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Physical and mathematical modelling of the process of cooking minced meat with spelt flour and champignon mushrooms

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Abstract. The introduction of additives of plant or animal origin into meat products is currently a steady trend in food technologies due to the possibility of obtaining unique properties of products and reducing their cost, which justifies the relevance of the conducted research. The purpose of the study was to build a mathematical algorithm that can determine the regularities of changes in the main parameters of the process of preparing minced meat semi-finished products with vegetable additives, which would help to establish the trends in the development of technical and technological efficiency of mechanisation of the system of fine grinding of raw materials for the production of sausage products. The addition of spelt flour and mushrooms as ingredients to the minced meat mass was investigated, which allows, together with reducing the cost of production of cooked sausage products, significantly improving the organoleptic quality indicators of products, reducing their caloric content and extending the shelf life for consumption. The wild variety of spelt used in this scientific work as an alternative to its cultivated varieties has significantly less allergic activity and, accordingly, a lower proportion of gliadins, which form the basis of wheat gluten; which justifies the practical significance of the study. A microstructural analysis of minced meat of control and experimental samples of boiled sausages was performed, which revealed that the latter category of meat product is characterised by increased density and elasticity due to the inclusion of spelt microparticles in the vacuole of the meat fraction. According to the results of experimental studies, using the "dimension analysis" method and the Federman-Buckingham theorem, it was possible to obtain a criterion equation for the process of heat and mass transfer under conditions of intensive mechanical mixing. These process characteristics were described using the Euler, Fourier, and Sherwood criteria. The compiled function contains the main factors of external influence on raw materials and their physical and mechanical characteristics, which allows adequately assessing the diffusion processes in the technological environment and creating the recommended range when designing technical and technological support for obtaining high-quality food products

Keywords: spelt; shear stress; minced meat mass; similarity theory; similarity numbers; diffusion; cooked meat products

Introduction

Currently, there is a steady trend of increasing the population's demand for meat products, which leads to a partial reorientation of meat processing enterprises to the production of combined meat products containing additives of plant and animal origin. One of the main priorities of the national policy in the field of healthy nutrition is a revolutionary restructuring of technologies to create completely new, qualitatively different food products that will meet the requirements of modern consumers and will have a targeted adjustment of chemical composition and functional characteristics. L.V. Bal-Prylypko *et al*. (2022) found that the eating habits of the country's population as a whole and its various regions are characterised by critically low levels of protein, vitamins, minerals, dietary fibre, and other vital components. According to the latest research, a revolutionary potential in the development of a new market for meat products through the creation of enriched and innovative combined products has been noted. This means using food additives and replacing some of the raw meat with plant components to achieve a more balanced composition. This approach will not only reduce the shortage of meat products, but also contribute to the development of new technologies in the food industry.

For a long time, the question of the possibility of providing the latest varieties of products with health-improving and medicinal properties remained for these recipes, which led to the development of the *FOSHU* (*Foods for Special Health Use*) concept in Japan in 1991. Based on the results of experimental studies by L.D. Díaz *et al*. (2020), it was found that in many countries the food market of meat products received quite a large number of products that became known under the brand of "functional" and focused primarily on consumers with special needs. Their purpose is to provide basic nutritional needs while simultaneously having a positive effect on the physiological state of a person, in particular, to normalise the concentration of cholesterol in the blood and the composition of the bacterial flora of the intestine, strengthen the immune system, give the product anti-inflammatory properties, prolong the active period and overall life expectancy.

Seven main types of additives characterised by therapeutic and preventive properties of ingredients of functional products, namely, dietary fibre; minerals; vitamins; antioxidants; polyunsaturated fatty acids; probiotics and prebiotics, have been consistently used at Ukrainian enterprises. In addition, to improve the conditions for preparing products for consumption, for hydration of dietary fibre concentrates, the formulations contain treated water, the quality of which is subject to strict requirements by the national standard for drinking water (DSTU 7525:2014, 2014).

It is common practice to add dietary fibre to the products, which is necessary for the normal functioning of the digestive tract, normalisation of metabolic processes that are not broken down by human digestive enzymes: cellulose, hemicellulose, and lignin. A.K. Das *et al.* (2020) argue that the need for dietary fibre is a consequence of the evolution of the human gastrointestinal tract, which since ancient times has consumed mainly fibre-rich plant foods recommended by Western diets, normalising the daily requirement of which from 14 to 30 g, depending on the age of the person. V. He *et al*. (2022) found that dietary fibre and whole grains include a unique range of bioactive components, among which starch compounds occupy a special place. It is worth noting that these starchy substances remain resistant to enzymes that work in the gastrointestinal tract (Takač *et al*., 2021).

As reported by S.K. Gill *et al*. (2021), the growing demand for the use of recipes for meat products with vegetable additives justifies the importance of the presented research object, the need to develop effective models for describing, evaluating and predicting the dynamics of changes in the characteristics of this product, which confirms relevance and prospects for the development of mathematical modelling methods shown in the paper. Therefore, the purpose of the study was to improve the production technology of cooked sausage products and the process of cooking minced meat with admixtures of spelt flour and champignons by applying similarity theory and modelling methods using the "dimension theory" method, developing a physical and mathematical model of the studied process of compiling the heat and mass transfer equation and graphoanalytical analysis of dependencies between the main parameters of the process.

