located on the periphery of the 3rd zone, values of D=5-9 mm and v=1-9 s\(^{-1}\).
The dynamics of changes in the metabolizable energy content (q, mJ/kg) is ascending at a fixed value of the die diameter and an increase in the rotation frequency of the feed drive. The indicator for which the metabolizable energy content is the maximum q=8.98 mJ/kg is D=7 mm and v=8.2 s\(^{-1}\).

The next stage of the study was to determine the optimal content of metabolizable energy (q, mJ/kg) based on experimental data on the degree of influence of the rotation frequency of the feed drive and the moisture of feedstock.

In variant 1, analysis of the behavior of the resulting three-dimensional surface showed the presence of five distinct zones: the 1st with metabolizable energy of 8.4-8.6 mJ/kg; the 2nd with metabolizable energy of 8.6-8.8 mJ/kg; the 3rd is characterized by values of 8.8-9 mJ/kg; the 4th, respectively, 9-9.2; the 5th has indicators of 9.2-9.4 mJ/kg.

Monitoring of the obtained results showed that increasing the rotation speed of the feed drive v from 1.7 to 9.8 s\(^{-1}\) leads to an increase in moisture W in the final product up to 9%. At the same time, the metabolizable energy q increases from 8.59 to 9.35 mJ/kg with an increase in the rotation frequency of the feed drive with a constant moisture index.

For example, at v=9.8 s\(^{-1}\) and W=9%, the metabolizable energy is 9.35 mJ/kg, while a decrease in the rotation frequency of the feed drive at a constant moisture value led to a sinusoidal decrease in the studied indicator q: at v=8.2 s\(^{-1}\), q=8.96 mJ/kg; v=5.8 s\(^{-1}\), q=9.09 mJ/kg, v=3.4 s\(^{-1}\), q=8.85 mJ/kg; v=1.7 s\(^{-1}\), q=8.64 mJ/kg. However, changing the moisture values W from 7 to 10% led to a harmonic oscillation of the metabolizable energy values with the maximum value of the studied indicator q at the peak point W=9.

Figure 5. Three-dimensional model in space that characterizes the dependence y,=f(W, v) of the raw material moisture (W, %) and the feed drive (v, Hz) on the metabolizable energy (q, mJ/kg) of variant 1

The optimal technological mode, based on the consideration of the dependence of moisture and rotation frequency of the feed drive on the metabolizable energy of extrudate, is v=8.2-9.8 s\(^{-1}\) and W=8-9%. The
Results of experimental studies indicate that the main indicator that affects the reduction of metabolizable energy is the rotation frequency of the feed drive.

In variant 2, the analysis of the behavior of the resulting three-dimensional surface showed the presence of five distinct zones:

1. Zone with a metabolizable energy content of 9.2-9.9 mJ/kg, in the range of values W=9% and v=8.2-9.8 s⁻¹;
2. Zone characterized by values of 8.8-9.0 mJ/kg in the range located on the periphery of the 1st zone, values W=7.7-11% and v=5.8-9.8 s⁻¹;
3. Zone, respectively, 8.6-8.8 mJ/kg in the range located on the periphery of the 2nd zone, values W=7-11% and v=3.4-8.2 s⁻¹;
4. Zone determined by the values of 8.4-8.6 mJ/kg in the range located on the periphery of the 3rd zone, values of W=7-11% and v=1-3.4 s⁻¹;
5. Zone with metabolizable energy of 8.2-8.4 mJ/kg, in the range of values W=11% and v=1 s⁻¹.

Figure 6 shows a three-dimensional model that characterizes the dependence of the feed drive rotation frequency and raw material moisture on the metabolizable energy of the extrudate of variant 2.

Figure 6. Three-dimensional model in space that characterizes the dependence \( y_n = f(D, \phi) \) of the moisture content of feedstock \( (W, \%) \) and the rotation speed of the feed drive \( (v, s^{-1}) \) for metabolizable energy \( (q, mJ/kg) \) of variant 2.

