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Контактна адреса:
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
E-mail: info@c-bulletin.com.ua
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Address for contacts:
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
E-mail: info@c-bulletin.com.ua
https://c-bulletin.com.ua/en

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Macronutrients composition of dry soluble gerodietetic products for enteral nutrition

Dmytro Antiushko*

PhD in Technical Sciences, Associate Professor
State University of Trade and Economics
02156, 19 Kioto Str., Kyiv, Ukraine
https://orcid.org/0000-0002-4135-6439

Abstract. In emergencies, including increased stress, injuries, diseases, traumas, and during the recovery period, the compliance of nutrition with the special metabolic body needs is critical. Considering this, the use of foods for special medical purposes, particularly enteral nutrition, has become quite widespread in modern dietary practice. The purpose of this study was to develop the suitable macronutrient composition of dry soluble gerodietetic products for enteral nutrition, which would meet consumer preferences with its organoleptic properties. For this, the study found that specialists in nutritional support for the emergency needs of representatives of older age groups recommend the ratio of protein, fats, and carbohydrate components in the total energy value (%) within 17-21/28-34/45-55, respectively. For people with type 2 diabetes, these values were 26-51/31-35/14-43. Based on this, the corresponding mass ratios of macronutrients were determined. This provided the base for dry soluble products for enteral nutrition development. Based on their organoleptic evaluation in the ready-to-consume liquid state, the most optimum were defined: 24.5/14.5/61.0 wt. % for representatives of older age groups without any metabolic complications, 61.0/16.0/23.0 wt. % for patients with type 2 diabetes. These products were selected for further use and enrichment with a specially designed functional composition in the further products development. The study also developed mathematical models to describe the relationship between the complex organoleptic quality indicators of macronutrient compositions for enteral nutrition and their protein, fat, and carbohydrate content. The practical value of this study lies in improving the methodological principles of dry soluble gerodietetic products for enteral nutrition development and in the possibility of using the developed mathematical models to optimise their macronutrient composition

Keywords: enteral nutrition products; assortment; metabolic needs; composition of macronutrients; organoleptic properties; mathematical modelling

Introduction

It is axiomatic that nutrition is one of the key factors determining the vital functions of the organism. For people in emergencies (with increased loads, lesions, diseases, injuries, during the recovery period), the alignment of nutrition with special metabolic needs becomes crucial. Considering this, the use of foods for special medical purposes, particularly for enteral nutrition, has become quite widespread in modern dietary practice (Prytulska & Antiushko, 2024).

The provided analysis of information on the state of the market for enteral nutrition products at both the global (Global enteral feeding formulas..., 2024) and European regional (Europe enteral nutrition market, 2024) levels revealed quite a dynamic development. At the same time, despite the war in Ukraine, almost all products presented on Ukrainian market were foreign-made. Ukrainian products of this assortment group were represented to a rather insignificant extent

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*Corresponding author

(The list of notifications about the intention..., 2025). This indicated the relevance of scientifically sound development and improvement of the existing assortment of products for enteral nutrition, including ensuring their Ukrainian production.

The author J. Doley (2022) analysed the benefits of using the studied products, the main cases in which their consumption (use) occurs. This researcher also provided recommendations for choosing these products based on their component differences, their complementarity with other different formulas, duration, and place of consumption (usage), measures to reduce possible risks. A. Church & S. Zoeller (2023) analysed the available products of this assortment group. Specifically, the key differences in composition of components, priority areas of application, results, and efficacy of usage were investigated. C. Compher *et al.* (2022) analysed the clinical results of using various types of products for enteral nutrition, which differed in energy value, protein content, and the presence of other macronutrients in the products content. The benefits of consumption (usage) of these products in combination with parenteral nutrition products were also explored.

Scientists A. Weimann *et al.* (2021) presented practical recommendations aimed at ensuring the nutritional aspects of the concept of postoperative recovery and care, preventing the occurrence of complications. Specifically, practical algorithms for using enteral nutrition were proposed to optimise blood glucose levels, reduce catabolic processes under the influence of stress, provide the suitable amount of protein components, and restore muscle functions.

The authors P.E. Wischmeyer *et al.* (2023) found that nutrition during periods of treatment and rehabilitation should meet the concrete needs of consumers and specific target groups representatives. Practical recommendations were provided on the proper satisfaction of needs and elimination of protein and microelement deficiencies, the use of definite special anabolic nutrients for this purpose. C. Compher *et al.* (2022) also presented recommendations on the proper provision of adult population representatives nutritional needs. The researchers established that the primary significance in eliminating physiological dysfunctions ensured the proper supply of energy and protein substrates, the amount of which should be determined based on individual anthropometric, gender-age, and metabolic characteristics.

Researchers D. Volkert *et al.* (2022) investigated the problem of insufficient provision of energy substrates and hydroresources in the treatment of older age groups representatives, the imbalance of the presented nutrients with the humans of mentioned target group's metabolism. S. Ekmekcioglu (2020) examined the materials on the specific features of metabolic needs in representatives of the older age groups, including in emergencies. The researcher explored the specific features of metabolism and needs of this group of people. In addition, practical recommendations for ensuring their content in food rations, including during increased loads, diseases, and injuries were proposed.

Scientists T.A.F. Wylie *et al.* (2022) analysed the data on the specific features of needs in this group of people and developed practical recommendations for quantitative macronutrient content in their diets, particularly in emergencies. At the same time, on the modern market, specifically in Ukraine, there were practically no specially developed products for enteral nutrition of older age groups, including for patients suffering from type 2 diabetes.

The purpose of this study was to investigate and model the optimum macronutrient composition of dry soluble gerodietetic products for enteral nutrition. To fulfil this purpose, the following tasks were set:

- to analyse data and recommendations of specialists on ensuring the nutritional needs of older age groups' representatives in emergencies;
- to evaluate the organoleptic characteristics of the primary variants of the macronutrient basis of dry soluble products for enteral nutrition, which would meet the established recommendations;
- to determine the optimum macronutrient composition of dry soluble gerodietetic products for enteral nutrition of gerodietetic purpose based on previously established data.

The scientific originality of this study lies in the systematisation of data on the recommended ratio of basic macronutrients in the general diet of older age groups, including patients with type 2 diabetes. Additionally, it improves the methodological principles of mathematical modelling of the complex quality index of organoleptic properties based on information regarding macronutrient content.

Materials and Methods

The study employed the methods of scientific research, analysis, comparison, establishment of correlations and systematisation to establish recommendations for the optimum ratio of proteins, fats, and carbohydrates in the diet of people belonging to older age categories. While converting the recommended ratio of macronutrients in the total energy value of the diet into the corresponding indicator per 100 g of a balanced food product, the following coefficients were used, kcal/100 g: proteins – 4.1, fats – 9.3, carbohydrates – 4.0 (considering the different energy value of their groups and types). The maximum, average, and minimum recommended values of the quantitative content of protein, fats, and carbohydrate components were used to develop the experimental samples of the macronutrient composition of dry soluble products for enteral nutrition. The raw materials that are most widely used in the manufacturing of dry soluble

products for enteral nutrition (whey protein concentrate (proteins – 80%, fats – 10%, carbohydrates – 5%), polyunsaturated fatty acids in a casein-starch matrix, maltodextrin, glucose (except for the product intended for people with type 2 diabetes), fructose were chosen to provide macronutrients in researched samples.

Sample preparation for organoleptic evaluation was performed by dissolving a portion of the dry mixture (50 g) in 200 cm^3 of boiled water at 15-40°C. The organoleptic properties of the test samples were evaluated by 5 qualified experts using a specially developed scale. The evaluation criteria were presented in Table 1.

Table 1. *Point-scale for evaluating the organoleptic properties of products for enteral nutrition macronutrient compositions' samples in a ready-to-consume liquid state*

Indices	Importance coefficient	Points	Characteristics
Consistency and external appearance	0.2	5	Homogeneous, without sediment or delamination, not viscous, slightly viscous
		4	Homogeneous, a small amount of undissolved particles is acceptable, not chewy, slightly viscous
		3	Homogeneous, with a small amount of sediment and delamination, viscous
		2	Homogeneous, with a small amount of sediment and a significant amount of delamination, viscous
		1	Heterogeneous, with a significant amount of delamination and sediment, viscous
Colour	0.1	5	Light-yellow to light-brown, uniform
		4	Light-yellow to light-brown, homogeneous, with a small amount of white inclusions
		3	Light-yellow to light-brown, heterogeneous
		2	Light-brown to brown, heterogeneous
		1	Brown to dark-brown, heterogeneous
Scent	0.15	5	Clean, pleasant, without foreign shades, with faint characteristic hints of additives
		4	Subtle, with faint characteristic hints of additives
		3	Empty, faint scent of fatty acids
		2	Unpleasant, distinct scent of fatty acids, foreign shades are felt
		1	Sharp, unpleasant, quite expressed scent of fatty acids with rich foreign shades
Taste	0.3	5	Pleasant, balanced, pronounced, sugary, with a faint aftertaste of the additives
		4	Pleasant, inadequately expressed, sugary, with a faint aftertaste of additives
		3	Empty, sugary, with faint notes of bitterness, a pronounced aftertaste of the additives
		2	Unpleasant, uncharacteristic, bitter, with pronounced aftertaste of fatty acids
		1	Unpleasant, bitter, with pronounced aftertaste of fatty acids
Aftertaste	0.25	5	Pleasant, balanced, sugary, lingering, without any foreign aftertaste
		4	Pleasant, unbalanced, sugary, brief, without any foreign aftertaste
		3	Empty, subtle, faintly felt, without any foreign aftertaste
		2	Unpleasant, weakly expressed, brief, with a slight foreign aftertaste
		1	Sharp, unpleasant, bitter, persistent, with a significant foreign aftertaste

Source: *developed by the author*

The complex quality index of the organoleptic properties of macronutrient composition in gerodietetic products for enteral nutrition was calculated based on expert assessments, factoring in rejected and reference values, according to the following formula:

$$I_{CQI} = \sum_{i=1}^{n} a_i \frac{P_i - P_i^{rej}}{P_i^{ref} - P_i^{rej}}, \quad (1)$$

where P_i – i-point index in natural form; P_i^{ref} – reference (best acceptable) point value of i-index; P_i^{rej} – rejected (worst acceptable) point value of i-index; a_i – importance coefficient of i-index, identified by range method; n – quantity of evaluated indices.

Using the results of the provided organoleptic research of the main samples of raw material component compositions that correspond with the mentioned ranges of protein, fats, and carbohydrate content, the optimum ones were determined. In addition, mathematical models for forecasting the complex quality index of the macronutrient compositions' organoleptic properties were developed using MS Excel 2016 software. The study was conducted following the standards of The Declaration of Helsinki (2013).

Results and Discussion

It was found that due to aging processes, which largely manifest after a person reaches 60-65 years old, the intensity of protein self-renewal, glucose utilisation, oxygen consumption, and biological enzyme oxidation decrease in the body. In addition, the accumulation of fats in tissues increases, and significant carbohydrate imbalances emerge (Kemoun *et al.*, 2022). As a result, the nutrition of people belonging to this category should accommodate age characteristics and be used not only to provide energy and compensatory effects, but also to perform plastic, protective, and rehabilitating functions, to exert

immuno- and bioregulatory effects on vital activity (Torres-Quesada *et al.*, 2022; Schippinger, 2022). Considering this, ensuring a high content of protein, specifically, presented by dairy and egg origin, poly- and monounsaturated fatty acids in the diet of older age groups becomes of increased significance for restoring and minimising the results of age-related changes (Antiushko, 2020).

The adequacy of nutritional substrate intake, supplied with food, becomes particularly significant in cases of increased stress, diseases, and injuries. Based on the findings of the analysis of scientific sources by S. Ekmekcioglu (2020), it was estimated that most specialists in the field of nutritional support for the needs of older age groups in emergencies recommend the following ratio of protein, fats, and carbohydrate components in the total food rations energy value, % – 17-21/28-34/45-55, respectively.

It was also found that one of the most common non-communicable diseases, which was also significantly prevalent among older age groups, was type 2 diabetes mellitus (Diabetes, 2024). Considering this, information on professional recommendations regarding the optimum ratio of the main macronutrients in their diet was also analysed (Holdoway, 2022; Dove *et al.*, 2024). It was found that for this group of target consumers, specialists recommend the following ratio, % – 26-51/31-35/14-43, respectively. Based on the established and analysed recommendations of specialists on the recommended ratios of protein, fats, and carbohydrate components in the total energy value of diets and using the energy coefficients of their oxidation, the recommended content per 100 g of a balanced food product for the mentioned consumers was calculated (Table 2).

Table 2. *Results of calculation of recommended macronutrient content in the diet of older age groups representatives in emergencies*

Macronutrients	Recommended content in total energy value, %		Recommended content, wt. %	
	for individuals without metabolic complications	for individuals with type 2 diabetes	for individuals without metabolic complications	for individuals with type 2 diabetes
Proteins	17.0-21.0	26.0-51.0	19.5-24.5	31.0-61.0
Fats	28.0-34.0	31.0-35.0	14.5-17.5	16.0-18.0
Carbohydrates	45.0-55.0	14.0-43.0	58.0-66.0	21.0-53.0

Source: *developed by the author*

Analysis of established data on the mass ratio of basic macronutrients recommended for older age groups representatives in emergencies revealed that to ensure the necessary body recovery, an increased content of easily digestible protein and fats should be ensured. Specifically, for older age groups without metabolic complications, this was 19.5-24.5 and 14.5-17.5 wt. %, respectively. For people with type 2 diabetes in this age group, this was 31.0-61.0 and 16.0-18.0 wt. %, respectively. Notably, it was vital to provide people with problems with carbohydrate metabolism with a low glycaemic load in their diet and the products under study.

Based on the established data on the mass ratio of basic macronutrients recommended for older age groups in emergencies, 9 experimental samples were developed. They were characterised by the maximum, average, and minimum content of each analysed macronutrient. The findings of the organoleptic assessment of the proposed samples of the macronutrient composition of products in a liquid ready-to-consume state, which was conducted by representatives of the expert group using a specially developed scale (Table 1), were presented in Table 3. The organoleptic assessment of modelled enteral nutrition products found that the fat component had the most significant influence on their macronutrient composition. Specifically, the study found that samples with lower content had higher scores on taste, aftertaste, and scent indices. In addition, it was found that samples with a higher protein content had more balanced organoleptic properties. Summarising the findings of the provided organoleptic evaluation of the modelled samples of products for enteral nutrition macronutrient composition, the results, presented in Table 4, were obtained.

Table 3. *Results of organoleptic evaluation of modelled samples of products for enteral nutrition macronutrient composition in liquid ready-to-consume state*

Samples	Composition			Assessments by indices, points																						
				Consistency and external appearance					Colour					Scent					Taste					Aftertaste				
	proteins	fats	carbo-hydrates	expert 1	expert 2	expert 3	expert 4	expert 5	expert 1	expert 2	expert 3	expert 4	expert 5	expert 1	expert 2	expert 3	expert 4	expert 5	expert 1	expert 2	expert 3	expert 4	expert 5	expert 1	expert 2	expert 3	expert 4	expert 5
for older age groups without metabolic complications																										
1	19.5	14.5	66.0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	4	4	4	4	4

Table 3. Continued

for older age groups without metabolic complications																										
2	19.5	16.0	64.5	4	4	4	4	4	4	4	4	4	4	4	4	3	4	4	4	4	4	4	4	4	3	4
3	19.5	17.5	63.0	4	4	4	4	4	4	3	4	4	4	4	3	4	3	4	4	3	4	4	4	4	4	3	3	4
4	22.0	14.5	63.5	4	4	4	4	4	4	4	5	4	4	4	4	5	4	4	4	4	5	4	4	4	4	4	4	4
5	22.0	16.0	62.0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	4	4
6	22.0	17.5	60.5	4	4	4	4	4	4	3	4	4	4	4	3	4	4	4	4	3	4	4	4	4	3	3	4	4
7	24.5	14.5	61.0	4	4	4	4	4	4	4	5	4	4	4	4	5	4	4	4	4	4	4	5	4	4	4	5	4
8	24.5	16.0	59.5	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
9	24.5	17.5	58.0	4	4	4	4	4	3	4	4	4	4	3	4	4	4	4	3	4	4	4	4	3	3	4	4	4
for older age groups with type 2 diabetes																										
1	31.0	16.0	53.0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
2	31.0	17.0	52.0	4	3	4	4	4	4	4	3	4	4	4	4	3	4	4	4	4	4	4	4	3	4	4	4	4
3	31.0	18.0	51.0	4	3	3	4	4	4	4	3	4	4	4	3	3	4	4	4	4	4	3	4	4	4	3	3	4
4	46.0	16.0	38.0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	4	4	4	4	4	4	5
5	46.0	17.0	37.0	4	4	4	4	4	4	4	3	4	4	4	4	3	4	4	4	4	4	4	4	4	4	4	4	4
6	46.0	18.0	36.0	4	4	3	4	4	4	4	3	4	4	4	4	3	3	4	4	4	4	3	4	4	4	4	3	4
7	61.0	16.0	23.0	4	4	4	5	4	4	4	4	4	4	4	4	4	4	5	4	4	5	4	4	4	4	5	4	4
8	61.0	17.0	22.0	4	4	4	4	4	4	4	4	4	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
9	61.0	18.0	21.0	4	4	4	4	4	4	4	3	4	3	4	4	3	4	4	4	3	4	4	4	4	3	4	4	4

Source: *developed by the author*

Table 4. *Summary data on the results of organoleptic properties evaluation of the researched gerodietetic products for enteral nutrition macronutrient compositions in a liquid ready-to-consume state*

Samples	Composition			Average value of scores by indices, considering their importance coefficients, points					Complex quality index of organoleptic properties, conventional units
	proteins	fats	carbo-hydrates	Consistency and external appearance	Colour	Scent	Taste	Aftertaste	
for older age groups without metabolic complications									
1	19.5	14.5	66.0	0.80	0.40	0.60	1.26	1.00	**0.7650**
2	19.5	16.0	64.5	0.80	0.40	0.57	1.20	0.95	**0.7300**
3	19.5	17.5	63.0	0.80	0.38	0.54	1.14	0.90	**0.6900**
4	22.0	14.5	63.5	0.80	0.42	0.63	1.26	1.00	**0.7775**
5	22.0	16.0	62.0	0.80	0.40	0.60	1.20	0.95	**0.7375**
6	22.0	17.5	60.5	0.80	0.38	0.57	1.14	0.90	**0.6975**
7	24.5	14.5	61.0	0.80	0.42	0.63	1.26	1.05	**0.7900**
8	24.5	16.0	59.5	0.80	0.40	0.60	1.20	1.00	**0.7500**
9	24.5	17.5	58.0	0.80	0.38	0.57	1.14	0.90	**0.6975**
for older age groups with type 2 diabetes									
1	31.0	16.0	53.0	0.80	0.40	0.60	1.20	1.00	**0.7500**
2	31.0	17.0	52.0	0.76	0.38	0.57	1.20	0.95	**0.7150**
3	31.0	18.0	51.0	0.72	0.38	0.54	1.14	0.90	**0.6700**
4	46.0	16.0	38.0	0.80	0.40	0.60	1.26	1.05	**0.7775**
5	46.0	17.0	37.0	0.80	0.38	0.57	1.20	1.00	**0.7375**
6	46.0	18.0	36.0	0.76	0.36	0.54	1.14	0.95	**0.6875**
7	61.0	16.0	23.0	0.80	0.40	0.63	1.26	1.05	**0.7850**
8	61.0	17.0	22.0	0.80	0.38	0.60	1.20	1.00	**0.7450**
9	61.0	18.0	21.0	0.80	0.36	0.57	1.14	0.95	**0.7050**

Source: *developed by the author*

Based on the established complex quality indices of the organoleptic properties of the researched samples of products macronutrient compositions, it was found that among those intended for older age groups without metabolic complications, the best value (0.7900 conventional units) was characterised by the ratio of protein, fats, and carbohydrate components 24.5/14.5/61.0 wt. %. For older age groups with

type 2 diabetes mellitus, the best value (0.7850 conventional units) was found in the sample with the ratio 61.0/16.0/23.0 wt. %, respectively. This was explained by the lower content of polyunsaturated fatty acids in these samples, which gave a fishy taste, aftertaste, and scent.

In addition, using the results of organoleptic properties evaluation of the main samples of raw components compositions and corresponding to the mentioned ranges of protein, fats, and carbohydrate content, mathematical models of the dependence of the complex quality indicator of organoleptic properties on the content of the specified components were developed using MS Excel 2016 software:

• for enteral nutrition products aimed at older age groups without metabolic complications:

$$y = 0.031 * x_1 + 0.0014 * x_2 + 0.0275 * x_3 - 1.65278; \quad (2)$$

• for enteral nutrition products aimed at older age groups with carbohydrate metabolism dysfunctions (particularly type 2 diabetes):

$$y = 0.0001086 * x_1 - 0.0445386 * x_2 - \\ - 0.0012164 * x_3 + 1.527482, \quad (3)$$

where y – complex quality index of macronutrient composition's organoleptic properties, conventional units; x_1 – content of protein component, g/100 g; x_2 – content of lipid component, g/100 g; x_3 – content of carbohydrate component, g/100 g.

The reliability of the obtained findings of mathematical modelling was above 97%. Notably, such developments in enteral nutrition products were the property of private companies and protected by patent law. Therefore, information about their manufacturing formula was not widely available. At the same time, A.K. Jansen *et al.* (2017) examined the principles of enteral nutrition development, prescribed by doctors, nurses, dietitians, pharmacists, and other providers of home enteral nutrition. Based on comparable ranges of macronutrient content of the studied products, recommendations for the combination of the most common ingredients in home use were provided. J.J. Patel *et al.* (2024) analysed modern tendencies of products for enteral nutrition usage, especially for patients with septic shock, risk factors for enteral feeding intolerance. It was found that using this type of nutrition provides benefits of introducing enteral nutrition on preserving gut barrier function. At the same time, the main risks connected with its usage should be carefully analysed. V. Kumari & A. Jayadeep (2019) analysed the composition of general or special products for enteral nutrition, and the effects of products with different macronutrient content on physical recovery in patients. H.J. Coelho-Júnior *et al.* (2022) noted that no clear relationship was found between protein distribution or sources and physical function.

C.L. Nelms (2018) analysed the compositional features of enteral nutrition for children with chronic kidney disease, specifically those related to macronutrient content. The researcher highlighted the primary ways of optimisation and criteria for selecting products with the most suitable composition for these children. K. Jones *et al.* (2017) found that to provide patients in critical conditions with enteral nutrition, it was most suitable to use standard formulas at the first stage. Then, based on the needs diagnosed by doctors, the mixtures should be enriched with additional specific nutrients. C.E. Mazur *et al.* (2021) analysed the level of energy and protein needs of patients after stroke based on the consumption of the most common commercial formulas (CF) for enteral nutrition, home-made products, and mixed diets. The researchers also studied, how these nutritional options allow meeting the needs of victims in macronutrients. In addition, within the development of enteral nutrition, the study of food processing mechanisms that reduced the risk of microbial contamination was significant (Pyatkovskyy, 2023). Thus, the analysis of enteral nutrition development highlighted key principles prescribed by medical professionals, emphasising the value of selecting common ingredients for home use.

Conclusions

Based on the analysis of information and recommendations of specialists in the field of ensuring the nutritional needs of older age groups representatives in emergencies, the study found that for people without metabolic complications, the following ratio of protein, fats, and carbohydrate components in the total energy value of food rations was recommended, % – 17-21/28-34/45-55, respectively. The study also found that for people of this age category with type 2 diabetes, the recommended ratio was 26-51/31-35/14-43, respectively.

While establishing the recommended mass ratio of macronutrients, it was found that to ensure the necessary recovery of older age category representatives in emergencies, increased content of protein and fats should be ensured. Thus, according to the analysed recommendations, their content for older age groups without metabolic complications should be 19.5-24.5 and 14.5-17.5 wt. %. At the same time, for people of the same age group with type 2 diabetes, the content should be 31.0-61.0 and 16.0-18.0 wt. %, respectively. Notably, for people with carbohydrate metabolism problems, low glycaemic load of diet should be provided. Therefore, 9 samples of macronutrient compositions were modelled and assessed for organoleptic properties, which were characterised by the maximum, average, and minimum content of each macronutrient in the established range of values.

Based on the findings of the provided assessment of analysed samples of macronutrient com-

positions' organoleptic properties, it was found that among those intended for older age groups additional metabolic complications, the best value of this index (0.7900 conventional units) was characterised by the ratio of protein, fats, and carbohydrate components of 24.5/14.5/61.0 wt. %; for those with type 2 diabetes mellitus (0.7850 conventional units) – 61.0/16.0/23.0 wt. %, respectively. This was explained by the lower content of polyunsaturated fatty acids in these samples, which provide a fishy taste, aftertaste, and scent. The prospect of further research is the selection and modelling of the components content of functional compositions for enteral nutrition products under development.

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Макронутрієнтний склад сухих розчинних геродієтичних продуктів для ентерального харчування

Дмитро Антюшко
Кандидат технічних наук, доцент
Державний торговельно-економічний університет
02156, вул. Кіото, 19, м. Київ, Україна
https://orcid.org/0000-0002-4135-6439

Анотація. В умовах надзвичайних ситуацій, включаючи підвищений стрес, травми, захворювання, травматичні ушкодження та під час періоду відновлення, відповідність харчування особливим метаболічним потребам організму є критично важливою. З огляду на це, використання продуктів для спеціального медичного призначення, зокрема ентерального харчування, стало широко поширеним у сучасній дієтичній практиці. Метою цього дослідження було розробити відповідний макронутрієнтний склад сухих розчинних геродієтичних продуктів для ентерального харчування, який би відповідав споживчим перевагам завдяки своїм органолептичним властивостям. Для цього було виявлено, що спеціалісти з харчової підтримки для надзвичайних потреб представників старших вікових груп рекомендують співвідношення білків, жирів і вуглеводів у загальній енергетичній цінності (%) у межах 17-21/28-34/45-55 відповідно. Для осіб з цукровим діабетом 2 типу ці значення становлять 26-51/31-35/14-43. На основі цього були визначені відповідні масові співвідношення макронутрієнтів. Це стало основою для розробки сухих розчинних продуктів для ентерального харчування. На основі їх органолептичної оцінки в готовому до вживання рідкому вигляді були визначені найоптимальніші: 24,5/14,5/61,0 мас. % для представників старших вікових груп без метаболічних порушень, 61,0/16,0/23,0 мас. % для пацієнтів з цукровим діабетом 2 типу. Ці продукти були обрані для подальшого використання та збагачення спеціально розробленим функціональним складом при подальшій розробці продуктів. У дослідженні також були розроблені математичні моделі для опису залежності між комплексними органолептичними показниками якості макронутрієнтних складів для ентерального харчування та їхнім вмістом білків, жирів і вуглеводів. Практична цінність цього дослідження полягає в удосконаленні методичних принципів розробки сухих розчинних геродієтичних продуктів для ентерального харчування та в можливості використання розроблених математичних моделей для оптимізації їхнього макронутрієнтного складу

Ключові слова: продукти ентерального харчування; асортимент; метаболічні потреби; склад макронутрієнтів; органолептичні властивості; математичне моделювання

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Labelling of allergens and intolerance-causing foods in Ukraine

Igor Dudarev*
Doctor of Technical Sciences, Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-2016-5342
Rostyslav Kukhar
Lecturer
Liubeshiv Technical Vocational College
44201, 7 Brestska Str., Liubeshiv, Ukraine
https://orcid.org/0009-0005-0952-1421

Abstract. The number of consumers with food allergies or intolerances is rapidly increasing worldwide. Legislation in many countries, including Ukraine, defined a list of substances and foods that cause allergic reactions or intolerances. It also establishes requirements for allergen labelling on food packaging, which manufacturers must comply with. The purpose of this study was to determine, how food manufacturers in Ukraine indicate the presence of substances and ingredients that may cause allergic reactions and intolerances, and whether such labelling meets the requirements of Ukrainian legislation. For the label analysis, food products were grouped into 10 categories: sausages, bakery products, cookies and waffles, dairy products, sauces and mayonnaises, cheeses, snacks, instant foods, confectionery and ice creams. The study was conducted by analysing food labels from local supermarkets in Lutsk, Ukraine. It was found that the majority of the foods analysed contained allergens or ingredients that cause intolerance. Between 8% and 22% of food products in different categories did not have allergens properly identified on the labels, even though they were present. On food labels, Ukrainian manufacturers mainly used bold type to highlight substances and ingredients that may cause allergies and intolerances (74.0-100.0% of products). Only 4.0-28.3% of product labels used capital letters to highlight these substances and ingredients. Text highlighting through colour, style, background and underlining was much less common and was most often combined with bold text. The terms "contains" and "may contain traces of" appeared on the labels of 6.0-36.0% and 6.0-76.1% of foods, respectively. The most common ingredients on the labels of the food products analysed were processed cereal products containing gluten, eggs, milk or dairy products, processed soy products, peanuts, and nuts. The results of the analysis showed that Ukrainian producers generally comply with Ukrainian legislation regarding the labelling of substances or ingredients in food products that may cause allergic reactions or intolerance

Keywords: allergy; consumer protection; label requirements; ingredient disclosure; regulatory standards

Introduction

Food allergy is a major public health problem with an increasing prevalence in urbanised areas, significantly impacting the lives of affected individuals with allergies and their families (Peters *et al.*, 2021). A. Muraro *et al.* (2022) found that food allergy affects approximately 2-4% of children and adults. In line with the global trends, food allergy is increasingly reported in Europe (Spolidoro *et al.*, 2022). The scientists A.B. Conrado *et*

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*Corresponding author

al. (2021) noted that commonly consumed foods, including milk, bread, eggs, fish, nuts, and soya, can cause food allergies, leading to potential health risks for those with intolerances. Globally, cow's milk and shellfish/crustaceans are among the most common causes of anaphylaxis, a life-threatening allergic reaction, alongside peanuts and tree nuts. The authors D. Gargano *et al*. (2021) stated that in some severely allergic individuals, even a very small amount of food can cause a life-threatening reaction.

Researchers C.L. Jansson-Knodell *et al*. (2020) emphasised that non-allergic food reactions, such as food intolerance, were often confused with food allergies. With prevalence rates ranging from 4% to 20% of the general population, food intolerances can present with a variety of symptoms, including gastrointestinal complaints such as flatulence, abdominal pain, bloating, and diarrhoea.

To protect food-allergic consumers from accidental exposure to allergenic foods, allergen labelling regulations and guidelines, including the Codex Alimentarius. International food standards (2025), have been developed and adopted, based primarily on the scientific research. EU countries and Ukraine require pre-packaged foods to be labelled with the 14 major allergens. In some countries, there are no regulations for pre-packaged foods that may be at risk of cross-contamination with food allergens during the manufacturing process, and food manufacturers often use precautionary allergen labelling (PAL) (i.e., "may contain" statements) to address this gap. As pointed out by J.C. Li *et al*. (2024), PALs, such as "may contain" or "may contain traces of", often cause confusion among consumers, as foods with these labels typically contain only low or trace levels of allergens. Consumers with allergies may find it difficult to assess, how safe such products were for them and whether consuming them may cause adverse health effects. Therefore, ongoing efforts were focused on defining thresholds for the presence of allergens in processed foods that would indicated the need for PALs (Stankovich *et al.*, 2023).

The authors W.M. Blom *et al*. (2021) noted that for consumers with food allergies, the allergen information section of food labels was an important and often crucial communication tool for avoiding the allergen(s). For allergens used as ingredients in specific foods, allergen labelling must be clear and understandable to consumers and comply with local regulations. M.L. Cunha *et al*. (2020) highlighted that identifying the possible allergens present in each food was a challenge for consumers, especially with derivatives (e.g. the term "vegetable oil" often does not specify the origin of the product, which could be soy, peanut, sunflower). In many countries, including Ukraine, regulations required that food products containing allergens or products causing intolerance (PCIs) must be highlighted from other information on the label by font, background colour, style.

The purpose of this research was to examine, how Ukrainian manufacturers label allergens and intolerance-causing products on pre-packaged food labels and whether they comply with Ukrainian legislation regarding the provision of allergen information to consumers.

Materials and Methods

Food sampling was carried out in Lutsk (Ukraine) from October to November 2024. Food samples were collected from the supermarkets "Salyut", "ATB", "Tam Tam", "Silpo", "Forta" and five local mini-markets. Food products were categorised into ten groups as shown in Table 1. From each product group, 50 samples of packaged foods from different manufacturers were randomly selected. Only food products produced in Ukraine were selected.

Table 1. *Food groups*

Food group	Foods included in the group	Number of samples
Sausages	Various types of cooked and fermented sausages	50
Bakery products	Various types of bread, loaves, buns, pita bread	50
Cookies and waffles	Various types of biscuits, waffles, crackers	50
Dairy products	Milk, butter, yogurt, kefir, fermented baked milk, sour cream, cream, ayran, milkshakes	50
Sauces and mayonnaises	Various types of mayonnaise, sauces, dressings, tomato pastes	50
Cheeses	Various types of hard, semi-hard and soft cheeses	50
Snacks	Toast, crackers, popcorn, potato chips, fruit chips, bars, peanuts, sunflower and pumpkin seeds	50
Instant food	Various types of instant noodles, pasta, soups, cereals and vegetable purées	50
Confectionery	Cakes, pastries, zefirs, marmalade	50
Ice creams	Various types of milk-based ice cream	50

Source: *developed by the authors*

For food products with multiple package sizes, only one size was included in the analysis to avoid bias (Battisti *et al.*, 2017). Duplicate food products found across the supermarkets and grocery stores were recorded only once (Ontiveros *et al.*, 2020). Information was captured via photo camera and consisted of the following (Soon, 2018): food product brand, place of manufacture, ingredients, declaration of food products

and substances that cause food allergies and intolerance (precautionary labelling statements), and special typography of allergen labelling (bold, font style, highlighted, coloured). Figure 1 showed an example of a photographed label of a confectionery product with allergen and PCI information.

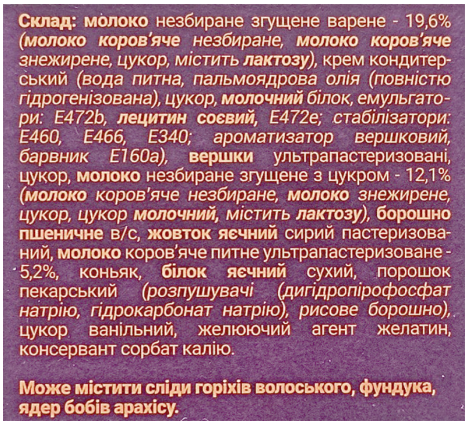

Figure 1. *Confectionery label in Ukrainian with allergens and PCIs highlighted in bold*

Note: ingredients: *condensed boiled* ***whole milk*** *– 19.6% (****whole cow's milk****, skimmed* ***cow's milk****, sugar, contains* ***lactose****), confectionery cream (water, palm kernel oil (fully hydrogenated), sugar,* ***milk*** *protein, emulsifiers: E472b,* ***soya lecithin****, E472e; stabilisers: E460, E466, E340; cream flavour, colour E160a), ultra-pasteurised* ***cream****, sugar, sweetened condensed* ***whole milk*** *– 12.1% (****whole cow's milk****, skimmed* ***cow's milk****, sugar,* ***milk sugar****, contains* ***lactose****),* ***wheat flour****, pasteurised raw* ***egg yolk****, ultra-pasteurised* ***cow's milk*** *– 5.2%, cognac, dried* ***egg white****, baking powder (raising agents (sodium dihydrogen pyrophosphate, sodium bicarbonate), rice flour), vanilla sugar, gelling agent: gelatine, preservative: potassium sorbate;* ***may contain traces of walnuts, hazelnuts, and peanuts***
Source: *developed by the authors*

Pre-packaged food products were verified for compliance with the Ukrainian regulation on food allergen labelling (Law of Ukraine No. 2639-VIII, 2018). Ukrainian legislation identified 14 substances and foods that may cause allergic reactions and intolerance in consumers (Table 2). These substances and foods must be declared to consumers on food labels. Pre-packaged foods were checked for correct labelling of food allergens and PCIs as defined by Ukrainian legislation. Taking into account the requirements of the Ukrainian legislation, the following characteristics of food labels were examined: identification of the food allergens or PCIs (using capital letters, bold letters, background colour, font style, different colours than the label, text underlining, etc.) among the other ingredients in the list of ingredients; labelling statements for allergens or PCIs with the legends "contains" or "may contain" or "may contain traces of"; number of allergens in the food product.

