Increasing the efficiency of the extruder in producing sunflower cake

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Abstract. The purpose of the research is to reduce the specific energy consumption of extruders in the protein feed preparation, namely a sunflower cake, and at the same time to increase productivity without product quality deterioration. The research objective is to develop a mathematical model that describes the performance of the improved extruder. As a result of the experimental and theoretical studies using experiment design methods, a mathematical model of the sunflower cake obtainment process was designed, it describes the performance of the improved extruder. The analysis of two-dimensional sections of the combination of $X_1$ – $X_2$ factors shows the nature of the response surface of an ellipsoid shape, $X_1$ – $X_1$, $X_2$ – $X_3$ are of a paraboloid, and the centers of the experiment are located in the investigated area, which allow determining rational parameters for combinations of these factors. As a result of a multifactorial experiment, the optimal values of the factors were determined: the mixture temperature at the exit from the extrusion auger of the matrix is 133.67 °C, the extrusion auger winding pitch is 7.58 mm, the area of the discharge hole of the matrix die is 323.89 mm$^2$. With a combination of factor optimal values, it is possible to obtain high-quality sunflower cake with the highest extruder capacity, which is 0.87 t/h.

1. Introduction
At present, the extrusion is used in the feed production, which makes it possible to improve its quality [1, 2]. The process consists in the preparation of feed for farm animals [3, 4] and is associated with processing the product in an extruder by softening or plasticizing and shaping the feed by forcing it through an extrusion die. The cross section of its die holes corresponds to the configuration of the product [5]. The use of such feeds contributes to an increase in the digestibility and nutritional value of products and a balanced nutrition of animals, a decrease in the costs of preparing them for feeding, transportation and storage, as well as an improvement in the distribution and dosing process [3].

The matter of greatest practical and scientific interest is the thermal method of preparing highly-concentrated food for feeding [5].

For the seeds extrusion, industrial press-extruders of PEC-125 × 8-75 type, of KMZ-2 series of various modifications are used [2, 6, 7]. Their auger should be with a variable decreasing step as the processed feed material moves along its axis. The advantages of press-extruders are ease of use, the absence of reciprocating (inertial) forces and the associated decrease in metal consumption, no light running, a wide range of changes in the physical and mechanical properties of the processed materials and the degree of impact on them [8].

However, these brands of extruders produced in Russia and abroad are not suitable for the preparation of a high-protein feed product from vegetable raw materials, namely from sunflower cake.
Therefore, acquiring great relevance, the issues of generalization of design work on the creation of extruders, which had low specific energy consumption in the protein feed preparation, namely sunflower cake, increased performance without deteriorating the product quality.

2. Materials
The scientific research aimed at increasing the extruder performance was conducted on its improved model according to Patent of the Russian Federation (RU 2693072) (Figure 1). It includes a body 2 equipped with a charging hopper 1 with an extrusion auger 3 with a conical head 4 and an intake auger 5 located in it, windings in the form of an ordinary helicoid. An intake auger 5 and an extrusion auger 3 are made of sections 6 connected in sequence in the form of catenoids. The top of the conical head 4 is of a paraboloid form. At the same time, on each section of the augers, there are at least no more than two windings in the form of an ordinary helicoid with a pitch equal to the average size of the seeds of the main crop. The joints of the sections are made in the form of a parabola according to the normal distribution law. Moreover, the width of the section 6 of the extrusion auger 3 is 3/4 of the width of the section of the intake auger 5. After the conical head 4, a clamping sleeve 7 is installed at the outlet.

![Figure 1. The extruder construction diagram for sunflower cake preparation according to Patent RU 2693072](image)

To study and analyze the factors impact on the sunflower cake obtaining process by improved extruder according to Patent RU 2693072, table 1 was built.

**Table 1.** Factors impacting on the sunflower cake obtaining process by improved extruder, their conventional signs and planned levels of variation

| Factors                                                                 | Symbols | Variation step | Variation level |
|------------------------------------------------------------------------|---------|----------------|----------------|
| Temperature of the material at the exit from the extrusion auger of the die [7] | $x_1$   | $t$            | −1  0  +1      |
| Extrusion auger winding pitch, mm                                       | $x_2$   | $h$            | 2  6  8  10    |
| Matrix die hole area [6], mm$^2$.                                       | $x_3$   | $F$            | 100 200 300 400|

The analysis of the mathematical model was conducted by searching for an extremum in space by processing the response surfaces in a two-dimensional space with a different number of variables [9].
3. **Results**

