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Modelling the centrifugal mixing process of minced meat to optimise the production of chopped meat semi-finished products

Igor Palamarchuk, Mikhailo Mushtruk, Volodymyr Vasyliv, Eugeniy Stefan, Olesia Priss, Iryna Babych, Inna Karpovych, Nataliia Pushanko

ABSTRACT

One of the most important problems in ensuring the quality of mincemeat preparation in the production of sausages is the effective structuring of components and mixing of their ingredients. To solve this problem, researchers added a multifunctional admixture based on whey protein in the process of centrifugal mixing of the components, which determined the composition of the factor space of the investigated process. Based on the results of the research, the effective content of whey protein, sodium alginate, and soy fiber in the developed recipe was proven, which showed high characteristics in terms of fat-retaining and moisture-retaining ability, digestibility, pH level – activity, and other parameters. The developed formulation made it possible to improve the general indicator of the balance of amino acids in the product and increase the functional-technological and quality parameters of the developed products. The physical and mechanical characteristics of the obtained meat product were evaluated based on the results of physical and mathematical modelling. Modelling was carried out using Federman-on-Buckingham's second similarity theory and the "dimension theory" method, which allows the processing of the obtained experimental data in the form of a criterion equation, which was compiled using Froude, Euler, and Sherwood criteria. The purpose of this study was to obtain dependencies between such process factors as product density, the coefficient of dynamic viscosity of the technological medium, the ultimate shear stress, the change in the concentration of the main impurities of lactic acid in the raw material, the value of the diffusion coefficient and the coefficient of mass transfer in the loading mass, the weight of one load of products, the angular frequency of rotation of the screws of the minced meat mixer, the radius of the rotating working bodies, the characteristic size of the products after grinding. Using the complex criterion equation and the developed program, we find a recommended set of operating mode parameters for preparing minced meat under the conditions of centrifugal influence on the mixing process and the action of the specified factors.

Keywords: dimension theory, similarity numbers, whey proteins, centrifugal driving forces, lactic acid admixture, chopped meat products, complex food additives

INTRODUCTION

To improve the nutrition structure, the tendency to create an assortment of products enriched with vitamins, minerals, dietary fibers, and other biologically active substances is becoming increasingly widespread. At the same time, preservation of the necessary taste qualities is achieved due to functional indicators, physical and chemical composition, and structural combination of the main components. The development of the meat industry involves the production of combined meat products due to the mutual enrichment of their structures, a combination of functional and technological properties, an increase in biological value, and an improvement in organoleptic properties, technical indicators of the finished product, a decrease in its value **[1]**. The generally accepted daily physiological norm of protein for an adult is 80 g on average, including about 50 g of animal protein **[2]**. The shortage of animal proteins contributes to the intensive development of food technologies with the optimal combination of meat and other raw materials to obtain biologically complete food products, which led to the development of the scientific direction of the development and production of meat products of combined composition. Serum proteins albumin and globulin have valuable biological properties, which allow us to assert the optimal set of vital amino acids from the point of view of nutrition physiology **[3]**. Such structures approach the amino acid scale of an "ideal" protein, a protein in which the ratio of amino acids meets the body's needs. Therefore, developing new food products using animal protein, particularly whey protein, allows providing meat products with complete animal protein, which is an urgent task.

The expansion and improvement of the range of chopped meat semi-finished products is traced in the works of Mushtruk et al. **[4]**; the development of meat-containing products by introducing multi-component additives into their composition for public catering establishments takes place in the works of Bal-Prylypko et al. **[5]**. The effective combination of proteins of animal and plant origin was proven by the works of Klymenko and Vinnikov, in particular, when replacing meat raw materials with complex additives to improve indicators of nutritional and biological value with enhanced organoleptic characteristics and a decrease in their cost **[6]**, **[7]**. Pasichny et al., Riabovol and Bal-Prylypko proved that the ratio of vegetable protein, animal, and food additives in the ratio of 45-50: 40-45: 5-15 in the composition of cooked sausage products provides the product with high functional and organoleptic properties **[8]**, **[9]**. Filin et al. and Kutlu et al. based on the study of the partial replacement of meat raw materials with wheat germ and fucus algae proved the enrichment of the food product with biologically active iodine, alginic acids, vitamins, and dietary fibers **[10]**, **[11]**. The positive effect of c on the formation of organoleptic and functional properties of sausage products was confirmed by the works of Sonko et al. **[12]**; in particular, the practical addition of boiled groats is salted in the works of Israelian et al. **[13]**, mashed beans – in the works of Shrana et al. **[14]**.

Research by Pylypchuk et al. revealed a nitrite-reducing bacterial preparation based on denitrifying microorganisms *Staphylococcus carnosus, S.cfrnosusssp*. utilize and cooled catholyte with a final pH of 8.86 and a redox potential (ORP) as part of the brine – 215-300 mV contributes to the formation of high organoleptic properties in sausage products and increases the nutritional value **[15]**.