Table 2. *Substances and foods that cause allergic reactions or intolerance*

Substance and food number	A substance or food that causes allergic reactions or intolerance	Exclusion
F1	Cereals containing gluten (wheat, spelt, kamut, rye, barley, oats), their hybrids and grain processing products	Wheat-based glucose syrups, including dextrose; wheat-based maltodextrins; barley-based glucose syrups
F2	Crustaceans and crustacean processing products	–
F3	Eggs and processed egg products	–
F4	Fish and fish products	Fish gelatin used as a carrier for vitamins, as a clarifying agent for beer and wine
F5	Peanuts and processed peanut products	–
F6	Soybeans and soy-based products	Fully refined soybean oil and fat
F7	Milk and dairy products	Whey used in the production of alcoholic distillates
F8	Nuts (almonds, hazelnuts, walnuts, cashews, pecans, Brazil nuts, pistachios, macadamias, Queensland nuts)	Nuts for the production of alcoholic distillates
F9	Celery and celery products	–
F10	Mustard and mustard products	–
F11	Sesame seeds and sesame products	–
F12	Sulpfur dioxide and sulphites in concentrations exceeding 10 mg/kg or 10 mg/L	–
F13	Lupine seeds and processed lupine products	–
F14	Molluscs and mollusc products	–

Source: *compiled by the authors based on the Law of Ukraine No. 2639-VIII (2018)*

All food ingredient lists were checked for the presence of undeclared allergens or PCIs. Foods without allergen or PCI labelling, but containing them as ingredients were included. Only foods with allergens and PCIs were included in the analyses of compliance with the Ukrainian regulation on food allergen labelling. Methods of descriptive statistics were used, and the results were presented as percentages. The sample size of foods in each food group was calculated with a confidence probability of P = 0.95, resulting in a sample size of 50 products for each group (Marmoza, 2009).

Allergen-free foods were only included, when calculating the percentage of products with no allergens or with varying amounts of allergens and PCIs. For all other indicators, allergen-free foods were not included in the calculation (the results of such calculations were marked with). Results were displayed using Excel 2016 software.

Results and Discussion

The labels of 50 food products manufactured in Ukraine were analysed to determine whether manufacturers complied with Ukrainian legislation on allergen labelling for packaged foods. In particular, it was important to identify the most common ways of labelling allergens or PCIs. For sausages, 24% of the products contained 2 allergens or PCIs, while 18% contained 6 allergens or PCIs (Fig. 2). 12% of the sausages contained either 3 or 5 allergens or PCIs, and 2% contained 1 or 8 such allergens or PCIs. 4 and 7 food allergens or PCIs were found in 16% and 14% of the sausages, respectively.

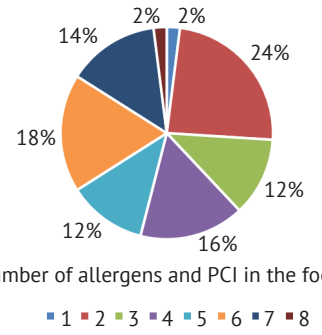

Figure 2. *Percentage of foods (sausages) containing different amounts of allergens and PCIs*
Source: *developed by the authors*

On the labels of 62% of the sausages, allergens and PCIs were listed following the phrases "contains" and "may contain traces of" (Table 3). In 44% of the sausages, allergens and PCIs appeared in the ingredient list. Manufacturers did not use the word "contains" to indicate allergens and PCIs on sausage labels. They also did not include the names of products or substances that may cause allergies or intolerances in the brand names of the sausages. In the names of sausage products, the word "sausage" was usually followed by the type of meat used to make it or the name of the town or region, where the product was traditionally made. For example, sausages may be named after the specific meat, such as "Pork sausage" or "Beef sausage", or after the geographical location, such as "Krakowska sausage" or "Lvivska sausage", reflecting the local culinary heritage.

Table 3. *Percentage of foods with different ways of indicating allergens or PCIs on the package label*

Food group	Percentage of foods in each group with different ways of indicating allergens or PCIs on the package label (%)			
	I	C	MC	P
Sausages	44.0	–	62.0	–
Bakery products	100.0	36.0	24.0	2.0
Cookies and waffles	100.0	18.0	76.0	42.0
Dairy products	100.0	–	6.0	–
Sauces and mayonnaises	83.8*	–	54.1*	–
Cheeses	100.0	6.0	12.0	–
Snacks	100.0*	–	61.4*	–
Instant food	87.0*	6.5*	76.1*	–
Confectionery	100.0*	15.2*	67.4*	–
Ice creams	100.0	–	60.0	–

Note: *I – Ingredients; C – Contains; MC – May contain or May contain traces of; P – the name of the product makes a clear reference to the allergen or PCI (milk, peanut butter, etc.); * – value excluding allergen-free products*
Source: *developed by the authors*

Allergens and PCIs were printed in bold on 100% of the sausage labels (Table 4). A combination of bold and capital letters was used to highlight allergens and PCIs on 6% of sausage labels. This helped quickly draw the buyer's attention to important information. Additionally, text underlining was used in combination with other methods to highlight allergens and PCIs on 2% of the labels. No sausages were found without allergen labelling. When indicating allergens and PCIs on sausage labels, manufacturers did not use text highlighting with colours, fonts or contrasting text backgrounds. Typically, the label featured black text on a white background. This was a classic option that offers high contrast and good readability.

Table 4. *Percentage of products with different ways of identifying food allergens or PCIs among the other ingredients in the list of ingredients*

Food group	Percentage of products with different typography of allergen labelling (%)						
	NLA	CL	BF	CLC	DBC	DLS	TA
Sausages	–	6.0	100.0	–	–	–	2.0
Bakery products	10.0	8.0	86.0	–	–	36.0	–
Cookies and waffles	–	12.0	100.0	–	–	16.0	12.0
Dairy products	–	–	94.0	–	2.0	20.0	–
Sauces and mayonnaises	–	–	100.0*	–	–	–	–
Cheeses	22.0	16.0	74.0	–	–	–	12.0
Snacks	–	–	84.1*	–	–	22.7*	9.1*
Instant food	–	28.3*	87.0*	–	–	2.2*	–
Confectionery	–	10.9*	89.1*	39.1*	–	–	–
Ice creams	8.0	4.0	92.0	8.0	–	8.0	4.0

Note: *NLA – non-labelled allergens and PCI; CL – capital letters; BL – bold font; CLC – contrasting letter colours; DBC – different background colours; DLS – different letter styles; TA – text underlining; * – value excluding allergen-free products*

Source: *developed by the authors*

The labels of 90% of the sausages (Table 5) indicated that the products contained milk or its derivatives (e.g. milk powder, cream powder, whey). 70% of sausage labels stated that the products may contain traces of gluten and mustard. 68% of the labels noted that the products contain or may contain traces of egg products (e.g. egg melange). Soy-based products (mainly hydrolysed soy protein) were mentioned on the labels of 64% of sausages. The possible presence of traces of nuts and celery was mentioned on 22% and 48% of labels, respectively. About 2% of labels stated that the products contain or may contain (may contain traces of) peanuts, sesame seeds and sulphites. Traditional sausage products for Ukrainian consumers usually do not contain fish or seafood in their recipes. As a result, these ingredients were generally not listed on the labels of sausage products from Ukrainian producers. This reflected the traditional preferences and culinary practices in Ukraine, where sausages were primarily made from meats such as pork, beef, or poultry, rather than seafood.

Table 5. *Percentage of foods containing different substances and ingredients that cause allergic reactions or intolerance*

Percentage of foods containing different substances and ingredients (%)	F14	–	–	–	–	–	–	–	–	–	–
	F13	–	6.0	4.0	–	–	–	–	–	–	–
	F12	2.0	–	26.0	–	–	–	6.8*	–	4.3*	-
	F11	2.0	24.0	48.0	–	10.8*	–	6.8*	28.3*	–	40.0
	F10	70.0	20.0	2.0	–	78.4*	–	13.6*	10.9*	–	–
	F9	48.0	8.0	2.0	–	2.7*	2.0	4.5*	26.1*	–	–
	F8	22.0	10.0	32.0	6.0	2.7*	12.0	31.8*	34.8*	6.5*	76.0
	F7	90.0	40.0	80.0	100.0	54.1*	100.0	56.8*	63.0*	71.7*	100.0
	F6	64.0	36.0	82.0	8.0	24.3*	–	63.6*	39.1*	15.2*	84.0
	F5	2.0	10.0	70.0	4.0	5.4*	–	54.5*	23.9*	6.5*	64.0
	F4	–	–	–	–	–	–	4.5*	–	–	–
	F3	68.0	26.0	52.0	4.0	59.5*	–	20.5*	17.4*	91.3*	52.0
	F2	–	–	–	–	–	–	4.5*	–	–	–
	F1	70.0	100.0	100.0	4.0	18.9*	–	70.5*	93.5*	76.1*	72.0
Food group		Sausages	Bakery products	Cookies and waffles	Dairy products	Sauces and mayonnaises	Cheeses	Snacks	Instant food	Confectionery	Ice cream

Note: *F1…F14 – substances and foods that cause allergic reactions or intolerance, as indicated in Table 2; * – value excluding allergen-free products*

Source: *developed by the authors*

About 42% of the analysed bakery products contained an allergen or PCI (Fig. 3). These products were mainly traditional wheat or rye bread. 2 allergens or PCIs were found in 12% of the bakery products, while 3

allergens or PCIs were present in 24%. Additionally, 8% of the products contained 4 allergens or PCIs, and 5% contained 5 allergens or PCIs. 4% of bakery products contained 6, 9, or 10 allergens or PCIs in their composition. A high number of allergens was characteristic of bakery products containing whole seeds and nuts. On the labels of 100% of the bakery products, allergens and PCIs were listed in the ingredient composition (Table 3), while on the labels of 10% of the products, allergens and PCIs were not highlighted in any way (Table 4). Before mentioning the allergen or PCI, 36% of the bakery product labels included the legend "contains", while 24% contained the phrase "may contain" (Table 3). In these cases, the most common labels were "contains gluten" or "may contain traces of mustard oil, dairy products". In 2% of the products, the name itself referred directly to the allergen or PCI (e.g., the product name "Sesame Burger Bun"). In the vast majority of bakery product labels (86%), allergens and PCIs were highlighted in bold in the product composition (Table 4). For 36% of bakery products, allergens and PCIs were indicated using bold, capital letters combined with a different font style. Only capital letters were used to indicate allergens and PCIs on the labels of 8% of the products. No bakery products had allergens or PCIs labeled in colour or with a different background.

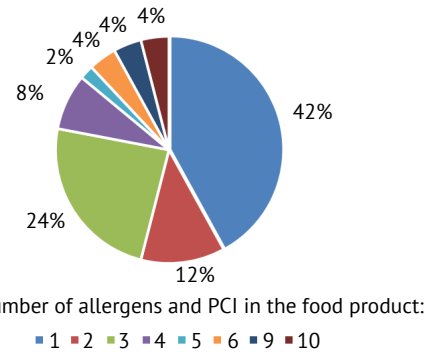

Figure 3. *Percentage of foods (bakery products) containing different amounts of allergens and PCIs*
Source: *developed by the authors*

All bakery products (100%) contained processed cereal products (Table 5), specifically wheat and rye flour, which include gluten. 40% of the products contained milk or dairy products, while 26% contained eggs or egg products. 36% of bakery products were labelled with soy-based products (mainly soy lecithin). About 20% of bakery products contained traces of mustard oil, and 24% contained sesame seeds. 10% of bakery products contained peanuts and tree nuts. Additionally, bakery products may contain traces of celery and lupine, which were labelled in 8% and 6% of products, respectively. When examining the cookie and waffle labels, it was found that 46% of the products contained 6 allergens or PCIs, while 22% contained 4 allergens or PCIs (Fig. 4).

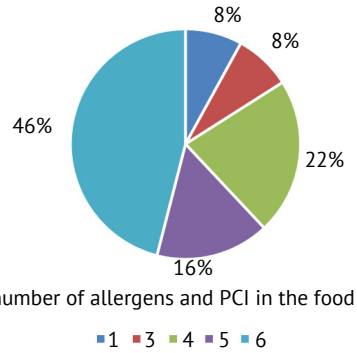

Figure 4. *Percentage of foods (cookies and waffles) containing different amounts of allergens and PCIs*
Source: *developed by the authors*

Additionally, 16% of the cookies and waffles contained 5 allergens or PCIs, and 8% contained 1 or 3 allergens. All cookie and waffle labels (100%) listed allergens and PCIs in the product composition (Table 3). However, in most cases (76%), the allergen or PCI was preceded by the phrases "may contain" or "may contain traces of". About 18% of cookie and waffle labels featured the legend "contains" before the allergen or PCI. In 42% of products, the name of the ingredient clearly indicated a specific substance or food product that was an allergen or caused intolerance (e.g., cow's milk). All labels (100%) of cookies and waffles presented allergens and PCIs in bold (Table 4). On the labels of 12% of the products, bold text was combined with capital letters, while on 16% of the packaged cookies and waffles, bold text was combined with a text style change for ingredients that are allergens or PCIs. For some products (12%), allergens and PCIs were not only highlighted in bold and with a text style change, but also underlined.

All cookies and waffles (100%) contained processed cereal products (Table 5), including wheat and oat flour, both of which contain gluten. 82% of the cookie and waffle labels reported the presence of processed soybean products (soy lecithin). Additionally, 80% of this product group contained cow's milk or its processed products (whey, etc.). A significant percentage of products (70%) contained peanuts or their derivatives. About 52% of the cookies and waffles contained eggs or processed egg products. The presence of sesame seeds, sesame products, or traces of sesame was mentioned on 48% of the labels. In addition, 32% of the products in this group contained nuts (unspecified type) or traces of nuts. Sulphur dioxide and sulphites, used as preservatives, were found in 26% of the products, as indicated on the labels. Some individual products in this group were labelled as containing traces of lupine (4%), celery (2%), and mustard (2%). About 90% of dairy products listed a single ingredient (cow's milk) on the label, the protein of which can cause allergy and the milk sugar (lactose) of which can cause intolerance (Fig. 5).

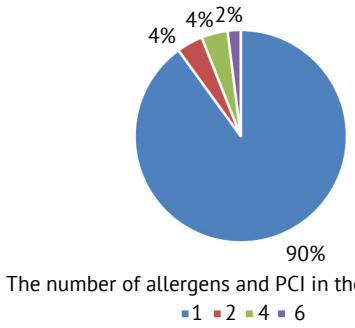

Figure 5. *Percentage of foods (dairy products) containing different amounts of allergens and PCIs*
Source: *developed by the authors*

4% of dairy products contained 2 allergens or PCIs, and a further 4% contained 4 allergens or PCIs. Additionally, 2% of products in this group contained 6 allergens or PCIs. Allergens and PCIs were listed in the product composition on the labels of all dairy products and beverages analysed (100%) (Table 3). Individual allergens or PCIs in the product composition were listed after the phrase "may contain" on the labels of 6% of the products. On the labels of dairy products, allergens and PCIs were mainly presented in bold (94% of products) (Table 4). However, some labels combined bold text with a different font style (20% of products) and a different background colour for the text (2% of products).

About 100% of dairy products contained milk or its processed derivatives (Table 5). About 8% of dairy products listed soybean products as ingredients. In this product group, 6% of products listed nuts or traces of nuts (mostly without specifying the type of nuts). Dairy products also included cereal products (4%), egg products (4%), and peanuts (4%) (e.g., yogurt with crunchy balls). In the sauce and mayonnaise group, 22% of products contained 1 allergen or PCI, 20% contained 3 allergens or PCIs, and 16% contained 2 allergens or PCIs (Fig. 6).

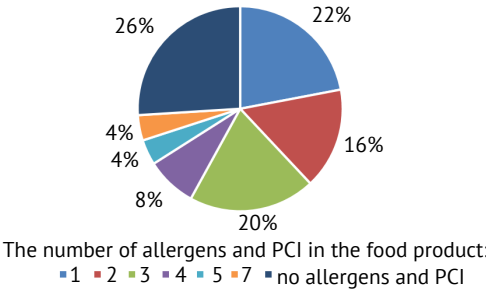

Figure 6. *Percentage of foods (sauces and mayonnaises) containing different amounts of allergens and PCIs*
Source: *developed by the authors*

4 allergens or PCIs were listed on the labels of 8% of the products in this group. 5 allergens or PCIs were listed in the composition of 4% of sauces and mayonnaises, and the same percentage of products in this group contained 7 allergens or PCIs. However, 26% of the analysed products in this group contained no allergens or PCIs. These products were tomato sauces and ketchup. On the labels of sauces and mayonnaises that contained allergens and PCIs, they were mostly (83.8%) listed in the product composition (Table 3). However, on the labels of 54.1% of the products, allergens and PCIs were listed after the phrases "may contain" or "may contain traces of". In all sauces and mayonnaises containing allergens and PCIs, these were only highlighted in bold (Table 4).

The vast majority of sauces and mayonnaises (78.4%) contained mustard or its processed mustard products (Table 5). In addition, 59.5% of the analysed products in this group (mainly mayonnaises) contained eggs or egg products (e.g., egg powder), as stated on the label. Dairy products or the possibility of their traces were listed on the labels of 54.1% of the products. Soy products or soybeans were included in the composition of 24.3% of mayonnaise and sauces. Cereal products containing gluten were listed in the composition of 18.9% of sauces and mayonnaises, following the phrase "may contain traces of". Additionally, sauces and mayonnaises could contain traces of sesame (10.8%), peanuts (5.4%), nuts (2.7%), and celery (2.7%), as indicated on the label.

The cheeses analysed mostly contained 1 allergen or PCI (86% of products) (Fig. 7). Only 14% of the cheeses contained 2 allergens or PCIs. No cheese analysed contained more than 2 allergens or PCIs. Allergens and PCIs were listed in the product composition on the label of all cheeses (Table 3). On 6% of the cheese labels, the allergens or PCIs were listed after the legend "contains". Allergens and PCIs were listed after the phrases "may contain" and "may contain traces of" on the labels of 12% of the cheeses analysed. Allergens and PCIs were mostly highlighted in bold on cheese labels (74% of products) (Table 4), or in a combination of bold and capital letters (4% of products). Allergens and PCIs were only highlighted in capital letters on 12% of the product labels. A combination of bold and underlined text was used to highlight allergens and PCIs on 12% of cheese labels. On the labels of 22% of cheeses, none or some allergens and PCIs were highlighted. In particular, on the labels of some cheeses, whole cow's milk, skimmed milk, and milk powder were not highlighted in the product composition.

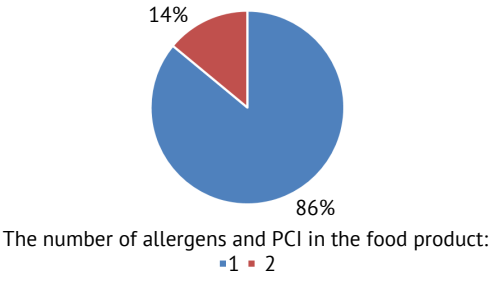

Figure 7. *Percentage of foods (cheeses) containing different amounts of allergens and PCIs*
Source: *developed by the authors*

All the cheeses analysed (100%) contained milk or milk products (Table 5). The labels of 12% of the cheeses mentioned the presence of nuts (without specifying the type) or the possibility of their traces in the product composition. In addition, 2% of the products contained traces of celery, as indicated on the label. Among snacks, the largest number of products (24%) contained 4 allergens and PCIs (Fig. 8).

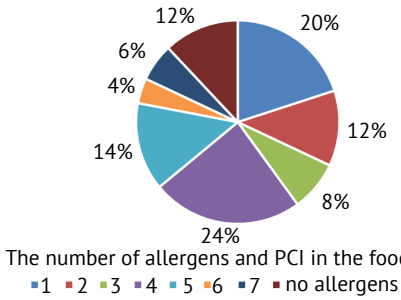

Figure 8. *Percentage of foods (snacks) containing different amounts of allergens and PCIs*
Source: *developed by the authors*

Approximately 20% of snacks contained 1 allergen and PCI, while 14% contained 5 allergens and PCIs. A smaller number of analysed snacks contained the following: 12% contained 2 allergens and PCIs, 8% contained 3 allergens and PCIs, 4% contained 6 allergens and PCIs, and 6% contained 7 allergens and PCIs. Additionally, 12% of snack products contained no allergens; these included sunflower and pumpkin seeds and dried fruit chips. The labels of all the analysed snacks (Table 3) that contained allergens and PCIs reported the presence of these substances in the product. Additionally, on 61.4% of the snack labels, the presence of allergens and PCIs was indicated after the phrases "may contain" and "may contain traces of". On the vast majority of snack labels (84.1%), allergens and PCIs were highlighted in bold (Table 4). On 22.7% of snack packages, allergens and PCIs were highlighted using a different text style, and on 6.8% of packages, a different text style was combined with bold. The labels of 9.1% of products combined bold or another style with underlined text. There were also products, where allergens and PCIs were highlighted using underlined text only.

The analysed snack products contained almost all allergens and PCIs defined by the legislation of Ukraine, except for lupine and molluscs (Table 5). The largest proportion of snacks (70.5%) contained cereal products containing gluten (rye and wheat flour). Soybean products (e.g., hydrolysed soy protein, soy lecithin) were found in 63.6% of the snacks, as indicated in the ingredients list or following the phrase "may contain". In most cases, the label simply indicated "soy product". Additionally, 56.8% of snacks contained dairy products (e.g., whey powder, cheese powder, milk protein). A significant number of snacks (54.5%) also contained peanuts or peanut paste, or the label mentioned the possibility of peanut traces. Furthermore, 31.8% of snacks contained nuts or indicated the possibility of their traces, often without specifying the type. Egg products (e.g., egg powder) were listed on the labels of 20.5% of snacks. Additionally, some labels included the statement, "The product may contain a small amount of egg protein". Snack labels also informed consumers about the content, possible content in small amounts, and traces of the following allergens or PCIs: mustard (13.6%), sesame (6.8%), crustacean products (4.5%), fish products (4.5%), celery (4.5%), and sulphur dioxide without indication of concentration (6.8%). From 1 to 7 allergens and PCIs were identified in instant foods (Fig. 9).

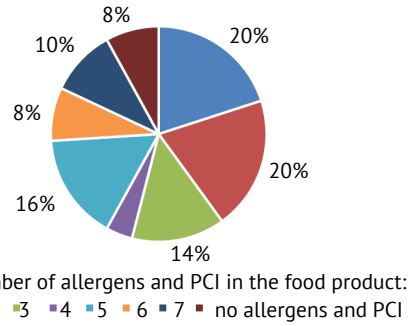

Figure 9. *Percentage of foods (instant food) containing different amounts of allergens and PCIs*
Source: *developed by the authors*

20% of the products in this group contained 1 allergen or PCI, while the same percentage contained 2 allergens or PCIs. 7 allergens and PCIs were found in 10% of the products in this group. No allergens were found in 8% of the analysed instant foods, which were instant soups in briquettes, particularly those with rice and dried vegetables. In most cases (87% of products), allergens and PCIs were listed in the product composition on the labels of instant foods (Table 3). Additionally, allergens and PCIs were mainly listed after the phrases "may contain" and "may contain traces of" in 76.1% of product labels. Only 6.5% of instant food labels listed allergens after the word "contains". Allergens and PCIs were mainly highlighted in bold in 87% of product labels (Table 4). Capital letters were used to highlight allergens and PCIs in 28.3% of products, and another style of text was used in 2.2% of products. Furthermore, on 19.6% of instant food labels, capital letters were combined with bold text.

The vast majority of the analysed instant foods (93.5%) contained processed cereal products (Table 5) containing gluten (e.g., wheat flour). These products included, among others, instant pasta and noodles, soups with croutons, and mixtures of cereals from various grains. Dairy products were listed as an ingredient in 63% of the products, with most stating, "the product may contain a small amount of dairy products". Products such as instant mashed potatoes contained cream powder and milk powder. The labels of instant foods

often included the following information: may contain egg products (17.4%), mustard (10.9%), sesame (28.3%), nuts (34.8%), soy (39.1%), peanuts (23.9%), and traces of celery (26.1%). In some products (e.g., muesli), nuts, peanuts, and sesame were included in the recipe. The highest number of allergens and PCIs listed on a confectionery label was 5 (Fig. 10).

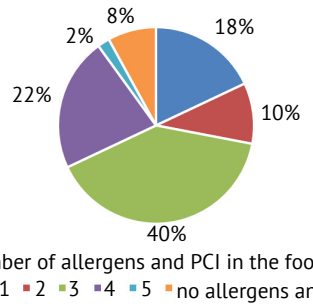

Figure 10. *Percentage of foods (confectionery) containing different amounts of allergens and PCIs*
Source: *developed by the authors*

3 allergens or PCIs were listed on the labels of 40% of the products analysed in this group. 4 allergens or PCIs were listed in 22% of the confectionery products. 1 and 2 allergens or PCIs were listed in 18% and 10% of the products, respectively. No allergens or PCIs were listed in 8% of the confectionery products, mainly craft zefirs and marmalade. All allergens and PCIs were listed in the product composition on the labels of confectionery products. In addition, on the labels of 67.4% of confectionery products, allergens and PCIs were listed after the phrases "may contain" and "may contain traces of", while on the labels of 15.2% of products, they were listed after the word "contains" (Table 3). Allergens and PCIs were highlighted in bold on the labels of 89.1% of confectionery products, and in capital letters on the labels of 10.9% of products (Table 4). On the labels of 39.1% of products, allergens and PCIs were also highlighted in a colour different from the main text.

The most common ingredient used in the recipe of confectionery products that may cause allergic reactions was eggs or their processed products (mainly dried egg white). Eggs or egg-based products were included in the composition of 91.3% of the confectionery products (Table 5). In addition, 76.1% of the confectionery products (e.g. cakes, pastries) contained processed cereal products containing gluten (e.g., wheat flour). Milk and dairy products (butter, milk protein, skimmed milk powder, whey powder, cream, sour cream) were listed in 71.7% of the confectionery products. A soy product (soy lecithin) was listed in 15.2% of the confectionery products. Confectionery products also contained peanuts (6.5%) and nuts (6.5%). Sulphur dioxide was listed on the labels of 4.3% of confectionery products without specifying the concentration, mainly in the composition of semi-finished products (e.g., apple puree). The ice cream products analysed contained between 2 and 5 allergens or PCIs (Fig. 11).

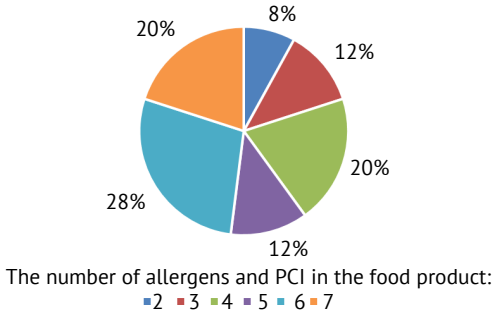

Figure 11. *Percentage of foods (ice cream) containing different amounts of allergens and PCIs*
Source: *developed by the authors*

28% of the ice creams contained 6 allergens or PCIs. 20% contained 4 or 7 allergens or PCIs, and 12% of the products in this group contained 3 or 5 allergens. Only 8% of the ice creams contained 2 allergens or PCIs. All allergens and PCIs were listed in the product composition on the ice cream labels (Table 3), and 60% of the products included the phrase "may contain" before the allergens. In most cases (92%), allergens and PCIs were highlighted in bold on the labels (Table 4). In addition, bold text was combined with capital letters on 4% of labels, and bold text was combined with another text style on 8% of labels. Allergens and PCIs were also highlighted by a combination of bold and underlined text on 4% of ice cream packs. A combination of bold text and a different shade of colour was used to highlight allergens and PCIs on 8% of ice cream packs. However, not all allergens and PCIs specified by Ukrainian legislation were highlighted on 8% of ice cream labels.

All the analysed ice creams contained milk or its processed products in their recipe (Table 5). The most frequently mentioned ingredients were cow's milk, skimmed milk powder, whey powder, butter, condensed milk with sugar, and milk protein. Soy lecithin was listed in the composition of 84% of ice creams. 76% of ice creams contained nuts, or it was stated that the product may contain nuts or their processed products. The most common nuts listed in ice cream were almonds, hazelnuts, walnuts, cashews, pistachios, and pistachio paste. Peanuts were included in the recipe of 64% of ice creams, either as a separate ingredient or with an indication that the product may contain them. About 72% of ice creams listed processed cereal products containing gluten. Wheat flour was used in ice cream recipes to make waffle cups, cones or plates into which ice cream was placed. Eggs and their derivatives, which were listed in the recipes of 52% of the ice creams, were also used to make waffle cups, cones or plates. Sesame seeds were listed on the labels of 40% of ice creams.

As noted by J. Muthukumar *et al*. (2020), public understanding of the potential consequences of consuming pre-packaged foods that trigger allergic reactions and intolerances remained limited. Therefore, consumer awareness of these consequences should be widely promoted. As proposed by S. Sansweet *et al*. (2024), an important component of reducing the risk of allergic reactions was educating all segments of the community, particularly in schools, so that individuals were aware of food allergen management issues and know, how to find the necessary allergen information on labels. It was also important to educate consumers of all ages about allergy prevention guidelines, food allergy diagnosing, and treating (Sampath *et al.*, 2021). F. Chang *et al*. (2023) recommended that individuals with food allergies pay close attention to the information on food labels, especially if it was unclear or ambiguous, and take precautions in places, where food was not labelled (e.g., restaurants, bars, airplanes, ships, and private gatherings).

Most of the analysed pre-packaged foods produced in Ukraine contained allergen and PCI labels on the packaging. Only 8.0% to 26.0% of products in the sauces, snacks, instant food, and confectionery categories did not include allergens or PCIs. Indicating allergens and PCIs on product packaging is an obligation of manufacturers in accordance with the requirements of Ukrainian legislation. As noted by B. Popping & C. Diaz-Amigo (2019), mandatory labelling of food allergens allowed consumers suffering from them to make informed choices. M.C. Lopez (2018) noted that most countries, including Ukraine, that regulate the declaration of allergens in pre-packaged foods used the list of allergens recommended by the Codex Alimentarius. International food standards (2025). Some countries have added other allergens or PCIs to this list based on statistical data on the causes of allergic reactions or product intolerance.

From 8% to 22% of the analysed products did not list allergens on the label, although they were present in the product composition. According to research by M.L. Cunha *et al*. (2020), 12.13% of the analysed foods in Brazil did not include the allergy alert. In the study, conducted in Lutsk (Ukraine), the highest proportions of such products were in the cheese category (22%) and milk-based ice creams (10%). This may be because manufacturers believed that consumers were aware that these products were made from milk or milk ingredients, and that the name of the product clearly refers to a specific substance or food item that was an allergen or causes intolerance.

According to research by N.B. Soogali & J.M. Soon (2018), most consumers believed that allergens should be highlighted in the ingredient list (e.g. in bold). This requirement was also included in the Ukrainian legislation. S. Doğan *et al*. (2023) found that consumers believed that allergy food labels would be more noticeable if symbols or bold text or both were used for labelling. The results of the analysis of pre-packaged foods showed that Ukrainian manufacturers highlighted allergens and PCIs on labels, mainly in bold (74-100% of products, depending on the food group). As noted by J. Choi & A. Choi (2016), consumers were also concerned about the font size of allergen information. They indicated that the font size should differentiate the food allergen information from the general nutrition information, which would improve PAL recognition. The study found that 4.0-28.3% of labels on Ukrainian products highlighted allergens and PCIs in a large font.

According to R. Baker (2018), such information on food labels made it difficult for consumers to distinguish between foods that pose a risk and those that do not. The use of PAL on food labels should be justified. Therefore, it was important that manufacturers assess the level of any unintended allergens present in their product and only use PAL, if the allergen level exceeds an agreed threshold (DunnGalvin *et al.*, 2019).

K.J. Allen *et al*. (2014) noted that PAL could be classified into 3 broad categories: "may contain", "produced on shared equipment" and "made in the same factory as". The statement "may contain traces of allergen(s)" was most common (Ontiveros *et al.*, 2020). This was also confirmed by the study by W.M. Blom *et al*. (2021), which found that for labels with a PAL, the most commonly used statement was "may contain traces of", with an overall score of 76%. H. Chafei *et al*. (2023) found that 42.9% of supermarket food products carried the precautionary allergen labelling "may contain traces of allergens". For the products of the analysed food groups of the Ukrainian manufacturers, such a PAL can be found on the labels of 6.0-76.1% of the products. At the same time, as noted by C.A. Marra *et al*. (2017), the use of precautionary statements, such as "may contain traces of peanuts", were the less important allergen-labelling attributes for consumers compared to the use of safety symbols and a safety statement (e.g., "does not contain soy, eggs or fish"). However, C.G. Mortz *et al*. (2024) noted that products labelled "may contain" do not provide consumers with information on whether the contamination was below their threshold for the specific allergen. Therefore, allergen labelling must be accurate and based on knowledge of threshold values for humans. Since lactose-containing products can also often cause allergies or intolerance that negatively affect the human body, ways to produce lactose-free products have long been studied. O. Shydlovska & A. Koiba (2023) noted that the production of lactose-free products was carried out using appropriate enzymes that help break down lactose. Accordingly, such products were easier to identify on store shelves.

According to a study by E. Mfueni *et al*. (2018), approximately 54.3% of food products carried a special allergen declaration in addition to the declaration in the list of ingredients. The analysis of food groups showed that most Ukrainian manufacturers, in addition to listing allergens or PCIs in the ingredient

list, also included them in a separate list following the word "contains" (6-36%).

The language, in which allergen information appeared on the labels of foods produced in different countries can be confusing to consumers, especially, if there wasn't translation of the label or if the translation is inaccurate. The labels analysed provided information on food composition and allergen content in Ukrainian. On some labels, this information was available in both English and Ukrainian. D. Seth *et al*. (2020) stated that the most common food allergens were eggs, milk, peanuts, tree nuts, soy, wheat, crustacean shellfish, and fish. In the food groups analysed, the most frequently detected allergens were products from processed cereals (gluten), eggs, milk, soy, peanuts and nuts.

This studies confirmed that the vast majority of Ukrainian food manufacturers comply with the requirements of Ukrainian law regarding the labelling of allergens and PCIs in food products. It used a variety of methods to indicate allergens and substances that may cause intolerance on the labels of packaged foods. This allergen labelling was in line with best practice in EU countries.

Conclusions

An evaluation of the characteristics of food allergen labelling in commercially available pre-packaged foods produced in Ukraine showed that manufacturers mostly comply with the requirements of Ukrainian legislation on allergen labelling. However, 22% of products in the cheese group, 10% of products in the bakery group, and 8% of products in the milk-based ice cream group were found to be lacking proper allergen or PCI labelling. This is probably due to the fact that the names of these products include an ingredient that is an allergen or PCI. In such cases, Ukrainian legislation allowed for allergens or PCIs not to be additionally indicated on the label. Food manufacturers prefered to highlight allergens or PCIs in the list of ingredients in bold, preferably black, as this meets the requirements of the legislation. Aware of the possibility of food cross-contamination with allergens or PCIs throughout the supply chain, including at primary production, during manufacturing, and at retail and food service endpoints, manufacturers additionally indicate allergens or PCIs that were not contained in the recipe on the labels using the phrases "may contain" or "may contain traces of". In this case, manufacturers typically indicated that the food product may contain traces of milk, eggs, nuts, peanuts, wheat (gluten), and soy.

Further research should focus on defining clear, acceptable levels of allergen content (thresholds) below which the risk of allergic reactions is minimised. It is also important to develop recommendations for indicating such levels for each allergen on labels, enabling consumers with allergies or intolerances to determine whether the product is safe for them.