To achieve this goal, the following main tasks were set: to analyse the current trends in the development of the meat industry regarding the use of vegetable proteins and enzymes in the production of semi-finished products; comprehensive studies of the functional and technological properties of plant additives in meat semi-finished products; to develop an improved technology for the production of meat semi-finished products with the addition of, in particular, spelt flour and mushrooms; to develop a physical and mathematical model of the process of cooking minced meat; to draw up an equation of heat and mass transfer of the process under study and determine the relationships between its main parameters.

The scientific hypothesis of this study is as follows: the development of a mathematical model of the minced meat preparation process is based on the analysis of the factor space, which reveals experimentally obtained physical and mechanical characteristics of the minced meat weight and the driving forces of the process, the dependencies between which were replaced by dependencies between similarity numbers that can adequately describe the process under study.

Literature Review

Many modern studies are increasingly focusing on the use of various additives of animal and vegetable origin in meat products. E.B. Rimm *et al*. (2022) argue that the lipids contained in the vast majority of seafood are rich in polyunsaturated fatty acids, docosahexaenoic, and eicosapentaenoic acids, which are present only in this type of raw material, making marine raw materials the basis for multicomponent functional food systems.

M.J. Keenan *et al*. (2009) concluded that dietary fibre in meat mixes stabilises the structure and increases the ability of minced meat to retain water in an amount that is 5-30 times their own weight due to the content of cellulose, hemicellulose, and lignin in them. S.K. Gill *et al*. (2021) proved that the body's main source of dietary fibre is legumes and cereals, whole grains, vegetables, fruits, and nuts. It is important to note that dietary fibre is divided into soluble and insoluble. Soluble fibre can be found in foods such as vegetables, fruits, and nuts, while insoluble fibre is mostly found in whole grains.

S. Guerra *et al*. (2021) proved that pectin is a valuable component of plant additives, which is included in the basic structure of fruit cells and green parts of plants. Pectin gels create the basis of the walls of the stomach and intestines, eliminate acute physical effects, significantly reducing inflammation of the mucous membrane. The addition of pectin contributes to the effective elimination of incorporated radionuclides from the body, as noted by V.P. Vasyliv *et al*. (2021), in particular, biogenic toxins, cholesterol, bile acids, urea, bilirubin, serotonin; increases immunity and post-radiation recovery of blood enzyme elements, improves the antioxidant activity of blood and liver tissues. Chitin, as a natural biological polymer found in fungi, in particular, champignons or yeast, performs the protective and resisting function of cells; effectively binds lipids, reducing the activity of fat absorption processes in the intestine, is necessary for the growth of hair and nails, according to L. Vyerchenko *et al*. (2019). G. Caio *et al*. (2020) conducted a study that used seeds of cereals such as wheat, rye, barley in sausage products, which allowed increasing the starch content to 4%, which leads to a reduction in production costs and allows simultaneously enriching the minced mixture with dietary fibre. However, it is important to consider that the high content of gluten in these additives can cause genetic diseases, such as celiac disease, which occurs in a certain part of the population, which ranges from 0.2% to 6%, depending on the region of the world.

The scientific manuscript by T. Pintado & S. Cofrades (2020), described a series of experiments on adding legumes to meat products, which were characterised by a significant content of essential amino acids and minerals, which allowed increasing the biological value of meat mixtures by 15-20% and the energy value by 3-5%. L.J. Deleu *et al*. (2020) proved that the spelt grain contains up to 24% protein against 12-13% in ordinary winter wheat, and gluten up to 53% compared to conventional varieties with a minimum amount of gluten, so it can be recommended for inclusion in the diets of gluten allergy sufferers. In contrast to the usual varieties of cultivated wheat, spelt protein is characterised by an increased content of most essential amino acids and unsaturated fatty acids (Allai *et al*., 2022). D.R. Shah *et al*. (2020) noted that the use of spelt as a starchy additive to minced meat avoids the need to introduce dietary fibre into the composition due to their high grain content (10.7%). When spelt is consumed, the body receives vital trace elements such as B vitamins, potassium, zinc, manganese, minerals and vitamins that help improve the body's immune system and lower blood cholesterol (Jančić *et al.*, 2022).

Thus, the use of spelt flour in the composition of the meat products under study can significantly improve the content of essential acids, vitamins, and valuable trace elements in the product, creating competition for traditionally used dietary fibre, justifying the prospects of the developed recipe.

Materials and Methods

Studies of boiled meat products of control and experimental samples were carried out using raw materials, the classification of which is presented in Table 1.