The analysis of the presented and other literary sources revealed the need for systematized data and methods of effectively modelling the quality of chopped semi-finished products with a combined composition of raw materials and insufficient justification of recommendations regarding the use of complex multi-component additives of a given composition.

Thus, evaluating the effectiveness of expanding the range of semi-finished meat products with a multifunctional additive based on raw animal and vegetable materials using physical and mathematical modelling is an urgent task. This study aims to obtain the dependence between the main parameters of the process of forming the structure of chopped meat semi-finished products with a multifunctional admixture based on milk whey protein by applying the necessary experimental basis, which was developed using the similarity theory.

Scientific Hypothesis

The main hypotheses of this scientific work can be considered as follows: when forming the mass of semi-finished meat, the Sherwood criterion was chosen as the primary evaluation criterion because the provision of lactic acid diffusion is paramount; the use of the Froude criterion will allow to assess the increase in the driving force of the process due to the centrifugal forces used; the need to overcome the resistance forces of the technological environment justified the introduction of the Euler number. It is expected that the comprehensive assessment of the presented similarity numbers will allow the creation of a mathematical algorithm for describing the researched process, taking into account the main factors affecting it.

MATERIAL AND METHODOLOGY

Samples

The following were used for conducting experimental research:

• beef bone, in which the muscle tissue with a mass fraction of connective and fatty tissue does not exceed 10%, realtor Agrofirma "Polyssya LTD", Kyiv region, Ukraine to DSTU 6030:2008 **[16]**;

• pork without cysts and semi-fat, in which muscle tissue with a mass fraction of fat tissue from 45% to 80%, realtor Agrofirma "Polyssya LTD", Kyiv region, Ukraine to DSTU 7158:2010 **[17]**;

• multi-component stuffing, which includes lean pork and beef;

• melange according to DSTU 8719:2017 **[18]**;

• onion, realtor Agrofirma "Polyssya LTD", Kyiv region, Ukraine;

• specialty, realtor ATB Market.

Chemicals

Sodium hydroxide, NaOH (grade A, analytical grade, (Khimlaborreakt) Limited Liability Company, Ukraine).

Methyl red, $C_{15}H_{15}N_3O_2$ (grade A, analytical grade, (Khimlaborreakt) Limited Liability Company, Ukraine).

Sulfuric acid, H_2SO_4 (grade A, chemically pure, (Khimlaborreakt) Limited Liability Company, Ukraine).

Petroleum ether, H_3C-O-CH_3 (excise, analytical grade, (Khimlaborreakt) Limited Liability Company, Ukraine).

Animals, Plants and Biological Materials

The meat of bulls obtained after the slaughter of animals up to 12 months of age and the meat of pigs up to 9 months of age, which came from the agricultural company "Polyssya LTD" in Kyiv region, Ukraine, were used for the research.

The system of proteinases, which consists of pepsin and trypsin, acts on protein substances (LLC "Alex", Kyiv, Ukraine)

Instruments

A mince mixer L5-FM2-M-340 was used to implement the mincemeat preparation process.

Drying cabinet (SNOL, producer (Khimlaborreaktyv) Limited Liability Company, Ukraine).

Muffle furnace (SNOL, producer (Khimlaborreaktyv) Limited Liability Company, Ukraine).

Fat analyzer (SOX 406, producer (Khimlaborreaktyv) Limited Liability Company, China).

Mineralizer (Velp Scientifica, producer (Khimlaborreaktyv) Limited Liability Company, Italy).

Distiller for steam distillation (Velp Scientifica UDK 129 producer (Khimlaborreaktyv) Limited Liability Company, Italy).

Automatic penetrometer (K95500, producer (Khimlaborreaktyv) Limited Liability Company, USA).

pH meter (HI8314 HANNA, producer (Spectro lab) Limited Liability Company, Ukraine).

Thermometer (digital laboratory thermometer TH310 Milwaukee, producer (Spectro lab) Limited Liability Company, Ukraine).

Laboratory scales (AXIS BDM 3, (Spectro lab) Limited Liability Company, Ukraine).

Laboratory Methods

The assessment of the chemical composition of sausage products was conducted following established protocols:

• Moisture content was determined using the drying method specified in DSTU ISO 1442:2005 **[19]**.

• Fat content was analyzed using the Soxhlet method by DSTU 8380:2015 **[20]**.

• Protein proportion was determined through the Kjeldahl method **[21]**.

• Ash content was measured using the Velp Scientifica DK6 device for ash mass fraction determination, employing the weight method as per DSTU ISO 936:2008 **[22]**.

• Active acidity was studied by assessing pH levels according to DSTU ISO 2917:2001 **[23]**.

• Protein mass fraction was determined utilizing the Lowry method with Folin's reagent, resulting in a blue coloration of the protein solution **[24]**.

• Plasticity of minced meat was evaluated through the pressing method based on the area of the meat stain on filter paper.

• Content of the mycotoxin patulin was assessed via liquid chromatography with spectrophotometric detection **[25]**.

• Heavy metal content was determined using the atomic absorption method **[26]**.