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Маркування алергенів та харчових продуктів, що викликають непереносимість, в Україні

Ігор Дударєв

Доктор технічних наук, професор
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-2016-5342

Ростислав Кухар

Викладач
Любешівський технічний фаховий коледж
44201, вул. Брестська, 7, м. Любешів, Україна
https://orcid.org/0009-0005-0952-1421

Анотація. Кількість споживачів із харчовими алергіями або непереносимістю швидко зростає у всьому світі. Законодавство багатьох країн, зокрема України, визначає перелік речовин і продуктів, що спричиняють алергічні реакції або непереносимість. Воно також встановлює вимоги до маркування алергенів на упаковках харчових продуктів, яких виробники повинні дотримуватись. Метою цього дослідження було визначити, як виробники харчових продуктів в Україні зазначають наявність речовин та інгредієнтів, що можуть викликати алергічні реакції та непереносимість, і чи відповідає таке маркування вимогам українського законодавства. Для аналізу маркування харчові продукти було згруповано у 10 категорій: ковбасні вироби, хлібобулочні вироби, печиво та вафлі, молочні продукти, соуси та майонези, сири, снеки, продукти швидкого приготування, кондитерські вироби та морозиво. Дослідження проводилося шляхом аналізу маркування харчових продуктів із місцевих супермаркетів у м. Луцьк, Україна. Було виявлено, що більшість проаналізованих продуктів містили алергени або інгредієнти, що спричиняють непереносимість. У різних категоріях від 8 % до 22 % харчових продуктів не мали належного позначення алергенів на етикетках, хоча вони були присутні. Українські виробники здебільшого використовували напівжирний шрифт для виділення речовин та інгредієнтів, що можуть викликати алергію або непереносимість (74,0-100,0 % продуктів). Лише 4,0-28,3 % етикеток продуктів використовували великі літери для виділення цих речовин та інгредієнтів. Виділення тексту кольором, стилем, фоном і підкресленням зустрічалося значно рідше і найчастіше поєднувалося з напівжирним шрифтом. Терміни «містить» і «може містити сліди» зустрічалися на етикетках 6,0-36,0 % і 6,0-76,1 % продуктів відповідно. Найпоширенішими інгредієнтами на етикетках аналізованих харчових продуктів були перероблені злакові продукти, що містять глютен, яйця, молоко або молочні продукти, перероблена соя, арахіс та горіхи. Результати аналізу показали, що українські виробники загалом дотримуються вимог українського законодавства щодо маркування речовин або інгредієнтів у харчових продуктах, які можуть спричиняти алергічні реакції або непереносимість

Ключові слова: алергія; захист споживачів; вимоги до маркування; розкриття інформації про інгредієнти; регуляторні стандарти

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Adaptive method of designing a swimsuit bra

Alla Slavinska

Doctor of Technical Sciences, Professor
Khmelnytsky National University
29016, 11 Institutska Str., Khmelnytsky, Ukraine
https://orcid.org/0000-0003-0663-9422

Serhii Matiukh

PhD in Technical Sciences, Associate Professor
Khmelnitsky National University
29016, 11 Institutska Str., Khmelnitsky, Ukraine
https://orcid.org/0000-0001-9899-109X

Viktoriia Mytsa*

PhD in Technical Sciences, Associate Professor
Khmelnitsky National University
29016, 11 Institutska Str., Khmelnitsky, Ukraine
https://orcid.org/0000-0002-5453-9787

Oksana Dombrovska

PhD in Technical Sciences, Associate Professor
Khmelnitsky National University
29016, 11 Institutska Str., Khmelnitsky, Ukraine
https://orcid.org/0000-0001-6086-5784

Oksana Syrotenko

PhD in Technical Sciences, Associate Professor
Khmelnitsky National University
29016, 11 Institutska Str., Khmelnitsky, Ukraine
https://orcid.org/0000-0002-6816-6467

Abstract. The relevance of the research lies in the need to develop accurate and effective methods for designing swimwear bras, considering the elastic properties of modern knitted fabrics, which will enhance the comfort and quality of the products. The purpose of the study was to develop a method of adjusting the size of the bra cup to the amount of stretching using the method of geodetic parallels. The study employed methods of mathematical modelling for the development and optimisation of swimsuit bra cups design and analysed the mechanical properties of knitted materials. The study identified representative groups of elastic knitted fabrics based on the analysis of their tensile characteristics. Two primary groups of fabrics were identified based on their fibrous composition: the first group consisted of polyamide threads blended with elastane, while the second group comprised polyester threads combined with elastane. Anthropomorphic factors affecting the inaccuracies in the unfolding of the hard surface of the cup have been identified. Recommendations have been developed for transforming the rigid unfolding into a soft shell of moulded cup parts, considering discrete elongations of knitted materials. The soft-shell construction method was based on recalculating the main dimensions of the cup, taking into account the deformation coefficients of the materials. The effectiveness of the proposed method was confirmed by comparing the deviation

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*Corresponding author

areas of the moulded cup sweeps of the basic design. The deviation of the area of 3.56% indicated the compliance of the rigid sweep with the breast surface. Mathematical models of modification methods for four types of bra cup separation have been developed. The practical value lies in the use of an effective method of designing swimwear bras that ensures precise fit and comfort by considering the elastic properties of knitted materials

Keywords: knitted fabric; bathing suit; fibrous composition; tensile characteristics; cup articulation; modification methods

Introduction

Modern trends in consumer behaviour and the high competition in the swimwear market require new approaches to traditional design technologies that consider the relationship between the consumer's body shape and the corresponding bra model. The development of swimwear bras is a challenging task due to the wide variety of materials used and the structural requirements for the parts, which must provide comfort, support, and enhance the aesthetic appearance of the body. The trend of using object dimensional control methods discussed in the study by Y. Tian & R. Ball (2020) expanded the possibilities for accurately reproducing the top part of the bra based on a moulded cup proposed by Z. Zhong *et al.* (2023). A strong correlation between the dimensional features of the cup and the product size, according to Y. Zhao (2024), allowed the use of a measuring bra to create a three-dimensional geometric model and simulate the material properties.

A promising area for creating a rigid shell of a moulded cup was the use of adaptive 3D printing technology, which was based on the principle of layer-by-layer growth of a solid object (Polishchuk *et al.*, 2023). The study by M. Riabchykov *et al.* (2023) proved that the use of 3D body scanning allowed creating accurate digital copies of the body, which significantly improved the process of developing clothing, ensuring accurate consideration of anatomical features.

The widespread use of three-dimensional scanning to build three-dimensional clothing was analysed in the study by H. Xie & Y. Zhong (2019). Replacing the contact measurement with scanning simplified the technology of virtual reproduction of the body surface by introducing it into the mesh frame. A plausible model for predicting and controlling the levels of clothing fit based on neural networks with the definition of tolerances in clothing for pressure parameters and mechanical properties of fabrics measured in a 3D-virtual environment were considered in the study Z. Wang *et al.* (2021). The model predicted the quality of free and tight fit from the position of the silhouette. However, the comparison with classical models of linear regression and reference vectors was not persuasive.

3D models of women's swimsuits were used as a database to illustrate the effectiveness of a clothing design system based on the interactive genetic algorithm (IGA) and the fuzzy clustering method (FCM) in the study by T. Zarezade & P. Payvandy (2019). The application of the FCM method simplified the sorting of the model range by comparing the similarity of compositional features according to style decisions, however, the modelling effect of shaping body parts significantly depends on both the design and the materials, as proven by A. Slavinska *et al.* (2020).

The comfort of a swimsuit required specific materials due to being in both the water environment and outdoors. The social determination of the attributes of using a swimsuit also affected gender differences in women's attitudes towards the uniqueness of swimsuit items both in material and design. The purpose of this study was to develop a method for adjusting the size of a bra cup to the amount of stretch using the geodesic parallel method.

Materials and Methods

For experimental studies of the fibrous composition of knitted fabrics for bathing suits, 300 samples from well-known manufacturers have been analysed. Two groups of ratios of fibrous composition of cloth were revealed: Group 1 was the combination of polyamide threads of RA with elastane EA (86%); Group 2 was the combination of PE polyester yarns with EA elastane (14%). Fibrous composition of RA 80 ± 5; EA 20 ± 5 occupied 36.4% of the sample. Type of weave and surface density in the ratio groups were given in Table 1.

Table 1. *Structural characteristics of knitted fabrics for bathing suits*

Type of weave		Surface density, g/m²						Total frequency of occurrence of weaves	
		155 ± 5	165 ± 5	175 ± 5	185 ± 5	195 ± 5	205 ± 5	pcs.	%
rib knit fabric		0	0	0	8	47	43	98	32.7
interlock stitch structure		8	33	90	49	8	0	188	62.6
others		2	3	6	3	0	0	4	4.7
total surface density	pc.	10	36	96	60	55	43	300	-
	%	3.3	12	32	20	18.4	14.3	-	100

Source: *developed by the authors*

The weight distribution of different weave types within the fabric groups, categorised by surface density, was illustrated in Figure 1. This graph highlighted the predominance of the interlock stitch structure across the tested samples, which constituted 62.6% of the total fabrics. Rib knit fabrics made up 32.7%, while other less common weaves account for only 4.7%. The figure clearly demonstrated that fabrics with interlock stitch structure dominate in surface densities ranging from 165 g/m² to 185 g/m², indicating their prevalence in materials designed for swimwear applications. In contrast, rib knit fabrics were primarily concentrated in the higher density range of 195 g/m² to 205 g/m², which may be attributed to their increased durability and structural stability.

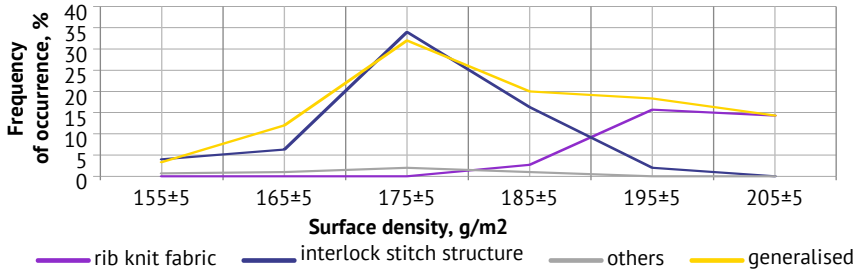


Figure 1. *Graph of the distribution of the type of weave in the structural characteristics of a knitted fabric*
Source: *developed by the authors*

Statistical characteristics of the distribution curve: arithmetic value = 175.5 g/m²; standard deviation S = 8.81; Pearson coefficient χ^2 = 3.78; the asymmetry coefficient γ_1 = 1.13, and the coefficient of variation γ_2 = 1.43 determined the choice of the base fabric for standard studies of the physiological properties of the swimsuit bra (DSTU 2319-93, 1995). This is a knitted fabric with a weave of interlock stitch structure and a surface density of 175.5 g/m²; fibrous composition – PA 80 EA 20; number of looped columns – 230 (horizontally), 270 (vertically); height looped step – 0.43, height looped row – 0.43; thread length in the loop – 1.93 mm. The classification features of a bathing suit are the completeness of the items, the established names of the swimsuits, the construction of the bra, the presence of divisions in the details (Fig. 2).

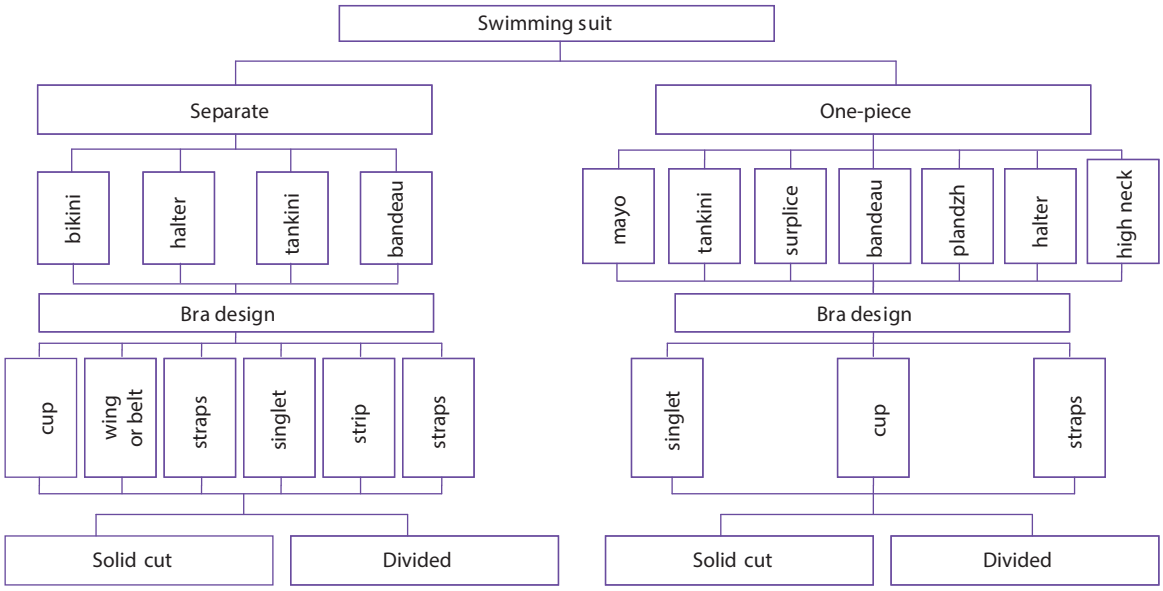


Figure 2. *Classification of bathing suits by bra construction*
Source: *developed by the authors*

According to the standard method of research on the explosive machine RT-250 used samples of 100 x 50 mm with a different surface thickness (DSTU 3045-95, 1996). The recommended duration of the ripping of the strips was 45-75 s, depending on the structural characteristics of the materials and their fibrous composition. The results presented in Table 2 summarised the statistical characteristics of discontinuous elongation along the looped columns and rows. Specifically, the table provided data on the magnitude of elongation, standard deviation (S), coefficient of variation (Cv), and margin of error (ME) for each tested fabric group.

Table 2. *Statistical characteristics of the discontinuous elongation of knitted fabrics*

No. fabric group	Fibrous composition, %, ±5	Weave type	Surface density, g/m², ±5	Magnitude of the discontinuous elongation							
				Along the looped columns				Along the looped rows			
				$\overline{X}$, mm	S, mm	*Cv*	ME, %	$\overline{X}$, mm	S, mm	Cv	ME, %
1	PA 70 EA 30	interlock stitch structure	155	95.5	2.47	2.58	1.74	161.25	2.86	1.77	2.02
2	PA 70 EA 30	interlock stitch structure	165	112.47	3.48	3.1	2.20	177.87	3.24	1.82	2.05
3	PA 80 EA 20	interlock stitch structure	175	156.58	2.64	1.69	1.87	155.08	3.24	2.09	2.29
4	PA 80 EA 20	interlock stitch structure	185	182.07	2.54	1.39	1.61	152.87	2.94	1.92	1.86
5	PA 80 EA 20	rib knit fabric	195	152.17	2.06	1.35	1.46	138.0	2.01	1.46	1.42
6	PA 90 EA 10	rib knit fabric	205	110.47	3.27	2.96	2.07	178.07	3.33	1.87	2.11

Source: *developed by the authors*

Analysis of the graph of variation of the coefficient of variation Cv (Fig. 3) showed that the largest deviations of the discontinuous elongation from $\overline{X}$ base density have 1, 2, and 6 groups of surface density. This indicated the heterogeneity in the elongation properties of these fabric groups, likely due to differences in their fibrous composition and structural characteristics.

Figure 3 illustrated the relationship between the coefficient of variation Cv and the surface density groups of knitted fabrics. The data pointed on the graph represent the values of Cv for each tested group, highlighting the variability within the samples. Groups 1 and 6 exhibited higher Cv values, which corresponded to a broader dispersion of elongation data, indicating less uniform behaviour under tensile stress. In contrast, Group 3 demonstrated a nearly normal distribution, as evidenced by the low Cv, making it the most stable group in terms of elongation characteristics.

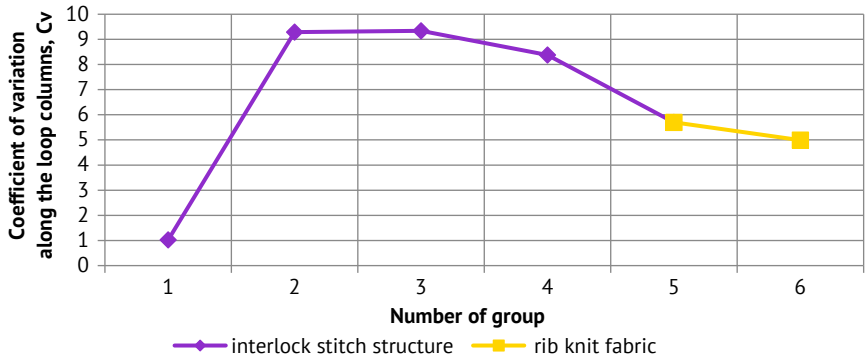


Figure 3. *Dependence of the coefficient of variation Cv on the group of knitted fabrics under study*
Source: *developed by the authors*

To determine the change in the size of the parts on the threads of the loop columns and rows was used the coefficient of proportional elongation *Cp.el*:

$$Cp.el = \frac{L_{ellgr}}{L_{elb}}, \quad (1)$$

where L_{ellgr} – index of strength elongation for the first group of fabric; L_{elb} – indicator of strength elongation for the base group of the fabric. The coefficient of change of the sizes of a pattern considering the structural characteristics of a knitted fabric was given in Table 3.

Table 3. *Coefficient of change in the size of the pattern depending on the structural characteristics of the knitted fabric*

Value of the coefficient, *Cp.el*	Number of fabric group					
	1	2	3	4	5	6
by looped columns	0.61	0.72	1.0	1.16	0.97	0.71
by looped rows	1.04	1.15	1.0	0.99	0.89	1.15

Source: *developed by the authors*

Evaluation of strength characteristics for compliance with the requirements of elasticity in ensuring the physiological and hygienic properties of the swimsuit (Table 2) was performed using the triangle method, built on three axes located at an angle of 120⁰ (Fig. 4). The plotted points represent the values of the elasticity parameters for each fabric group, and their positioning within the triangular field indicates the balance of tensile deformation in these directions. Fabrics that exhibit balanced elasticity properties fall closer to the centre of the triangle, while those with pronounced anisotropy (higher elasticity in one direction compared to others) deviate towards the triangle's edges.

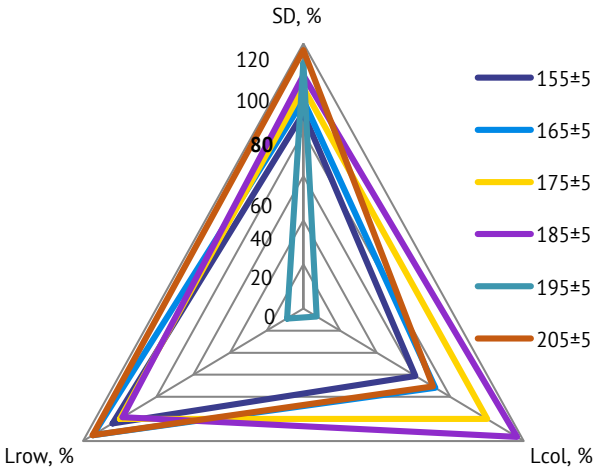


Figure 4. *Determination of complex elasticity of six groups of knitted fabrics by the triangle method*
Source: *developed by the authors*

A comprehensive study of the elasticity of knitted fabrics from Groups 2, 3, 5, 6 confirmed their belonging to the fabrics with a deviation of elastic deformation within 2... 5% in relation to Group 3. The state of skew before the appearance of folds in the fabric is called critical, and the angle between the loop rows and columns is called critical angle ϕ. The smaller the angle ϕ, the higher the ability of the fabric to shape.

Engineering methods based on the approximation of unfolded surfaces with a sufficiently high degree of accuracy in the shell, which was strictly coordinated on the surface, take into consideration two principles (Kämmerer, 2024):

- methods of Chebyshev scans from mesh materials for the formation of the surface lining;
- replacement of the unfolded surface with unfolding sections.

Since the shape of the cup surface was set by a rigid model of the shape of the breast, the equilibrium state of the lining provided a method of geodetic parallels (Fig. 5), which preserved the changed network angle during the transition to the state of UV-grids (Fan *et al.*, 2024).

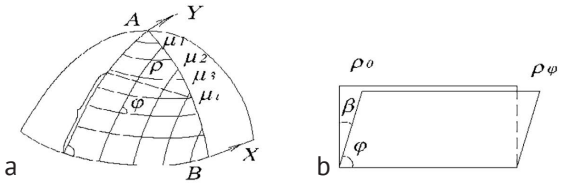


Figure 5. *Reproduction of the shape of the breast by the method of geodetic parallels*

Note: *a – geodetic coordinates of points in the shell of a spherical surface; b – change in the area of the scan during the skew of the fabric threads*
Source: *developed by the authors*

The property of changing the network angles when converting flat knitwear into a lining state was called moulding. It was accepted to estimate formation not by a networking angle ϕ, and an additional angle βmax: $\beta max = 90° - \phi$. βmax depended on the structure of the material and the type of equipment. The non-uniformity of the change of ϕ_{crit} as the tensile deformation increases both along the loop rows and along the loop columns was illustrated in Figure 6.

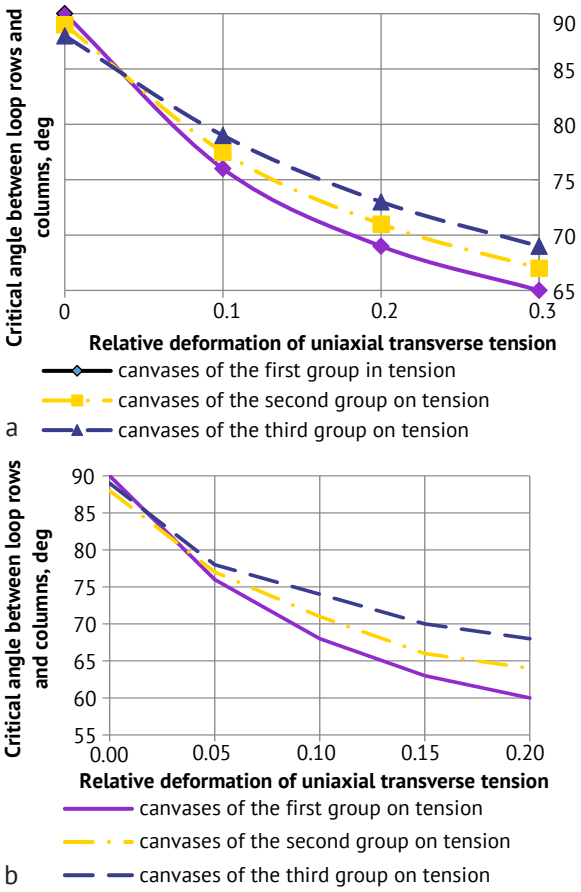


Figure 6. *Change in the ability of the canvas to skew*

Note: *a – in a transverse; b – in a longitudinal tension*
Source: *developed by the authors*

The process of warping the fabric was described by equation (Bobrova *et al.*, 2018):

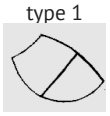
$$\cos\phi = \frac{1}{2}\left[\frac{1}{(1\pm E_x)^2} + \frac{1}{(1\pm E_y)^2}\right](1+E_g)^2 - 1, \quad (2)$$

where ϕ – angle between the loop rows and columns, deg; *Ex* – relative deformation of the fabric along the loop rows that accompanies the skew; *Ey* – relative deformation of the fabric along the looped columns, which accompanied the skew; *Eg* – relative deformation of the web in the diagonal direction, when the fabric was skewed. Consideration of the pressure on the body and changes in the wear resistance of the web to assess the moulding properties of practical importance were tensile deformations *Ex* from 0 to 0.3, *Ey* from 0 to 0.15.

If the error of the corners in the shells of knitwear was assumed to be permissible ± 1.5°, based on the accuracy of the calculations, the intervals of indifference of the forming indicators will be equal to: $\Delta\beta_0 = \pm 1.5\%$, $\Delta C = \pm 6.0°$, $\Delta\mu x = \Delta\mu = \pm 0.07$. These average values of the formed indicators were used to characterise all the fabrics of the group. Therefore, when designing knitted products by the method of shells, it was advisable to obtain a shape skewed in combination with uniaxial transverse tension of the fabric.

Since the bathing suit was made on the basis of underwear, the initial data for the construction were similar to corsetry. The construction of the swimsuit bra was based on the construction of the general-purpose bra, which ensured the formation of the breasts. As the bra determines the shape and location of the breasts, its construction was closely related. Classification features of the construction formation of the moulded cup as a prototype of the breast were the indentation and internal divisions, which determined the model decisions of the cup relative to the neckline. The results of the analysis of structural types of the top of the moulded cup were presented in Table 4.

Table 4. *Analysis of the construction features of the moulded cup top*

Quantitative indicator		Sketch of a model of the moulded cup top				
		type 1 	type 2 	type 3 	type 4 	∑
Total value	pcs.	38	72	71	65	246
	%	15	30	29	26	100

Note: *type 1 – vertical relief; type 2 – vertical or horizontal indentation; type 3 – horizontal relief; type 4 – drapery*
Source: *developed by the authors*

The most common types of cup divisions were vertical relief and indentation – 45%, horizontal relief – 29%, drapery at the bottom of the bra – 26%. Model of moulded bra cup, size 75B corresponded to size 158-88-96 according to DSTU ISO/TR 10652:2006 (2009) and hemispherical shape of the breast. In the direction of division, the original deployment lines, in order to reduce the values of skew angles, should be allocated in the form of geodetic lines: the *X* axis passed through the point O (convex point of the nipple) parallel to the neckline, the *Y* axis – through the point O perpendicular to the *X* axis. Thus, the bra cup was divided into four structural zones within a Cartesian coordinate system, which characterised the anthropometric correspondence to the shape of the breast: the upper part of the cup – I and III zone, the lower part of the cup – II and IV zone, the front part of the cup – III and IV zone, the side part of the cup – I and II zone (Fig. 7).

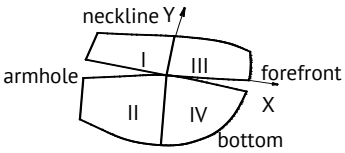


Figure 7. *Constructive zones of the bra cup in the Cartesian coordinate system*
Source: *developed by the authors*

The accuracy class of deployment was determined by the step of the location of geodetic lines relative to the original axes of deployment, which in study was equal to 10 mm. To build a scan with a vertical relief (type 1), it should connect the cells in the form of transverse stripes relative to the axis B, starting from the armhole of the cup in zone II – with the transition to zone IV and respectively in zone III – with the transition to zone I (Fig. 8, a). For vertical indentation (type 2), the construction of the scan can be started from the vertical geodetic line (*Y* axis) in the directions of the cup edges (armhole, front), connecting the cells in transverse strips (Fig. 8, b).

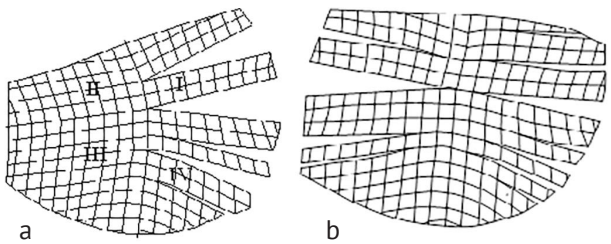


Figure 8. *Drawing of a cup scan with a vertical articulation of the top*
Source: *developed by the authors*

For horizontal division, the construction of the scan started from the horizontal geodetic line (*X*-axis),

connecting the cells in the form of longitudinal strips. To scan the horizontal relief (type 3) longitudinal strips of zones were formed by connecting cells from the neckline to the geodetic line of the *X* axis, longitudinal stripes of zones II and IV were obtained by connecting cells from the *X* axis to the edge lines relative to the *Y* axis (Fig. 9). The option of forming a geodetic indentation (type 2) considered the minimum deviation of the contours of the zone from the geodetic lines of the *X*, *Y* axes.

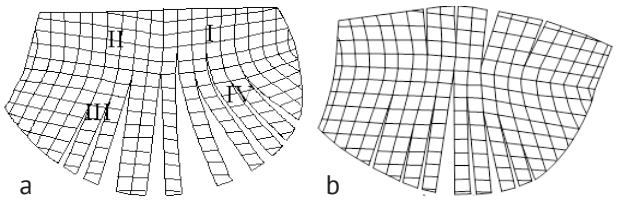


Figure 9. *Drawing of the cup sweep with a horizontal division of a bra top (type 3)*
Source: *developed by the authors*

To form draperies in a certain area, the construction should be started on the opposite side of the cup from the location of the drapery, using techniques for constructing a scan with vertical relief for draperies from the armhole (Fig. 10, a), techniques for modelling horizontal relief – for draping from the bottom (Fig. 10, b). Figure 10 illustrated two approaches to constructing draperies on the cup top. On Figure 10 (a), the method for creating draperies starting from the armhole was demonstrated. The scan was formed by connecting cells in vertical stripes, ensuring a smooth transition of relief folds across the cup surface. This approach was particularly suitable for designs emphasising vertical symmetry and structural stability. Figure 10 (b) showed a technique of forming the horizontal drapery, where cells were connected longitudinally, starting from the lower edge of the cup. This method created a softer visual effect and was commonly used for aesthetic enhancement in the lower section of the cup.

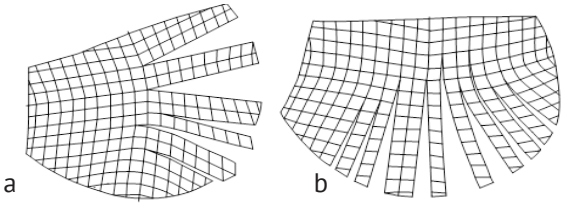


Figure 10. *Drawing of the sweep of the cup top with drapery (type 4)*
Note: *a – from the armhole; b – from the bottom*
Source: *developed by the authors*

The presented data and graphical illustrations comprehensively highlight the structural and mechanical characteristics of the tested fabrics, emphasising the relationship between surface density, weave type, and elasticity parameters. The developed drawings of the bra cup design with different types of division (vertical, horizontal, drapery) provide flexibility in choosing design solutions, in particular, considering the characteristics of the fabric and anthropometric parameters.

Results and Discussion

The results focused on identifying optimal fabric characteristics, analysing deformation properties, and creating mathematical models to ensure precise fit and comfort. The interlock stitch structure fabric was selected for approbation of the engineering method of the construction in the sample, which belongs to the third group of elasticity (L ⩾ 100 mm). According to the set of combinations *Ex*, *Ey* using the graph of skew lines (Fig. 8) determined the relative deformation of uniaxial transverse *Ex* and longitudinal tension Ey. The coordinates of new points were found using the equation:

$$X_i = X_{0i}(1 \pm E_x), Y_1 = Y_{0i}(1 \pm E_y), \quad (3)$$

where X_i, Y_i – new coordinates of points; X_{0i}, Y_{0i} – initial coordinates of the points.

The results of calculations Ex, Ey, Xi, *Yi* were given in Table 5.

Table 4. *Results of calculations Ex, Ey, Xi, Yi*

Zone number	Ex_i	X_i, mm	Ey_i	Y_i, mm	$\overline{\varphi_i}$
I	-0.016	$O_2 = 0$; $X_1 = 9.5$; $X_7 = 9.8$ $X_4 = 0$	0.05	$O_2 = 0$; $Y_1 = 0$ $Y_7 = 4.1$; $Y_4 = 8.9$	79.2^0
II	-0.009	$O_1 = 0$; $X_1 = 9.5$; $X_5 = 8.8$ $X_3 = 0$	0.03	$O_1 = 0$; $Y_1 = 0$ $Y_5 = 3.3$; $Y_3 = 5.3$	97.2^0
III	-0.012	$O_3 = 0$; $X_2 = 9.3$; $X_6 = 8.5$; $X_5 = 0$	0.04	$O_3 = 0$; $Y_2 = 0$; $Y_6 = 3.5$; $Y_3 = 5$	80.0^0
IV	-0.043	$O_4 = 0$; $X_2 = 9.3$; $X_4 = 0$	0.14	$O_4 = 0$; $Y_2 = 0$; $Y_4 = 8.1$	109.1^0

Source: *developed by the authors*

The resulting points, calculated based on the relative deformations *Ex* and *Ey*, were connected by smooth lines to form the contours of the top details of the moulded cup. These contours accurately reflect the deformation characteristics of the fabric under transverse and longitudinal tension, ensuring a precise fit of the moulded cup to the body. The data presented in Table 6 summarised the calculated

coordinates X_i and Y_i for each zone of the cup, derived from the base measurements and adjusted for the material's deformation properties. The drawing of the soft scan, illustrated Figure 11, highlighted the adjusted contours, which ensure the cup maintains its intended shape and fits comfortably. By incorporating deformation coefficients into the design process, the resulting scan achieves a balance between aesthetic appeal and functional performance, particularly in terms of elasticity and comfort. This approach enhanced the overall quality and precision of the moulded cup construction, making it suitable for applications in swimwear and other garments requiring complex 3D shapes.To test the resulting construction in the sample seam allowances were added to the templates, the details were cut out, the parts were sewn together and placed on the moulded cup, checking the conformity of the contours and the shape of the top of the moulded cup surface. To determine the limit values of the parameters of the forming elements, namely the indentations, the obtained scans of the elementary sections were oriented in the basic grid of drawings of the basic structure relative to the lines passing through the nipple point. Slice lengths were measured along these lines in the base structure and rigid scan structures (Table 6) to within ± 1 mm.

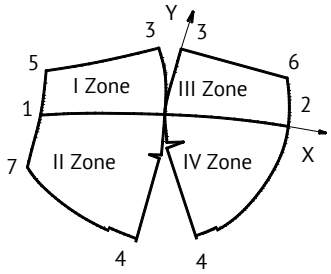


Figure 11. *Drawing of the modified cup construction*
Source: *developed by the authors*

Table 6. *Determination of the sections' lengths of the of the divisions of the cup in the base construction (BC) and the matrix construction (MC) of the rigid scan of the moulded cup*

Name of the scan option	Cut length, cm				Deviation of the length of sections of RSS BS, %	
	BC		MC			
	x	y	x	y	x	y
Scan of the cup top with vertical relief	18.8	14.7	18.8	14.7	0	0
Scan of the cup top with horizontal relief	18.8	14.7	18.4	13.8	2.1	6.1
Scan of the cup top with a dart	18.8	14.7	18.5	14.5	1.6	1.2
Scan of the cup top with drapery	18.8	14.7	19.2	14.5	2.1	1.2

Source: *developed by the authors*

The error in determining the length of the curve, when replacing it with a broken relative to the original horizontal was determined by the equation:

$$\delta_e = \frac{l_{BC} - \sum l_{MC}}{l_{MC}} \times 100\% \ , \qquad (4)$$

where l_{BC} – horizontal length of the BC at the level of the nipple point, cm; l_{MC} – length of the matrix construction at the level of the nipple point, cm. The error δ_e for rigid scans of the matrix structure was respectively 0.75%, which does not exceed 2%. The rationality of the construction was investigated by comparing the areas of deviation of the darts formed on the surface and shown in Table 7. The deviation of the sum of the areas of deviation of the darts was determined by the equation:

$$\delta_S = \frac{S_{BC} - \sum S_{MC}}{S_{BC}} \times 100\%, \qquad (5)$$

where S_{BC} – area of the base structure, cm^2; S_{MC} – area of the matrix structure, cm^2.

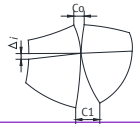
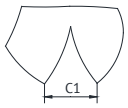
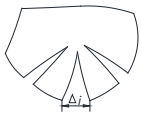
Table 7. *Determination of the divergence areas of the cup darts in the matrix construction of the scan*

Basic construction (BC) of knitted fabric, sm^2	Matrix construction (MC) of the scan, sm^2	Deviation of areas, %
16.85	16.27	3.56

Source: *developed by the authors*

The sum of the areas of darts in the MC was less than the area in the BC within 5%, which does not exceed the value of the error established for light industry. Therefore, MC was more rational for transformation into a model construction The results of the study using a rigid shell to build a matrix structure of the moulded cup of the breast confirmed the conformity of the original surface, and the soft shell was built by recalculating the control measurements by the values of tensile strain coefficients. According to the results of the analysis of modified rigid scans in the corresponding type of model construction of the cup top, the corresponding mathematical models of MM were obtained, which described the analytical dependences of a general look on the values of design parameters. Examples of mathematical models describing the modification functions of 4 types of construction were given in Table 8.

Table 8. *Mathematical models for modifying (MM) the types of design solutions on the top of the moulded bra cup*

Modifying function	Conversion scheme	Mathematical model
Type 1 F16 – design of vertical division		$P_{ud} = C_o + \Delta$ $P_{ld} = C1 + \Delta$ $\Delta = \sum \Delta_i$ P_{ud} – the slope of an upper dart P_{ld} – the slope of a lower dart
Type 2 F13 – distribution of the slope of the darts in a typical place of formation		$C1 = C1 + \Delta$
Type 3 F16 – design of horizontal division		$P_{fd} = C_o + \Delta$ $P_{ltd} = C1 + \Delta$ $\Delta = \sum \Delta_i$ P_{fd} – the slope of a forefront dart P_{ltd} – the slope of a lateral dart
Type 4 F14 – conical extension of the part for draping		$C1 = l_{ltd} = C_0 + \Delta$ $\Delta = \sum \Delta_i$ l_{ltd} – the slope of a lateral dart

Note: *C1 – the value of the i-th section of the structure obtained by transforming the BC; Co – initial length of the contour of the i-th section of the BC; Δ – the slope of the dart*

Source: *developed by the authors*

The use of modern digital tools for developing computer-based 3D models of moulded bra cups according to gradation parameters significantly reduces the preparation time for 3D printing of inserts, ensuring an aesthetic breast shape. Additionally, digital technologies enable the creation of a graphical representation of the modification process for four types of moulded bra cup designs, followed by simulation fitting on a 3D model, which facilitated the optimisation of structural solutions. This process provided a comprehensive understanding, of how different materials and design features interact, allowing designers to achieve superior results, while minimising errors and material waste.