Table 1. *List of raw materials for conducting experimental studies*

No.	Experimental samples
1	red and white meat of broiler chickens (DSTU 3143:2013, 2014)
2	pink salmon caviar (DSTU 8096:2015, 2017)
3	skimmed milk powder (DSTU 4273:2015, 2016)
4	dried crushed champignons (DSTU ISO 7561-2001, 2003)
5	spelt flour (DSTU 46.004-99, 1999)
6	nori algae (DSTU 5013:2008, 2009)
7	olive oil (DSTU 5065:2008, 2009)
8	refined sunflower oil (DSTU 4492:2017, 2019)
9	drinking water (DSTU 7525:2014, 2014)
10	table salt (DSTU 3583:2015, 2017)
11	white sugar according to (DSTU 4623:2023, 2023)

Source: developed by the authors

The moisture binding capacity (MBC) was determined by the amount of water released from 300 g of the sample after pressing three times for 10 minutes with a 1 kg load. *Plasticity* was determined by pressing the sample sample after determining the MBC parameter. The calculation was performed using the spot area formed by the crushed sample when it was pressed on filter paper with a static load of 1 kg for 10 minutes. The *penetration coefficient* of the finished products was determined by the depth of immersion of the needle indenter into the test sample. Maximum shear stress τ_m was determined using the plasticity values and penetration numbers obtained from studies of the corresponding samples (Table 2).

Table 2. *Functional and technological indicators of control and experimental samples of boiled sausages*

Indicator	Control of TU U 10.1-37792346-002:2021,%	Experimental sample No. 1	Experimental sample No. 2	Experimental sample No. 3
Content of hydrated spelt flour in minced meat, %	–	5.0	7.0	8.0
Content of champignon mushrooms in minced meat, %	–	1.5	2.0	3.0
Plasticity X, cm^2/g	7.80	8.44	8.66	8.79
Penetration, Pa	1,609.06	1,660.86	1,769.36	1,766.44

Source: developed by the authors

Modelling was performed using the second Federman-Buckingham similarity theory and the "dimension theory" method, which allows processing the obtained experimental data in the form of a criterion equation (Palamarchuk *et al.*, 2021).

The following calculation methods were used to calculate the similarity criteria required for the study.

The Euler criterion can be determined by the equation:

$$Eu = \frac{P}{\rho \cdot S \cdot \upsilon^2}, \quad (1)$$

where P – resistance of the medium, H; S – area of the force contact action, m^2; ρ – density of the food mass; υ – speed of the product flow in the bowl of the mincer

The Sherwood Criterion *Sh* is typically calculated as

$$Sh = \beta \cdot \ell / D, \quad (2)$$

where ℓ – characteristic size under the conditions of the mass exchange under study, which can be identified with the average particle size of the dispersed phase, which can be taken for the cutting process: $\ell = 0.4$ *mm*; D – diffusion coefficient, which can be accepted for minced meat masses $D = 0.5 \cdot 10^{-9}$ m^2/s.

The mass transfer coefficient can be determined by the following ratio:

$$\beta = \frac{\Pi_\upsilon}{\Delta C \cdot S}, \quad (3)$$

where Π_υ – volumetric process performance, kg/m^3; ΔC – difference in spelt concentrations in developed and traditional technologies, %

The plasticity value can be determined by the equation:

$$X = \frac{S}{m} = \frac{S \cdot g}{m \cdot g} = \frac{S \cdot g}{P} = \frac{g}{\tau_m}. \quad (4)$$

The diffusion Fourier number can be determined by the equation:

$$Fo_\partial = \frac{D \cdot t}{\ell^2}, \quad (5)$$

where t – processing time of a single product load: for research conditions, the cutting time – t=8 min

Statistical evaluation of the results was performed using standard methods using statistical software Statgraphics Centurion XVII (StatPoint, USA) – multivariate analysis of variance (MANOVA), LSD test. Statistical processing was performed in Microsoft Excel 2016 in combination with XLSTAT. The values were estimated using the mean value and standard deviations.

Results and Discussion

When choosing the most acceptable meat raw materials from the standpoint of physiological value, the content of the most consumed types of meat – beef, pork, and chicken – of constituent proteins (18.9%, 16.4%, 20.3%, respectively) and fats (12.4%, 27.8%, 13.1%, respectively) was considered. Chicken has the advantage of being the closest in these respects to beef, which is in acute shortage in the diet. However, due to the relatively lower content of macro- and micro-elements in it, the search for additives that would compensate for this shortcoming of chicken has become a subject of further study, given that the ongoing decline in the supply of raw meat requires the use of protein-rich plant-based ingredients to make up for the lack of protein. Therefore, it is effective to use vegetable proteins as a substitute for traditionally used wheat flour for wild spelt flour, enriched with dietary fibre, minerals and fatty acids, and to enrich the taste and smell with the addition of crushed mushrooms.

The main factors of the process of preparing a mixture of beef, pork, and chicken with the presented vegetable additives are the density of products ρ, maximum shear stress τ_m, changes in the concentration of spelt flour and champignons in products ΔC, value of the diffusion coefficient D and the mass recovery coefficient in the technological mass β, product processing time in the mincer t, kinematic characteristics of the process, in particular, the speed of product flow promotion in the mincer bowl υ and its rotation speed ω.