• The content of radionuclides was measured using the gamma spectrometric method.

• The temperature of the samples was recorded using a TH310 Milwaukee thermometer.

• Sample weighing was carried out using AXIS BDM 3 scales.

Description of the Experiment

Sample preparation: The preparation of samples for the above studies was carried out by the DSTU 7963:2015 standard **[27]**. Sample selection was carried out by the requirements specified in DSTU 7992:2015 **[28]** and DSTU 8051:2015 **[29]**.

Number of samples analyzed: 8 samples were examined: 4 samples using pork and 4 from beef.

Number of repeated analyses: The study was repeated 5 times, with the experimental data processed using mathematical statistics.

Number of experiment replications: Each study was carried out five times, and the number of samples was three, resulting in fifteen repeated analyses.

Design of the experiment: In the first stage, raw materials were prepared. The meat raw material, after curing, was ground into a sieve with a grid diameter of 2-3 mm, i.e., the characteristic size of the product after grinding is ℓ = 2 mm. During experimental research, mélange, a food additive, onion, spelled flour, and spices were used as additional components in the production of chopped semi-finished products. The L5-FM2-M-340 minced meat mixer is used to implement the process of preparing minced meat, in the working capacity of which screws with screw-type blades are mounted, which rotate towards each other.

In the second stage, the resulting mass with admixtures of mélange, onion, breadcrumbs, and spices, with the addition of water, was processed in a minced meat mixer.

The third stage was the laboratory analysis of the obtained substance. The main characteristics of the obtained semi-finished meat were determined, namely, moisture content, protein content, fat content, table salt content, moisture-binding capacity, plasticity of minced meat, digestibility of proteins, and amino acid composition of proteins. The critical stage was the statistical analysis of the obtained experimental data.

Statistical Analysis

The results were evaluated using statistical software Statgraphics Centurion XVII (StatPoint, USA) – multifactor analysis of variance (MANOVA), LSD test. Statistical processing was performed in Microsoft Excel 2016 in combination with XLSTAT. Values were estimated using mean and standard deviations. The reliability of the research results was assessed according to the Student's test at a significance level of $p \leq 0.05$

RESULTS AND DISCUSSION

The main factors of this process are the product density ρ, the coefficient of dynamic viscosity of the technological medium μ, the ultimate shear stress τ, the change in the concentration of the main impurities in the raw material ΔC, the value of the diffusion coefficient D and the mass transfer coefficient in the loading mass β, the weight of one loading of products Pz, angular frequency ω of rotation of the screws of the minced meat mixer, the radius of rotating working bodies r, the characteristic size of products after grinding ℓ.

Modelling was carried out using Federman-Buckingham's second similarity theory and the "theory of dimensions" method, which allows the processing of the obtained experimental data in the form of a criterion equation.

The authors of the scientific manuscripts **[30]**, **[31]** investigated the centrifugal and vibrational technological effects on the hydrolysis of plant raw materials for producing pectin. The researchers found that with pulsed amplification of such a process, it is possible to increase its efficiency and design compact equipment, reduce electricity consumption, and improve the final product quality **[32]**. The authors confirmed the scientific hypothesis according to which vibrocentrifugal intensification of hydrolysis increases the driving force of the process, not only by activating the material flows of raw materials and reagents, due to the reduction of stability in the technological environment, therefore, a similar series of experiments should be repeated in our research **[33]**, **[34]**.

Taking into account the presented factors of the researched process and the peculiarities of its course, it is advisable to use the following criteria of similarity in the calculation: the Froude number Fr, as a measure of the ratio of inertial forces and weight **[35]**; Euler's number Eu, as a measure of the ratio of pressure forces and pressure velocity **[36]**; Sherwood's number Sh, as a measure of the ratio of the intensity of diffusion flows at the boundary of separation of interacting phases **[37]**, **[38]**. At the first stage of the calculation, the parameters of the studied process presented above were decomposed according to the dimensions in Table 1.

Table 1 Initial data for determining the strength characteristics of the researched process of minced meat preparation.

No	τ, Pa	μ, Pa·s	ΔC	t, s	Δh_i, mm	$\Delta\tau$, Pa	$\frac{\Delta\tau}{\tau}$	$\varrho \frac{kg}{m^3}$
1	300	850	0,04	420	0,5	80	0,26	1100
2	400	1020	0,06	420	0,7	120	0,3	1150
3	500	1100	0,08	420	0,9	200	0,4	1180

The Froude criterion can be represented by the ratio of the acceleration of the force field induced in the process of mixing by centrifugal forces to the acceleration of free fall g:

$$Fr = \frac{a_B}{g} = \frac{r \cdot \omega^2}{g} \tag{1}$$

Where:
the acceleration of the force field $a_B = r \cdot \omega^2$; g is the acceleration of gravity.