In the study by H. Han *et al.* (2020), a method for designing swimwear patterns based on the anthropometric characteristics of the consumer was proposed. However, the material properties, which were crucial for ensuring proper fit and comfort, were not considered in their approach. The study by E.D. Kocak *et al.* (2024) focused on analysing the properties of fabrics used for swimwear, highlighting their mechanical and elastic characteristics. Nevertheless, the design and construction aspects of swimwear products, such as bra cups, were left unaddressed, limiting the practical application of their findings in comprehensive garment development.

The authors Y. Sun *et al.* (2019) proposed a personalised modelling system for bra cups and the human body using the finite element method. While their research offered valuable insights into the geometric and structural aspects of bra cup design, it does not take into account the material properties, which significantly influence the deformation and wearability of the final product. X. Wen *et al.* (2022) analysed the visual perception of bras based on their main structural elements, focusing on aesthetic and perceptual characteristics without addressing technical and functional properties. In contrast, this study focused on adapting the design of swimsuit cups to the elastic properties of knitted materials to ensure fit accuracy and comfort.

B. Baidak *et al.* (2023) discussed the use of 3D body scanning to create customised bras, focusing on the use of digital technology to improve design accuracy. In contrast, this study focused on adapting the design of swimwear cups to the elastic properties of knitwear materials, which ensured comfort and precise fit. The study by J. Zhou *et al.* (2023) explored the relationship between the design attributes of sports bras and the perception of their comfort among elderly women, focusing on social and anatomical aspects without addressing the technical aspects of design. In contrast, this study emphasised the adaptation of swimsuit cup constructions to the elastic properties of knitwear materials to ensure precise fit and comfort.

In the study by J.C.L. López *et al.* (2024), a method for classifying swimsuit fit on the body was presented, with a focus on utilising artificial intelligence to analyse fit parameters. In contrast, this study emphasised the adaptation of swimsuit cup designs to the elastic properties of knitted materials to ensure precise fit. Both papers aimed to optimise garment design; however, the researchers focused on AI tools, while this study highlighted the physical and mechanical properties of materials. C. Malbon *et al.* (2020) investigated the impact of breast size and bra type on the comfort of female police officers in the UK, while wearing body armour, focusing on ergonomics and comfort in specific operational conditions. This study focused on adapting the design of swimsuit cups to the elastic properties of knitted materials to ensure a precise fit and comfort without addressing the broader technical aspects of design.

The study by A. Yu *et al.* (2022) considered the development of a bra cups made of three-dimensional knitted material based on full fashioned knitting technology, which allows the cups to be manufactured seamlessly in one step, starting with yarn. The main focus was on optimising the production process and using innovative materials to create a structured and comfortable cup shape. Both papers were aimed at optimising the cup design, but A. Yu *et al.* (2022) focused on improving production methods and technologies, while this paper emphasised on the physical and mechanical properties of materials and their impact on the final fit of the garment.

This study stood out because it focused on adapting swimwear cup design to the elastic properties of knitwear materials to ensure a precise fit and comfort, unlike other papers that emphasised different aspects of garment design. By placing a strong emphasis on the interaction between material science and garment construction, the study provided valuable insights into the role of fabric stretchability and deformation in achieving an ideal fit. It highlighted the importance of integrating materials science into practical design processes to achieve optimal fit, comfort, and functionality, particularly for swimwear, which requires a delicate balance between support, durability, and flexibility. Furthermore, the research underscored the significance of precision in the design of moulded bra cups to meet diverse consumer needs, setting a new benchmark for the innovative application of engineering principles in textile design. This approach not only enhanced user satisfaction, but also introduced a methodology that can be extended to other categories of functional apparel, demonstrating the potential for interdisciplinary collaboration in advancing garment design technologies.

Conclusions

Classification features of knitted fabrics for bathing suits are fibrous composition, surface density of loop rows and loop columns, type of weave. Evaluation of the complex indicator of elasticity to ensure the physiological and hygienic characteristics of the swimsuit confirmed the feasibility of using as a base fabric canvas of the third group with a fibrous composition of PA 80.5%, EA 20.5% (36.4%) weave interlock stitch structure with a surface density 175.5% g/m^2, with the coefficient of elongation on the loop row and column Quid = 1. The results of the study adequately characterised the elastic deformation of 4 from 6 groups of fabric samples.

Construction of details' scans of the top of a formed bra cup by an engineering method of geodetic parallels considered types of divisions of bra models on a sign of reflection of fashion tendencies and observance of the conditions of preserving the aesthetic functionality formulated by leading manufacturers. To verify the morphological features of the shape of the breast in the configuration of the divisions of the top of the moulded cup, an experimental test of mathematical models describing four types of internal divisions of the cup construction by a rational route of modification of a rigid scan constructed by a grid of geodetic parallels. The swerving of the deviation areas of the darts of the matrix construction of the moulded cup and the base structure for the knitted fabric was 3.56%. The soft shell was built by recalculating the main dimensions of the cup according to the values of the coefficients of tensile strain.

Prospects for further research include the development of integrated digital platforms for automating design processes and optimising designs based on individual anthropometric data and fabric characteristics.

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Conflict of Interest

None.

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Адаптивний метод конструювання бюстгальтера для купальника

Алла Славінська
Доктор технічних наук, професор
Хмельницький національний університет
29016, вул. Інститутська, 11, м. Хмельницький, Україна
https://orcid.org/0000-0003-0663-9422
Сергій Матюх
Кандидат економічних наук, доцент
Хмельницький національний університет
29016, вул. Інститутська, 11, м. Хмельницький, Україна
https://orcid.org/0000-0001-9899-109X
Вікторія Мица
Кандидат технічних наук, доцент
Хмельницький національний університет
29016, вул. Інститутська, 11, м. Хмельницький, Україна
https://orcid.org/0000-0002-5453-9787
Оксана Домбровська
Кандидат технічних наук, доцент
Хмельницький національний університет
29016, вул. Інститутська, 11, м. Хмельницький, Україна
https://orcid.org/0000-0001-6086-5784
Оксана Сиротенко
Кандидат технічних наук, доцент
Хмельницький національний університет
29016, вул. Інститутська, 11, м. Хмельницький, Україна
https://orcid.org/0000-0002-6816-6467

Анотація. Актуальність дослідження зумовлена необхідністю розробки точних і ефективних методів проєктування бюстгальтерів для купальників з урахуванням еластичних властивостей сучасних трикотажних тканин, що сприятиме підвищенню комфорту та якості виробів. Метою дослідження була розробка методу коригування розміру чашки бюстгальтера відповідно до ступеня розтягування за допомогою методу геодезичних паралелей. У дослідженні використовувалися методи математичного моделювання для розробки та оптимізації конструкції чашок бюстгальтера купальника, а також аналізувалися механічні властивості трикотажних матеріалів. Визначено репрезентативні групи еластичних трикотажних тканин на основі аналізу їхніх розтяжних характеристик. Виділено дві основні групи тканин за їхнім волокнистим складом: перша група складалася з поліамідних ниток у поєднанні з еластаном, друга – з поліестерових ниток у поєднанні з еластаном. Виявлено антропоморфні чинники, що впливають на неточності у розгортанні жорсткої поверхні чашки. Розроблено рекомендації щодо трансформації жорсткого розгортання у м'яку оболонку формованих деталей чашки з урахуванням дискретних подовжень трикотажних матеріалів. Метод побудови м'якої оболонки ґрунтувався на перерахунку основних розмірів чашки з урахуванням коефіцієнтів деформації матеріалів. Ефективність запропонованого методу підтверджено шляхом порівняння площ відхилення формованих розгорток чашки базової конструкції. Відхилення площі на 3,56 % свідчило про відповідність жорсткого розгортання поверхні грудей. Розроблено математичні моделі методів модифікації для чотирьох типів поділу чашки бюстгальтера. Практична цінність роботи полягає у застосуванні ефективного методу проєктування бюстгальтерів для купальників, що забезпечує точну посадку та комфорт, враховуючи еластичні властивості трикотажних матеріалів

Ключові слова: трикотажна тканина; купальний костюм; волокнистий склад; розтяжні характеристики; членування чашки; методи модифікації

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Optimising the adsorption characteristics of spent coffee grounds by thermal and chemical activation

Iryna Moroz

PhD in Chemistry, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0001-9167-4876

Abstract. The aim of this study was to optimise the adsorption parameters of methylene blue on spent coffee grounds by combining thermal exposure and orthophosphoric acid treatment. The study was carried out using a spectrophotometric method, infrared spectroscopy, and a method for determining the specific surface area by water vapour adsorption. A possible mechanism for the adsorption of the cationic dye methylene blue on coffee grounds has been proposed. It was found that an increase in the processing temperature wasn't led to a linear increase in the specific surface area and adsorption characteristics of spent coffee grounds. It was discovered that coffee grounds' adsorption properties were inferior to those of untreated samples at temperatures of 400°C and 800°C. However, thermal activation of spent coffee grounds at 600°C led to a 72% increase in the specific surface area (from 561 to 958 m^2/g). Treatment of the waste with 60% orthophosphoric acid solution increased the specific surface area by 23% (up to 690 m^2/g) compared to untreated coffee grounds. The most effective in terms of adsorption characteristics of the adsorbent was the combined treatment of coffee grounds with orthophosphoric acid followed by thermal activation at 200°C, which provided a maximum specific surface area of 1078 m^2/g and water vapour adsorption of 0.543 g of water per 1 g of sample, exceeding the characteristics of some commercial activated carbon samples. Under these conditions, the highest removal efficiency of methylene blue from model solutions was achieved – 57% in 30 min and almost 90% of the dye in 180 minutes of contact. The proposed conditions for the modification of spent coffee grounds make it possible to obtain an effective biosorbent for wastewater treatment from organic dyes, which is of practical importance for solving environmental problems in the textile and printing industries and the rational use of coffee production waste

Keywords: biosorbent; coffee waste; thermal modification; phosphate activation; methylene blue

Introduction

Despite controversial evidence on the health benefits of coffee drinks, N. Zhao *et al.* (2024) indicated that their popularity was growing globally and, in some countries, where coffee had become part of the cultural tradition. G.D. Gebreeyessus (2022) stated that coffee was currently the most popular beverage after water and was the best-selling commodity after oil and oil products. According to the Coffee Market Report (2024), global coffee consumption in 2024 was reported at 177.0 million 60 kg bags, up 2.2% from the 2023. The per capita consumption of coffee per year in North America was about 5.0 kg, in Europe – 4.2 kg, in Asia and Oceania – 0.58 kg. According to K. Johnson *et al.* (2022), only about 30% of the weight of coffee beans can be extracted into a coffee drink, and 70% ended up as spent coffee grounds, which were mostly disposed of as waste. H. Ahmed *et al.* (2024) noted that spent coffee grounds (SCGs) were solid waste generated after coffee was brewed using various methods. About $6 \cdot 10^6$ tonnes of SCGs were produced annually worldwide,

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*Corresponding author

half of this amount was from the production of instant coffee. Small coffee shops, restaurants, and individuals generated 50% of the SCGs produced globally.

Spent coffee grounds were mostly not recycled, but disposed of in solid waste landfills. Greenhouse gasses including carbon dioxide and methane are released, when the organic components of SCGs break down anaerobically. As noted by G. La Scalia *et al.* (2021), greenhouse gas emissions from coffee waste decomposition had a significant impact on climate change and atmospheric degradation. However, the implementation of innovative processing technologies allowed to transform the environmental challenges associated with the disposal of SCGs into a number of promising opportunities for resource-efficient use of this raw material. In this regard, the high content of lignin, cellulose, hemicellulose, proteins, lipids and other bioactive substances in spent coffee grounds made it a valuable and cheap raw material for further processing. P.J. Ong *et al.* (2023) proposed the possibility of using spent coffee grounds to create structural, energy-saving, and packaging materials. S. Hechmi *et al.* (2023) studied the possibility of using SCGs for composting and soil structuring.

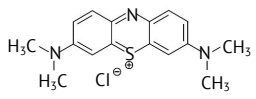
The use of coffee waste as a biosorbent had gained worldwide attention due to a number of physical and chemical properties, including the unique porous structure of spent coffee grounds. Because heavy metals and dyes are easily dispersed, toxic, can build up in the human body, and cannot biodegrade, treating water of these contaminants has proven to be a very difficult problem. Coffee waste had a large specific surface area and can be used as an alternative to traditional adsorbents such as activated carbon, silica gel and zeolites. A significant advantage of adsorbents based on coffee waste was their low cost, availability and natural origin. The study by V. thi Quyen *et al.* (2021) examined the use of coffee grounds as an adsorbent for water treatment. In the work of A. Skorupa *et al.* (2023), it was proposed to use raw coffee grounds for the adsorption of dyes, heavy metals, microplastics and other pollutants. Many scientific works focused on the systematic study of the influence of key parameters of the adsorption process, such as adsorbent dosage, solution pH, contact time, temperature, on the efficiency of dye removal. Dye adsorption parameter optimisation on wasted coffee grounds was a challenging problem that required more work.

The aim of this study was to optimise the adsorption parameters of methylene blue, a hazardous dye commonly used in the textile and printing industry, onto SCGs by combining thermal exposure and orthophosphoric acid treatment.

Materials and Methods

The coffee grounds used for the study were those that had been brewed in a coffee machine in the canteen of Lutsk National Technical University during 2024. The coffee grounds were washed with hot water until the washing liquid became colourless. Distilled water was used to rinse the garbage one last time. After being completely cleaned, the coffee waste was dried for 24 hours at 100°C to 110°C in an oven. For chemical activation of the spent coffee grounds, H_3PO_4 (60%) was used. To study the adsorption characteristics, a methylene blue solution with a concentration of 20 mg/l of the initial solution was used, which was prepared before each adsorption test. The main characteristics of methylene blue were given in Table 1.

Table 1. *Main characteristics of methylene blue*

Chemical structure	Molecular formula	Chemical name	Molecular weight (g/mol)	λ, nm
	$C_{16}H_{18}ClN_3S \cdot 3H_2O$	3.7-bis (Dimethylamino)-phenothiazin-5-ium chloride	319.85	665

Source: *developed by the author based on M. Clark (2016)*

The absorption of water vapour was used to assess the adsorbent's specific surface area. Using an analytical balance, the coffee waste sample was weighed in a porcelain crucible. After weighing, the sample was placed in a desiccator, the lower chamber of which was filled with water, for 48 hours. After that, it was weighed again and the mass of adsorbed water vapour was determined. The water vapour absorption experiments were carried out in triplicate, and the average value was presented in the article.

Specific surface area, which was defined as the ratio of the interfacial surface of a substance to its mass:

$$S_A = S/m, \quad (1)$$

where S_A – specific surface area; S – interfacial surface of a substance; m – mass.

The area of the interfacial surface can be determined by the formula:

$$S = n \cdot N_A \cdot A(H_2O), \quad (2)$$

where n – amount of water substance (mol); N_A – Avogadro's constant; $A(H_2O)$ – the area occupied by 1 water molecule ($5.94 \cdot 10^{-20} m^2$, based on the assumption that a water molecule was spherical and had a diameter of $2.75 \cdot 10^{-10}$ m).

For the physical activation, the coffee grounds were dried to a constant weight at a temperature of 100°C-110°C, after being washed with hot water. For

one hour, the coffee grind samples were maintained at 400°C, 600°C, and 800°C in a muffle furnace. A desiccator was used to bring the samples down to room temperature. A 60% orthophosphoric acid solution, made from a 90% solution, was utilised for chemical activation. After being cleaned and dried, the coffee grounds were combined with the orthophosphoric acid solution in a 1:1 ratio and allowed to activate for 48 hours in a closed flask. After activation, the treated coffee waste was rinsed with plenty of water until the rinsing water became discoloured and dried in an oven at 110°C.

The adsorption efficiency was determined on an aqueous solution of methylene blue containing 20 mg/l of the dye. The test was carried out at room temperature. Accordingly, the prepared coffee waste weighing 5 g was dispersed in 200 ml of the solution. The pH of the solutions was maintained at 7 by adding 0.1 MHCl or NaOH solutions. The suspension was continuously stirred for 10 min to ensure better contact between the pollutant in solution and the active centres of the adsorbent. After the determined contact time of the dye solution and coffee waste, the suspension was filtered and the optical density of the filtrate was determined using a photoelectrocolourimeter AP-120 APEL (Japan) at 670 nm. The amount of dye removed was determined by equation:

$$Q = \frac{C_0 - C_e}{C_0} \cdot 100\%, \quad (3)$$

where Q – amount of dye removed; C_0 and C_e – initial and final concentrations of methylene blue in solution (mg/l).

Adsorption tests were repeated 3 times, and the averaged adsorption value was used in the work.

Results and Discussion

A basic pre-treatment, which included hot water rinsing and drying, was performed following the collection of coffee trash in the university canteen. W.E. Oliveira *et al.* (2008) stated that the purpose of thoroughly washing used coffee grounds was to remove impurities to avoid their influence on the adsorption process. The composition of coffee waste was important in the context of its use as a sorbent, since the properties of coffee grounds and their suitability for surface modification depend on the specific functional groups on their surface, as well as on the chemical bonds that the coffee grounds will form during adsorption with the adsorbate.

The FTIR spectrum of the spent coffee grounds was shown in Figure 1. The analysis of the coffee grounds spectrum showed the presence of intense bands of *v* CH alkyl groups (3000-2800 cm^{-1}) and a band in the region of 3650-3500 cm^{-1} (*v* OH). This showed that the sample included a lot of hydroxyl OH functional groups and hydrocarbon chains. There were a lot of triple carbon-carbon C ≡ C bonds in the sample in organic chains, as evidenced by the strong absorption band in the triple bonds region (2300-2360 cm^{-1}). Ketones and esters were detected in the sample at a frequency of 1750-1735 cm^{-1}, which corresponded to the absorption band of the carbonyl group *v* C = O; the absorption band of aromatic aldehydes was detected at a frequency of 1710-1685 cm^{-1}. The presence of absorption bands in the region of 1605-1555 cm^{-1} indicated the presence of solid amino acids.

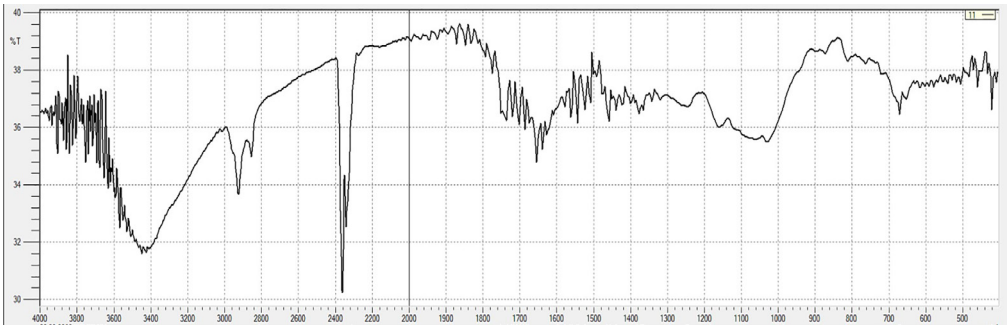


Figure 1. *FTIR spectrum of spent coffee grounds*

Source: *developed by the author*

The diverse cavity and porous structures of hemicellulose, cellulose and lignin with a large number of different functional groups indicated a high adsorption capacity of spent coffee grounds for pollutants, even after simple pre-treatment. The study by Q.-A. Trieu *et al.* (2022) reported the pH of the medium as a crucial element in the methylene blue adsorption process on discarded coffee grounds. The surface charge of spent coffee waste has been determined by many scientists. In particular, R. Lafi *et al.* (2014) indicated that for untreated coffee waste, the surface charge was negative above pH 5.5, and F. Aouay *et al.* (2024) found that, when coffee waste was treated with orthophosphoric acid, the surface charge of coffee waste became negative already at pH 2.4. The authors M. Samilyk *et al.* (2024) also used a methylene blue solution, when they studying the microbiological indicators of kefir drinks. Thus, an increase in the pH of the medium led to a change in the surface charge from positive to negative:

$$SCGs^{+} \xrightarrow{pH>2.4} SCGs^{-}, \quad (4)$$

where *SCGs* – spent coffee grounds; *pH* – hydrogen index.

S. Bouzikri *et al.* (2022) described many factors that contribute to the adsorption of dyes on coffee waste: hydrogen bonds, electrostatic attraction, Van der Waals forces, π-π bonds. The synergistic process that was the adsorption mechanism of dyes included both the physical adsorption of dye molecules onto the coffee waste substrate and the formation of chemical interactions through surface contacts. The interaction between these physicochemical processes was demonstrated by Figure 2, which depicted the suggested mechanistic pathway for methylene blue adsorption onto wasted coffee grounds.

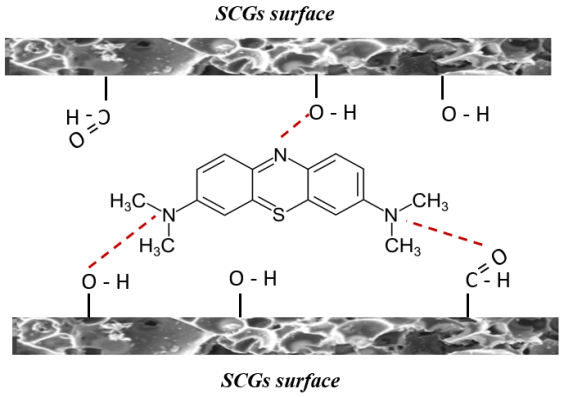


Figure 2. *The mechanism of methylene blue adsorption on the surface of spent coffee grounds*
Source: *developed by the author based on S. Bouzikri et al. (2022)*

The electrostatic interaction of the cationic dye with the negatively charged coffee waste surface and the bonding of the dye's nitrogen of two amino groups with the oxygen of hydroxyl or carbonyl groups were the main reasons, why the dye and SCGs interact:

$$(MB)N^{+}Cl^{-} \rightarrow (MB)N^{+} + Cl^{-};$$
$$SCGs^{-} + (MB)N^{+} \rightarrow (MB)N^{+}SCGs^{-}, \quad (5)$$

where *MB* – methylene blue; *SCGs* – spent coffee grounds.

Under alkaline conditions, the interaction between methylene blue and coffee grounds was optimised through robust electrostatic forces between the positive charge of the cationic dye ($(MB)N^{+}$) and the negative charge of the coffee grounds surface ($SCGs^{-}$) (Trieu *et al.*, 2022). Physical and chemical modification methods were used to increase the adsorption activity of untreated coffee waste and optimised its properties (Kang *et al.*, 2022). A. Młynarczykowska & M. Orlof-Naturalna (2024) shown that physical techniques do not show a significant boost in the effectiveness of removing dyes and heavy metals from aqueous solutions, despite their technological simplicity. Research focused on chemical modification of spent coffee grounds surface with acids and alkalis to incorporate functional groups that enhance its ability to absorb heavy metal ions and dyes (Taleb *et al.*, 2020).

Heat treatment increased the specific surface area and encourages the conversion of cellulose, hemicellulose, and lignin into a porous structure (Chen *et al.*, 2021). O. Senneca *et al.* (2020) found that the first step in the destruction of polysaccharides, which were the basis of coffee grounds, was depolymerisation into oligosaccharides. Moreover, hemicellulose was the most labile component, decomposing at 200°C–260°C. Cellulose was relatively more stable, decomposing in the temperature range of 240°C–350°C, lignin was the most thermally stable of all, had the widest decomposition interval, and began to decompose between 280°C and 500°C. At significantly higher temperatures, the hemicellulose, cellulose, and lignin polymer chains oxidised, forming carbon monoxide, carbon dioxide, and methane. The decomposition, evaporation and depolymerisation of hemicellulose, cellulose and lignin without heat treatment and activator occur at different rates. Thus, according to H.M. Boundzanga *et al.* (2022), the mass loss of hemicellulose, cellulose and lignin at a temperature of 800°C was 76.5%, 80.9% and 55.1%, respectively.

Activated carbon was formed only as a result of heat treatment of lignin in the temperature range of 1200°C–1800°C in an environment of nitrogen and carbon dioxide. For the purpose of physical activation, the pre-cleaned coffee grounds were subjected to heat treatment in the temperature range of 400°C–800°C, and the waste was chemically activated with orthophosphoric acid without and with temperature exposure. Water vapour adsorption and specific surface area were determined for each sample. The effects of different treatment types on the specific surface area and adsorption capacity of the coffee grounds were shown in Table 2.

Table 2. *Adsorption capacity and specific surface area of coffee grounds*

Sample	Mass of adsorbed water vapour, g per 1 g of sample	Specific area S_A, m^2/g
Activated carbon (Red star)	0.355 ± 0.02	705 ± 0.08
Dry raw coffee grounds	0.283 ± 0.01	561 ± 0.07
Coffee grounds after temperature treatment at 400°C	0.262 ± 0.01	515 ± 0.08
Coffee grounds after temperature treatment at 600°C	0.482 ± 0.03	958 ± 0.08
Coffee grounds after temperature treatment at 800°C	0.212 ± 0.01	422 ± 0.08

Table 2. Continued

Sample	Mass of adsorbed water vapour, g per 1 g of sample	Specific area S_A, m^2/g
Coffee grounds after H_3PO_4 treatment	0.347 ± 0.03	690 ± 0.08
Coffee grounds after H_3PO_4 treatment and temperature treatment at 200°C	0.543 ± 0.04	1078 ± 0.1
Coffee grounds after H_3PO_4 treatment and temperature treatment at 400°C	0.402 ± 0.03	798 ± 0.08
Coffee grounds after H_3PO_4 treatment and temperature treatment at 600°C	0.152 ± 0.01	300 ± 0.05

Source: *developed by the author*

Significant variations in specific surface area and adsorption capacity were observed, when the coffee grounds samples under investigation were compared. The base raw coffee grounds actually had the lowest values: the surface area was 561 m^2/g and the water vapour adsorption was 0.283 g H_2O/g. Exposure of the coffee grounds to 400°C did not change the porosity, which was in good agreement with the literature. At this temperature, only cellulase and hemicellulose began to decompose, while lignin decomposition had not yet begun. Increasing the processing temperature to 800°C led to a degradation of properties: the surface area decreased sharply to 422 m^2/g, and the adsorption decreased to 0.212 g of H_2O per 1 g of sample. The coffee grounds' structure was destroyed and their porosity decreased as a result of the high temperature. It was found that the greatest impact on the porosity of coffee grounds was caused by their treatment at a temperature of 600°C – the specific surface area increased from 561 to 958 m^2/g, i.e. by 72%.

Orthophosphoric acid (H_3PO_4) was an effective activating agent that catalysed the dehydration of the primary material. Consequently, the lignocellulosic complex's heat degradation threshold was lowered (Ivanichok *et al.*, 2023). Activation with orthophosphoric acid enhanced the yield of the carbonised product and developed the porous structure of the material. The emission of volatile chemicals during thermochemical processes led to the creation of pores. M. Myglovets *et al.* (2014) pointed to the destruction of polymeric lignin chains and carbon oxidation. Water vapour, carbon monoxides (both carbon monoxide and carbon dioxide), and volatile phosphorus compounds were the products of these processes. The work of H.M. Boundzanga *et al.* (2022) found that during activation with orthophosphoric acid, lignin forms micropores in the adsorbent, unlike hemicelluloses and cellulose, which were responsible for the formation of mesopores in it. Therefore, treating coffee waste with an orthophosphoric acid solution will help to destroy the lignin-cellulose complex and form additional pores of different sizes. By creating phosphorus-containing surface groups, orthophosphoric acid also contributed to the stabilisation of the carbon backbone.

After treating the coffee grounds samples with orthophosphoric acid without the influence of temperature, the specific surface area of the adsorbent was 690 m^2/g, an increase in surface area of 23% compared to untreated coffee grounds. The most effective was the chemical activation with orthophosphoric acid followed by a temperature treatment at 200°C. Under these conditions, the maximum performance was achieved: specific surface area of 1078 m^2/g and water vapour adsorption of 0.543 g H_2O per 1 g of sample, which exceeded the characteristics of some commercial activated carbon samples (705 m^2/g). Studies had shown that combined chemical and heat treatment does not always provide a linear improvement in properties. For example, activation at 400°C and 600°C after chemical treatment showed a gradual decrease in adsorption capacity. The results of the correlation between the adsorption time and the amount of methylene blue elimination were displayed in Figure 3.

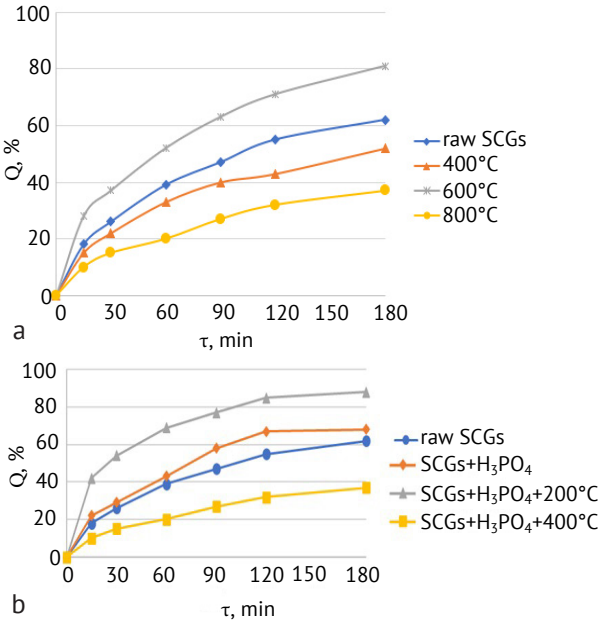


Figure 3. *Dependence of methylene blue adsorption (Q, %) on time*

Note: *a – for thermal treated coffee grounds samples; b – for coffee grounds samples after treatment with orthophosphoric acid and combined treatment (thermal + H3PO4)*
Source: *developed by the author*

When the adsorption characteristics of coffee grounds were examined at several temperature ranges,

the findings revealed patterns that were mostly consistent with their specific surface area value. The coffee grounds' adsorption capabilities were merely average without heat treatment, reaching only roughly 60% of the maximal value. At 400°C, there was no significant improvement in the ability to adsorb substances. The most optimal heat treatment temperature for achieving maximum adsorption performance was 600°C. Figure 3, a showed that the methylene removal reached about 80-85% of the highest possible value, which was the best result among all studied regimes. Increasing the temperature to 800°C significantly reduced the adsorption capacity of the spent coffee grounds and led to a decrease in the number of pores in the adsorbent and a decrease in the diversity and number of surface functional groups.

When compared to the unaltered samples, the adsorption capacity of coffee grounds was marginally enhanced by the chemical treatment with orthophosphoric acid. The best adsorption properties were shown by the samples after combined treatment with orthophosphoric acid and a temperature of 200°C. For these samples, a 57% adsorption rate was achieved at an adsorption time of 30 min, and almost 90% of methylene blue was adsorbed in 180 min. The optimal conditions for modifying used coffee grounds were low-temperature combined treatment of spent coffee grounds with orthophosphoric acid.

Conclusions

The study of the adsorption characteristics of spent coffee grounds showed that modified SCGs were a promising biosorbent for wastewater treatment from organic dyes. The optimisation of adsorption properties was achieved by combined thermal and chemical activation.

The study's findings demonstrated that raising the heat treatment temperature does not necessarily result in a linear rise in the specific area and enhancement of the adsorbent's adsorption properties. It was found that the treatment of coffee grounds at 400°C and 800°C does not improve the adsorption efficiency of methylene blue, but rather worsens it compared to untreated samples. The most effective thermal activation temperature was 600°C, which increased the specific surface area to 958 m^2/g.

Treatment with a 60% solution of orthophosphoric acid improved the adsorption characteristics, in particular, increased the specific surface area by 23% (up to 690 m^2/g). However, a combination of chemical and heat activation produced the best outcomes. The treatment of coffee grounds with orthophosphoric acid followed by thermal activation at 200°C resulted in a specific surface area of 1078 m^2/g and water vapour adsorption of 0.543 H_2Og per 1 g of sample, which exceeded the characteristics of some commercial activated carbon samples. The most successful method for eliminating methylene blue from model solutions was combined treatment, which combined thermal and chemical effects. It enabled the adsorption properties to be improved and the activation temperature to be drastically lowered. The sorbent prepared under these conditions was capable of removing 57% of methylene blue after 30 min of contact with the model solution, and 90% of the dye was removed after 180 min of adsorption.

Further research will be aimed at expanding the range of pollutants that can be removed using modified coffee grounds and investigating the possibility of multiple uses in adsorption and regeneration processes.

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Conflict of Interest

None.

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Оптимізація адсорбційних характеристик відпрацьованої кавової гущі шляхом термічної та хімічної активації

Ірина Мороз
Кандидат хімічних наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0001-9167-4876

Анотація. Метою цього дослідження була оптимізація параметрів адсорбції метиленового синього на відпрацьованій кавовій гущі шляхом поєднання термічної обробки та обробки ортофосфорною кислотою. Дослідження проводилося за допомогою спектрофотометричного методу, інфрачервоної спектроскопії та методу визначення питомої поверхні шляхом адсорбції водяної пари. Запропоновано можливий механізм адсорбції катіонного барвника метиленового синього на кавовій гущі. Було встановлено, що підвищення температури обробки не призводило до лінійного збільшення питомої поверхні та адсорбційних характеристик відпрацьованої кавової гущі. Виявлено, що адсорбційні властивості кавової гущі при температурах 400°C і 800°C були гіршими порівняно з необробленими зразками. Однак термічна активація відпрацьованої кавової гущі при 600°C забезпечила збільшення питомої поверхні на 72 % (з 561 до 958 м²/г). Обробка відходів 60 % розчином ортофосфорної кислоти підвищила питому поверхню на 23 % (до 690 м²/г) у порівнянні з необробленою кавовою гущею. Найефективнішою за адсорбційними характеристиками виявилася комбінована обробка кавової гущі ортофосфорною кислотою з подальшою термічною активацією при 200°C, що забезпечило максимальну питому поверхню 1078 м²/г та адсорбцію водяної пари 0,543 г води на 1 г зразка, що перевищує характеристики деяких зразків комерційного активованого вугілля. За таких умов досягнуто найвищу ефективність видалення метиленового синього з модельних розчинів – 57 % за 30 хвилин і майже 90 % барвника за 180 хвилин контакту. Запропоновані умови модифікації відпрацьованої кавової гущі дозволили отримати ефективний біосорбент для очищення стічних вод від органічних барвників, що має практичне значення для вирішення екологічних проблем у текстильній та поліграфічній промисловості, а також сприяє раціональному використанню відходів кавового виробництва

Ключові слова: біосорбент; кавові відходи; термічна модифікація; фосфатна активація; метиленовий синій

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Fermentation activity of rye sourdough as a quality factor of wheat-rye bread

Vasylyna Shemet*

PhD in Chemistry, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0001-8952-5097

Svitlana Panasyuk

PhD in Technical Sciences, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0001-9734-3998

Olha Hulai

Doctor of Pedagogical Sciences, Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-1120-6165

Abstract. The purpose of the article was to determine the best fermentation activity of rye sourdough starter for the production of wheat-rye bread for health purposes. Natural sourdough bread is popular in the Ukrainian flour market due to its high taste and nutritional value. The developed recipe of wheat-rye sourdough bread contained high-grade wheat flour, rye flour, rye bran, olive oil, salt and sugar, as well as rye sourdough on different days of its fermentation. The sensory analysis was performed and the organoleptic characteristics of wheat-rye sourdough bread were determined. A sensory profilogram of model compositions of wheat-rye bread was constructed and, based on the results of expert evaluation, the model composition with the best organoleptic characteristics was determined. According to the experiment, the starter of the sixth day of fermentation allowed to achieve the highest gas retention capacity and optimal spreading of the dough ball. In the process of fermentation in all the tested samples, an increase in the active acidity of the dough was observed, which affected its quality characteristics. The moisture content and porosity of the finished product obtained with the sourdough starter of the sixth day of fermentation increased by 2.3% and 7.4%, respectively, compared to the values recorded for bread with the sourdough starter of the fourth day of fermentation. There was a slight increase in the fragility of the finished product due to an increase in its porosity. Wheat-rye bread with rye sourdough was beneficial due to dietary fiber, which improved digestion, normalises the microflora, reduces the risk of heart disease, and vitamins and minerals that strengthen the immune system and support energy metabolism

Keywords: moisture; porosity; recipe; organoleptic evaluation; nutritional value

Introduction

In Ukraine, human life and health are defined as the highest social value. S. Kvasha *et al.* (2024) argued that food security was a systemic element of national security, which guaranteed effective management of

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*Corresponding author

the food system, ensuring that food needs were met in the proper quantity and quality for every citizen of the country. Similarly, O. Ivanishcheva & O. Pakhomska (2021) pointed out that food quality and safety were one of the key indicators of population well-being. In this context, the production of bakery products with functional properties was of particular relevance.