Considering the presented factor space and the features of the course of the process under study, the following criteria or similarity numbers can be noted that define it:

➢ *Euler number Eu as a measure of the ratio of pressure forces and head velocity;*

➢ *Sherwood number Sh, as a measure of the ratio of the intensity of convective and diffusion flows at the interface of separation of interacting phases;*

➢ *the Fourier number is diffuse, as a measure of the ratio of the mass of a substance transmitted by diffusion and local ripples in a non-stationary flow.*

At the first stage of the calculation, the parameters of the process under study presented above are decomposed into dimensions in Table 3.

Table 3. *Basic design parameters of the mincing process*

No.	List of parameters of the process under study	Dimension
1	Product density ρ, *kg/m³*	$kg \cdot m^{-3}$
2	Processing time for a single product load t, *s*	s
3	Maximum shear stress τ_m, *Pa*	$kg \cdot s^{-2} \cdot m^{-1}$
4	Diffusion coefficient D, *m²/s*	$m^2 \cdot s^{-1}$
5	Average particle size of the dispersed phase ℓ, *m*	m
6	Speed of product flow in the mincer bowl υ, *m/s*	$m \cdot s^{-1}$
7	Mass transfer rate in load weight β, *m/s*	$m \cdot s^{-1}$
8	Free fall acceleration g, *m/s²*	$m \cdot s^{-2}$

Source: developed by the author

The presented similarity criteria determine the main physical, mechanical and rheological factors of the process.

Equation (1) is modified to determine the Euler criterion in the form:

$$Eu = \frac{P}{\rho \cdot S \cdot \upsilon^2} = \frac{\tau_m}{\rho \cdot \upsilon^2}, \quad (6)$$

where P – resistance of the medium, N; S – area of force contact, m²; $\tau_m = \frac{P}{S}$ – maximum shear stress, Pa; υ – speed of the product movement in the mincer bowl: $\upsilon = \frac{2\omega R}{k_{on}} = \frac{\pi \cdot n_S \cdot R}{15 k_{on}}$; R – geometric size of the mincer bowl (Fig. 1); n_s, ω – rotation speed and angular velocity of the mincer bowl: can be adopted n_s within $n_s = 8\text{-}20$ *rpm*; k_{on} – coefficient of driving force consumption when moving minced meat to overcome the resistance of the knife mechanism: can be taken within the limits of $k_{on} = 1.5\text{-}2.0$.

The speed of the product flow is defined as

$$\upsilon = \frac{2\omega R}{k_{on}} = \frac{\pi \cdot n_S \cdot R}{15 k_{on}} = \frac{3.14 \cdot 15 \cdot 0{,}233}{15 \cdot 1{,}7} = 0.43 m/s.$$

The product density can be taken within $\rho = 1{,}100 - 1{,}180$ kg/m³

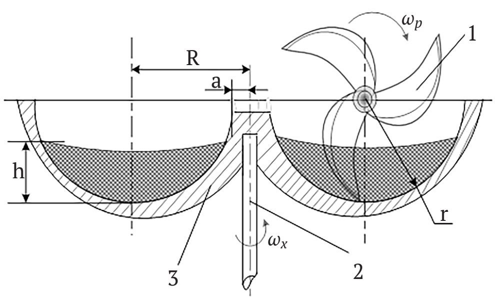

Figure 1. Diagram of a mince cutter for fine mincing

Notes: 1 – cutting mechanism, 2 – bowl drive shaft, 3 – mincer bowl

Source: developed by the author

When determining the mass transfer coefficient, equation (3) is transformed as:

$$\beta = \frac{\Pi_v}{\Delta C \cdot S} = \frac{m}{t \cdot S \cdot \Delta C \cdot \rho} = \frac{m \cdot g}{t \cdot S \cdot \Delta C \cdot g \cdot \rho} = \frac{\tau_z}{t \cdot \Delta C \cdot g \cdot \rho}, \quad (7)$$

where g = 9.81 m/s² – free fall acceleration; $\tau_z = m \cdot g / S = P/S$.

When determining plasticity, equation (4) is transformed as follows:

$$X = \frac{S}{m} = \frac{S \cdot g}{m \cdot g} = \frac{S \cdot g}{P} = \frac{g}{\tau_m}. \quad (8)$$

Then when using (8):

$$\tau_m = \frac{g}{X}. \quad (9)$$

Using that the penetration index is proportional to the shear stress of the minced meat mass τ_G, penetration coefficient Q determined from the dependency:

$$Q = \frac{P}{h^2} = \tau_m \cdot k_{pr}, \quad (10)$$

where k_{pr} – proportionality coefficient; h – depth of indenter depth in the mass of minced meat under a certain load P, which was determined from experimental studies

Then when using (6):

$$\tau_m = \frac{Q}{k_{pr}}. \quad (11)$$

Given a fairly large number of factors that determine the process, the relationship between them will be replaced by the dependencies between the presented similarity criteria. To do this, the dimension matrix is compiled using Table 4.