The formula can determine Euler's criterion:

$$Eu = \frac{P}{\rho \cdot S \cdot \upsilon^2} = \frac{\tau}{\rho \cdot r^2 \cdot \omega^2} \tag{2}$$

Where:
P is the resistance of the medium, H; S – an area of force contact action, m^2; $\tau = \frac{P}{S}$ – ultimate shear stress, Pa; υ is the speed of movement of the executive bodies of the stuffing mixer: $v = r \cdot \omega$.

The Sherwood criterion *Sh* is classically calculated as:

$$Sh = \beta \cdot \ell / D = \beta \cdot A / D \tag{3}$$

Where:
ℓ – the characteristic size of the product after grinding, which we accept ℓ = 2 mm under the conditions of the studied mass transfer; *D* – the diffusion coefficient, which for minced masses can be taken $D = 0.5 \cdot 10^{-9}$ m^2/s.

The following ratio can determine the mass transfer coefficient for the process under study:

$$\beta = \frac{m}{(t \cdot \Delta C \cdot S)} = \frac{\tau}{(t \cdot \Delta C \cdot g)} \tag{4}$$

Where:
t is the processing time and one product load.

In further studies, we use experimental data for control samples, in particular, ultimate shear stress; minced meat density $\varrho_{\circ}$ = 1100-1180 kg/m³; coefficient of dynamic viscosity; the depth of penetration of the cone into the mass of products according to studies of the penetration process **[39]**, **[40]**.

When the concentration of the main impurities in the raw material ΔC changes, the ultimate shear stress increases significantly, which leads to a significant increase in the density of minced meat ρ. For the specified power characteristics, we assume that $\Delta\tau/\tau = \Delta\varrho/\varrho = \Delta\mu/\mu$, where Δτ, Δϱ, Δμ are the growth of the parameters of the mincemeat preparation process, respectively, when the ingredients under study are added to the mincemeat, i.e., for changes in its concentration in the form of ΔC, which is illustrated in Table 1.

Then by the method of linear extrapolation:

$$\rho_i = \rho_0 \left(1 + \frac{\Delta\rho}{\rho_i}\right) \tag{5}$$

Where:
g values Δh_i is the reduction of the immersion depth of the cone according to studies of the penetration process in three product samples.

Given a fairly large number of factors determining the process, let's replace the relationship between them with dependencies between the presented criteria of similarity. For this, we use the matrix of dimensions, which we compile with the help of Table 2.

Table 2 Matrix of dimensions of the studied process of mixing the ingredients of minced sausages.

Options	***ρ***	***D***	***ℓ***	***ω***	***τ***	***g***	***r***	***β***
M, Kg	1				1			1
L, m	-3	2	1		-1	1	1	
T, s		-1		-1	-2	-2		-1
Power coefficients	*n*	*m*	*c*	*h*	*t*	*f*	*j*	

In general, the relationship between the presented parameters can be written in the form of a function: *β = f (ρ, D, r, ω, τ, ℓ, g)*.

Based on the matrix of dimensions compiled in Table 2, we rewrite the presented function in the form of a power series:

$$\beta = K\cdot \rho^{n}\cdot D^{m}\cdot r^{j}\cdot \omega^{h}\cdot \tau^{t}\cdot g^{f}\cdot \ell^{c} \tag{6}$$

Where:
K is a constant coefficient.

For the presented factor space, the number of variables is 6 and the number of dimensionless components is 6 – 3 = 3 according to the π – theorem, that is, it corresponds to the number of selected similarity criteria, in particular, Sherwood, Euler, and Froude numbers. The matrix of dimensions compiled in Table 3 is reproduced in the system of equations for the power coefficients of the mass transfer equations (6):

$$\begin{gathered} n+t=1 \\ -3n+2m+c+t+f+j=0 \\ -m+h-2t-2f=-1 \end{gathered} \tag{7}$$

From equations (7) and (8) we obtain the following dependencies:

$$-2n+2m+c+f+j=1 \tag{8}$$

From equation (7):

$$t=1-n \tag{9}$$

From equation (9):

$$h=1-m-2t-2f \tag{10}$$

From equation (8):

$$j=1-2n-2m-c-f \tag{11}$$

From equation (7):

$$2n=2-2t \tag{12}$$

Using the obtained equations (7) – (12), we transform the mass transfer equation (6) of the studied minced meat preparation process sequentially in the following forms.

$$\beta\cdot\ell/D = Sh = (\omega^{2}\cdot r/g)^{-2m}\cdot \ell^{(c+1)}\cdot \omega^{(1+3m-2t-2f)}\cdot r^{(1+2n-c-f)}\cdot g^{(3n-c+t-j)}\cdot \rho^{(1-t)}\cdot D^{(m-1)}\cdot \tau^{t} \tag{13}$$

$$Sh = Fr^{-2m}\cdot [\tau/(\rho\cdot\omega^{2}\cdot r^{2})]^{t}\cdot \omega^{(1+3m-2f)}\cdot \rho\cdot r^{(3-c-f)}\cdot g^{(2n-c-j)}\cdot D^{(m-1)}\cdot \ell^{(c+1)} \tag{14}$$

$$Sh = Eu^{t}\cdot Fr^{(-2m-2f)}\cdot \omega^{(1+3m)}\cdot r^{(3-c)}\cdot g^{(2n-c-j-f)}\cdot D^{(m-1)}\cdot \ell^{(c+1)} \tag{15}$$