Modern bakeries were faced with the task of expanding the range of products aimed at preventing diseases and maintaining consumer health. This required the development of new recipes and the enhancement of current production processes to guarantee the addition of biologically active substances to bakery goods. Therefore, an innovative approach to the baking industry was becoming an important tool in improving the quality of life of the population.

Sourdough starter cultures had attracted considerable attention of scientists. K. Papadimitriou *et al.* (2019) studied its impact on bread quality, focusing on the prospects for using alternative raw materials, innovative fermentation technologies, and expanding the range of bakery products. O. Naumenko & V. Chizh (2022) divided sourdoughs into four types depending on the preparation process and the metabolic activity of the bacteria and yeast they contain. Type I starters were a mixture of flour and water to which a pre-fermented starter was added. It was usually a viscous with a pH range of 3.8 to 4.5, which was fermented at a temperature of 20°C to 30°C. A primarily liquid blend of flour and water, the Type II starting culture fermented for up to five days at temperatures higher than 30°C. Type III sourdough was made by drying a flour and water mixture to induce dormancy in microorganisms. Before use, it was reactivated and re-suspended in water, most often it was used for large-scale baking. Type IV sourdough (mixed), consisted of a mixture of types I and II.

Scientists N. Hernández-Parada *et al.* (2023) noted that the ratio of lactic acid bacteria and yeast, their growth and metabolic activity, which determined the physical, chemical, biochemical and sensory characteristics of sourdough bread, depend on the fermentation and storage temperature of the sourdough. Most often, a temperature equal to 30°C was used for fermentation of sourdough. At the same time, A.S. Amr & A.M. Alkhamaiseh (2022) emphasised that the growing popularity of sourdough bread was driven by consumer demand for a natural product with a rich taste, balanced properties, and a long shelf life, which met modern ideas of healthy eating.

The authors V. Bandura & K. Teplyuk (2024) devoted their study to the development of a recipe for the latest technologies of bakery products with a low sugar content. In particular, it was proposed to introduce stevia extract into the recipe of bakery products, which can reduce the sugar content in products and give them functional properties. C.B. Munch-Andersen *et al.* (2024) investigated the impact of fermentation temperature on the pH stability of starter cultures and the shift in microflora during the fermentation of bean flour starter cultures. The findings demonstrated that fermentation can raise the nutritional content and quality of goods made from beans.

I.T. Akamine *et al.* (2023) investigated microorganisms from sourdough that produse enzymes (glutenase, amylase, cellulase, peptidase) that contribute to the reduction of allergenic molecules in wheat flour, while preserving its baking properties. The results of the study opened up opportunities for the development of innovative starter cultures with improved properties and increased nutritional value.

The aim of this study was to evaluate the effect of the fermentation time of rye sourdough on the quality and nutritional properties of wheat-rye bread.

Materials and Methods

The research was carried out in 2024 at Lutsk National Technical University. Model samples of craft wheat-rye bread on rye sourdough were made according to the recipe indicated in Table 1. To determine the best fermentation property of rye sourdough, samples of dough were prepared from premium wheat flour, rye flour and rye bran with the addition of rye sourdough on the fourth (sample 1), fifth (sample 2), sixth (sample 3) and seventh (sample 4) days of its fermentation. Sampling of flour used as the main raw material in the recipe was carried out in accordance with GOSTU 46.004-99 (1999) and DSTU 8791:2018 (2019). For the production of bread and bakery products, it was necessary to use flour that had a good ability to form dough with appropriate structural and mechanical properties. This ability was characterised by an indicator of the strength of flour – a physical property that can be assessed by the spread of a ball of dough during proofing. Accordingly, the strength of flour affected the quality of finished bakery products and determined their volume, texture and porosity.

Table 1. *Recipe for wheat-rye bread on rye sourdough*

Raw material	Mass, kg	Moisture, %	Dry matter weight, kg
Premium wheat flour	46.0	14.0	39.6
Rye flour	30.0	14.0	25.8
Rye bran	3.0	14.0	2.6
Sourdough (rye flour)	21	50.0	10.5

Table 1. Continued

Raw material	Mass, kg	Moisture, %	Dry matter weight, kg
Olive oil	5.0	–	–
Food salt	3.0	–	3.0
Granulated sugar	6.0	–	6.0
Together	114		87.5

Source: *developed by authors*

The study was carried out using physicochemical and organoleptic methods in accordance with regulatory documents DSTU 7045:2009 (2010) and DSTU 9188:2022 (2023). Using sensory testing techniques, the organoleptic properties of wheat-rye bread on rye sourdough were ascertained by H.T. Lawless & H. Heymann (2010). The assessment was carried out by the method of expert assessments on a 5-point scale. Figure 1 displayed cross-sectional prototypes created using the recipe listed in Table 1.

Figure 1. *Sections of test samples of bread*

Note: *a – sample 1; b – sample 2; c – sample 3; d – sample 4*
Source: *developed by the authors*

According to the method described by V. Drobot *et al.* (2021), the influence of the fermentation time of the starter culture on the structural and mechanical properties of the dough was experimentally determined, and the gas-forming ability of the dough was determined according to the method described by Z.I. Kucheruk & O.S. Tsukanova (2014). Active acidity was determined using a generally accepted technique by D. Hasenay *et al.* (2006). Using the approach outlined by C. Simons (2018), the moisture content of wheat-rye bread samples was ascertained, also in compliance with DSTU 7045:2009 (2010). The approach outlined by T.V. Bozhko *et al.* (2019) was used to investigate the porosity of bread. For this purpose, the Zavyalov method was used using Zhuravlev's device (Ukraine), by weighing three cylindrical samples with a volume of 27 ± 0.5 cm^3 each, which was designed to isolate a sample of a certain volume from a bakery product, according to the results of weighing which the porosity of bread was determined by calculation. Bread staleness was assessed using the method of T.A. Sylchuk (2004). The research was conducted in accordance with standards of The Declaration of Helsinki (2013).

Results and Discussion

To determine the best fermentation activity of rye sourdough, dough samples were prepared according to the recipe given in Table 1, changing the type of sourdough depending on its fermentation time. The spread of the dough ball was used to examine, how the various sourdough fermentation activities affected the dough's viscosity. The dough sample was shaped into 50 mm-diameter balls. The dough ball's diameter was measured after the fermentation procedure, which lasted four hours at 30°C, was finished. The dough balls' diameter changed during the fermentation process, as seen in Figure 2. The diameter of the dough ball changed the least in sample 1, indicating that the starter was not active enough. Sample 3 had the highest sourdough activity, as seen by the dough ball's biggest diameter. Additional variations in the dough ball's diameter were negligible. V. Drobot *et al.* (2021) also investigated the effect of different amounts of rice flour on the viscosity of the dough by changing the volume of the dough ball during its fermentation process. It was found that the diameter of a ball of dough with rice flour during fermentation decreased by 3.7-18.5%, depending on the dosage. In this study, an increase in the diameter of the dough ball with an increase in the fermentation activity of the starter culture has been experimentally established.

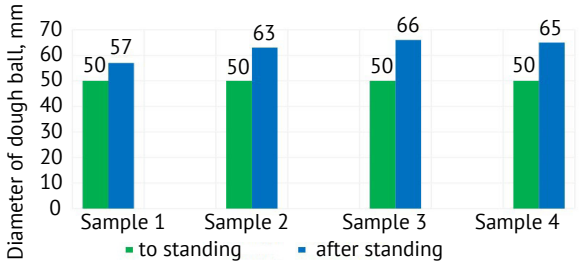

Figure 2. *Changing the diameter of the dough ball*
Source: *developed by authors*

During the study of the gas-forming capacity, the change in the volume of dough samples during fermentation was determined. The initial volume of dough samples was measured by placing them in a measuring cylinder. The dough was left to ferment for 4 hours in a proofing cabinet at 30°C. After the fermentation process was completed, the volume of dough samples was determined (Table 2).

Table 2. *Dough volume before and after fermentation*

No. sample	Dough volume, cm³				
	0	60	120	180	240
1	10.0	11.3	12.8	15.7	19.1
2	10.0	11.5	16.4	21.1	22.3
3	10.0	12.2	17.1	22.2	24.5
4	10.0	12.5	16.6	22.6	23.9

Source: *developed by authors*

The dough of sample 3 had the highest gas retention capacity, while sample 4 had a slightly lower value. The study found that the sourdough reaches its maximum activity on the sixth day of fermentation, so it is during this period that it is most advisable to use it to obtain a finished product. The gas-forming ability of the dough was determined according to the method described by Z.I. Kucheruk & O.S. Tsukanova (2014) and their experimental studies showed that with an increase in the amount of xanthan to 0.3% to the weight of starch, the specific volume of the dough improves, and with the amount of xanthan 0.5% to the weight of starch, this figure decreases, which may be due to the inhibition of fermentation. It was demonstrated in this study that, when the starter's fermentation activity increased, so did the dough's volume.

Understanding the acidity of the dough and bread medium was crucial for comprehending the chemical reactions that take place during baking and for advancing the technology used to produce bakery goods. The final product's quality, especially its taste and texture, can be better controlled as a result of these scientific advancements. Thus, the authors I. Banu *et al.* (2011) found that the pH value of the starter culture differs for samples of dark rye flour and whole grain rye flour that were fermented at 30°C and 37°C for 24 hours using different microbiological cultures. The pH value varies depending on the composition of the flour and the physicochemical properties. Rheological analysis of samples carried out by R. Mūrniece *et al.* (2023) showed that the pH value varies between 4.09 and 5.15 for rye bread and from 4.26 to 4.89 for barley bread made by brewing flour and without brewing, respectively. This indicates the effectiveness of fermentation of the dough by brewing with a high content of reducing sugars.

Because wheat flour was used in the recipe, the active acidity values of the dough samples for wheat-rye bread on rye sourdough created in this study were greater than the initial data from the literature (pH 6.1-6.3). It had been demonstrated that the dough's acidity reduces in all samples throughout the fermenting process. This indication dropped to 5.2 in samples 1 and 2, then declines to 5.4 in samples 3 and 4. (Fig. 3). Therefore, using starting cultures increases the dough's acidity buildup, which speeded up its maturation and enriches goods with organic acids, minerals, and dietary fiber found in flour. In addition, studies by authors K.S. Aplevicz *et al.* (2013) and A. Korzhenivska *et al.* (2019) experimentally confirmed a decrease in the pH value of dough and bread with increasing fermentation time. Laboratory tests of this research also confirmed this pattern.

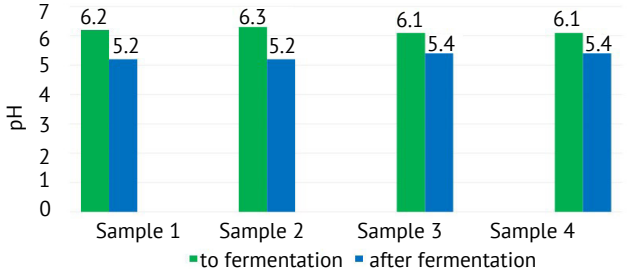

Figure 3. *Diagram of changes in the acidity of dough during its fermentation*

Source: *developed by authors*

Two important measures of the quality of wheat-rye sourdough bread were the crust's moisture content and the crumb's porosity. As noted by M. Gharekhani *et al.* (2021), these qualities relied on the type of starting culture, and how long it was stored after baking. The researchers discovered that as the crumb's storage time increased, its moisture content gradually dropped. When examining the porosity of sourdough bread samples from microbiological cultures, I. Banu *et al.* (2011) determined that this indicator is lower for bread made from whole grain rye flour compared to bread made from dark rye flour. Figure 4 displayed the findings of identifying these markers for the research samples.

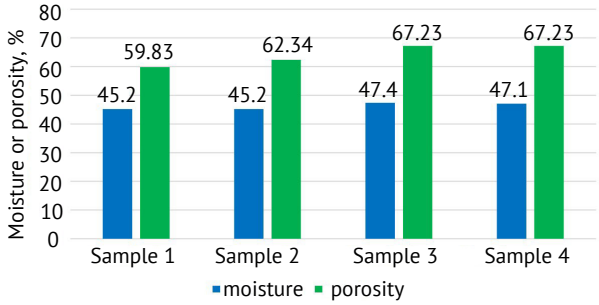

Figure 4. *Calculated values of moisture and porosity of bread crumb*

Source: *developed by authors*

The moisture content of bread made from a mixture of rye and wheat flour should be no more than

41.0-53.0% (DSTU 4583:2023, 2024). Sample 3 had the highest moisture content (47.4%), whereas samples 1 and 2 had the lowest (45.2%). The moisture content of each examined sample was within allowable bounds. The porosity of bread made from a mixture of rye and wheat flour according to (DSTU 4583:2023, 2024) must be not less than 46.0%. The porosity of the final product increases as the sourdough's activity increases, according to the study of the bread crumb's porosity values. The porosity of bread samples 3 and 4 was the highest and amounted to 67.23%. This was a 7.4% increase compared to sample 1.

The length of time that bread and bakery goods were preserved was one of the most crucial markers of their freshness. Numerous factors affect bread's freshness, including its composition, the way the dough was prepared, and the addition of ingredients that slow down the staleness process, which can be measured using the fragility indicator. The estimated average values of brittleness of bread samples were given in Table 3.

Table 3. *Average values of bread brittleness*

Sample	Brittleness, %		
	3 hours after baking	24 hours after baking	48 hours after baking
1	0.9	2.5	3.5
2	1.1	3.1	4.4
3	1.4	3.2	5.5
4	1.4	3.3	5.6

Source: *developed by authors*

Samples 3 and 4 lost freshness the fastest (the maximum brittleness value 48 hours after baking was 5.5% and 5.6%, respectively) due to the higher porosity of the finished products. Sourdough-made wheat-rye bread had a long-lasting freshness, a strong scent, and a mildly sour taste. The specialists' organoleptic examinations and data from the literature verified that the bread had an elastic texture and a porous crumb with thin pore walls. The results of sensory evaluation of bread samples carried out by D. Djukić *et al.* (2014) showed that depending on the method of kneading, bread with different organoleptic and physicochemical parameters can be obtained. Optimising the rye sourdough fermentation process helped provide a rich profile of flavour and volatile chemicals that enhance the bread's sensory qualities, when added. The process of reproduction resulted in the activation of beneficial components and the formation of new compounds with various functional qualities that improved the bread's quality. The biodiversity of lactic acid bacteria (LAB) for fermentation was investigated by L. de Vuyst & M. Vancanneyt (2007), while M.G. Gänzle *et al.* (2023) showed that recent advancements had modified the selection criteria for starter cultures and expanded tools for assessing their metabolic potential. The results of expert evaluation of bread samples were presented in Table 4.

Table 4. *Organoleptic parameters of bread samples*

No. sample	Sample 1	Sample 2	Sample 3	Sample 4
Indicator	From wheat and rye flour, rye bran and sourdough on the fourth day of fermentation	From wheat and rye flour, rye bran and sourdough on the fifth day of fermentation	From wheat and rye flour, rye bran and sourdough on the sixth day of fermentation	From wheat and rye flour, rye bran and sourdough on the seventh day of fermentation
Surface condition	Smooth, slightly rough, without undermining, with small cracks	Smooth, slightly rough, without undermining, with small cracks	Smooth, slightly rough, without undermining and cracks	Smooth, slightly rough, without undermining and cracks
Crust colour	Light brown	Light brown	Light brown	Light brown
Colour of the crumb	Light brown with brown bran blotches	Light brown with brown bran blotches	Light brown with brown bran blotches	Light brown with brown bran blotches
Porosity	With uneven pores, thin-walled and small	With uneven pores, thin-walled and small	With uniform pores, thin-walled and small	With uneven pores, thin-walled and large
Taste	Characteristic of products made from wheat and rye flour and bran, a slightly sour taste characteristic of rye products	Characteristic of products made from wheat and rye flour and bran, a slightly sour taste characteristic of rye products	Characteristic of products made from wheat and rye flour and bran, a slightly sour taste characteristic of rye products	Characteristic of products made from wheat and rye flour and bran, a slightly sour taste characteristic of rye products
Smell and aroma	Characteristic of products made from wheat and rye flour and bran	Characteristic of products made from wheat and rye flour and bran	Characteristic of products made from wheat and rye flour and bran	Characteristic of products made from wheat and rye flour and bran

Source: *developed by authors*

All of the bread samples that were analysed had smooth, somewhat rough surfaces, and samples 3 and 4 showed no signs of undermining or cracking, according to the experts. Every sample had a light brown

crust, and the crumbs had light brown bran blotches throughout. In sample 3, the porosity is fairly uniform with thin-walled and small pores, in samples 1, 2 and 4 it is uneven with small and large pores. All of the samples under study had a taste that was typical of goods derived from wheat and rye flour and bran, with rye items having a somewhat sour flavour. Products created from wheat and rye flour and bran also had a distinct scent and aroma. According to the results of the expert evaluation, sample 3 received the highest overall score: its porosity was rated at 4.9, and all other indicators were rated at 5. Sample 4 was the best rated for crust and crumb colour, taste, smell and aroma, but received 4.9 points for surface condition and 4.8 points for porosity. Sample 2 received the highest scores for crust colour, smell and aroma, while taste was rated at 4.8 and surface condition, crust colour and porosity at 4.9. The lowest scores were for sample 1: surface condition, crumb colour and taste received 4.9 points, while crust colour, porosity, smell and aroma received 4.8 points. A sensory profilogram of bread samples was presented in Figure 5.

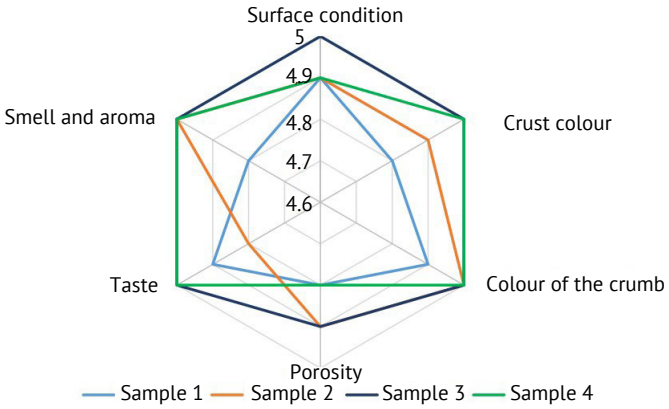

Figure 5. *Sensory profilogram of bread samples*

Source: *developed by authors*

The calorie content of wheat-rye sourdough bread is slightly higher compared to bread baked using yeast. S. Plessas (2021) and A.S. Subaşı & R. Ercan (2023) emphasised that sourdough starter enriches bakery products with dietary fibre, vitamins, in particular vitamin A, group B, PP, and minerals: potassium, calcium, magnesium, sodium, phosphorus, and others. A technological plan for making wheat-rye bread on rye sourdough was created as a result of fermentation process analysis and experimental research, and it was shown in Figure 6. Based on the findings of research on the physical and chemical features of raw materials and final products, as well as the effectiveness of employing rye sourdough, this plan considered the ideal criteria for attaining the desired taste qualities and quality of the final product.

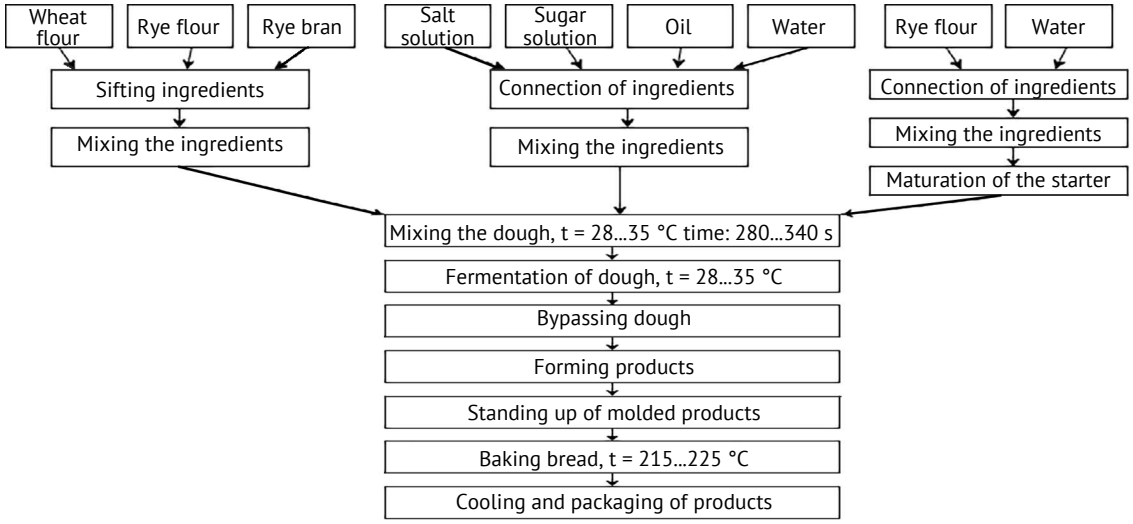

Figure 6. *Technological scheme of bread production*

Source: *developed by authors*

The rye sourdough was prepared as the first step in making sourdough bread. Water and rye flour were used to make it. According to experimental research, the starting culture from the sixth day of fermentation was the most active, and using it produced satisfactory quality indicators for the final product. Then dry ingredients, namely premium wheat flour, rye flour and bran, were prepared, sifted and passed through a magnetic separator to remove impurities from them. Next, the purified dry components in the quantities determined by the recipe were served for mixing to obtain a homogeneous mixture. Water, vegetable oil, and premade table salt and sugar solutions were added to the container separately. After adding sourdough to the mixture, the dough was kneaded for 280-340 s and allowed to ferment for 40-50 min at 28-35°C. Once the dough was prepared, it was kneaded and used to create bread with a specific mass and shape. The formed products were placed on a baking sheet and left to stand in a proofing cabinet for 40…60 min. The next step was to bake bread in a convection oven at a temperature of 215…225°C for 25…30 min. Finished products were cooled, packaged and stored for transportation to retail chains.

The authors I. Shevchuk *et al.* (2016) investigated the directions of regional food security policy of developed countries in the context of interrelated economic, social and environmental components, emphasising the importance of innovations in this area. In this context, the developed technology of bread production will contribute to strengthening food security both at the regional and national levels. Determining the ideal sourdough fermentation period was one of the most important aspects of bread quality. As noted by M. Sluková *et al.* (2021), the prolonged fermentation of rye sourdough had a positive effect on the texture of the bread, as well as on the characteristic sour taste and distinct aroma of the bread. Studies by Z. Alkay *et al.* (2024) demonstrated, how sourdough fermentation impacted a variety of nutritional elements, such as dietary fiber, vitamins, phenolic compounds, glycemic index, salt reduction, mineral bioavailability, and the digestibility of starch and protein. Sourdough fermentation increased nutrient availability, which benefited customers' general health and wellbeing. R. Laatikainen (2023) highlighted that the employment of various sourdough fermentation techniques resulted in a more noticeable sour flavour and improved bread texture, and that the selection of yeast strains and bacteria that affect bread flavour was crucial. According to M. Gharekhani *et al.* (2021), bread with reduced hardness and more flexibility was made possible by starters fermented by lactic acid bacteria that had high levels of EPS synthesis, proteolytic activity, and acidification qualities. V. Chechitko (2024) noted that during fermentation, some microorganisms can become probiotics, which were beneficial for the intestinal microflora. The paper by R. Mūrniece & D. Klava (2022) focused on the selection of LAB strains that produce exopolysaccharides (EPS) in rye sourdough. A lengthy sourdough fermentation period and the use of scorching rye flour were crucial because they influenced the quantity of sugars needed for fermentation and the substrate needed to produce EPS, which enhanced the bread's quality and postponed its staleness. The impact of the sourdough period on bread quality parameters as moisture, porosity, shelf life, and fragrance and aroma was validated by this study.

Conclusions

Fermentation processes play a key role in the production of bread, as they significantly affect its physicochemical and organoleptic properties. Specifically, the length of fermentation, the type of starter culture, and the flour composition can alter the dough's pH as well as the final product's texture, flavour, and scent. Numerous studies pointed to the significance of these factors for improving the quality of baked goods.

As a result of the research, it was found that the best quality indicators of wheat-rye dough and finished products were achieved, when using sourdough on the sixth day of its fermentation. In comparison to products made on the sourdough on the fourth day of fermentation, the dough's maximum gas-retaining capacity was reached during this time, the dough ball spread optimally, and the final products' moisture and porosity increased by 2.3% and 7.4%, respectively. A slight increase in the fragility of products was due to an increase in their porosity.

The resulting bread samples had a mild sour taste, pronounced aroma and long-term freshness. Their crumb was porous, with thin pore walls, which gave the bread an elastic texture. These signs indicated the high quality of bread. As a result of experimental research and analysis of literature sources, a technological scheme for the production of wheat-rye bread on rye sourdough had been developed. The resulting wheat-rye bread was of high quality, enriched with dietary fiber, vitamins: vitamin A, group B, PP, and minerals – potassium, calcium, magnesium, sodium, phosphorus thanks to rye sourdough.

Further research will be aimed at testing the addition of vegetable and fruit powders to wheat-rye bread, which will increase the range of health bread.

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Conflict of Interest

None.

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Бродильна активність житньої закваски як фактор якості пшенично-житнього хліба

Василина Шемет
Кандидат хімічних наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0001-8952-5097
Світлана Панасюк
Кандидат технічних наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0001-9734-3998
Ольга Гулай
Доктор педагогічних наук, професор
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-1120-6165

Анотація. Метою статті було визначення найкращої ферментаційної активності житньої закваски для виробництва пшенично-житнього хліба для оздоровчих цілей. Натуральний заквасний хліб популярний на українському ринку борошняних виробів завдяки високим смаковим і поживним властивостям. Розроблений рецепт пшенично-житнього хліба містив борошно пшеничне вищого ґатунку, житнє борошно, житні висівки, оливкову олію, сіль і цукор, а також житню закваску на різних стадіях її ферментації. Було проведено сенсорний аналіз і визначено органолептичні характеристики пшенично-житнього хліба. Побудовано сенсорну профілограму модельних зразків пшенично-житнього хліба, і, за результатами експертної оцінки, визначено модельну композицію з найкращими органолептичними властивостями. За результатами експерименту, закваска шостого дня ферментації забезпечила найвищу газоутримувальну здатність і оптимальне розтікання тістового шару. У процесі ферментації у всіх досліджуваних зразках спостерігалося підвищення активної кислотності тіста, що впливало на його якісні характеристики. Вміст вологи та пористість готового виробу, отриманого із закваскою шостого дня ферментації, збільшилися на 2,3 % та 7,4 % відповідно порівняно з хлібом на заквасці четвертого дня ферментації. Відзначено незначне збільшення крихкості готового виробу через зростання його пористості. Пшенично-житній хліб на житній заквасці був корисним завдяки вмісту харчових волокон, що покращують травлення, нормалізують мікрофлору, знижують ризик серцевих захворювань, а також вітамінів і мінералів, які зміцнюють імунну систему та підтримують енергетичний обмін

Ключові слова: вологість; пористість; рецепт; органолептична оцінка; поживна цінність

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Development of technology and study of properties of gluten-free shortbread biscuits

Yurii Hunko
PhD in Technical Sciences, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-1441-9625
Serhii Holiachuk
PhD in Agricultural Sciences, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-4835-8154
Yurii Fedorus*
PhD in Technical Sciences, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-6700-7712

Abstract. The number of persons with gluten intolerance is rising in the modern world, which calls for the creation of specialised goods that may satisfy their demands. The aim of the research was to develop a recipe for gluten-free shortbread biscuits with cherry filling. The research was carried out using the expert method, sensory analysis and statistical methods of processing research data. To achieve this goal, it was proposed to use a mixture of almond and coconut flour as a raw material for shortbread buiscits. It had been determined that the development of gluten-free products required the implementation of innovative technologies, the incorporation of alternative ingredients, and the analysis of the properties of raw materials and final products. Various model compositions of shortbread biscuits were developed based on mixtures of almond and coconut flour with different proportions of the mixture components (MC1 – 75:25, MC2 – 50:50, MC3 – 25:75). A sensory analysis of the model compositions of gluten-free shortbread biscuits was carried out, and their organoleptic characteristics were determined. As a result of the studies, a sensory profilogram of model shortbread compositions was obtained, which can be used to determine, which model composition was characterised by the best indicators (it was found that MC1 had the best indicators). The brittleness index of gluten-free shortbread biscuits was also determined depending on the content of almond flour in the mixture. The physicochemical parameters of various model compositions of gluten-free shortbread biscuits were determined and the results of these studies were analysed. The development of gluten-free shortbread biscuits with cherry filling allows expanding the range of flour confectionery products with a healthful orientation

Keywords: gluten; almond flour; coconut flour; moisture; organoleptic evaluation; nutritional value

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*Corresponding author

Introduction

Over the 2000-2020 years, a growing emphasis on developing new, healthier goods has been placed on flour production. In this aspect, the problem of increased sensitivity of the human body to gluten should be highlighted. Wheat flour, which was a component of confectionery flour products, contained gluten, a substance that belonged to the group of vegetable proteins (gluten). Many consumers are sensitive to gluten. And according to H.F. Hassan *et al.* (2024), up to 1% of people in the world were affected by an autoimmune reaction in the small intestine caused by gluten consumption.

Gluten contained the proteins glutenin and gliadin, which interacted to give the product its viscoelastic properties. Historically, access to gluten-free products had been limited, with few types of gluten-free raw materials available and almost all gluten-free production done in the home. The gluten-free diet, which was becoming increasingly relevant, provided health benefits, helped to lose excess weight, improved digestion, and strengthened the immune system. A. Lerner *et al.* (2019) noted that in conditions, where the human body was dependent on gluten, a gluten-free diet was the cornerstone of treatment, improving health and quality of life, and treating or preventing related complications. M. Tanveer & A. Ahmed (2019) stated that the only available treatment for celiac disease, wheat allergy, was to avoid gluten. Gluten-free products provided relief to people with gluten intolerance, and therefore the need to produce gluten-free products and provide such products to the food market was becoming relevant.

Therefore, the task was to replace wheat flour with alternative types of flour for the preparation of confectionery flour products that do not contain gluten, the natural allergen. In particular, coconut flour can be such an alternative type of flour. Rich in vitamins, minerals, and dietary fiber, coconut flour had a distinct flavour and scent that may find use in baking and human nutrition. M. Raczyk *et al.* (2021) suggested using coconut or chestnut flour as an alternative raw material in the manufacture of bakery products to replace wheat flour, which can give the product an attractive taste and improved nutritional characteristics, in particular, a higher fiber content. Coconut flour, as noted by R. Jiamjariyatam *et al.* (2021), when used for the production of biscuits, gave the product crumbliness, coconut flavour and aroma.

S. Azizi *et al.* (2020) suggested the use of quinoa flour in bread production. The authors noted that the lipase and protease enzymes can had a positive effect on the quality of the product, in particular by slowing down staling. The features of the use of hydrocolloids in gluten-free breads were studied by M. Belorio & M. Gómez (2020). This innovative approach was a strategy to improve bread quality and obtain a product with improved structural and textural properties.

Additionally, confectionery flour items can be made with almond flour. Almonds were gluten-free and almond flour had a high fat content (about 50% of the total weight). This flour also had a sufficient amount of high quality proteins (about 20%). Vegetable fats do not contain cholesterol, and the complex of omega fatty acids contained in almonds had a beneficial effect on blood vessels. Almond flour was also characterised by a high zinc content of 2.12 mg/100 g of product (17.7% of the daily requirement for this micronutrient).

According to B. Sustriawan *et al.* (2021), during manufacturing of biscuits, replacing wheat flour with almond flour and adding vegetable fat can significantly affect the final properties of the product and improve the flavour. In addition to almond flour, they also considered sorghum flour as an alternative to wheat biscuits. R. Gillespie & G.J. Ahlborn (2021) considered about using oat bran and almond flour instead of wheat flour to make gluten-free ketogenic bread. The authors claimed that using these alternatives improved the product's quality metrics. Different fruit fillings can be used to make shortbread cookies. M. Alam *et al.* (2024) claimed that the quality of fillings can be improved by using a variety of hydrocolloids in the formulations of fillings for different types of fruits. According to the authors, the properties of fruit fillings were influenced by factors such as fruit choice, fruit processing methods and hydrocolloid properties.

The aim of the study was to develop a recipe for craft shortbread cookies with fruit filling and to determine the organoleptic, physicochemical characteristics of the new product.

Materials and Methods

Model examples of artisanal shortbread biscuits prepared using the recipe in Table 1 were the subject of a 2024 study at Lutsk National Technical University. Model compositions (MC) of shortbread cookies without gluten were made using varying proportions of almond and coconut flour. During of the research, coconut and almond flour were analysed, and its samples were analysed for the following quality indicators: moisture content, particle size distribution, and organoleptic characteristics. The dough was prepared from a mixture of almond and coconut flours at different ratios. Samples of flour mixtures were prepared by mechanical mixing of flour weights. The dough was made according to the recipe. The mixture of almond and coconut flour was prepared in the proportions: 75:25, 50:50, 25:75.

Table 1. *Model ingredients of shortbread almond-coconut biscuits*

No.	Name of raw material	Raw material consumption per 10 pcs, g		Raw material consumption per 100 pcs, g	
		Gross	Net	Gross	Net
1	Almond flour	128	125	1280	1250
2	Coconut flour	42	42	420	420

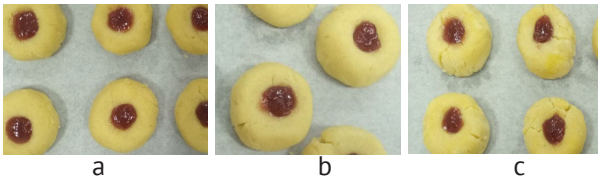
Table 1. Continued

No.	Name of raw material	Raw material consumption per 10 pcs, g		Raw material consumption per 100 pcs, g	
		Gross	Net	Gross	Net
3	Sugar	42	42	420	420
4	Eggs	107	107	1070	1070
5	Honey	13	13	130	130
6	Salt	2	2	20	20
7	Butter	83	83	830	830
8	Amaretto	8	8	80	80
	Weight of n/f dough:		422		4220
9	Cherry	75	75	750	750
10	Starch	1	1	10	10
11	Sugar	11	11	110	110
	Weight of n/f filling:		80		800
	Weight of raw n/f:		502		5020
	Total output of the product:		400		4000

Source: *developed by the authors*

For different flour mixtures, the mass fraction of moisture was by the air-thermal method of determining the mass fraction of moisture using SESh-3M (Ukraine). The moisture content of the cooked dough was determined using the Chizhov machine (Ukraine). From a physicochemical point of view, dough prepared for the production of flour confectionery should be classified as structured masses. By changing the proportions of raw materials or the parameters of the technological process, doughs with different properties and structures can be obtained. The inclusion of new components in the recipe affected the rheological properties of the dough and there was a need to adjust the process parameters, when using new types of raw materials in the dough recipe. The inclusion of new components in the recipe affected the rheological properties of the dough and it was necessary to adjust the process parameters, when using new types of raw materials in the dough recipe. Shortbread biscuits were baked according to a specific mode (baking time – 10...12 min, baking temperature – 180...200℃).

The biscuit samples were tested using physicochemical and organoleptic methods in accordance with the requirements of regulatory documents: DSTU 4683:2006 (2007) and DSTU 3781:2014 (2015). Figure 1 showed samples of semi-finished dough products with different proportions of almond and coconut flour.



a b c

Figure 1. *Model compositions of semi-finished dough products with different proportions of almond and coconut flour*

Note: *a – MC1 (ratio of almond to coconut flour – 75:25); b – MC2 (ratio of almond to coconut flour – 50:50): c – MC3 (ratio of almond to coconut flour – 25:75)*
Source: *developed by the authors*

The experimental samples of shortbread biscuits (Fig. 2) were made according to the recipe given in Table 1. Figure 2 showed the model compositions of gluten-free shortbread biscuits with different ratios of almond and coconut flour (the ratio was 75:25, 50:50 and 25:75).

a b c

Figure 2. *Model compositions of gluten-free shortbread biscuits with different proportions of almond and coconut flour*

Note: *a – MC1 (ratio of almond to coconut flour – 75:25); b – MC2 (ratio of almond to coconut flour – 50:50); c – MC3 (ratio of almond to coconut flour - 25:75)*
Source: *developed by the authors*

The studies monitored the ratio of almond and coconut flour and the moisture content of each type of flour and the mixture. The moisture content was also determined for each sample of semi-finished dough products. The moisture content of various biscuit samples was compared to the data collected. The study was conducted in accordance with the requirements of The Declaration of Helsinki (2013).