Table 4. *Dimension matrix of the investigated process of vibrational mixing of sausage mince ingredients*

Parameters	ρ, kg/m³	υ, m/s	τ_m, H/m² kg/(m·s²)	t, s	β, s/m
M, kg	1		1		
L, m	-3	1	-1		1
T, s		-1	-2	1	-1
Power coefficients	ε	n	m	α	

Source: developed by the author

In general, the relationship between the presented parameters can be written as a function:

$$\beta = f(\rho, \upsilon, \tau_m, t).$$

Based on the dimension matrix compiled in Table 2, the presented function is rewritten as a power series:

$$\beta = K \cdot \tau m\ m \cdot \rho \varepsilon \cdot \upsilon n \cdot t \alpha, \quad (12)$$

where K – constant coefficient.

For a given factor space, where we have 6 variables, by the π theorem, the number of dimensionless components is 6 - 3 = 3. This corresponds to the number of similarity criteria selected, such as the Sherwood, Fourier, and Euler numbers.

In Table 3, the dimension matrix can be represented as a system of equations for the power coefficients of the mass transfer equation (11).

Equation (11) provides

$$\begin{cases} n + \varepsilon = 0 \\ n - m - 3\varepsilon - l = 1 \\ -n - 2m + \alpha = -1. \end{cases} \quad (13)$$

$$\varepsilon = \text{-m}. \quad (14)$$

From the term of equations (13) and (14):

$$0 = -3m - 3\varepsilon + \alpha. \quad (15)$$

From equation (15):

$$n = \alpha - 2m + 1. \quad (16)$$

From equation (16):

$$\alpha = 3m + 3. \quad (17)$$

Given equation (10)

$$\beta = \rho^{-m} \cdot \upsilon^{(\alpha-2m+1)} \cdot t^{(3m+3\varepsilon)} \cdot \tau^{m}. \quad (18)$$

Given equation (2)

$$\frac{\beta \cdot \ell}{D} = Sh = \frac{\ell}{D} \cdot \left[\frac{\tau_m}{\rho \cdot \upsilon^2}\right]^m \cdot t^{(3m+3\varepsilon)} \cdot \upsilon^{(\alpha+1)}. \quad (19)$$

Given equation (6)

$$Sh = Eu^m \cdot \upsilon^{(\alpha+1)} \cdot t^{\alpha} \cdot \frac{\ell}{D}. \quad (20)$$

Given equation (1)

$$Sh = Eu^m \cdot \mathrm{Fo}_{\partial}{}^{\alpha} \cdot \left[\frac{\upsilon}{D}\right]^{(\alpha+1)} \cdot \ell^3. \quad (21)$$

Then the general expression of the mass transfer equation of the process under study takes the form:

$$Sh = Eu_m \cdot \mathrm{Fo}_{\partial}{}^{\alpha} \cdot \mathrm{K}; \quad (22)$$

$$K = \left[\frac{\upsilon}{D}\right]^{(\alpha+1)} \cdot \ell^3. \quad (23)$$

Using the data in Table 4 and the method of graphoanalytical estimation of power functions, a graph of the function *Sh = f(Eu)* was constructed; this function is linear, the graph of which consists of the abscissa axis and the angle φ (Fig. 2). To obtain initial data during the graphoanalytical analysis of the process under study, the values of the above-mentioned Fourier, Sherwood, and Euler criteria, and the mass flow coefficient, were determined using the corresponding equations (1, 2, 3, 5, 6) according to experimental data obtained based on the results of the conducted studies (Table 3).

Then the value of the first power coefficient is $m = tg\varphi = tg72° = 3.08$

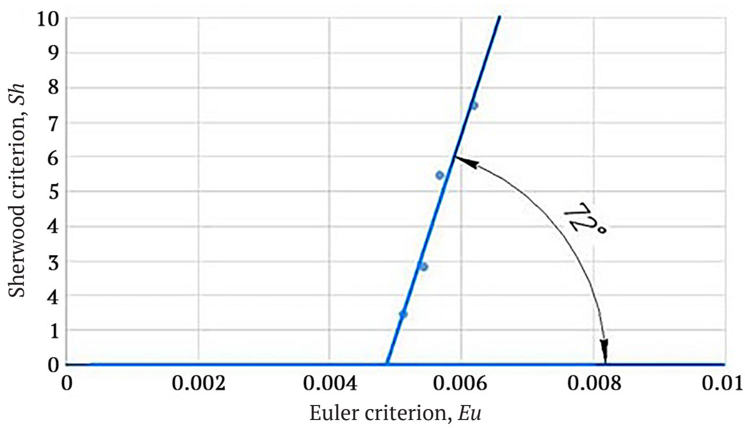

Figure 2. Function graph *Sh = f (Eu)*

Source: developed by the authors

Table 5. *Values of similarity criteria for the process of minced meat preparation*

Process parameter	Control of TU U 10.1-37792346-002:2021,%	Experimental sample No. 1	Experimental sample No. 2	Experimental sample No.3
Penetration number, Pa	1,609.06	1,660.86	1,769.36	1,766.44
Content of hydrated spelt flour and mushrooms in minced meat ΔC	-	0.065	0.09	0.11
Maximum shear stress τ_m, *kPa*	1.26	1.16	1.13	1.12
Minced meat density ρ, kg/m^3	1,100	1,110	1,130	1,180
Diffusion coefficient ***D, m²/s***		$0.5 \cdot 10^{-9}$		