Taking into account equations (13-18), we obtain the general expression of the mass transfer equation of the process under study:

$$Sh = K \cdot Eu^{t} \cdot Fr^{(-2m-2f)} \quad (16)$$

$$K = \omega^{(1+3m)} \cdot r^{(3-c)} \cdot g^{(2n-c-j-f)} \cdot D^{(m-1)} \cdot \ell^{(c+1)} \quad (17)$$

To obtain initial data when performing a graph-analytical analysis of the researched process, the values of the similarity criteria presented above, parameters when using experimental data, and the results of the calculations were determined (Table 2). Using the data in Table 4 and the graph-analytical method of studying power functions, a graph of the function Sh = f (Eu) was constructed. This function is linear, the graph of which makes an angle α with the abscissa axis (Figure 1).

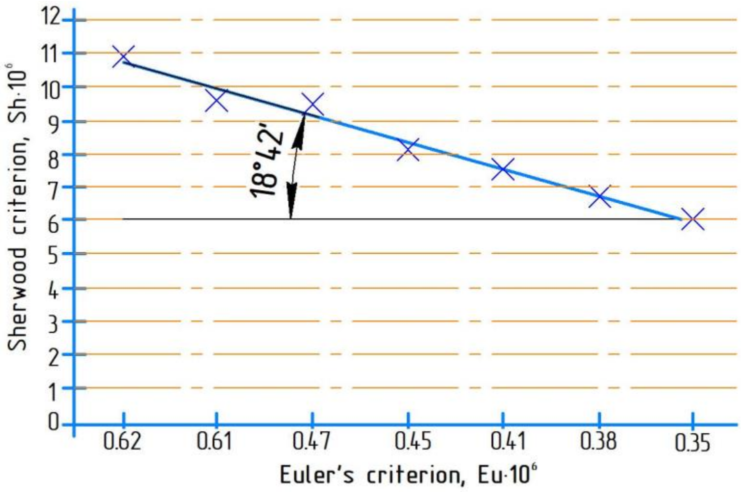

Figure 1 Graph of a linear function *Sh = f (Eu).*

Then the value of the first power coefficient is:

$$t = tg\ \alpha = 0{,}333 \quad (18)$$

Using the previous method of calculation, we built a function graph using experimental data, found the angle γ (Figure 2) of its inclination to the abscissa axis, and determined the value of the second power coefficient.

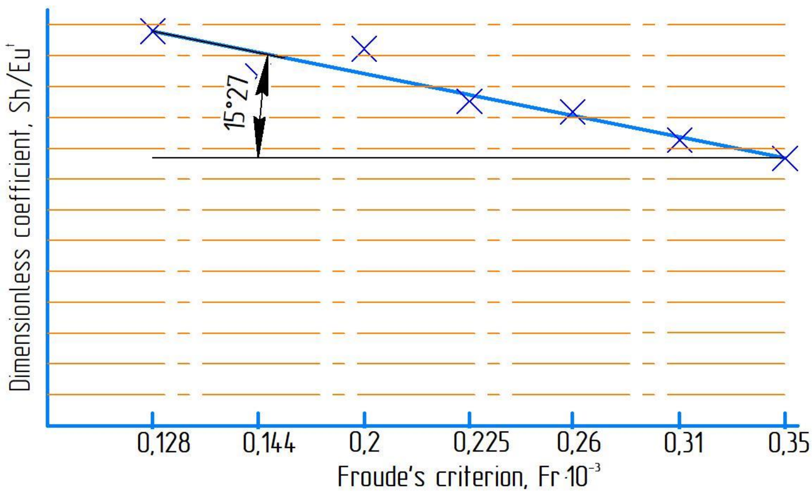

Figure 2 Graphic functions $Sh/Eu^{t} = f(Fr)$.

$$-2m = tg\gamma = 0.237 \text{ та } m = -0.1365 \quad (19)$$

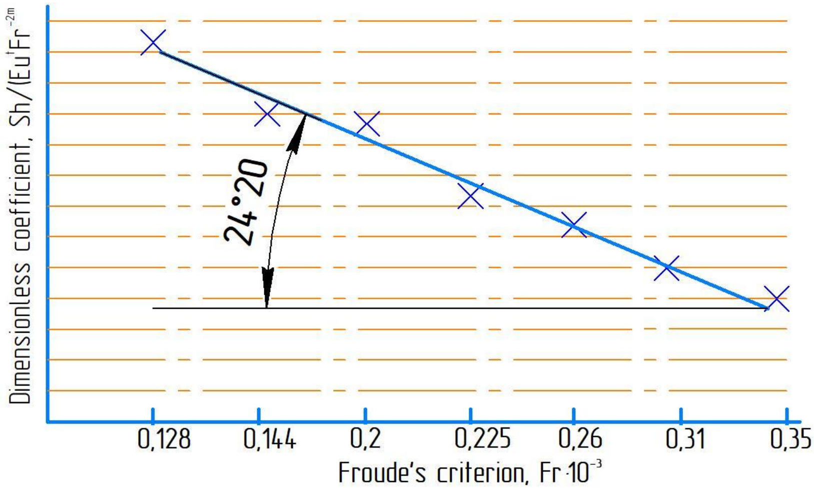

Figure 3 Graphic functions Graphic functions $Sh/(Eu^t \cdot Fr^{-2m}) = f(Fr)$.