Results and Discussion

The study determined the indicators of gluten-free shortbread biscuits with cherry filling made from a mixture of almond and coconut flour. The almond flour used in the biscuits gave the products a better density

and higher moisture content, which helped to reduce the overall brittleness (compared to classic shortbread). Due to the high fat content of this flour, it was possible to achieve a higher crispness and a slight crumbling of the biscuits. The coconut flour, which was part of gluten-free shortbread cookies, had a high ability to absorb moisture, which gave the cookies increased dryness and crumbliness. Figure 3 showed the results of the study of the effect of almond flour content on the brittleness of biscuits.

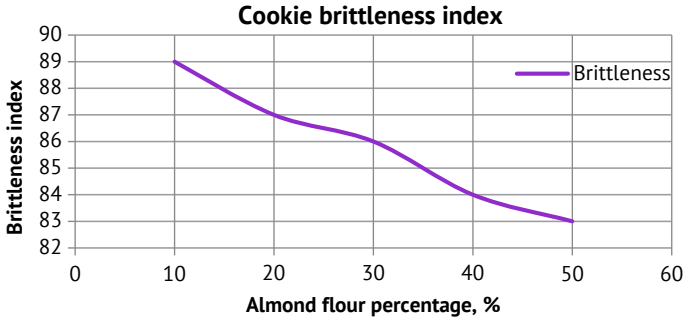


Figure 3. *Dependence of brittleness index on almond flour content*

Source: *developed by the authors*

The brittleness of these gluten-free products primarily depends on the ingredients of the dough (Mushtruk & Mushtruk, 2023). Classic shortbread biscuits made with wheat flour had a brittleness index of 85...95 according to the conventional crumbliness scale. According to the graphical dependence shown in Figure 3, an increase in the content of almond flour in the mixture reduced the fragility of the products. The analysis of physical and chemical parameters of gluten-free shortbread cookies was carried out (three model compositions (MC) of biscuits with a percentage of almond and coconut flour, respectively, 75:25, 50:50, 25:75 were studied). The experiments' findings demonstrated that altering the proportion of almond and coconut flour also altered the goods' moisture content (Table 2).

Table 2. *Results of the study of biscuit moisture content*

No. of MC	Ratio of almond and coconut flour	Moisture content of the finished biscuits
1	75:25	7.5%
2	50:50	9%
3	25:75	10.5%

Source: *developed by the authors*

Table 3 showed the results of determining the physicochemical parameters of biscuits with different contents of almond and coconut flour. In particular, such indicators as the mass fraction of sugar, the mass fraction of fat, and the wettability were determined for model compositions with different ratios of almond and coconut.

Table 3. *Physical and chemical characteristics of gluten-free biscuits*

Indicators	MC1	MC2	MC3
Mass fraction of sugar, %, not more	28.0	26.0	24.0
Mass fraction of fat, %	24.3	21.5	19.2
Wetting capacity, %, not less	170	165	155

Source: *developed by the authors*

DSTU 3781:2014 (2015) specified that the final product must have a moisture content of 5.50 ± 1.5%. The results showed that MC1's moisture content (7.5%) was the most similar to the standard. The final shortbread biscuits from MC2 and MC3 exhibited greater moisture contents (9% and 10.5%, respectively). Products' shelf life was directly impacted by their moisture content; the lower the moisture level, the longer the shelf life. To analyse the organoleptic characteristics of gluten-free shortbread biscuits, a profilogram of organoleptic evaluation of MC1, MC2, MC3 and a control sample of shortbread biscuits made on the basis of wheat flour in accordance with the requirements of DSTU 4683:2006 (2007). Methodology for determination of organoleptic quality indicators, size, net weight and components was obtained (Fig. 4).

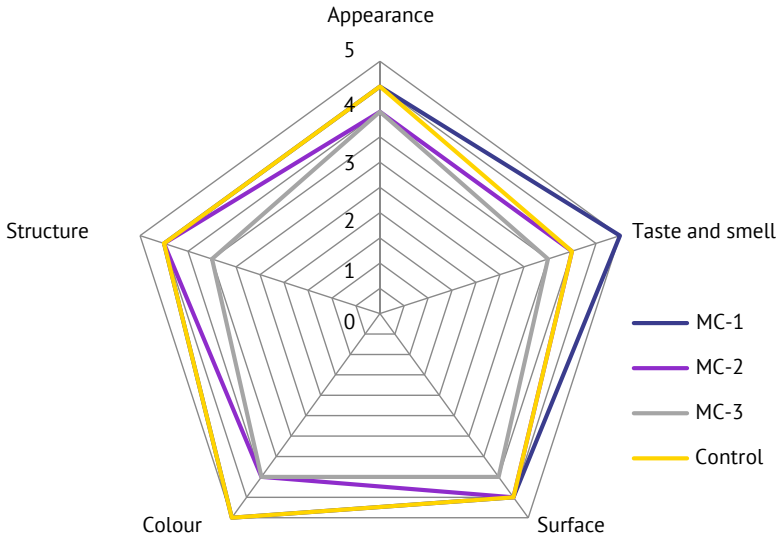


Figure 4. *Profilogram of organoleptic evaluation*

Source: *developed by the authors*

The resulting profilogram of organoleptic evaluation showed that MC1 received the highest scores for organoleptic quality indicators and was the closest in terms of organoleptic indicators to the control sample. Different proportions of coconut and almond flour in the tested samples mainly determine the taste, aroma and texture of gluten-free shortbread biscuits.

In particular, MC3, in which the percentage of coconut flour was 75%, received the lowest organoleptic scores, this sample was characterised by an overly pronounced coconut flavour, as well as a sticky structure and a dense consistency. The low starch and high fat content of coconut flour help to explain this. When developing gluten-free shortbread biscuits made with almond and coconut flour, the filling was selected. The filling was selected – cherry jam. When choosing the filling, consideration was given to the fact that it was best to choose the filling according to the distinct flavour characteristics of the ingredients, when making biscuits using non-standard types of flour. The flavours should be harmoniously combined. For almond and coconut flour, cherry flavour was a compositional match. Cherry jam adds a pleasant sour flavour and a balanced sweet taste. This combination results in good organoleptic characteristics. Table 4 displayed the organoleptic properties of the three almond-coconut shortbread biscuit test samples.

Table 4. *Organoleptic characteristics of gluten-free shortbread biscuits*

Indicators	MC1	MC2	MC3
Surface condition	Smooth, with small cracks in some places	Smooth, with cracks over the entire surface	Uneven, rough, with cracks over the entire surface
Taste and smell	There is a nutty and cherry flavour, the smell is typical for shortbread biscuits	Tangible coconut flavour, cherry flavour, smell typical of shortbread biscuits	Pronounced coconut flavour, smell typical of coconut biscuits
Colour	Light golden over the entire surface	Golden almost over the entire surface, darker at the edges, baked	Dark golden over the entire surface
Shape	Round on the entire surface, without dents and swelling	Round on the entire surface, no damage to the edges	Round, with slight deformations
View in a fracture	The product is baked, the structure is evenly porous, without cavities and signs of unprocessed products	The product is baked, the structure is evenly porous, without cavities and signs of unprocessed products	The product is baked, the structure is dense, without cavities and signs of unprocessed products

Source: *developed by the authors*

The flow chart for the production of gluten-free shortbread biscuits with cherry filling was shown in the Figure 5. The names and order of technological procedures that must be carried out in order to produce a new product were displayed in this figure. The diagram also provided information on the necessary parameters of the technological modes of the operations of the technological process of making gluten-free shortbread biscuits.

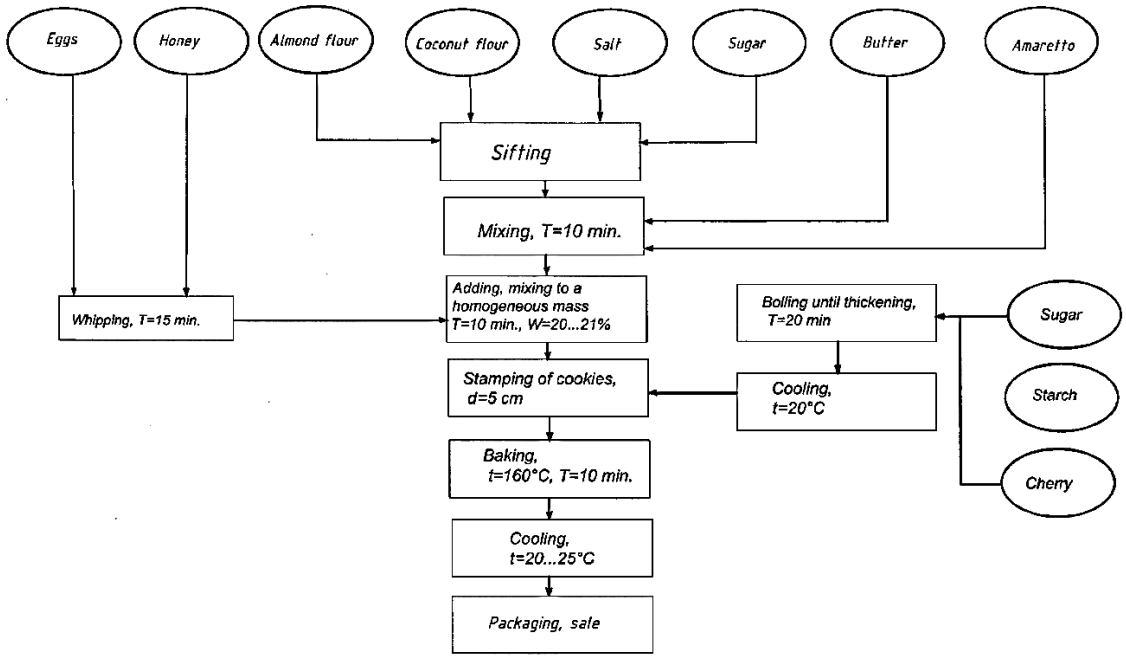


Figure 5. *Process flow diagram of gluten-free shortbread biscuits with cherry filling*
Source: *developed by the authors*

To make biscuits, the first step was to prepare the raw materials. Almond and coconut flour, salt, and sugar were sifted. Next, the eggs and honey were whisked for 15 min until the volume doubles. The jar was filled with a mixture of amaretto, sugar, salt, and almond and coconut flour. After that, the mixture was well combined. The butter was melted and added to the dry mixture and mix for 10 min. The resulting mixture was gradually added to the egg and honey mass and mixed until a homogeneous consistency was obtained. The dough obtained as a result of mixing was rolled out to a 7 mm thick layer and stamped using a round mold with a diameter of d = 5 cm. The cherry filling was obtained by cooking pitted fruit with sugar and starch. The filling was cooked for 20 min until it thickens. After cooking the cherry filling, it was cooled to a temperature of 20℃. Portions of the chilled cherry filling were placed in the center of the dough circle. After that, the dough piece was placed on a tray and baked at 160℃ for 10 min. The finished product was cooled to a temperature of 20...25℃, packaged and sold. It was more acceptable to utilise multiple types of gluten-free flour for shortbread biscuits rather than just one type since the dough and its derivatives had better structural qualities and were more biologically and nutritionally valuable. The mixture of almond and coconut flour used to make shortbread biscuits had a high content of proteins, dietary fiber, healthy fats and minerals, which made the products more nutritious and healthy than cookies made with wheat flour. Almond-coconut biscuits had a lower glycemic index than biscuits made from wheat flour and can therefore be recommended for consumers, who are sugar-conscious. The new product also had an improved flavour profile and texture. The use of almond flour in the recipe results in biscuits with a pleasant nutty flavour, while coconut flour gave the product a special coconut flavour and soft texture.

Research conducted by L. Deinychenko *et al.* (2021) discovered that adding 14.5% by weight of almond flour to the recipe for the doughy semi-finished product "Almond" for cheesecakes increased the product's protein and fat content, while decreasing its carbohydrate content. It also increased the product's zinc, potassium, calcium, magnesium, and phosphorus content. The recipe's use of flaxseed flour and vegetable raw materials allowed for the production of vegetarian-friendly biscuits with 5% more calories than the control sample.

In the study by L. Hopkin *et al.* (2022), ketogenic (low-carbohydrate) gluten-free muffins containing different amounts of almond and coconut flour were investigated for evaluation of textural and sensory properties. It was discovered that the size of the coconut flour particles affected both the product's volume and the muffin crumb's structure; specifically, a smaller flour particle size resulted in a higher product volume and a lower crumb density. It was also found that the particle size of almond flour was not significantly affect the properties of muffins, but an increase in volume was noted in products with a higher content of almond flour, and a higher content of almond flour allowed for a more delicate structure. The studied indicators of adhesion and cohesion for cupcakes showed no statistical difference after 24 hours, and during the subsequent periods of the study, these indicators were insignificant. The authors noted that muffins containing almond flour

contain more moisture and were more tender. Therefore, according to the authors, almond and coconut flours were good substitutes in gluten-free ketogenic muffins, with almond flour providing better results in the parameters evaluated.

The study by A. Bravo-Núñez *et al.* (2019) examined, how protein blends (egg white, whey protein, and pea protein) affected the physical properties of dough and baked gluten-free cakes after substituting 45% of the flour. The addition of new ingredients affected the hardness of the products. The study by H.N. Ramya & S. Anitha (2020) was aimed at investigating the effect of adding honey and different percentages of coconut flour on the quality of cupcakes. In particular, four samples of cupcakes were studied, such as T1 (0% coconut flour content), T2 (5% coconut flour content), T3 (15% coconut flour content) and T4 (25% coconut flour content). Cupcake sample T4 was found to have the finest chemical and physical characteristics. The cupcake samples' sensory qualities were enhanced by adding 25% coconut flour to the batter, which also raised the cupcakes' nutritional content.

In the research by L. Polozhyshnikova *et al.* (2023), rice flour (RF) and coconut flour (CF) were selected as new recipe components for the manufacture of flour confectionery. It was determined that obtaining finished products of the required quality can be achieved by using a composition based on the ratio of RB:CB – 50:50%. The paper by Y. Matsuk *et al.* (2019) scientifically substantiated the recipes and technologies of gluten-free muffins made on the basis of buckwheat and rice flour using chia seeds. The products were characterised by high quality and long shelf life.

The study by Z. Saeidi *et al.* (2018) sought to ascertain, how the physicochemical, sensory, and textural characteristics of a gluten-free rice flour cake were affected by the addition of pomegranate seed powder (0-50%) and transglutaminase enzyme (0-1.2%). The study's findings demonstrated that adding these elements improved the fiber content, ash content, and porosity. The article by O. Shapovalenko *et al.* (2020) discussed the conditions for the use of gluten-free flour obtained from coconuts and brown rice in the technology of gluten-free chocolate muffins. It was found that the complete replacement of wheat flour with the proposed mixture with a ratio of 40:60 (coconut flour to brown rice flour) allowed to achieve the best sensory characteristics.

The authors M. Sahagún *et al.* (2018) examined, how the proteins – rice, peas, egg white, and whey – affected the properties of gluten-free layer cakes. The scientists investigated the qualities of gluten-free cake and examined the dough's density, viscosity, and moisture parameters. Whey protein cakes had the highest acceptance rates among the evaluated samples. M. Kravchenko *et al.* (2021) confirmed the use of a walnut and sesame meal composition to enhance the nutritional qualities of shortbread cookies, which maintained their flavour and odour for 45 days since the higher vitamin E concentration slowed down oxidative processes.

M.H.F. Felisberto *et al.* (2019) evaluated the impact of partial replacement (15%) of wheat flour with young bamboo flour in biscuit recipes. The authors noted positive changes in the characteristics of the new product. Research by M.M. Sanchez-Rivera *et al.* (2019) found a positive effect of plantain flour in the biscuit recipe on the carbohydrate nutritional properties of the product. The study of the properties of fruit fillings was conducted by O. Hrabovska *et al.* (2020). The ability of fillings to maintain the organoleptic, physical, and chemical characteristics of baked goods for the duration of their shelf life was one of the primary needs for flour confectionery items. Therefore, in order to achieve the required properties of heat resistance, viscosity, and harmony of taste, the fruit filling was improved by using stabilising compositions of pectin and modified starch. Thus, the targeted search for innovative solutions for the production of gluten-free flour products in many cases results in a healthy food product with high quality indicators.

Conclusions

A technological plan for making gluten-free shortbread biscuits with cherry filling was created as a result of the study. The resultant biscuits, which had a high protein, dietary fiber, healthy fat, and mineral content, were produced with a blend of almond and coconut flour. The biscuits created by the cutting-edge technology were a result of comprehensive and healthful nourishment because of their qualities.

Model compositions of the new product with different contents of almond and coconut flour in the recipe were studied (for MC1 this ratio was 75:25, for MC2 – 50:50, and for MC3 – 25:75). The physical and chemical parameters for the developed model compositions were determined. Specifically, it was discovered that MC3 had the highest moisture content (10.5%), while MC1 had the lowest and most comparable moisture content (7.5%). The shelf life of biscuits was mostly dictated by their moisture content; the lower the moisture content, the longer the shelf life. The highest fat content was in MC1 (24.3%) and the lowest in MC3 (19.2%), and the wettability index was the highest for MC1 (170) and the lowest for MC3 (155). It was also found that the brittleness of gluten-free shortbread biscuits depended on the content of each type of flour in the biscuit recipe. In particular, with an increase in the content of almond flour from 10% to 50%, the brittleness of the biscuits decreases from 89% to 83%.

According to the results of the expert evaluation, MC1 was characterised by the best organoleptic characteristics (and the closest to those of the control sample), and the lowest scores were given to MC3. Thus, MC1 of gluten-free shortbread biscuits proved to be the

best in terms of its performance, and accordingly, the technology of preparing products according to this recipe was the most promising for recommending the production of nutritious and healthy food products. Fruit fillings using hydrocolloids look promising as a filling for gluten-free shortbread cookies.

So, the growing demand for gluten-free products and the need to expand the range of such products, the development of new innovative ingredients require a wider range of research aimed at developing new technological approaches, the use of which will allow to obtain a new high-quality product for healthy eating. Promising direction for solving the analysed problems is to study the properties of gluten-free flour mixtures in combination with innovative ingredients.

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Розробка технології та дослідження властивостей безглютенового пісочного печива

Юрій Гунько
Кандидат технічних наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-1441-9625
Сергій Голячук
Кандидат сільськогосподарських наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-4835-8154
Юрій Федорусь
Кандидат технічних наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-6700-7712

Анотація. Кількість людей з непереносимістю глютену зростає в сучасному світі, що вимагає створення спеціалізованих продуктів, здатних задовольнити їхні потреби. Метою дослідження було розробити рецептуру безглютенового пісочного печива з вишневою начинкою. Дослідження проводилося із застосуванням експертного методу, сенсорного аналізу та статистичних методів обробки дослідницьких даних. Для досягнення цієї мети було запропоновано використовувати суміш мигдального та кокосового борошна як сировину для пісочного печива. Визначено, що розробка безглютенових продуктів вимагає впровадження інноваційних технологій, використання альтернативних інгредієнтів та аналізу властивостей сировини й готової продукції. Було розроблено різні модельні склади пісочного печива на основі сумішей мигдального та кокосового борошна у різних пропорціях (МС1 – 75:25, МС2 – 50:50, МС3 – 25:75). Проведено сенсорний аналіз модельних складів безглютенового пісочного печива та визначено їх органолептичні характеристики. У результаті досліджень отримано сенсорну профілограму модельних складів пісочного печива, яка дозволяє визначити, який склад характеризується найкращими показниками (було встановлено, що МС1 мав найкращі показники). Також визначено індекс крихкості безглютенового пісочного печива залежно від вмісту мигдального борошна у суміші. Визначено фізико-хімічні параметри різних модельних складів безглютенового пісочного печива та проаналізовано результати цих досліджень. Розробка безглютенового пісочного печива з вишневою начинкою дозволяє розширити асортимент борошняних кондитерських виробів оздоровчого спрямування

Ключові слова: глютен; мигдальне борошно; кокосове борошно; вологість; органолептична оцінка; харчова цінність

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Improving the technology of producing dietary pâtés

Iryna Taraimovych*

PhD, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0003-4129-2671

Tamara Sydoruk

Assistant
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0009-0006-9008-9556

Abstract. The aim of the study was to improve the technology for the production of dietary pâtés by applying Sous vide technology, which will preserve the maximum amount of nutrients, improve the organoleptic properties of the product, increase its safety and shelf life. The paper investigated the possibility of using Sous vide technology for the preliminary thermal processing of the prescription components of liver pâté and the use of ricotta cheese and cashew nuts as enriching additives. Replacing 15.0% of chicken liver in the liver pâté with a similar amount of ricotta cheese and using Sous vide technology for preliminary heat treatment contributed to the formation of a slightly sweet taste, more delicate texture and lighter colour of the finished product; reducing the fat content of the finished product by 15% and increasing the ash content (by 6.3%). The practical feasibility of applying the Sous vide technology and using ricotta cheese in the amount of 10.0% and cashew nuts in the amount of 2.5% in the production of dietary liver pâté was established. The use of gentle heat treatment modes and control of the heating rate preserve the nutritional value of the product and its digestibility, reduce moisture loss and improve the organoleptic characteristics of the finished product. The elimination of added frying oil in the recipe of the finished product made it possible to reduce the proportion of fat by 15% and to classify the resulting pâté as a dietary product. A recipe for a liver pâté of increased biological value for dietary use had been developed. All this allowed to create original natural products of high quality and with high consumer properties. Practical recommendations on the production technology of pâtés of increased biological value based on chicken liver are given

Keywords: pâté products; chicken liver; Sous vide technology; quality; dietary product

Introduction

The production of functional foods is an urgent task for the modern food industry. The growing interest of consumers in maintaining and improving their health through the use of healthy foods has led to the development of many new functional foods. Most of them are dairy products, plant-based products, specific fats, and combined meat, vegetable and offal products. Meat and by-products can be modified by adding ingredients that are beneficial to health while eliminating or reducing components that are considered harmful. The use of these ingredients in meat products provides an opportunity to improve the nutritional and health benefits of their products. Some success has been achieved by being able to balance the composition of ingredients, which enhances the absorption of nutrients. In the production of meat products, innovative thermal

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*Corresponding author

processing methods are hardly ever used to preserve the biologically active substances of raw materials, eliminate the effects of added fat and ensure the functional properties of the resulting products.

Ukrainian food industry was going through an intensive stage of development, introducing innovative technologies and modern equipment. According to A. Antoniv *et al.* (2023), the goal of improving existing processing methods was to ensure the rational use of food resources and reduce raw material losses at all stages of the technological cycle. As noted by E. Choi & W.S. Shin (2020), the use of traditional technologies and equipment for heat treating of raw materials led not only to a loss of weight, aroma and taste of the product, but also to the loss of biologically active components (vitamins, minerals).

Scientists T. Semko *et al.* (2024) noted that the use of Sous vide technology was of interest. Liver pâté was a popular product in the culinary and meat processing industry, characterised by its delicate texture, high nutritional value and rich flavour. Chicken liver was a valuable by-product that contained a large amount of protein (approximately 18-20 g per 100 g of product), fat (4-6 g per 100 g of product, including healthy unsaturated fatty acids), carbohydrates (up to 1-2 g), minerals (Fe, Zn, Cu, Se) and vitamins (A, B, D), and was used to make this dish. In addition to its high nutritional value, the liver is easily absorbed by the body and was also the best source of iron and folic acid, which were necessary for pregnant women, children and people with iron deficiency anaemia. There were also some contraindications, namely high cholesterol, liver or kidney disease, or individual intolerance.

Sous vide technology can be used to make dishes from any product type. As noted by D. Kathuria *et al.* (2022), any raw meat will benefit from this culinary treatment, while vegetables also retained their bright fresh colour and delicate, elastic texture. The standard process for cooking meat products using Sous vide technology was to immerse and hold raw, chilled, vacuum-packed raw meat in water heated to 55-70°C for several hours. According to A. Antoniv (2024), adding marinade to meat in vacuum bags allowed to get a product that was balanced in all its organoleptic properties. The marinade penetrated deep into the fibres of the meat under vacuum during cooking, which enhanced the flavour. This also created the conditions for better absorption of flavours and ingredients from the marinade by the product, resulting in an intense and uniform taste. At the same time, all useful microelements were retained in the product to the maximum extent possible, as during traditional cooking (boiling, stewing, frying), many nutrients are destroyed by high temperatures, oxygen or dissolve in water.

Another important advantage of Sous vide technology was a 15-35% reduction in weight loss of the finished product, as this processing method ensured even heat distribution over the entire mass of the product, cell membranes were preserved, and, according to S. Zavadlav *et al.* (2020), the juice was retained inside the product. In the process of cooking meat raw materials, volatile flavour compounds were retained in their own juice and minimal nutrient loss was ensured.

Among the disadvantages of this processing method was the possible increase in bacterial contamination, if the cooking temperature and time are not carefully observed, or if the required storage temperature was not ensured after cooking. H. Onyeaka *et al.* (2022b) recommend that, when using Sous vide technology, it was necessary to combine the technological process of product production with additional technological processes to ensure maximum product safety and the destruction of microorganisms in the process of food preparation. The authors argued that the use of Sous vide technology improved both the quality and nutritional value of the product and the shelf life of food products. Researchers H. Onyeaka *et al.* (2022a) indicated the superiority of products in terms of flavour profile compared to products prepared in the traditional way, as the use of Sous vide technology involves the presence of airtight packaging that retained volatile aromatic compounds. Z. Cui *et al.* (2021) cited the following advantages of using Sous vide technology in food preparation: precise temperature control and a significant improvement in quality characteristics such as colour, taste and nutritional value of the finished product.

Given the relevance and benefits of Sous vide technology in food production, this study aimed to integrate vacuum cooking into liver pâté preparation.

Materials and Methods

The object of study in this article was the effect of two heat treatment methods on chicken liver and, in general, on the process of making chicken liver pâté. The following ingredients were used to prepare chicken liver pâté based on a traditional recipe: chicken liver, onions, carrots, sunflower oil, butter, and salt. In addition to studying the effect of heat treatment, the chicken liver pâté was based on ricotta cheese, which is used as an additional ingredient to improve the texture and taste of the pâté, and cashew nuts were added to increase the nutritional value.

The model compositions (MC) contained an almost identical ratio of recipe components (differing only in the presence of olive oil used for frying the ingredients) (Table 1): chicken liver, onion, carrot, ricotta cheese, butter, garlic, cashew nuts, olive oil, ground nutmeg, salt, ground black pepper. All ingredients were purchased at a local supermarket (Lutsk, Ukraine). The preparation of chicken liver pâtés began with the weighing and preparation of the recipe components. The liver was cleaned of bile ducts, veins, and, if necessary, films. Some cooking techniques included soaking the liver in milk or water with salt to eliminate possible

bitterness. This was not necessary for chicken liver, as it was tender, unlike beef or pork liver. It was cut the peeled chicken liver into 2-3 cm pieces, rinsed it under cold water and dried with a paper towel. It was peeled the onions and garlic, rinsed under cold water, cut the onions into strips and the garlic into slices. Also, it was peeled the carrots, rinsed them under cold running water and grated some of them on a coarse grater for frying, and cut the rest into small pieces for Sous vide. The butter was left at room temperature to soften. The ricotta cheese was drained of excess moisture, cashew nuts were fried in a dry frying pan and chopped with a knife. Once prepared, the recipe ingredients can be used directly in the cooking process.

Table 1. *Mass fraction of recipe components in model pâté compositions*

Formulation component	Mass fraction of formulation components in MC, wt. %	
	MC1	MC2
Chicken liver	62.0	64.5
Onion	6.0	6.4
Carrot	6.0	6.4
Butter	6.0	6.4
Ricotta cheese	12.0	12.8
Cashew nuts	2.0	2.5
Garlic	0.4	0.4
Ground nutmeg	0.1	0.1
Salt	0.4	0.4
Ground black pepper	0.1	0.1
Olive oil (for frying)	5.0	–

Note: *MC1 – cooked by frying; MC2 – cooked using Sous vide technology*
Source: *developed by the authors*

Two heat treatment methods were used for comparison: frying and Sous vide technology:

1. Using the frying method (MC1): first, fry the onions and garlic until transparent in a preheated frying pan (200°C) with olive oil, then add the prepared carrots and sauté until tender. The vegetables were placed on a plate to cool. Next, the prepared chicken liver was fried until cooked for 8-10 min. The frying was done using a ProfiCook PC-DKI 1067 (Germany) tabletop induction cooker. At the end, salt, ground nutmeg and ground black pepper were added. The fried liver was covered with a lid to prevent the surface from getting weathered and allowed to cool. The cooled vegetables and chicken liver, ricotta cheese, and softened butter were placed in a bowl and ground using a Liberton LHB-0312 (China) immersion blender until a uniform consistency was obtained without lumps of individual recipe ingredients. Cashew nuts were added to the pâté and mixed with a spoon. The finished pâté was spread on a shallow dinner plate using a moulding ring.

2. Using Sous vide technology (MC2): the prepared vegetables (onions, carrots, garlic) and chicken were placed separately in special plastic bags and vacuumed in a ProfiCook PC-VK 1134 (Germany) vacuum packer, which extracted excess air and sealed the open edges. For this method of heat treatment, a Sous vide Sirman Softcooker S GN1/1 (Italy) was used and two programmes were set up to cook vegetables and chicken liver separately, as they had different temperature conditions and cooking times, as shown in Table 2.

Table 2. *Temperature conditions for different products*

Product	Temperature, °C	Cooking time
Beef	54…56	1…2 hours
Chicken breast	60…65	1…2 hours
Chicken liver	65	45 min
Pork	58…70	1…4 hours
Fish (salmon, tuna)	50…52	30…60 min
Vegetables (carrots, potatoes)	85…90	1…2 hours

Source: *based on D. Kathuria et al. (2022)*

After cooking in the Sous vide apparatus, the bags of vegetables and chicken liver were cooled to room temperature. After cooling, the contents of the bags were opened, placed in a bowl, and soft butter, ricotta cheese, salt, ground nutmeg, and ground black pepper were added. Then the ingredients were ground using a Liberton LHB-0312 (China) immersion blender until a uniform consistency was obtained without lumps of

individual recipe ingredients. Cashew nuts were added to the pâté and mixed with a spoon. The finished pâté was spread on a shallow dinner plate using a moulding ring.

The finished chicken liver pâté samples were examined for physicochemical parameters, in particular, the moisture content was determined according to DSTU ISO 1442:2005 (2007), namely, the samples were dried to a constant weight at a temperature of 103℃ ± 2℃; the mass fraction of fat according to DSTU ISO 1443:2005 (2007), according to the Soxhlet method, which used the extraction of fat from a dried product sample with a solvent and then removing the solvent.

A comparative determination of losses during heat treatment in samples of fried liver and liver cooked using the Sous vide technology was performed as the ratio of the mass of a piece of liver before and after heat treatment, expressed as a percentage, as well as the total losses of the finished pâté in relation to the mass of raw materials. For organoleptic evaluation, a standard method was applied using the method of quantitative descriptive analysis (QDA). The expert evaluation of QDA was carried out using a point scale, according to which the organoleptic characteristics of the finished products were evaluated by the tasting commission of the Department of Food Technology and Chemistry of LNTU, which consisted of 10 people. To ensure the objectivity and reliability of the results, the experts, who tasted the product were informed about the evaluation methodology in advance. The evaluation was based on the following parameters: appearance, colour, consistency, taste and smell. Each indicator was evaluated on a scale to obtain generalised data on the quality of the samples.

Statistical processing of the experimental data and the calculation part were performed using the built-in functions of Microsoft Excel 365. The study was conducted in accordance with the requirements of The Declaration of Helsinki (2013).

Results and Discussion

During the study, a comprehensive analysis of pâté samples was carried out, evaluating their physicochemical parameters and organoleptic properties. The methods used allowed to determine the impact of Sous vide technology on the quality and nutritional value of the product. The results obtained became the basis for the development of optimal production modes that ensure high nutritional value and safety of the finished product. For all cooking methods, the same set of products and spices were used: chicken liver, onions, carrots, butter, ricotta cheese, cashew nuts, garlic, ground nutmeg, salt, ground black pepper and extra virgin olive oil (only for the frying method) (Fig. 1).

a b

Figure 1. *Prepared ingredients for the preparation of pâté samples*

Note: *a – frying (MC1); b – cooking using Sous vide technology (MC2)*
Source: *developed by the authors*

Table 3 contained a scoring system for assessing the organoleptic characteristics of ready-made chicken liver pâté samples. It consisted of five main columns: group descriptor (general evaluation category), single descriptor (specific parameter), verbal description (qualitative characteristic of the attribute's intensity), and point scale (numerical rating system). Several key evaluation categories were presented in this table. The "Appearance" parameter included only one descriptor – "Colour" – which was rated on a scale from 1 (dark brown) to 5 (light cream). The "Smell" parameter determined the degree of preservation of the liver's characteristic aroma, ranging from 1 (none) to 5 (significantly pronounced). Similarly, the "Taste" parameter was assessed based on the intensity of the liver's flavour retention, from 1 (none) to 5 (significantly pronounced). The "Consistency" category included two parameters: "Density" and "Tenderness". Density was rated from "very soft" (1 point) to "dense" (5 points), while tenderness was assessed from "rigid" (1 point) to "delicate" (5 points). Also, the Table 3 provided a standardised evaluation system that allowed for an objective analysis of the organoleptic characteristics of chicken liver pâté. The use of numerical scores alongside verbal descriptions helped to unify the assessment process and ensured the comparability of expert tasting results.

Table 3. *Scoring scale for determining the organoleptic characteristics of samples of ready-made chicken liver pâté*

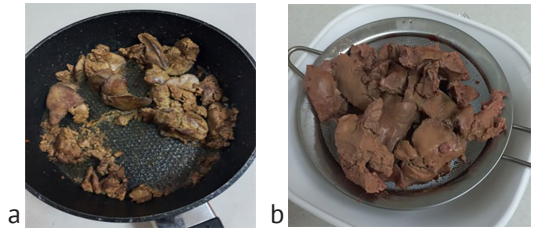
Group descriptor	Single descriptor	Verbal description	Points
Appearance	Colour	Dark brown	1.0
		Dark orange with a reddish tint	2.0
		Light brown with a reddish tint	3.0
		Light brown	4.0
		Light cream	5.0

Table 3. Continued

Group descriptor	Single descriptor	Verbal description	Points
Smell	The degree of preservation of the smell inherent in the product (liver)	None	1.0
		Barely perceptible	2.0
		Slightly pronounced	3.0
		Moderately pronounced	4.0
		Significantly pronounced	5.0
Taste	The degree of preservation of the taste inherent in the product (liver)	None	1.0
		Barely perceptible	2.0
		Slightly pronounced	3.0
		Moderately pronounced	4.0
		Significantly pronounced	5.0
Consistency	Density	Very soft	1.0
		Soft	2.0
		Mild	3.0
		Sealed	4.0
		Dense	5.0
	Tenderness	Rigid	1.0
		Slightly rigid	2.0
		Very delicate, close to smeary	3.0
		Tenderness is not expressed intensely enough	4.0
		Delicate	5.0

Source: *developed by the authors*

In Figure 2 samples of chicken liver were shown after the application of two heat treatment methods. Sample in Figure 2, a was liver pan-fried, which provided intense thermal action and the formation of a crust. Sample in Figure 2, b was liver cooked using the Sous vide technique, which helped preserve a more delicate structure and the natural colour of the product. The analysis of visual characteristics allowed for the evaluation of changes in colour, structure, and the degree of thermal processing, which affected the further organoleptic properties of the finished pâté. Figure 3 displayed finished pâté samples made from previously heat-treated chicken liver using the two methods. Sample Figure 3, a was pâté made from pan-fried liver (method MC1), which had a darker shade and a denser texture. Sample Figure 3, b was pâté made from liver cooked using the Sous vide technique (method MC2), which had a lighter colour and a more delicate consistency. Special attention was given to the consistency uniformity during the analysis, as it was an important indicator of quality and consumer properties of the pâté.



a b

Figure 2. *The appearance of the prepared chicken liver samples after heat treatment*

Note: *a – frying; b – cooking by Sous vide technology*
Source: *developed by the authors*

a b

Figure 3. *The appearance of the finished samples of chicken liver pâtés*

Note: *a – frying (MC1); b – cooking using Sous vide technology (MC2)*
Source: *developed by the authors*

The results of the organoleptic study of chicken liver pâtés made by frying and using Sous vide technology were presented in the form of organoleptic profiles in Figure 4. The analysis of the profiles allowed to visualise differences in the perception of key quality indicators such as texture, aroma, taste, and appearance. The pâté prepared using Sous vide technology, presented in Figure 4, b demonstrated a more uniform texture, enhanced flavour retention, and a more delicate aroma, which was often preferred in dietary products. On the other hand, the pâté made by frying, presented in Figure 4, a tended to have a more pronounced and slightly more intense flavour due to the Maillard reaction, but the texture was less consistent, and there was a noticeable difference in moistness. The data obtained allowed to determine the advantages of each cooking method, with Sous vide technology providing a more controlled and gentle cooking environment that enhanced the preservation of the nutritional and sensory qualities of the pâté. This justified the feasibility of using Sous vide technology

to improve the production of dietary pâtés, offering a healthier and more refined product for consumers.