Table 5. Continued

Process parameter	Control of TU U 10.1-37792346-002:2021,%	Experimental sample No. 1	Experimental sample No. 2	Experimental sample No.3
Particle size of the dispersed phase ℓ, *m*	$1\cdot10^{-3}$	$0.8\cdot10^{-3}$	$0.6\cdot10^{-3}$	$0.4\cdot10^{-3}$
Processing time *t, s*		480		
Speed of flow in the mincer bowl υ, m/s		0.43		
Mass transfer rate in load weight β, *m/s*	$3.74\cdot10^{-6}$	$3.42\cdot10^{-6}$	$2.37\cdot10^{-6}$	$1.83\cdot10^{-6}$
Sherwood criterion, *Sh*	7.4712	5.4739	2.8386	1.4608
Euler criterion, *Eu*	0.0062	0.0057	0.0054	0.0051
Fourier criterion, Fo_d	0.240	0.375	0.667	1.500

Source: developed by the authors

Using the previous calculation methodology, the function graph was plotted using the data from Table 4. From this graph, the angle γ (Fig. 3) of its slope to the abscissa axis was found and the value of the second power coefficient was determined by the equation:

Table 6. *Calculated data for determining power coefficients*

Process parameter	Control of TU U 10.1-37792346-002:2021,%	Experimental sample No. 1	Experimental sample No. 2	Experimental sample No.3
Dimensionless component Fo_d^{α}	0.130	0.246	0.560	1.786
Dimensionless component Eu^m	$1.574\cdot10^{-7}$	$1.201\cdot10^{-7}$	$1.05\cdot10^{-7}$	$8.776\cdot10^{-8}$
Dimensionless component Sh/Eu^m	$4.75\cdot10^{7}$	$4.56\cdot10^{7}$	$2.7\cdot10^{7}$	$1.66\cdot10^{7}$
Dimensionless component $\frac{Sh}{Eu^m\cdot Fo_\partial{}^{\alpha}}$	$3.65\cdot10^{8}$	$1.85\cdot10^{8}$	$4.83\cdot10^{7}$	$9.32\cdot10^{6}$
Parameter *K*	$5.14\cdot10^{12}$	$2.63\cdot10^{12}$	$1.11\cdot10^{12}$	$3.29\cdot10^{11}$

Source: developed by the authors

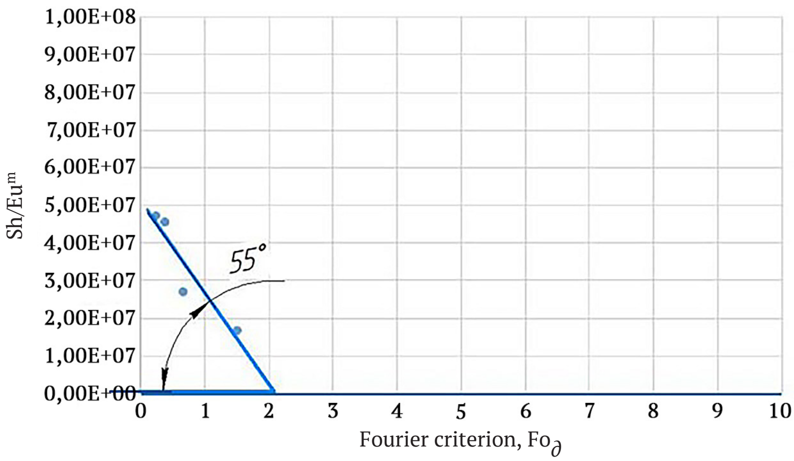

Figure 3. Function graph $\frac{Sh}{Eu^m} = f(\mathrm{Fo}_d)$

Source: developed by the authors

The next step was to plot the function $\frac{Sh}{Eu^m \cdot \text{Fo}_d{}^{\alpha}} = f(K)$ (Fig. 4). Using the data from Table 4, the process constant K was determined.

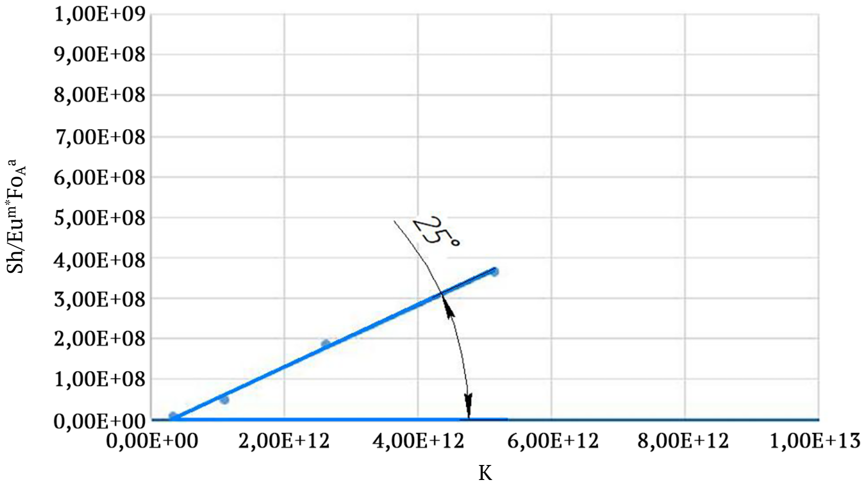

Figure 4. Function graph $\frac{Sh}{Eu^m \cdot \text{Fo}_d{}^{\alpha}} = f(K)$

Source: developed by the authors

Thus, the criterion equation of the process of vibrational mixing of the ingredients of the studied process was finally determined in the form of