Next, we built a graph of the function $Sh/(Eu^t \cdot Fr^{-2m}) = f(Fr)$ (рис. 3), from which the angle of the φ was determined:

$$-2f = tg\varphi = 0.449 \quad (20)$$

Then f = - 0.2245
From the equation (7):
n = 1- t = 0.667
From the equation (9):
h = 1 – m -2t – 2f = 1+ 0.1365 – 0.667 + 0.449 = 0.9195
From the equation (8):
– c - j = -3n + 2m – t + f = - 3·0.667 – 0.273 – 0.333 – 0.2245 = - 2.8315
Next, let's find the necessary dependencies:
1 + 3m = 1 - 3·0.1365 = 0.591
m -1 = - 1.1365
2n – c –j – f = 2·0.667 – 2.883 + 0.2245 = - 1.273
$g^{(2n-c-j-f)} = g^{-1.273} = 1/9.81^{1.273} = 0.055$
-2m -2f = 0.273 + 0.449 = 0.772

Taking into account the dependencies (16) and (17), the criterion equation of the studied process of cooking minced meat can be represented as:

$$Sh = 0.055 \cdot Eu^{0,333} \cdot Fr^{0,722} \cdot D^{-1,1365} \cdot \omega^{0,591} \cdot r^{(3-c)} \cdot \ell^{(c+1)} \quad (21)$$

Dependencies $r^{(3-c)} \cdot \ell^{(c+1)}$ can be neglected due to their insignificant impact on the minced meat preparation process under study. Thus, the definitively sought criterion equation of the process of cooking minced meat with given components is:

$$Sh = 0.055 \cdot Eu^{0.333} \cdot Fr^{0.722} \cdot D^{-1.1365} \cdot \omega^{0.591} \quad (22)$$

To improve the quality and functional-technological characteristics of semi-finished meat, in the developed recipe, a combination of such elements as milk whey protein, sodium alginate, and soy fiber was provided, encouraging the synergistic effect of the resulting composition (Table 1).

Table 1 The main components of the food additive to the meat products under investigation.

Product	Content, %			
	Protein	Moisture	Fat	Ash
Soy fiber	25.0	8.0	0.8	6.5
Whey protein	69.5	8.0	6.0	7.2
Sodium Alginate	-	9.0	-	18.0

Based on research, increasing the amount of whey protein and soy fiber in experimental samples, the viscosity of the mixture decreases under the conditions of increasing the speed of rotation of the working capacity. The best characteristics were shown by product samples containing 7.5 g of sodium alginate, 2 g of whey protein, and 3 g of soy fiber per 100 g of product.

According to such evaluation criteria, the fat-retaining and moisture-retaining ability was observed in the test sample, which contained a food additive of 60% sodium alginate, 16% whey protein, and 24% soy fiber. At the same time, the indicators of fat-holding capacity were 1.5 ml of fat/g of product and moisture-holding capacity – 1.32 g of water/g of product.

With a change in the content of food additives from 8 to 16% in the mass of chopped semi-finished meat, the best digestibility indicators were observed, respectively within (72-74) %, which can be explained by the fact that in the presence of pepsin and trypsin, whey proteins quickly and are almost completely digested, while raw meat is digested by trypsin more slowly and incompletely.

The influence of the content of the food additive on changes in the values of fat and water-holding capacity is presented in Table 2. All experimental samples showed sufficiently high indicators of these evaluation criteria, samples 4 and 5 were the best.

Table 2 Indicators of functional and technological properties of a complex food additive.

No	Ingredients of food additives, g (per 100 g of product)			Fat-retaining capacity, ml/g (1 ml of fat per 1 g of product)	Water-holding capacity, g/g (1 g of water per 1 g of product)
	Sodium alginate, g	Whey protein, g	Soy fiber, g		
1	7.5	1	4	1.25 ±0.021	1.11 ±0.016
2	7.5	1.5	3	1.15 ±0.041	1.12 ±0.016
3	7.5	2	2	1.25 ±0.041	1.23 ±0.024
4	7.5	2	3	1.5 ±0.163	1.32 ±0.016
5	7.5	2	4	1.7 ±0.163	1.44 ±0.033

According to the comparative analysis of the values of the active acidity of the mixture as a whole and its components (Table 3), it can be noted that in general the complex admixture is characterized by less than that of the components, except for sodium alginate; and a sufficiently low pH indicator, which justifies the feasibility of using the developed admixture in meat products.