As can be seen from Figure 4, during the tasting, the highest number of points was given to the sample of chicken liver pâté made using the Sous vide technology, which was assessed by experts as the sample with the most acceptable organoleptic characteristics, which was consistent by J. Ruiz-Carrascal *et al.* (2019). The main changes occur with the organoleptic indicator "Consistency", which is consistent with the results of physicochemical studies. The individual descriptors "Density" and "Tenderness", which are part of the group descriptor "Consistency", directly depend on the water content of the product samples after heat treatment.

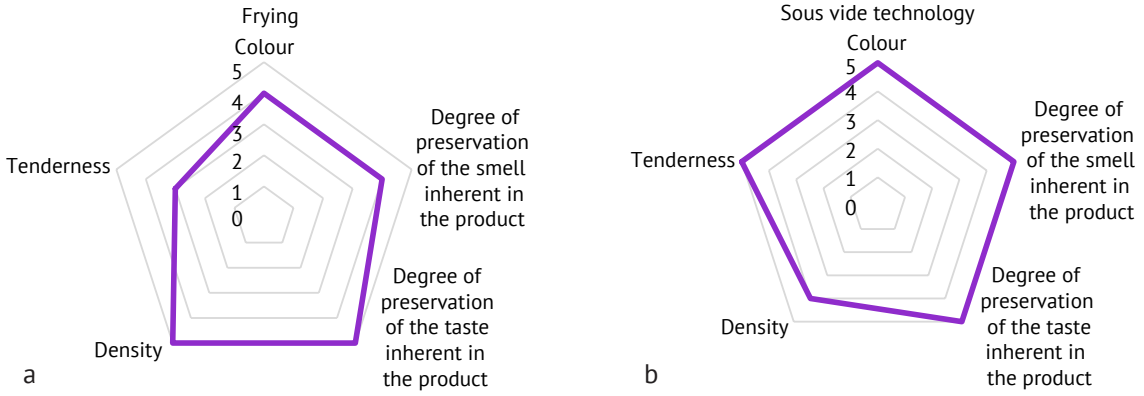


Figure 4. *Organoleptic profiles of finished samples of chicken liver pâtés using different heat treatment methods*

Note: *a – frying (MC1); b – cooking using Sous vide technology (MC2)*
Source: *developed by the authors*

The colour of the finished product is shaped by the presence of natural pigments in the liver muscle tissue, which include carotenoids, melanin's, haemoglobin and some other chemical compounds. Scientists I. Djekic *et al.* (2021) noted in their works that products cooked at 60°C have the most pronounced reddening, and an increase in temperature and cooking time leads to yellowing of the product. During traditional heat treatment, a significant portion of the pigments sensitive to light, heat and oxygen is destroyed, and a small portion of them is converted to oil during frying, which is why experts described the colour of such liver as dark.

Using the Sous vide technology, it is possible to avoid a significant change in the finished colour of the product, thus creating a positive consumer assessment. In addition, vacuum-packed products can be stored after heat treatment until further processing, which helps to preserve the properties of semi-finished products with minimal microbiological contamination. S. Yıkmış *et al.* (2018) noted in their work that if the temperature is maintained at 1-4°C after cooking, the product can be stored for a long period of time, ensuring rapid cooling after thermal processing. The authors H.C.J. Godfray *et al.* (2018) and E. Pogorzelska-Nowicka *et al.* (2018) had shown that processing and storage in vacuum packaging with low oxygen permeability eliminates the influence of air on the product, which in turn provides much better texture, colour, taste and microbiological stability for a much longer time than a product that is not packaged under vacuum.

Sous vide cooking ensures precise temperature control, which guarantees even cooking of the raw material. The semi-finished product is tender, juicy, and has a homogeneous texture without overdried or undercooked areas. Also, cooking at low temperatures reduces the loss of important nutrients, vitamins and trace elements in the finished product, which often occurs during traditional heat treatment methods, such as frying. The liver pâtés made using different types of heat treatment were investigated for physicochemical parameters: moisture, fat and ash content. The results of physicochemical studies of model pâté samples in a comparative aspect were grouped in Table 4.

Table 4. *Results of physicochemical tests of model pâté samples*

Indicator	Research results	
	MC1	MC2
Freshly prepared samples		
Mass fraction of moisture, %	42.7 ± 0.6	46.8 ± 0.5
Mass fraction of fat, %	32.7 ± 0.9	23.7 ± 0.3
Mass fraction of ash, %	1.45 ± 0.1	1.63 ± 0.2
Samples after 24 hours of storage		
Mass fraction of moisture, %	41.7 ± 0.7	44.0 ± 0.7

Source: *developed by the authors*

Tests of the analysed liver pâté samples showed that the mass fractions of ash were in the same quantitative range, and the mass fractions of moisture in the MK2 samples were 11.6% higher than in the MK1 samples. According to N.T. Elsharawy *et al.* (2018), liver pâtés usually contained about 25% animal fats, which were mainly saturated fatty acids. Consumption of animal fats can be a risk factor for diabetes, obesity, cardiovascular and other diseases, as well as provoke an increase in cholesterol. The data on the fat content of the finished product allowed to control the information on the shelf life. Researchers Y. Zhu *et al.* (2022) emphasised that the lower the fat content in the finished product, the slower the oxidation processes and, consequently, the spoilage. Also, one of the positive effects of the Sous vide technology was a higher moisture content in the finished product and a reduction in tissue juice losses compared to the product obtained by traditional heat treatment. The results of studies of the amount of tissue juice loss during heat treatment were presented in Table 5.

Table 5. *Weight loss during different methods of liver heat treatment*

Heat treatment method	Weight of pieces before heat treatment, g	Weight of pieces after heat treatment, g	Losses during heat treatment, %
Frying	34.55-52.27	24.31-41.15	29.6
Sous vide	40.56-55.20	35.07-51.37	13.5

Source: *developed by the authors*

Thus, the use of Sous vide allowed maintaining such product quality indicators as juiciness, taste and aroma, nutritional value at the highest possible level compared to traditional heat treatment; increasing the bioavailability of various nutrients to the body; increasing the shelf life of products by reducing the fat content of the finished product; reducing weight loss during the technological process; and reducing lipid oxidation. Therefore, for the technological process of production of liver pâté with cashew nuts, a technological flow chart was developed, which was shown in Figure 5.

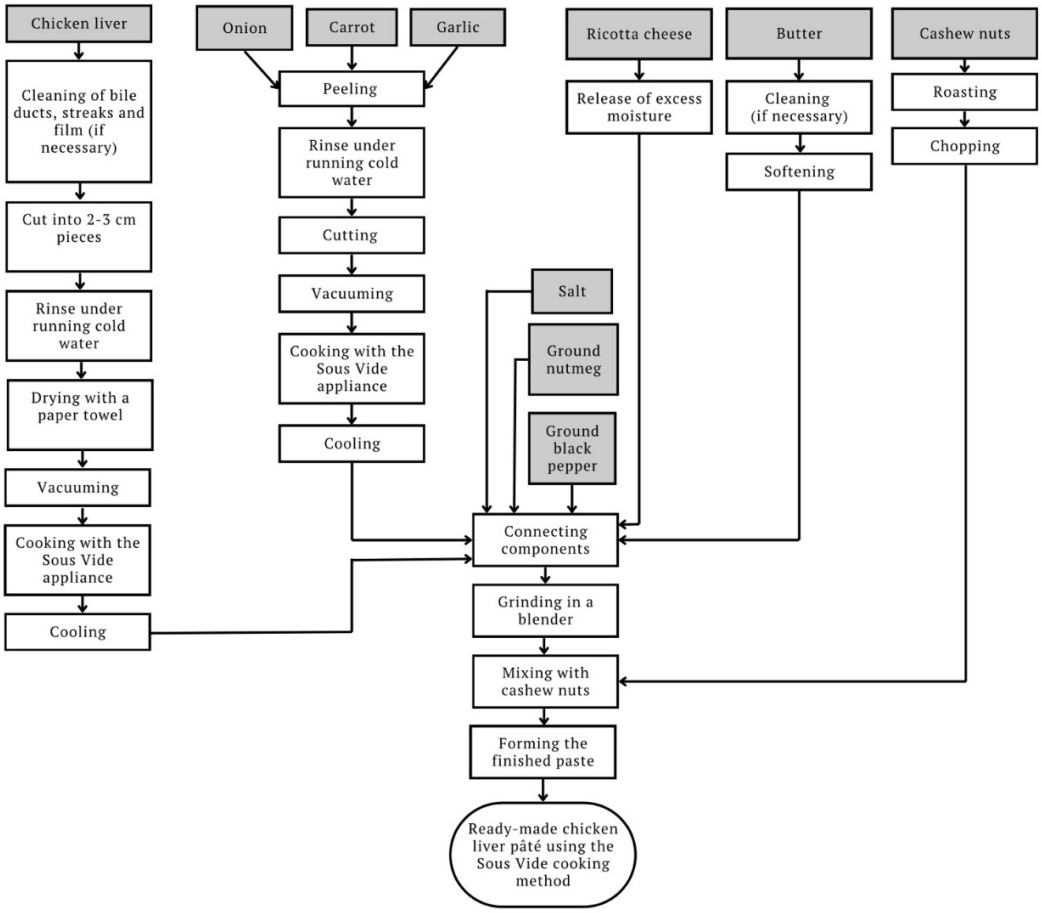


Figure 5. *Technological scheme of cooking chicken liver pâté using the Sous vide cooking method*
Source: *developed by the authors*

So, the technological process of preparing chicken liver pâté using the Sous vide method consisted of several key stages. First, the ingredients were prepared: the chicken liver was cleaned of bile ducts, veins, and membranes, then cut into pieces, rinsed in cold water, and dried. The vegetables were cleaned separately, washed, and chopped. Next, the prepared products were vacuum sealed into bags: the liver separately, and the vegetables separately. The vacuum-sealed ingredients were placed in the Sous vide machine, where they undergo heat treatment at a temperature of 65°C for 1-1.5 hours. After cooking, the products were cooled. At the stage of forming the pâté, all components were combined, and spices such as salt, black pepper, and nutmeg were added. The mixture was blended into a smooth, creamy consistency, after which chopped roasted cashews were added. The resulting mass was shaped into the desired structure and cooled.

A significant number of authors noted that one of the most important qualities of the finished product, when using the Sous vide technology was its appearance, which, in turn, was a consumer preference. In particular, the results of the assessment of the colour characteristics of meat raw materials were noted in the works of many scientists. A. Kicińska *et al.* (2019) focused on the impact of Sous vide cooking on the colour retention of different types of meat, emphasising that the controlled environment of this technology helped preserve the natural colour of the meat. The author noted that Sous vide cooking, when applied to poultry and red meat, prevented the typical colour loss seen with traditional cooking methods. Similarly, K. Jeong *et al.* (2018) investigated the effects of Sous vide technology on the appearance of various meat products, particularly pork and beef. They concluded that the low-temperature cooking environment of Sous vide helped preserve the myoglobin content in the meat, which was responsible for its red colour. B. Uttaro *et al.* (2019) also conducted research examining, how Sous vide technology affected the colour and texture of different types of meat. The author found that the improvement in colour quality was related to the precise control of temperature and cooking time, which prevented the formation of undesirable colour changes typically seen in overcooked products or heat-induced browning. Additionally, Y. Ding *et al.* (2018) conducted research to determine the effect of temperature and the duration of Sous vide processing on the profile of volatile compounds in pork ham. Their study showed that the colour of the meat depended not only on the temperature and cooking time, but also on the retention of specific volatile compounds that affected the aroma and overall sensory experience. The use of equipment for the production of liver pâté using the Sous vide technology does not require significant skills, or constant monitoring, and was easy to operate and, as noted by A. Głuchowski *et al.* (2020), was a common way of producing products in craft production.

So, these studies underlined the importance of Sous vide technology in improving the visual and sensory characteristics of meat products, with particular emphasised on colour preservation, which directly influenced consumer preferences.

Conclusions

As a result of the conducted research, the advantages of using Sous vide technology for the production of liver pâté with the addition of cashew nuts were established, namely the improvement of organoleptic indicators, which was ensured by the maximum disclosure of the true flavours of the product, preservation of its consistency, uniformity and nutrients. And since the products were made without preservatives, stabilisers, or thickeners, the result is dietary nutrition by reducing the amount of salt and saturated fats, reduced weight losses (increased yield) and increase in the nutritional and biological value of dishes. Microbiological contamination was prevented, as the manufacturing process ensured enhanced control of production, losses and quality of the finished product. Also, it was determined data about extended shelf life of semi-finished products, as products made using Sous vide technology were protected by vacuum packaging from external contaminants and pathogenic microorganisms and can be stored for a long time at a temperature of 0 to +3°C. In this study was noted that reduced cooking time for semi-finished products, which, in turn, led to increased efficiency and optimisation of production in the conditions of a craft enterprise. Such an organisation of the technological process allowed for a rational distribution of personnel employment during the working day.

The priority direction for further development of technological processes in the production of pâté products is the search for technologies for the production of products of increased nutritional and biological value using non-traditional additives, which will allow expanding the overall range of functional food.

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Conflict of Interest

None.

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Удосконалення технології виробництва дієтичних паштетів

Ірина Тараймович
Доктор філософії, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0003-4129-2671
Тамара Сидорук
Асистент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0009-0006-9008-9556

Анотація. Метою дослідження було удосконалення технології виробництва дієтичних паштетів шляхом застосування технології Sous vide, що дозволяє зберегти максимальну кількість поживних речовин, покращити органолептичні властивості продукту, підвищити його безпечність та збільшити термін зберігання. У роботі було досліджено можливість використання технології Sous vide для попередньої термічної обробки рецептурних компонентів печінкового паштету, а також застосування сиру рікота та кеш'ю як збагачувальних добавок. Заміна 15,0 % курячої печінки в складі паштету на таку ж кількість сиру рікота та використання технології Sous vide для попередньої теплової обробки сприяли формуванню дещо солодкуватого смаку, більш ніжної текстури та світлішого кольору готового продукту; зниженню вмісту жиру в готовому продукті на 15 % та підвищенню зольності (на 6,3 %). Встановлено практичну доцільність застосування технології Sous vide і використання сиру рікота в кількості 10,0 % та горіхів кеш'ю в кількості 2,5 % у виробництві дієтичного печінкового паштету. Використання щадних режимів теплової обробки та контроль швидкості нагрівання дозволяють зберігати поживну цінність продукту та його засвоюваність, зменшувати втрати вологи та покращувати органолептичні характеристики готового продукту. Виключення доданої олії для смаження з рецептури дозволило знизити вміст жиру на 15 % та класифікувати одержаний паштет як дієтичний продукт. Розроблено рецептуру печінкового паштету підвищеної біологічної цінності для дієтичного використання. Усе це дозволило створити оригінальні натуральні продукти високої якості та з високими споживчими властивостями. Надано практичні рекомендації щодо технології виробництва паштетів підвищеної біологічної цінності на основі курячої печінки

Ключові слова: паштетна продукція; куряча печінка; технологія Sous vide; якість; дієтичний продукт

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Research of flax fiber production by innovative technology

Yurii Berezovskyi*

Doctor of Technical Sciences, Professor
Kyiv National University of Construction and Architecture
03037, 31 Povitrianykh Syl Ave., Kyiv, Ukraine
https://orcid.org/0000-0002-9645-2743

Tetyana Kuzmina

Doctor of Technical Sciences, Professor
Kherson National Technical University
29016, 11 Instytutska Str., Khmelnytsky, Ukraine
https://orcid.org/0000-0002-6113-1923

Natalia Lialina

Doctor of Technical Sciences, Professor
Kyiv National University of Construction and Architecture
03037, 31 Povitrianykh Syl Ave., Kyiv, Ukraine
https://orcid.org/0000-0002-9364-0925

Galina Boyko

PhD in Technical Sciences, Associate Professor
Kherson National Technical University
29016, 11 Instytutska Str., Khmelnytsky, Ukraine
https://orcid.org/0000-0001-8773-5525

Tetiana Holovenko

Doctor of Technical Sciences, Senior Researcher
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-1792-9364

Abstract. Modern needs of consumers require expanding the range of environmentally friendly products, as well as providing Ukrainian industry with raw materials for the manufacture of military and special-purpose goods. It can be done with the help of Ukrainian production of fibrous flax products using new technologies and innovative developments. The purpose of the work was to search for improved production conditions for processing long-fibred flax and develop a method of processing trusts without dividing the fiber into long and short to provide the national producer with a high-quality fibrous product with the possibility of expanded conditions for its use. An analysis of the technical and technological capabilities of fiber producers was carried out, consumer demand for natural fiber was determined, theoretical approaches to cleaning the fibrous material were clarified to achieve this goal. The study of qualitative and quantitative characteristics of the fibrous product were carried out according to organoleptic and instrumental methods of evaluation in the conditions of production control. The most significant factors of influence, which have the greatest influence on the passage of the processes of breaking stems and scutching fibrous raw flax were determined during the a priori experiment. Regression models of the boonness

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*Corresponding author

process in different parts of the proposed equipment were obtained through the use of software and the use of regression analysis by modeling the technological process of obtaining the same type of fiber according to the developed innovative components. This process was designed to determine the rational parameters of the process of cleaning the fibrous product. The conditions of use of the proposed equipment and the influence of the work of different parts of the equipment on the economic result of the processing of the long-fibred flax straws were clarified in the work. Directions for further use of the obtained fibrous product were also established. The obtained results of research can help the national producer of goods of everyday use and special and military purposes to solve the problem of providing high-quality fiber raw materials, to increase the competitiveness of Ukrainian products in the internal and foreign markets of goods and services

Keywords: innovations; raw material; fibrous product; breaking; scutching; quality; boonness

Introduction

Ukraine has not lost the desire to cooperate in a single European family of civilised countries, where all issues are resolved in a compromise, and not by armed means. Although the period from 2014 to 2024 was characterised by constant aggressive actions by the Russian Federation. The European Union supported this aspiration and contributed to the integration of the Ukrainian economy into the overall economic structure of Europe.

The EU textile development strategy was put into effect and taken into account by the Ukrainian light industry in such a situation. This strategy was based on reducing environmental impact and promoting sustainability and transparency in the value chain of the final product. The strategy Challenges for Ukrainian producers in view of the EU Textile Strategy-2030 (2023) provided for the reform of legislation in the direction of real technical implementation with a change in the technical regulation of the economy, the creation of demand for environmentally friendly textiles both from individual consumers and from government agencies through the introduction of specific measures to create a competitive advantage with sustainable high-quality textiles. The main components of this strategy were improving the efficiency of this sector, covering the field of innovation and digitalisation, skills development, support for startups and internationalisation, access to open energy through significant funding.

Since 2014, Ukraine has gradually increased interest in the production of military and special purpose clothing from both the private sector and the state. Lubofiber crops acquire special importance in modern conditions of growing demand for ecological goods and increasing demand from manufacturers of military and special purpose products. Flax, hemp, and jute were sources of natural fibers that can be used in various industries. The expansion of production capacities and the increase in the volume of processing of lubofiber crops was an important step in providing raw materials for both the light and textile industries. Specialised materials can be used both in the defense sector and in other areas of special purpose.

Authors H.A. Al-Gaoudi *et al*. (2024) noted that natural fibers from lubofiber crops can be used in the manufacture of environmentally friendly fabrics. The scientists highlighted various engineering techniques and mechanisms adopted to develop a sustainable flexible composite based on natural fibers as an alternative to leather material.

Natural cellulose-based fibers, such as lubofiber crops, have unique properties, namely: attractiveness in the manufacture of products of various technical applications, have a high modulus of elasticity, tensile strength and moderately high friction coefficient, adequate air permeability and environmental friendliness, abrasion resistance and light weight. S. Basak *et al*. (2024) noted that the addition of natural fiber to the rubber composition increases its tensile strength, coefficient of friction, the use of natural fiber components in leather alternatives. It also improved flexibility indicators, thermal conductivity, and throughput, made the material softer, and improved protection against odor, moisture, and dust. All of the above were very important indicators for end users of products.

Scientists R.M. Iqbal *et al*. (2024) and R. Natesan & P. Krishnasamy (2024) revealed the mechanisms for improving the properties of composites reinforced with natural fibers and noted that they were a promising alternative to synthetic fiber composites due to their favourable environmental characteristics, economic efficiency and decent mechanical properties. In addition, approaches to mitigate the problems associated with moisture absorption, degradation of structural integrity and lack of homogeneity of fibers were disclosed by the authors.

Products, made from canvases, obtained from blended yarns, began to enjoy significant demand among modern consumers due to their unique properties (2013-2023). These canvases combine the advantages of different fibers, which ensured their popularity in the textile industry, contribute to their demand due to the presence of improved characteristics. Researcher U. Bilen (2021) noted that flaxseed fabrics mixed with artificial cellulose fiber do not have significant differences in heat absorption compared to other fabrics, however, this contributes to improved air permeability, bending and shear ability. The fabric, woven from 80% lyocell and 20% flax, showed the best results in terms

of heat and steam permeability, as well as the ability to form and elongate. The obtained data showed that the fabric with 100% cotton base, 80% lyocell and 20% linen weft provided optimal temperature indicators and comfort in the production of bed linen.

In the scientific work of N. Senthil & B. Dhurai (2021) noted that linen yarn produced by wet spinning and treated with OWL softener has improved softness, elongation, bending, stiffness, fleeciness and unevenness values. This made it possible to get a knitted fabric from the threads of this yarn and demonstrate a good knitting without any fabric defects.

Combining the properties of different materials was an effective strategy for creating textiles that combine comfort and functionality. Natural bast fibers provide pleasant tactile properties, air permeability, hygiene, hypoallergenicity, while artificial, synthetic materials give strength, wear resistance, crease resistance and ease of care. This made this combination ideal for the production of products in the sphere of defense and special purpose.

N.P. Bukhonka (2023) noted the advantages of combined materials in knitwear, focused on the "practical" advantages of synthetic fibers in combination with the environmental and tactile properties of natural ones, pointed to a change in the structural characteristics, air permeability and creasing of knitted products from all types of yarn in operation and after washing.

As noted by L. Navone *et al*. (2020), textile waste, which combines natural and synthetic fibers, consisting of mixed textile materials was a serious environmental problem. Only a small part of the products of the fashion industry was collected, reused or recycled. The processing of textile waste is a difficult task due to the need to separate the fibers into separate components, which is complicated by the multi-component structure of clothing. Critical environmental conditions such as humidity, temperature, ventilation and allergic reactions from materials can affect human health. The use of natural components in products that provide optimal conditions for the psychophysiological state and functioning of the body is important for consumers. Therefore, the development of the processing branch of light industry should include the creation of mechanisms for expanding the range of modern products using natural fibers of bast crops, which are traditionally grown in Ukraine.

The purpose of the study was to search for opportunities to improve the processing conditions of long-fibred flax to provide the Ukrainian producer with a significant volume of natural fiber products, to improve the qualitative and quantitative characteristics of the light industry processing industry. For this purpose, the following tasks were determined: to analyse the factors of influence on the processes of processing bast raw materials; to identify the factors that most affect the qualitative and quantitative characteristics of the processing of stem material; to develop mechanisms and method of processing long-fibred flax for providing the national producer with high-quality fibre of various functional purposes.

Materials and Methods

The object of the study was the flax straws of long-fibred flax, grown in the northern regions of Ukraine. Factors of influence on the process of processing stalks of long-fibred flax, factors of formation of qualitative and quantitative characteristics of fibrous products during processing of stem material of bast raw materials were taken into account.

Production tests using experimental equipment at processing enterprises of Lviv and Zhytomyr regions were conducted to confirm the results of theoretical studies in 2020-2022. The efficiency of the work was to indicate an improvement in the processing of bast raw materials and the quality characteristics of the resulting fiber with the possibility of further expanding the scope of its application. Processing and analysis of the obtained research data was carried out in 2023-2024. Long-fibred flax of modern varieties – Esman, Gladiator, which according to the Order of the Ministry of Agrarian Policy and Food of Ukraine No. 306 (2018) were included in the Register of plant varieties of Ukraine and were used for experimental research as bast raw materials.

The requirements of the state standards of Ukraine were met during the study of the processing process of long-fibred flax stalks: DSTU 4015-2001 (2002), DSTU 4149-2003 (2004), DSTU 4511:2006 (2006), DSTU 5015:2008 (2009). The requirements described in DSTU ISO 2370:2009 (2011), ISO 2370:2019 (2019) and ASTM D7076-10 (2021) e1 (2021) have also been met.

The study of the process of processing the stem material of long-stem flax trusts was carried out under the same conditions as the mechanical processing of oilseed flax to comply with the principle of unambiguity. The degree of stock compress, breaking load, fiber output, output of chaff, which most characterise the processes for producing fiber and its final quality, were chosen to study the process of processing flax stalks and evaluate the quality of fiber products the most important indicators. Mathematical methods of experimental planning were used to determine the intensity of the influence of factors on the process of mechanical processing of bast raw materials and the separation of non-fibrous impurities from the fibrous part of the stem. In particular, a complete factor experiment, the value of the optimisation parameters of which for all possible combinations of levels of factor variation, was determined during implementation. This method allowed to investigate the influence of various factors on the process, since it implemented all possible combinations of levels of the studied parameters. The implementation of all possible combinations of levels of factors made it possible to study the process in detail and provided scientifically sound conclusions on the most

significant factors that affect the quality of mechanical processing of long-fibred flax. The study performed rotable second-order planning (Box plan). The Student's test was used to assess the significance of long-fibred flax deboning process.

The dependence of the content of chaff in linen fiber on changes in the parameters of significant factors that affect the processing of this bast raw material was characterised as a result of regression analysis. Modern means of computer modeling and mathematical data processing were used to analyse and obtain regression equations. The main tools were SOLIDWORKS, MathCAD-2015, Microsoft Office Word 2007, and Microsoft Office Excel 2007. The use of these software tools made it possible to automate calculations and create accurate mathematical models that reflect the influence of various factors on the efficiency of the processing of bast raw materials.

Results and Discussion

Since the beginning of 2022, the Ukrainian light industry has faced a controversial situation, with production following a downward trend. In 2023, the number of light industry producers in Ukraine increased by 22%, reaching more than 19700 companies, of which 72% were individual entrepreneurs, and large enterprises make up only 1% of the total, which indicated a significant dominance of small and medium-sized businesses in this sector of the economy (The 10 largest manufacturers of clothing, footwear and textiles in Ukraine..., 2024). However, despite the growth in the number of producers, their total income in 2023 decreased by 13%, amounting to 47.1 billion UAH. Most of the income was received by clothing manufacturers, who earned 23 billion UAH. This pointed to the important role of this sector in light industry. The unstable situation in light industry in sub-sectors can be seen from the data of Ukrlegprom on procurement for the Armed Forces of Ukraine and other areas of work (2024).

It is worth noting that manufacturers relied on the production of clothing for the military and sales abroad in 2022-2024. Ukrainian light industry often faced fierce competition in the internal fashion market, despite the growing number of manufacturers. The influx of cheap goods from Asia and the return of Western mass-market brands were the main factors that made it difficult to stop. Products from Asian countries were often offered at lower prices, making them more attractive to many consumers. Western brands have strong marketing strategies, well-known brands and large-scale distribution channels, which made it difficult for Ukrainian manufacturers to compete in such an environment.

The decline in production indicators in light industry was observed in 2024. This was due to both internal challenges and global market processes. Light industry felt these negative processes more sharply and with acceleration. Although the decrease in production volumes is typical for the entire processing industry in Ukraine. The situation in the Ukrainian light industry deteriorated significantly in the second quarter of 2024. According to research V. Volokita (2024), 33% of companies reported a reduction in production due to the following factors: lack of labour, power outages, rising prices for raw materials. This significantly affected the overall production indicators of the industry.

New promising areas of light industry were beginning to take shape in Ukraine, despite a 13% decline in revenues in 2023 and the challenges associated with a full-scale war. They were not only focused on internal market demand, but were also export-oriented, which opened up additional opportunities for further growth. Key areas: production of military products and special clothing for law enforcement agencies, the demand for which has increased sharply due to the war; production of home clothing, which was in demand among ordinary consumers; production of wedding dresses, caused by increased demand from foreign orders. In this case, you can use the experience of scientists in obtaining a variety of materials. For example, L. Kohan *et al.* (2019) noted that natural fibers from lubofiber crops can be used in the manufacture of artificial leather. Scientists L. Samant *et al.* (2023) revealed ways to improve the mechanical properties of natural rubber composites by using reinforced flax natural fiber with a 9% and 27.4% increase in tensile and breaking strengths in the NaOH-treated and flax fiber-reinforced composite. S. Huo *et al.* (2013) noted improved strength characteristics of polymer matrix composites using reinforced flax fiber. At the same time, it is worth noting that the treatment with acrylic acid increased both the interfacial shear strength and the interlayer shear strength by about 30% compared to untreated linen composites. In a scientific paper, the authors J. Summerscales *et al.* (2010) argued that bast fibers were widely used in the textile industry and were increasingly being considered as reinforcing materials for polymer matrix composites, because they were perceived as "stable". Scientists have noted that predicting the properties of natural fiber-reinforced composites in view of their potential application and environmental considerations can accelerate or limit the adoption of these composites in application.

Clothing and textiles always play a key role in times of economic crisis, while these products are essential goods. Consumers focus on basic needs in conditions of economic instability, but textiles and clothing remain indispensable. This can make light industry one of the most stable sectors of the economy, as well as the processing sector, engaged in the production of natural fiber from bast crops.

Ukraine can use this as an advantage in the process of becoming an economy, since the production of clothing and textiles from natural fiber can not only satisfy internal demand, but also open up new opportunities

for export. This is especially true for niche segments, such as workwear, wedding dresses or innovative textiles. In addition, light industry is a labour-intensive industry. It can create jobs, supporting the country's economy during the war. According to the research Ukrlegprom on procurement for the Armed Forces of Ukraine and other areas of work (2024), clothing and textiles not only quickly find their consumers, but also make the production of light industry products a source of income and stability in international trade (Fig. 1).

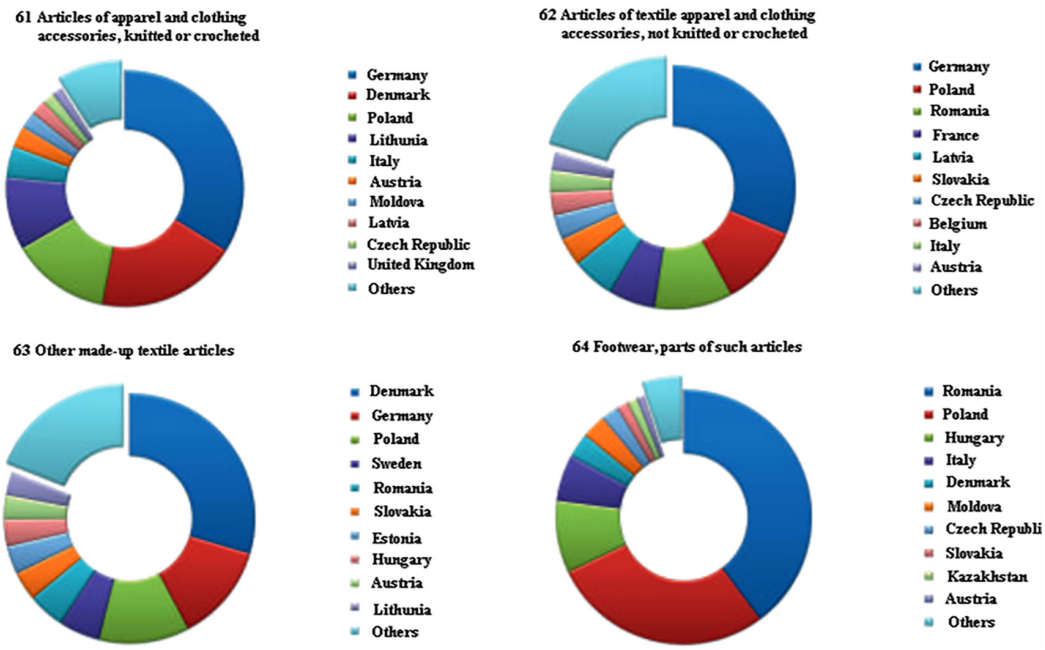

Figure 1. *Top countries of textile exports of Ukraine in 2022*
Source: *based on Ukrlegprom. Fashion & Production (2023), Official website of Diia. Business (2024)*

According to Figure 1, it can conclude that Ukrainian light industry products were in demand in Western Europe, in the countries of high fashion legislators, such as France, Italy, Germany. This gave Ukraine the opportunity to use the current trends in the development of the industry, to perceive the needs and requirements of consumers on time, to navigate the changes in the market of goods. The spread of the trend of using environmentally friendly products acquired in the world in the period 2000-2015. This situation can serve as a good guarantee in expanding its position in the market of goods and popularising the Ukrainian brand of manufacturers of light industry products, which largely used linen fiber (Fig. 2).

Figure 2. *Foreign trade in light industry goods for 2023*
Source: *based on Ukrlegprom on procurement for the Armed Forces of Ukraine and other areas of work (2024)*

The results of trade in light industry goods for 2023 indicated that the military situation in Ukraine affected the results of trade activities, reduced or suspended production capacities, canceled tender and

procurement procedures, and reduced the volumes of contracts. All this influenced the increase in the negative balance. It should be noted that such a situation may become the basis for the interest of Ukrainian manufacturers of light industry in the production of demanded military and special-purpose products using linen fiber potential. Important for the conduct of state policy in modern conditions of management is the preservation of jobs.

Association "Ukrlegprom" according to the source Ukrlegprom on procurement for the Armed Forces of Ukraine and other areas of work (2024) reported and provided industry information to the newly created state enterprises of the Ministry of Defense of Ukraine "State Logistics Operator" and "Defense Procurement Agency" to ensure maximum involvement of manufacturers to participate in procurement. Namely: in the context of manufacturing enterprises that produce raw materials for finished products and are strategic for Ukraine's light industry; in the context of manufacturing enterprises that produce finished products, grouped according to a homogeneous technological production process; criteria for Ukrainian manufacturers according to the Procedure for granting the status of national producer to an enterprise, confirming or revoking this status (2022). Figure 2 highlighted the special role of producing strategically important goods. The state ready to pay particular attention to the raw materials used in their production. This serves as an additional factor encouraging the processing of bast raw materials, emphasising the need to improve the technological processes involved in the processing of long-fibred flax (Yaremova *et al*., 2024).

Ukraine was one of the world leaders in the production of flax fiber until 1992, providing more than 100 thousand tons of raw materials annually. This accounted for 13-16% of the world volume. Approximately, 40 thousand tons of flax fiber were processed by Ukrainian enterprises, while the rest were exported for more than 40 million USD. Flax cultivation was a key agricultural sector, ensuring high profitability for both producers and processing enterprises. Long-fibred flax products constituted a significant portion of monetary income from crop production, contributing to the economic development of rural areas, particularly in Polissia, where this crop was traditionally grown. Long-fibred flax provided three types of products: fiber, seeds, and chaff (Berezovsky, 2016).

Climate changes in the direction of warming, the complex technological process of processing flax, metal capacity and energy intensity of processing equipment for 2005-2010 reduced the importance of processing the stems of this crop, made it more relevant to grow oilseed flax, especially in the southeastern regions of Ukraine. However, the industrial production of long-fibred flax products has significant potential, which must be realised through modernising the technical facilities of the flax processing industry, applying advanced stem processing technologies, and integrating innovations at all stages of obtaining natural fiber while reducing energy and material consumption (Lialina *et al.*, 2023; Didukh *et al.*, 2024).

The mechanical processing of bast crops, such as flax and hemp, has been the subject of research by numerous scientists, who have made significant contributions to the development of the theory and practice of stem material processing. Their work has improved technological processes and enhanced the efficiency of producing bast-fiber materials. For instance, B.V. Lesyk (1969) noted that flax fiber is a completely environmentally friendly, natural folding material, does not create a negative impact on the environment after disposal, it is an ideal universal raw material for the production of clothing, bed linen and technical materials. However, its use was accompanied by certain difficulties, such as high production cost and the ability to crumple easily, which required manufacturers to optimise production processes and use modern technologies to eliminate shortcomings, which can increase the competitiveness of flax-containing products in the consumer market.