As a result of the experimental and theoretical studies using the methods of planning experiments, a mathematical model of the process of obtaining sunflower cake was obtained, which describes the performance of the improved extruder in the form of a polynomial of the second degree:

\[
y_s = 0.8785 - 0.0195x_1 + 0.0245x_2 - 0.057x_3 - 0.00375x_1x_2 + 0.00375x_1x_3 - 0.1088x_2x_3 - 0.1681x_1^2 - 0.0031x_2^2 + 0.0719x_3^2.
\]

(1)

The validation of the obtained mathematical model (1) was checked using the Fisher criterion, the tabular value of which at a 5% significance level for the extruder performance and the number of degrees of freedom \(f_1 = 4, f_2 = 10\) was \(F_{0,05} = 4.74\). The calculated value of the Fisher criterion for the mathematical model (1) was:

\[
F_{calc} = \frac{0.0035}{0.0054} = 0.654,
\]

i.e., the validation of the mathematical model (1) is confirmed.

To find the maximum of the response function, we equate its partial derivatives to zero and solve the resulting system of equations [9, 10].

Solving the system of equations gives the following coordinates of the maximum point (coded values):

\[
x_1 = -0.053; \quad x_2 = -0.2103; \quad x_3 = 0.2389.
\]

Substituting the obtained results of the coded values into the equation (1), we determine the maximum performance of the improved extruder, which is \(y_s = 0.8697\) t/h.

The coefficients of the regression equation in a canonical form for the extruder performance will be found by composing differential equations.

As a result of the calculation, the following coefficients were obtained for finding the extruder performance for the model (1), respectively, will be:

\[
B_1 = -0.1681; \quad B_2 = -0.0317; \quad B_3 = 0.1004.
\]

(2)

The obtained coefficients (2) for the regression equation in a canonical form for the extruder performance will have the form:

\[
Y - 0.8697 = -0.1681X_1^2 - 0.0317X_2^2 + 0.1004X_3^2.
\]

(3)

After substituting various values of the optimization criterion into the equation (3), we obtain the equations in a canonical form, which characterize the extruder performance in changing the following factors:

- the temperature of the sunflower cake at the exit from the extrusion auger of the matrix and the extrusion auger winding pitch (Figure 2 a):

\[
y - 0.8697 = -0.1681X_1^2 - 0.0317X_2^2;
\]

(4)

- the temperature of the sunflower cake at the exit from the extrusion auger of the matrix and the matrix die hole area (Figure 2 b):

\[
y - 0.8697 = -0.1681X_1^2 + 0.1004X_3^2;
\]

(5)

- the extrusion auger winding pitch and the matrix die hole area (Figure 2 c):

\[
y - 0.8697 = -0.0317X_2^2 + 0.1004X_3^2.
\]

(6)
Figure 2. Two-dimensional sections of the response surface of the extruder performance versus: a – the material temperature at the exit and the extrusion auger winding pitch; b – the material temperature at the exit and the matrix die hole area; c – the extrusion auger winding pitch and the matrix die hole area

The response surface of the X₂ and X₃ factors is an ellipsoid (Figure 2 a), and its center is an extremum, since the canonical coefficients of the equations (4) have the same signs.

The response surface of the X₁ and X₃, X₂ and X₃ factors is a paraboloid (Figure 2 b, c), since the canonical coefficients of the equations (5) and (6) have different signs.

The analysis of two-dimensional sections X₁ – X₂, X₁ – X₃, X₂ – X₃ (Figure 2) shows that with a decrease in the X₁ and X₃ factors, the extruder performance index decreases uniformly, and increases with an increase in the X₃ factor.

The nature of the contour curves shows the predominance of the impact of the X₃ factor over the X₁ and X₂ factors.

4. Conclusion
The analysis of two-dimensional sections X₁ – X₂ (Figure 2 a) shows that the nature of the response surface has the shape of an ellipsoid, X₁ – X₃ (Figure 2 b), X₂ – X₃ (Figure 2 c) is a paraboloid, and the centers of the experiment are in the studied zone, which allows determining the rational parameters for combinations of these factors. At the same time, the ellipsoid major axis is located along the X₂ factor and the paraboloid – along the X₃ factor, which is explained by the large impact of the X₁ factor on the extruder performance indicator.
Having analyzed all the given two-dimensional sections of the response surfaces, the optimal values of the factors were determined:

– the material temperature the outlet of the matrix extrusion auger \( t = 133.67 \, ^\circ\text{C} \);
– the extrusion auger winding \( h = 7.58 \, \text{mm} \);
– the matrix die hole area \( F = 323.89 \, \text{mm}^2 \).

With these optimal values of the factors, it is possible to obtain high-quality sunflower cake with the highest extruder performance \( W = 0.87 \, \text{t/h} \).

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