$$Sh = Eu^m \cdot \text{Fo}_d{}^{\alpha} \cdot K = Eu^{3{,}08} \cdot \text{Fo}_d{}^{1.43} \cdot \left[\frac{v}{D}\right]^{2.43} \cdot \ell^3;$$

$$K = \left[\frac{v}{D}\right]^{(\alpha+1)} \cdot \ell^3;$$

$$\frac{\beta \cdot \ell}{D} = \left[\frac{\tau_m}{\rho \cdot v^2}\right]^{3.08} \cdot \left[\frac{D \cdot t}{\ell^2}\right]^{1.43} \cdot \left[\frac{v}{D}\right]^{2.43} \cdot \ell^3;$$

The presented mass transfer equation illustrates the dominant effect of the fine grinding process on the change in the concentration of spelt flour and champignons in production ΔC. This effect is determined by the value of the diffusion coefficient D, the particle size of the dispersed phase, and the mass flow coefficient in the loading mass β. Using equation (26) and the developed programme, the recommended set of operating mode parameters for the process of fine grinding in the production of cooked sausages is established, considering the above factors.

The paper by J.M. Ramos-Diaz *et al*. (2022) described an experiment aimed at creating a recipe for minced meat for semi-finished poultry products with the addition of porcini mushrooms. The main approach was to identify the optimal combination of ingredients to create a balanced meat mix. Various types of meat, dairy products, and herbal supplements were used in the model recipes. The use of turkey and chicken fillet provided complete animal proteins, and partial replacement of fatty meat raw materials with milk fat was carried out to reduce fat content. Additionally, the researchers developed a technology for making sausage products with the addition of vegetable ingredients for frying and indicated the main technological parameters of the production and heat treatment process. They also investigated the rheological properties of minced meat, such as adhesion, viscosity, and shear structural and mechanical properties. However, the researchers should substantiate in more detail the use of meat offal and dairy ingredients to stabilise protein and fat in the meat mixture, and prove that replacing the main meat raw materials with vegetable ones will allow obtaining high-quality sausages for grilling. In addition, the researchers did not perform sensory analysis of the finished product after heat treatment, which may be an important step in determining its quality.

The study by K. Chen *et al*. (2022) investigated promising developments for the meat processing industry – the production of dry snack products, in particular, meat chips. The main purpose of the study was to investigate the functional and technological characteristics of minced meat systems consisting of beef and seafood. These systems were designed to be improved with special food additives to increase quality and properties. The study showed that minced meat systems were high in protein (30.0-34.8%), lipids (2.2-3.7%), and carbohydrates (0.8-2.5%). Systems with the addition of seafood were characterised by a high ability to retain moisture (74.52-90.3%), which indicates their properties during drying. However, the researchers did not consider a number of important rheological parameters, such as maximum shear stress and dynamic viscosity, nor did they perform an organoleptic assessment. To improve the results obtained, it may be useful to conduct mathematical modelling based on these indicators.

H. Eshgarf *et al*. (2021) investigated the thermophysical properties of model dissected masses based on meat and fish with a functional additive. The influence of the multiplicity of grinding and additive concentration on the ratio between frozen (free) and non-frozen (bound) water and optimal technological parameters for the production of semi-finished products was determined. It was found that a functional vegetable additive in minced meat of split meat and fish products contributes to an increase in the proportion of undemanding moisture at temperatures up to -18°C. For double grinding, the rational value of the additive should be considered 25%, and for triple grinding – up to 30%. But it is not clear why the researchers did not analyse the factors that limit the introduction of additives, and what organoleptic characteristics of the finished products they studied while maintaining the high moisture retention capacity of the semi-finished product.

The purpose of the study by M. Nasiru *et al*. (2021) consisted in establishing the relationship between prescription components and production parameters of a new type of meat product. The paper offered solutions to the problem of creating a model recipe for a meat product with a high content of dietary fibre in a composite mixture. The goal was to develop mathematical tools that could serve as a basis for evaluating the component composition and parameters of cooking semi-finished meat products with specified structural and technological characteristics. The features of cooking semi-finished meat products using a composite mixture containing unconventional vegetable raw materials were revealed. The researchers developed a mathematical model that considers the dependence of the quality of finished meat semi-finished products on the number of components in the recipe and cooking conditions. They also determined the optimal dosage of the composite mixture and the values of the cooking parameters.

However, a comprehensive study of the mechanisms of development of structural and technological effects in ready-made meat systems under various conditions of their production process was not presented. The main finding was a model describing nonlinear relationships between the structural parameters of a semi-finished meat product and technological indicators from the conditions of the production process, in particular, temperature. To clarify the study, the researchers should analyse the dosage of the components of the composite mixture, explain the purpose of their introduction, which is aimed at improving the physical properties of the meat product that they enrich.