Table 3 Indicators of active acidity for the structural components of the investigated food additive based on animal and vegetable raw materials.

No	Title	Active acidity (pH)
1	Whey protein	6.501 ±0.002
2	Sodium Alginate	6.375 ±0.079
3	Soy fiber	6.93 ±0.065
4	Food additives based on animal and vegetable raw materials	6.462 ±0.066

For conducting experimental studies, the following rate of products (net) was used per 1 kg of meat pulp, g: wheat bread – 250 (25%), milk – 300 (30%), salt – 20 (2%), ground pepper – 1 (0.1%). Cutlets and balls were made from the prepared mass. The cutlet mass was portioned (1-2 pieces per portion), rolled in breadcrumbs, and given an oval-flattened shape up to 2.0 cm thick, 10-12 cm long, and 5 cm wide and fried (Figure 4).

a)

b)

Figure 5 Samples of chopped semi-finished products: a – experimental sample, b – control sample.

The organoleptic valuation of taste and physicochemical properties of tested products showed that all tested parameters of quality of the experimental product surpassed the ones of the control one (Figure 5).

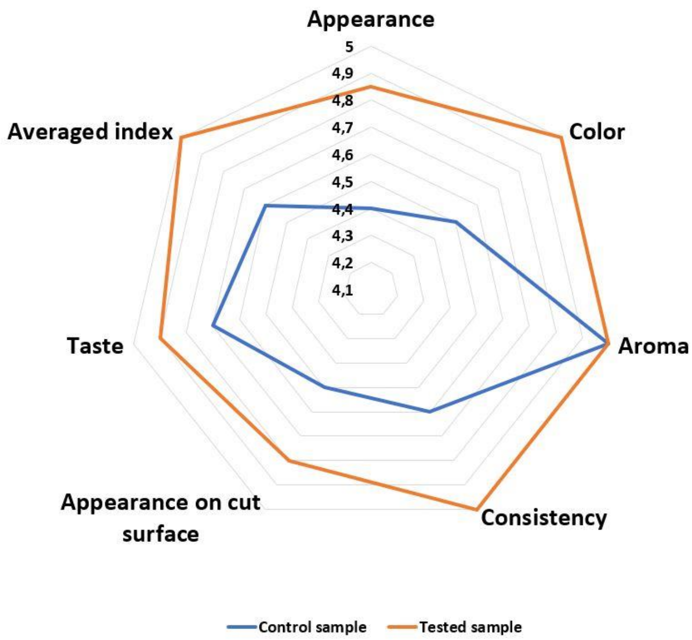

Figure 5 Results of organoleptic valuation of control quality and experimental mincemeat samples.

Several scientific papers discuss modelling processes related to sausage product production. These papers introduce various models, employing up to 10 main parameters in some cases **[41]**. However, some models neglect reference indicators or incorporate only one reference indicator **[42]**. This omission makes it challenging to verify the reliability of the results obtained. In contrast, the authors of the paper **[43]** conducted a modelling process using only 2 parameters, potentially leading to imprecise results.

Similar studies are outlined in the scientific works of diverse research groups, focusing on the design of technological equipment **[44]**, **[45]**, sausage product production **[46]**, **[47]**, and the development of technological schemes for various food industry products **[48]**. However, these studies often need to pay more attention to time parameters, which can significantly impact the quality indicators of the final products.

In scientific works **[49]**, **[50]**, research was conducted on mixing minced meat, such as traditional mixing, vacuum mixing, and mechanical mixing. The authors claim that compared to the traditional method, which uses mechanical mixing, the centrifugal method is characterized by greater mixing efficiency with less processing time.

The authors of the scientific works **[51]**, **[52]** claim that the process of vacuum mixing in combination with the centrifugal method can be faster and more efficient because it uses the force of rotation to mix the components homogeneously and allows to reduce the effect of oxidation and preserve more natural taste and improve indicators quality of the finished product. However, organoleptic studies of the finished product were not conducted in the above-mentioned robots.

From an economic point of view, considering the costs of energy, time, and materials, the authors **[53]**, **[54]** confirmed the benefits of using the centrifugal method. Reducing processing time leads to lower energy costs, and efficient mixing can reduce raw material waste, contributing to savings.

The authors **[55]** studied the possibility of adapting the centrifugal method for different types of meat, such as chicken, pork, or beef. This can significantly impact the universality of the method and its applicability in various branches of the meat processing industry.

Therefore, the proposed method can be a promising solution for optimising the production process of semi-finished meat products, ensuring improved quality and economic efficiency.

The results obtained from the research can help improve production efficiency and final product quality. Below are the possible directions of research in this area:

Simulation of the process of centrifugal mixing:

- Development of mathematical models that describe the physical processes of centrifugal mixing of minced meat.
- It considers various parameters, such as the speed of the centrifugal device, the size and shape of the centrifugal drum, the composition of the minced meat, and other factors that affect the mixing quality.