The dynamics of changes in the metabolizable energy content \( (q, mJ/kg) \) is ascending at a fixed value of moisture and an increase in the rotation frequency of the feed drive. The indicator for which the metabolizable energy content is the maximum \( q=9.02 \) mJ/kg is \( W=9\% \) and \( v=10.6 \) s⁻¹.

The given dependencies are \( y_n = f(D, \phi) \), \( y_n = f(D, v) \), \( y_n = f(W, v) \) from the variable parameter of the technological process for obtaining extrudate from flax cleaning waste of 2 variants - D (mm), W (%), v (s⁻¹), allow to predict with sufficient accuracy the change in the values of the optimization criteria \( y \) in the studied range of values of factors - metabolizable energy \( q \) (J/kg).
It is possible to establish a dominant effect of each investigated factor on the quality of the final product, that allows with sufficient approximation to describe the process of obtaining an extrudate from the flax cleaning waste of 2 variants (particle size – 3 mm and 1.5 mm). The results obtained will allow to optimize the process under study by applying the developed mathematical model.

Next, the identification of factors affecting the change in the values of optimization criteria \( y \) in the investigated range of values of extrudate factors from raw materials of 2 options is carried out.

As a result of analysis of the dependence \( y_v=f(D,\varphi) \), \( y_v=f(D,v) \), \( y_v=f(W,v) \) of a variable parameter of technological process of production of extrudate from flax cleaning waste of variant 1, the optimal mode, providing moderate specific energy costs per unit of production \( W_p=60-80 \) W/kg, and moderate specific energy costs for a period of time \( W_B=6-8 \) kW/h at optimum metabolizable energy content \( q=8.5-9 \) mJ/kg is the die diameter \( D=7 \) mm, moisture of the raw materials \( W=9 \) %, rotation frequency of the drive feed \( v=5.8 \) s\(^{-1}\).

Due to the fact that the grinding of raw materials increases costs: specific energy costs per unit of production \( W_p=25 \) W/kg and specific energy costs for a period of time \( W_B=4 \) kW/h; to obtain a pilot batch, the optimal mode for obtaining extrudate from flax cleaning waste of variant 1 (with a size of 3 mm), with parameters: the die diameter \( D=7 \) mm, moisture of the raw material \( W=9\% \), rotation speed of the feed drive \( V=5.8 \) s\(^{-1}\) was selected. These parameters correspond to the experimental batch number 14, which is in the results of the experimental data of variant 1.

Thus, the recommended modes of extrusion of feed raw materials from the waste of flax post-harvest processing are presented in Table 7.

| Table 7. Modes of extrusion of feed raw materials from waste of flax post-harvest processing |
|-----------------------------------------------|-----------------|-----------------|-----------------|-----------------|
| Size of raw material, mm | The moisture content of feedstock, % | Die diameter, mm | Rotation frequency of the feed drive, Hz | Raw material heating temperature, °C |
|---------------------------|------------------------|-----------------|-----------------|-----------------|
| 3                         | 9                      | 7               | 5.8             | 90-95           |

4. Discussion

The studies were conducted building models in three-dimensional space representing a plane, which characterizes the dependence of the effect of die diameter (D, mm), the moisture content of feedstock (W %), rotation frequency of the feed drive (v, s\(^{-1}\)) specific energy costs per unit of production (\( W_p \), W/kg) specific energy costs for period of time (\( W_B \), kW/h), the metabolizable energy (q, mJ/kg).

5. Conclusion

The study on optimization of waste from the flax cleaning in which the optimum mode of extrusion are the die diameter \( D=7 \) mm, moisture of raw materials \( W=9\% \), rotation frequency of the feed drive \( v=5.8 \) s\(^{-1}\), with a size of 3 mm. Production testing of the research results showed that the mathematical regression model is adequate with 95% confidence probability, and the results can be used to optimize the extrusion process of waste post-harvest processing of oilseeds with the aim of obtaining highly nourishing combined feed.

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