Common varieties of cereals widely used in the food industry have significantly lower content of dietary fibre, essential amino acids, and unsaturated fatty acids compared to wild spelt. The use of spelt as a substitute for traditional cereal varieties in food can help increase the consumption of dietary fibre and other useful components of food, which was determined by O. Kochkodan *et al*. (2020).

L.V. Bal'-Prylypko *et al*. (2018) argue that adding pectin to food may prove to be an effective method of removing harmful compounds such as biogenic toxins and radionuclides from the body, especially after exposure. Such techniques can improve the function of the immune system and contribute to the overall state of human health, but to confirm the results of these studies, the researchers need to present the results of organoleptic and physicochemical properties of the finished product.

Thus, replacing traditional food components with spelt and using pectin as a supplement may prove to be effective strategies for improving a person's eating habits and overall health, as confirmed by scientific research.

Conclusions

The developed formulation allowed simultaneously increasing the protein content in the minced meat composition by replacing wheat flour containing 11-12% protein with spelt flour, where the protein content reaches 20-22%; and also reducing the allergic danger due to the fact that the gluten of spelt flour contains significantly less highly allergic gliadin present in traditional wheat flour in fairly large quantities. To compile a mathematical algorithm that relates the main parameters of the process of preparing minced meat, the choice of Froude, Euler, Fourier and Sherwood similarity criteria was substantiated, which allowed estimating the forces of inertia and weight, pressure and head velocity, intensity of convective and diffusion flows at the interface of interacting phases, and intensity of the mass transfer process in the process of minced meat preparation.

When using graph-analytical methods, a mathematical model was compiled in the form of a mass transfer equation containing the ratio between such process parameters as product density ρ, coefficient of dynamic viscosity of the process medium μ, maximum shear stress τ_m, change in the concentration of methylcellulose in raw materials ΔC, value of the diffusion coefficient D and the mass transfer coefficient in the load mass β**.** Using the compiled criterion equation and the developed programme, the main graphical relationships between the presented parameters were revealed, which allowed creating a recommended number of operating mode parameters for the studied process of preparing minced meat and sausage production technology using a food additive based on spelt flour and champignon mushrooms.

The developed mathematical algorithm based on the results of physical and mathematical modelling allowed optimising the product formulation, analysing the nutritional value of minced meat and other multicomponent mixtures, developing new products and analysing their impact on health at a new level; this significantly expands the potential of process, technological and organisational aspects of designing new food products with a combined formulation, considering a wide range of mechanical and heat and mass transfer factors; thereby significantly increasing their competitive ability in the industrial food production market. A promising area for further research is to determine the effect of various ratios between spelt flour, mushrooms, and other ingredients on the taste, texture, and nutritional properties of minced meat using mathematical modelling.

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Conflict of Interest

None.

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Фізико-математичне моделювання процесу приготування фаршу із домішками спельтового борошна та грибів печериці

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Анотація. Введення до м'ясопродуктів домішок рослинного або тваринного походження складає на теперешній час стійку тенденцію у харчових технологіях через можливості отримати унікальні властивості продукції та зниження її собівартості, що обгрунтовує актуальність проведених досліджень. Метою статті є побудова математичного алгоритму, що дозволяє визначити закономірності зміни основних параметрів процесу приготування фаршу м'ясних напівфабрикатів із рослинними домішками, що дозволить визначити тенденції розвитку технічної та технологічної ефективності засобів механізації системи тонкого подрібнення сировини для виготовлення ковбасних виробів. Досліджено застосування у якості інгредієнтів до фаршевої маси використовують домішки спельтового борошна та грибів печериці, що дозволяє разом із зниженням собівартості виробництва вареної ковбасної продукції, значно покращити органолептичні показники якості продуктів, зменшити їхню калорійність та подовжити терміни придатності до споживання. Дикорослий різновид спельта, що використовується у даній науковій роботі як альтернатива її культурним сортам, володіє значно меншою алергійною активністю та відповідно меншою часткою гліадинів, які складають основу пшеничного глютену або клейковини; що обгрунтовує практичну цінність роботи. Був виконаний мікроструктурний аналіз фаршу контрольного та дослідних зразків варених сосисок виявив, що остання категорія м`ясного продукту характерна підвищеними щільністю та пружністю завдяки включенню мікрочасток спельти у вакуолі м`ясної фракції. Згідно з результатами експериментальних досліджень, використанням методу «аналізу розмірностей» та теореми Федермана-Букінгема вдалося отримати критеріальне рівняння для процесу тепломасообміну в умовах інтенсивного механічного перемішування. Дані процесні характеристики були описані при допомозі критеріїв Ейлера, Фур'є та Шервуда. Складена функція містить основні фактори зовнішнього впливу на сировину та її фізико-механічні характеристики, що дозволяє адекватно оцінити процеси дифузії у технологічному середовищі та сформувати рекомендований ряд при проектуванні технічного та технологічного забезпечення для отримання якісної харчової продукції

Ключові слова: спельта; напруга зсуву; фаршева маса; теорія подібності; числа подібності; дифузія; варені м'ясопродукти