Process optimisation:

- Development of optimisation algorithms that allow finding optimal parameters of the centrifugal mixing process.
- Consideration of budget, production volume, and product quality constraints.

Study of the effect of minced meat properties:

- Analysis of the influence of different types of meat, texture, moisture, and other characteristics of minced meat on the mixing process and the quality of the final product.
- Development of recommendations on the optimal selection of the composition of minced meat for a certain type of chopped semi-finished products.

Improvement of equipment:

- Development of new technologies and improvement of centrifugal devices to increase mixing efficiency.
- We are studying the possibility of using automated control systems to control process parameters.

Quality control:

- Development of product quality control methods at each stage of the process, including control of the homogeneity and structure of minced meat.
- I use modern analysis methods like data mining and machine learning to identify anomalies and improve product quality.

Study of the influence of environmental factors:

- Study the influence of temperature, humidity, pressure, and other environmental factors on the mixing process and product quality.
- Development of methods to compensate for the influence of variable conditions on the process. These studies can be helpful for meat cut manufacturers, helping to increase production efficiency, reduce costs, and improve product quality.

CONCLUSION

The presented similarity numbers show both the depth of penetration of the oscillatory effect of the force field inside the product and the impact of the change in the concentration of the projected components in minced meat ΔC on the value of the diffusion coefficient D and the mass transfer coefficient in the loading mass. It should be noted that the ω parameter, which characterizes the action of centrifugal forces during minced meat preparation, significantly impacts the studied process. Using the Composite criterion equation and the developed program, we find the recommended range of operating parameters for the process of cooking minced meat under conditions of centrifugal influence on the mixing process and the action of these factors in the implementation of the developed technology using an additive based on whey protein. When making mincemeat from chopped semi-finished products based on cutlet beef and lean pork, it turned out to be effective to use the researched complex food additive based on animal and vegetable raw materials in the amount of 0.5 to 1.5% in dry form; an increase in the mass fraction of whey protein in the range of (1.32-1.44)% was observed; which improves the general indicator of the balance of amino acids in the product, increases the functional-technological and quality parameters of the developed products. Taking into account the above-mentioned aspects will allow you to get a more complete picture of the effectiveness and advantages of the centrifugal method compared with other techniques for producing semi-finished meat products.

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Contact Address:

Igor Palamarchuk, National University of Life and Environmental Sciences of Ukraine, Faculty of Food Technology and Quality Control of Agricultural Products, Department of Processes and Equipment for Processing of Agricultural Production, Heroes of Defense Str., 12 B, 03040, Kyiv, Ukraine,
E-mail: vibroprocessing@gmail.com
ORCID: https://orcid.org/0000-0002-0441-6586

***Mikhailo Mushtruk**, National University of Life and Environmental Sciences of Ukraine, Faculty of Food Technology and Quality Control of Agricultural Products, Department of Processes and Equipment for Processing of Agricultural Production, Heroes of Defense Str., 12 B, 03040, Kyiv, Ukraine,
E-mail: mixej.1984@ukr.net
ORCID: https://orcid.org/0000-0002-3646-1226

Volodymyr Vasyliv, National University of Life and Environmental Sciences of Ukraine, Faculty of Food Technology and Quality Control of Agricultural Products, Department of Processes and Equipment for Processing of Agricultural Production, Heroes of Defense Str., 12 B, 03040, Kyiv, Ukraine,
E-mail: vasiliv-vp@ukr.net
ORCID: https://orcid.org/ 0000-0002-2109-0522

Eugeniy Stefan, National Technical University of Ukraine, Department of Reprography, Peremohy Ave., 37, 03056, Kyiv, Ukraine,
E-mail: eshtefan@ukr.net

ORCID: https://orcid.org/0000-0002-0697-7651

Olesia Priss, Tavria State Agrotechnological University, Faculty of agricultural technology and ecology, Department of Food Technology and Hotel and Restaurant Business, B. Khmelnitsky ave., 18, 72312, Melitopol, Ukraine,
E-mail: olesia.priss@tsatu.edu.ua
ORCID: https://orcid.org/0000-0002-6395-4202

Iryna Babych, National University of Food Technologies, Faculty name, Educational and Scientific Institute of Food Technology, Department of Biotechnology of fermentative products and wine-making, Volodymyrska Str., 68, 01601, Kyiv, Ukraine,
E-mail: 5613694@ukr.net
ORCID: https://orcid.org/0000-0002-3058-3062

Inna Karpovych, National University of Food Technologies, Department of Sugar Technology and Water Preparation, Volodymyrska Str., 68, 01601, Kyiv, Ukraine,
E-mail: inkarp@ukr.net
ORCID: https://orcid.org/0000-0002-5912-7466

Nataliia Pushanko, National University of Food Technologies, Department of Sugar Technology and Water Preparation, Volodymyrska Str., 68, 01601, Kyiv, Ukraine,
E-mail: oks-n@ukr.net
ORCID: https://orcid.org/0000-0001-7369-2827

Corresponding author: *