Authors T.M. Holovenko *et al*. (2018) and G.A. Boyko *et al*. (2018) pointed out that outdated equipment and technologies are used in Ukraine's industrial production of flax and hemp fiber, negatively impacting the economic state of enterprises. Therefore, updating the technical and technological base was urgently needed. P.M. Valko (2011) emphasised the need to create more efficient crumpling rollers to improve the process of crumpling, while T.M. Holovenko (2013) demonstrated that nonwoven materials from oil flax straw can be produced using foreign equipment adapted to a proposed technological scheme for obtaining fibrous products. R.N. Helyazetdinov (2009) stated that to achieve high-quality fiber products, it was necessary to use specialised machines and units both sequentially and simultaneously, significantly improving fiber production efficiency. According to S. Yaheliuk *et al*. (2022), the main requirements for a processing line were complexity and versatility. By employing various technical developments and improvements, production facilities obtain both parallelised and disoriented fibers, enabling manufacturers to apply different technologies depending on the final product desired. Consequently, research focused on developing technological innovations and refining existing processes to produce uniform flax fiber.

The development and application of innovative technical and technological solutions in the mechanical processing of long-fibred flax were based on improved components of crumpling and scutching sections of processing equipment. These advancements significantly enhanced the efficiency of fiber separation and cleaning from non-fibrous components,

positively influencing the quality of the final product and expanding its application areas (Berezovsky, 2016; Berezovsky, 2018).

The key stages of the new technology for obtaining uniform fiber from bast crops include (Fig. 3):

1. Unwinding of rolls on a reel, which provides for the supply of bast crop stems from rolls for further mechanical processing.

2. Crumpling with rolls of various types with simultaneous stretching, using proposed rolls of ribbed, slatted, disc, and comb types to soften the stems and separate the fiber from the shives while simultaneously stretching the fibers. This ensures an even distribution of fibers in the processed layer for further processing of the raw material.

3. Scutching, performed using a proposed scutching drum design equipped with beaters and knives, effectively cleaning the flax fiber from impurities.

4. Final fiber cleaning, using shaking machines equipped with shaking-vibrating devices to remove residual non-fibrous materials, significantly improving the quality of the final fiber product.

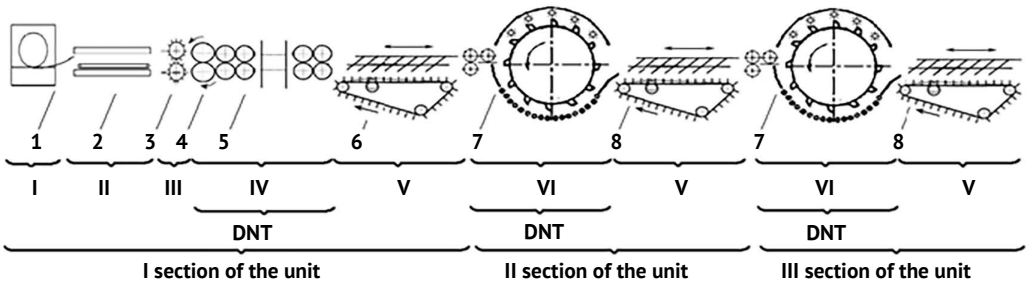

Figure 3. *The technological scheme of the experimental unit for obtaining uniform fiber from bast crops and the equipment and equipment for its implementation*

Note: *DNT – device of a new type; I – unrolling section; II – drying section; III – layer-forming section; IV – crumpling section; V – shaking section; VI – scutching section; 1 – bundle unwinder; 2 – drying machine; 3 – peg mechanism; 4 – pair of enlarged-diameter rolls; 5 – breaking machine; 6 – preliminary cleaning shaking machine equipped with a vibrating device; 7 – scutching unit; 8 – shaking machine equipped with a vibrating device*

Source: *developed by the authors*

Due to the processing of the stem material of long-fibred flax with a wide differentiation of mechanical actions, the integrity of the stems was disrupted, the bond between the fiber and the wood was broken. Conditions for effective separation of the fibrous part from the wood part are formed. A special role in the processing of stem material was played by scraping and thinning the raw material layer on cleaning rollers. Their action, in combination with a shaking device, allows for uniform processing and cleaning of the fibrous material. The integration of a shaking-vibrating device between the processes of breaking and scutching enables more effective removal of woody particles and other impurities, reducing the loss of valuable fiber and improving its quality.

Thanks to the proposed structural innovations in the breaking and scutching zones of the processing equipment, it became possible to achieve a higher-quality separation of fibrous material from non-fibrous components. This not only improved the purity of the obtained fiber, but also increased the productivity of the process. The improved quality of the fiber allows it to be used in a wider range of industrial and consumer products, expanding the market and enhancing the economic appeal of bast crop production. A significant number of technological factors and parameters of the working bodies of the equipment affect the efficiency of processing the long-fibred flax trusts. The efficiency of raw processing and the formation of fiber quality characteristics depends on these factors.

The depth of entry of the riffles; density of raw material loading; fiber layer thickness; linear velocity of material movement in flax pairs; grooving pitch; moisture content of raw materials; number of corrugations of crushing rolls; the state of the bast trusts; method of feeding a crushing unit; specific pressure in a pair of crushing rolls were determined during studying the process of crushing. Their influence on the process of processing the stems of linen raw materials was considered.

The three most significant factors were determined by the results of the a priori experiment. They have the greatest impact on the quality of passing the stems of long-fibred flax:

1. Specific pressure in the breaking roller pair. This determines the forc,e with which the rollers compress the raw material, significantly affecting the efficiency of separating fiber from woody material and the extent of fiber damage, when excessive pressure is applied.

2. Raw material moisture content. This critically impacts the mechanical processability of the stem material, influencing efficiency due to the excessive flexibility of wet raw material or the potential damage to overly dry stems.

3. Degree of retting. This indicates the readiness of the raw material for processing and directly affects

quantitative and qualitative losses of the fibrous part of the stem.

Factors influencing scutching, such as drum rotation frequency, raw material layer thickness, spacing between flail bars and the grid, spacing between the scutching knife and flail bar, retting degree, raw material moisture content, spacing between the scutching drum and feed unit, raw material density, the number of flail bars on the drum, feeding speed, material preparation level, material layer structure, and installation design features, were analysed for their impact on scutching fibrous raw flax in the process study.

Three key factors were found to have the most significant impact on the quality and quantity of the fibrous product obtained according to the results of a priori experiment:

1. Scutching drum rotation frequency. This determines the intensity of the scutching process, ensuring effective cleaning without significant quantitative fiber loss at the optimal frequency.

2. Spacing between flail bars and the grid. This impacts the intensity of the flail bars' effect on the raw material, directly influencing cleaning efficiency and minimising fiber damage.

3. Spacing between the scutching knife and flail bar. This determines the precision and effectiveness of separating woody particles from the fiber, significantly affecting fiber losses.

The effects of the identified factors on the processing of flax straw stems, their critical role in shaping the quantitative and qualitative characteristics of the Gladiator and Esman flax varieties were determined during the studies. Change in the quality of the fibrous product was controlled by the content of foreign impurities. This is one of the main parameters that affects the choice of the direction of further use of fiber in the production of final products. Rotatable planning of the second order (Box plans) of the process of mechanical processing of bast raw materials of various parts of processing equipment was applied during the experiment.

The study of the dewatering process in the first part of the processing equipment was carried out with the following parameters:

- specific pressure per 1 linear cm of the stem layer in a pair of crumpling rolls, P = 8.12-11.48, daN/cm;
- raw material moisture content, W = 8.96-19.04, %;
- degree of ripen of trusts, *B* = 2.64-9.36, units.

Regression models of processes of processing of long-fibred flax stalk material in different parts of the proposed equipment were obtained as a result of data processing (Table 1).

Table 1. *Regression models of the process of boonness the fibrous flax product*

Place of determination	Long-fibred flax variety	Regression model
First part of the equipment	Gladiator	$y_1 = 49.834 - 1.201x_1 + 0.547x_1^2 + 0.518x_2^2 + 0.401x_3^2$
	Esman	$y_1 = 48.451 - 1.228x_1 + 0.576x_1^2 + 0.516x_2^2 + 0.403x_3^2$
Second part of the equipment	Gladiator	$y_2 = 3.489 - 0.241x_4 + 0.27x_4^2 + 0.224x_5^2 + 0.219x_6^2$
	Esman	$y_2 = 3.594 - 0.328x_4 + 0.211x_5 - 0.262x_6 + 0.3016x_4^2 + 0.306x_5^2 + 0.306x_6^2$
Third part of the equipment	Gladiator	$y_3 = 1.848 - 0.118x_4 + 0.171x_4^2 + 0.148x_5^2 + 0.148x_6^2$
	Esman	$y_3 = 1.864 - 0.14x_4 - 0.08x_6 + 0.155x_4^2 + 0.153x_5^2 + 0.148x_6^2$

Note: *y_1 – content of boon in fibrous raw material, %; x_1 – specific pressure per 1 linear cm of the stem layer in the breaking roller pair, daN/cm; x_2 – raw material moisture content, %; x_3 – degree of ripen of trusts, units; y_2 – content of boon in fibrous material; x_4 – scutching drum rotation frequency, min^{-1}; x_5 – spacing between flail bars and grid, mm; x_6 – spacing between scutching knife and flail bar, mm; y_3 – content of boon in processed flax fiber*

Source: *developed by the authors*

Regression models describing the process of unchaffyness of flax stalk material of long-fibred flax during its processing in the proposed equipment in its various parts were given in Table 1. Coefficients of the second-order model were determined, and their significance was evaluated using the Student's criterion, excluding insignificant coefficients from the dependency equations. Equations 1 and 2 indicated that the specific pressure on the stem layer in the breaking roller pair significantly affects the unchaffyness process in the first section of the equipment. Equations 3 and 4 revealed that during scutching in the second section, the scutching drum rotation frequency significantly impacts the cleaning process of fibrous raw material. For the Esman variety, the spacing between flail bars and the grid, as well as the spacing between the scutching knife and flail bar, also play a role. Equations 5 and 6 demonstrated the importance of drum rotation frequency during the cleaning process. It should be noted that the process of separating fiber from foreign impurities of the Esman variety was also affected by the amount of dilution between the tip knife and the beating bar.

Figures 4-12 presented response surfaces of regression models for the cleaning process and fiber quality characteristics during the processing of Gladiator and Esman flax varieties.

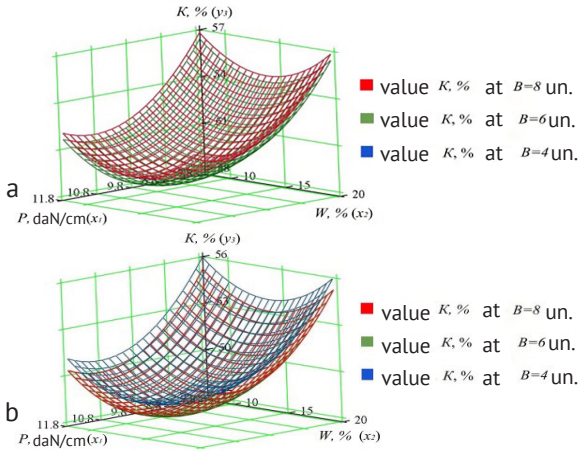

Figure 4. *Response surface of dependence of initial values of boon content index, K, % (y_1) of long-fibred flax trusts of Gladiator (a) and Esman (b) varieties on input factors when considering the levels of the state of the trust, expressed by the degree of tracking B, units in the first part of the proposed equipment*

Source: *developed by the authors*

According to the analysis of the response surfaces (Fig. 4) of the regression model y_1, it can be stated that during mechanical processing in the first section of the proposed equipment, at raw material moisture levels of W = 14% and the retting degree of B = 6-8 units, the lowest content of woody core in the fibrous material of Gladiator (a) and Esman (b) flax varieties was achieved. This occurred at a specific pressure of 9.8-10.8 daN/cm per linear cm of the stem layer in the pair of breaking rollers.

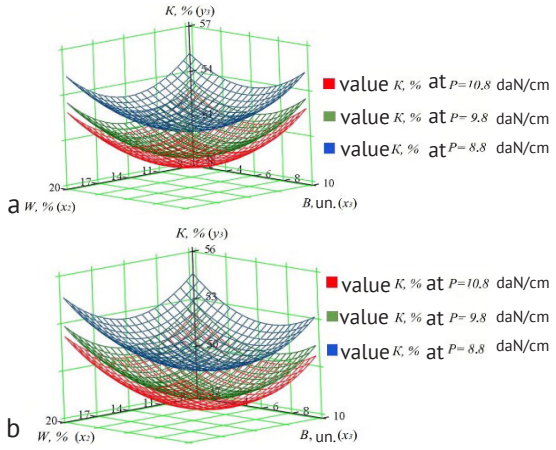

Figure 5. *Response surface of the dependence of output values of the woody core content indicator K, % (y_1) in the flax retting of Gladiator (a) and Esman (b) varieties on the input factors considering the levels of raw material moisture W, % in the first section of the proposed equipment*

Source: *developed by the authors*

According to the analysis of the response surfaces (Fig. 5) of the regression model y_1, it can be stated that during mechanical processing in the first section of the proposed equipment, at a raw material moisture content of W = 14% and a retting degree of B = 6.0 units, the lowest values of boonness in the flax fiber of long-fibred flax of Gladiator (a) and Esman (b) varieties were achieved with a specific pressure on 1 cm of the stem layer in the pair of crushing rollers P = 9.8-10.8 daN/cm.

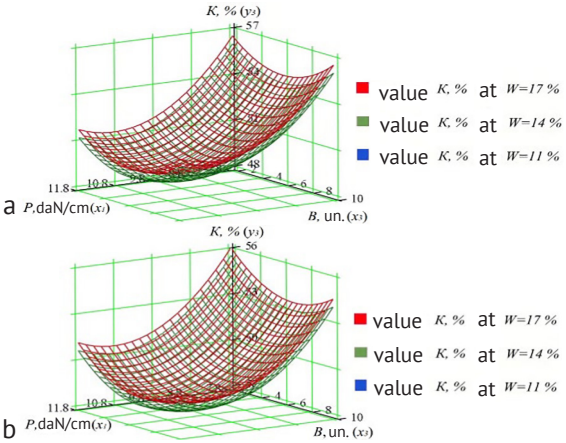

Figure 6. *Response surface of the dependence of output values of the boon content indicator, K, % (y_1), in the retted flax of Gladiator (a) and Esman (b) varieties on the input factors considering the raw material moisture levels W, % in the first section of the proposed equipment*

Source: *developed by the authors*

The analysis of the response surfaces (Fig. 6) of the regression model y_1 demonstrated that at a specific pressure of 9.8 daN/cm per linear cm of the stem layer in the pair of breaking rollers and a ripen degree of 6.0 units during machining in the first part of the proposed equipment. The lowest values of boonness in the flax fiber of long-fibred flax of Gladiator (a) and Esman (b) varieties were observed at the humidity of the raw materials W = 11-14%.

The analysis of the research results and response surfaces of regression models y_1 indicates that, under rotatable planning, the best results of mechanical processing of Gladiator and Esman flax stem material can be achieved at specific pressures of 9.8-10.8 daN/cm, raw material moisture levels of W = 11-14%, state trusts and a ripen degree (B) at 6-8 units. The identified optimal parameters for mechanical processing in the first section of the experimental equipment provide rational values for achieving the lowest woody core content in the fibrous material.

The study of the influence of these factors on stem material processing showed that their effect on the quantitative and qualitative characteristics of Gladiator and Esman flax fibers is consistent. The mechanical processing of the Gladiator and Esman flax varieties was analysed through the constructed response surfaces of regression models for cleaning fi-

brous material from woody core and foreign impurities in the second section of the proposed equipment, as shown in Figures 7-9.

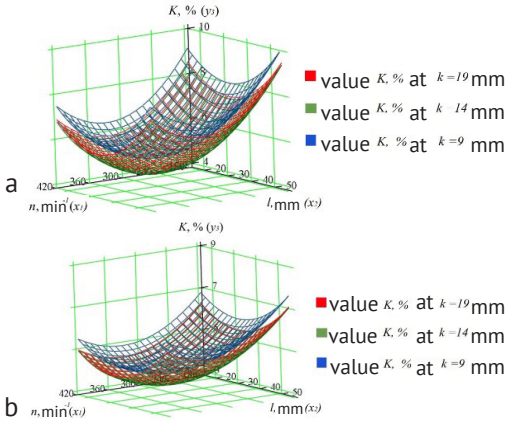

Figure 7. *Response surface of the dependence of output values of the boon content indicator, K, % (y_2) of raw flax of Gladiator (a) and Esman (b) varieties on the input factors considering the clearance between the scutching knife and the batten bar of the scutching drum k, mm in the second section of the proposed equipment*

Source: *developed by the authors*

It can be stated that the the smallest values of boonness of fibrous material of long-fibred flax of Gladiator (a) and Esman (b) varieties was achieved at a clearance between the scutching knife and the batten bar of the scutching drum k = 14-19 mm were obtained during mechanical processing in the second section of the proposed equipment, at a scutching drum rotation speed n = 300 min^{-1} and a dilution value between the scutching drum and the grid of the scutching unit l = 36 mm, according to the analysis of the response surfaces of the regression model y_2 (Fig. 7).

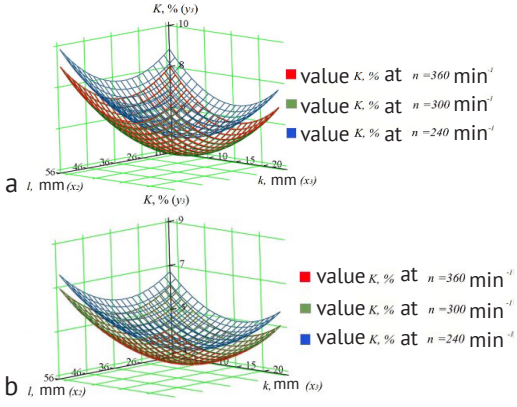

Figure 8. *Response surface of the dependence of output values of boon content indicator, K, % (y_2) of raw flax of Gladiator (a) and Esman (b) varieties on the input factors considering the scutching drum rotation speed n, min^{-1} in the second section of the proposed equipment*

Source: *developed by the authors*

The analysis of the response surfaces (Fig. 8) of the regression model y_2 demonstrates that at a dilution value l = 36 mm between the scutching drum and the grid of the scutching unit, and dilution value k = 14 mm between the scutching knife and the batten bar of the scutching drum, the smallest values of boonness of fibrous material of long-fibred flax of Gladiator (a) and Esman (b) flax varieties were observed at scutching drum rotation speeds n = 300-360 min^{-1}.

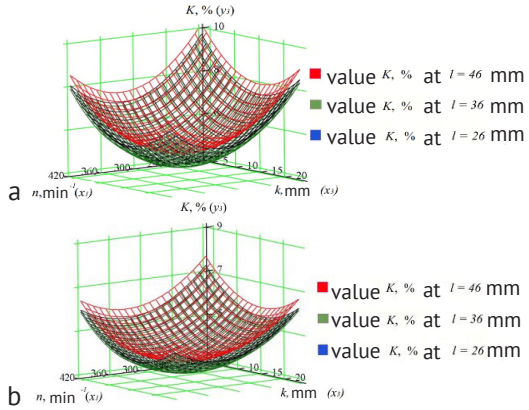

Figure 9. *Response surface of the dependence of output values of the boon content indicator, K, % (y_2) of raw flax of Gladiator (a) and Esman (b) varieties on the input factors considering the clearance between the grid and the scutching drum l, mm, in the second section of the proposed equipment*

Source: *developed by the authors*

According to the analysis of the response surfaces (Fig. 9) of the regression model y_2, it can be stated that during mechanical processing in the second section of the proposed equipment, at a scutching drum rotation speed n = 300 min^{-1} and dilution value k = 14 mm between the scutching knife and the batten bar of the scutching drum, the smallest values of boonness of fibrous material of long-fibred flax of Gladiator (a) and Esman (b) varieties were achieved at a dilution value l = 26-36 mm between the scutching drum and the grid of the scutching unit.

The analysis of the research results and response surfaces of regression models y_2 indicates that, under rotatable planning, the best results of mechanical processing of Gladiator and Esman flax fibrous material can be achieved at a dilution value k = 14-19 mm, a scutching drum rotation speed n = 300-360 min^{-1} and a dilution value l = 26-36 mm. The identified optimal parameters for mechanical processing in the second section of the experimental equipment provide rational values for achieving the smallest values of boonness of fibrous material. The study of the influence of these factors in the second section of the experimental equipment showed that their effect on the quantitative and qualitative characteristics of Gladiator and Esman flax fibers was consistent.

The mechanical processing of the Gladiator and Esman flax varieties was analysed through the constructed response surfaces of regression models for cleaning fibers from the boon and foreign impurities in the third section of the proposed equipment, as shown in Figures 10-12.

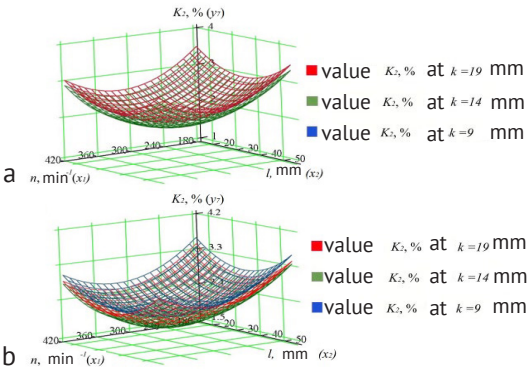

Figure 10. *Response surface of the dependence of output values of the boon content indicator K_2, % (y_3), in the fibrous mass of Gladiator (a) and Esman (b) flax varieties on the input factors considering the dilution value between the scutching knife and the batten bar of the scutching drum k, mm, in the third section of the proposed equipment*

Source: *developed by the authors*

The analysis of the response surfaces (Fig. 10) of the regression model y_3 demonstrated that at a scutching drum rotation speed $n = 300$ min^{-1} and dilution value $l = 36$ mm between the scutching drum and the grid of the scutching unit, the smallest values of boonness of fibrous material of long-fibred flax of Gladiator (a) and Esman (b) varieties during mechanical processing in the third section of the proposed equipment were observed, when the clearance between the scutching knife and the batten bar of the scutching drum was approximately $k = 14$ mm.

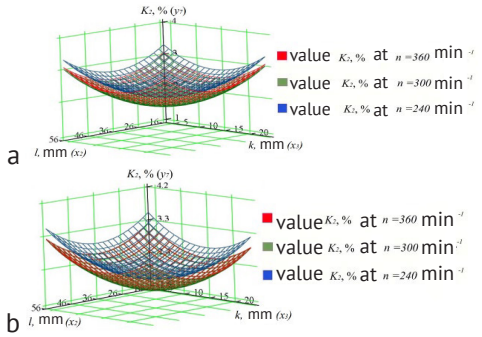

Figure 11. *Response surface of the dependence of output values of the woody core content indicator K_2, % (y_3), in the fibrous mass of Gladiator (a) and Esman (b) flax varieties on the input factors considering the rotation speed of the scutching drum n, min-1, in the third section of the proposed equipment*

Source: *developed by the authors*

The analysis of the response surfaces (Fig. 11) of the regression model y_3 indicated that during mechanical processing in the third section of the proposed equipment, at a dilution value $l = 36$ mm between the scutching drum and the grid of the scutching unit and a clearance $k = 14$ mm between the scutching knife and the batten bar of the scutching drum, the lowest boon content in the flax fibers of Gladiator (a) and Esman (b) varieties was achieved at a scutching drum rotation speed range $n = 300$-360 min^{-1}.

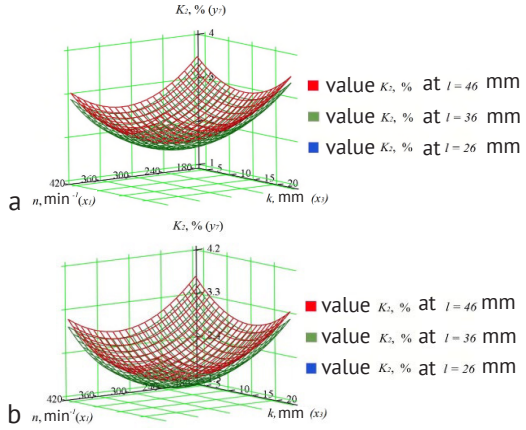

Figure 12. *Response surface of the dependence of output values of the boon content indicator K_2, % (y_3), in the fibrous mass of Gladiator (a) and Esman (b) flax varieties on the input factors considering the clearance between the grid and scutching drum l, mm, in the third section of the proposed equipment*

Source: *developed by the authors*

The analysis of the response surfaces (Fig. 12) of the regression model y_3 indicates that at a scutching drum rotation speed $n = 300$ min^{-1} and dilution value $k = 14$ mm between the scutching knife and the batten bar of the scutching drum, the lowest values of boonness of fiber content in the flax fibers of Gladiator (a) and Esman (b) varieties were achieved, when the clearance between the scutching drum and the grid of the scutching unit was approximately $l = 36$ mm during mechanical processing in the third section of the proposed equipment.

The analysis of the research results and the response surfaces of the regression models y_3 showed that under optimal rotational planning, the best results of mechanical processing of Gladiator and Esman flax fibers could be achieved with a dilution value was approximately $k = 14$ mm between the scutching knife and the batten bar of the scutching drum, a dilution value was approximately $l = 36$ mm between the scutching drum and the grid of the scutching unit, and a scutching drum rotation speed was approximately $n = 300$ min^{-1}. This was because increasing the rotation speed of the scutching drum leads to greater fiber damage, which was economically unfeasible for the final processing result. The optimal parameters for the mechanical

processing of flax fiber in the third section of the proposed equipment would involve rational values that minimise the content of boonness in the raw fiber.

The study of the impact of the mentioned factors on the process of processing the stem material in the third section of the proposed equipment revealed that their effect on the quantitative and qualitative characteristics of Gladiator and Esman flax fibers were of the same character of action and passes for them unambiguously for both varieties.

The research results showed that by processing uniform flax stem material in the proposed method, it was possible to obtain the raw fiber in the crushing section at a specific pressure of 9.8 daN/cm in the pair of crushing rollers, with raw material moisture at 14%, and the normal degree of ripen trusts at 6 units, with a compress of trusts was approximately 25%. Under these conditions, crushing in the first section of the proposed equipment results in flax fiber with a boon content of 48-49%. It was also found that the most optimal conditions for mechanical processing of raw flax fiber in the second section of the proposed equipment with properly adjusted scutching unit parameters include a scutching drum rotation speed $n = 300$ min^{-1}, a dilution value $l = 36$ mm between the scutching drum and the grid of the scutching unit, and a dilution value $k = 14$ mm between the scutching knife and the batten bar of the scutching drum, which allows obtaining a fibrous mass with foreign impurities at 3.5%.

Research of the third section of the proposed equipment showed that the most rational conditions for scutching flax fiber occur at a scutching drum rotation speed $n = 300$ min^{-1}, a dilution value $l = 36$ mm between the scutching drum and the grid of the scutching unit, and a dilution value $k = 14$ mm between the scutching knife and the batten bar of the scutching drum, resulting in fiber with foreign impurities at a level of 1.86%.

The obtained research results suggested that the proposed method of processing flax stems and the developed equipment can be used in the production of natural, ecologically clean fiber, enabling manufacturers to produce fiber products with low levels of boon content, which can be of interest to both Ukrainian and foreign investors. Considering the current trends in consumer demand for "green" products, this could be an additional factor in spreading this innovative development in the processing sector of the light industry, as well as provide the national producer with the essential raw materials for making everyday products and those for military and special purposes.

Conclusions

A method of processing the trusts without dividing the fiber into long and short, which allows manufacturers to process the stalk material of flax and obtain fiber products of proper quality with a low boon content of about 1.86%, was proposed as a result of the study. The technological process for obtaining uniform fiber based on the innovative mechanical processing scheme for non-oriented flax stems involves the possibility of applying double scutching and shaking, with the need for these steps depending on the technical necessity and economic feasibility of completing the full processing cycle to obtain high-quality final products.

It is recommended to carry out processing of long-fibred flax trusts in the first part of the equipment at a specific pressure of 9.8 daN/cm in a pair of rolls, a raw material humidity 14%, a normal degree of ripen trusts at 6 units on the proposed equipment for obtaining high qualitative and quantitative characteristics of fibrous products. In the second and third sections, the processing should involve a scutching drum rotation speed $n = 300$ min^{-1}, a dilution value $l = 36$ mm between the scutching drum and the grid of the scutching unit, and a dilution value $k = 14$ mm between the scutching knife and the batten bar of the scutching drum, which can be considered the most rational mode for processing the fibrous material.

The innovative technical and technological developments used in the study have made it possible to obtain flax fiber with low foreign impurity content, expanding its use in the textile, pulp and paper, furniture, construction, medical, and automotive industries, as well as in the production of items for military and special purposes, which are especially in demand in Ukraine.

The obtained research results indicated the possibility of widespread application of the proposed innovations in the production of natural fiber, as well as the need to explore the potential for processing other types of bast fiber raw materials on the proposed equipment. Further research should focus on detailed studies of other processing parameters and the characteristics of the fibrous product. Therefore, an important task for future research is the development of modern equipment or the modernisation of existing equipment to provide the industry with the capabilities to improve the qualitative and quantitative characteristics of natural fibers obtained from traditional bast fiber crops in Ukraine.

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Conflict of Interest

None.

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Дослідження виробництва волокна льону-довгунця за інноваційною технологією

Юрій Березовський

Доктор технічних наук, професор
Київський національний університет будівництва і архітектури
03037, просп. Повітряних сил України, 31, м. Київ, Україна
https://orcid.org/0000-0002-9645-2743

Тетяна Кузьміна

Доктор технічних наук, професор
Херсонський національний технічний університет
29016, вул. Інститутська, 11, м. Хмельницький, Україна
https://orcid.org/0000-0002-6113-1923

Наталя Ляліна

Доктор технічних наук, професор
Київський національний університет будівництва і архітектури
03037, просп. Повітряних сил України, 31, м. Київ, Україна
https://orcid.org/0000-0002-9364-0925

Галина Бойко

Кандидат технічних наук, доцент
Херсонський національний технічний університет
29016, вул. Інститутська, 11, м. Хмельницький, Україна
https://orcid.org/0000-0001-8773-5525

Тетяна Головенко

Доктор технічних наук, старший дослідник
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-1792-9364

Анотація. Сучасні потреби споживачів вимагають розширення асортименту екологічно чистої продукції, а також забезпечення української промисловості сировиною для виготовлення товарів воєнного та спеціального призначення. Це можна здійснити за допомогою українського виробництва волокнистої продукції з льону-довгунця з використанням нових технологій та інноваційних розробок. Метою роботи став пошук покращених виробничих умов переробки льону-довгунця та розробка способу переробки трести без розподілу волокна на довге та коротке для забезпечення національного виробника якісним волокнистим продуктом з можливістю розширених умов його використання. Для досягнення поставленої мети було проведено аналіз технічних і технологічних можливостей виробників волокнистої продукції, визначено попит споживачів на натуральне природне волокно, з'ясовано теоретичні підходи у вирішенні питань очищення волокнистого матеріалу. В умовах виробничого контролю дослідження якісних і кількісних характеристик волокнистого продукту здійснювалося за органолептичними та інструментальними методами оцінки. Під час проведення апріорного експерименту було визначено найбільш значимі фактори впливу, які мають найбільший вплив на проходження процесів проминання стебел та тіпання волокнистого сирцю льону-довгунця. Для визначення раціональних параметрів проходження процесу очищення волокнистого продукту з використанням програмного забезпечення та застосування регресійного аналізу шляхом здійснення моделювання технологічного процесу отримання однотипного волокна за розробленими інноваційними складовими, одержано регресійні моделі процесу знекострічення в різних частинах запропонованого обладнання. У роботі було з'ясовано умови використання запропонованого обладнання та вплив роботи різних частин устаткування на економічний результат переробки трести льону-довгунця, а також встановлено напрямки подальшого використання отриманого волокнистого продукту. Одержані результати досліджень можуть допомогти національному виробнику товарів повсякденного використання та спеціального і воєнного призначення вирішити проблему забезпечення якісною волокнистою сировиною, забезпечити підвищення конкурентоспроможності української продукції на внутрішньому та зовнішньому ринках товарів і послуг

Ключові слова: інновації; сировина; волокнистий продукт; м'яття; тіпання; якість; знекострічення

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Improving the consumer properties of compression knitwear with a given pressure based on modelling of nonlinear deformations

Mykola Riabchykov*

Doctor of Technical Sciences, Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-9382-7562

Abstract. The article was devoted to the current problem of ensuring rational parameters of compression textile products, which affect the qualitative parameters of their functioning. The purpose of this work was to substantiate the pattern-making methods of compression clothing, taking into account individual features of the human body structure, anisotropy of materials, deviations from linear laws of deformation, and large deformations that have values similar to geometric dimensions. Discrete-continuous model was developed, which represented a conditionally continuous compression textile material in the form of cells, the elements of which have certain characteristics determined based on macro experiments. The individual geometry of the human body was determined by 3D scanning methods. The use of a structural model allowed the creation of a pattern that ensured a given pressure on the human body. The proposed approach allowed the creation of patterns of compression clothing to ensure a given pressure on the human body. The created discrete model for simulating textiles used additional structural elements, which allowed for taking into account the material's resistance to shear stress and the anisotropy of the textile material. The deviation from the linear law of deformation of the textile material was provided by the characteristics of the structural elements. Significant deformations of the product were taken into account with compiling the system of nonlinear equations. Experimental studies had proven the adequacy of the results obtained. The proposed model allowed for the first time to take into account all real effects during the deformation of textile materials, which ensured the adequacy of the results in the process of creating compression clothing. The obtained results allow the creation of compression textile products with specified pressure parameters along the length

Keywords: textile medical materials; compression textile; discrete model; pattern making; 3D surface

Introduction

There is a tendency in the world to increase research in the field of medical use of textile products as was shown by S. Grycuk & P. Mrozek (2023). Among such products, a special place was occupied by compression textile products that can be used both in medical and sports clothing. This fact was noted by C.S. Buset *et al.* (2021). O. Kyzymchuk *et al.* (2020) noted, that the creation of compression clothing should be based on ensuring the necessary pressure between the clothing and the human body. In particular, special measuring devices have been developed for this purpose, which controlled the real parameters of the interaction, although real recommendations for construction taking into account the elastic characteristics of textile materials were given in the study of C. Ho *et al.* (2024).

Study of K.M. Bourne *et al.* (2021) claimed a positive effect of compression garments in the treatment of translational orthostatic tachycardia. Real studies were conducted on the effect of compression in different places of the human body. Leveling of heart rate and blood

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*Corresponding author

pressure was noted. The study of M. Lozo *et al.* (2021) offered basic approaches to the design of compression products. An attempt was made to provide real pressure values. However, this study does not take into account the real mechanical characteristics of stocking materials. The article of L. Zhang *et al.* (2019) was devoted to the determination of pressure distribution during the process of compression clothing use. At the same time, loads of ready-made clothes were determined without proposals for the actual design of the products to ensure the necessary parameters. Quite high hopes for the prospects of using compression textiles, including in the design of smart clothes, can be placed on systems of intimate textiles. D.B. Datta & P. Seal (2022) noted that this type of clothing at the present moment was not only an element of functional necessity or style.

Modern requirements for intimate clothing include, first of all, hygienic properties, which, in particular, were largely provided using compression textiles. The compressive properties of these materials can additionally have an aesthetic role of improving the appearance of the human body figure using intelligent intimate clothing. Considering the problems of intimate clothing in some publications, the problems of breast support with bras were solved by L. Haworth *et al.* (2022). Moreover, this problem was considered both from a medical point of view and for aesthetic purposes. The use of incorrect structures affected several biomechanical reactions, worsed the condition, and affected well-being. The use of compression textile materials made it possible to create designs of smart clothes with adjustable compression and support.

The analysis of research on the problems of creating compression clothing indicated the need to implement design methods that were based on the real mechanical characteristics of materials, including taking into account anisotropy and nonlinear effects. An attempt at such modelling was made in the study of M. Riabchykov *et al.* (2024). Such methods weren't take into account the real structure of textile materials. So, geometric modelling wasn't fully ensured compliance with the real characteristics of materials.

The purpose of this study was to substantiate the improvement of consumer properties of compression clothing based on modelling real material properties.

Materials and Methods

Requirements for materials for compression products determined a complex of elastic, durable, hygienic properties. In this research, knitted fabrics with a content of 73% polyamide and 27% elastin were used. Specification of the fabric was done in Table 1.

Table 1. *Specification of the fabric used in investigations*

Specification	Meaning
Fabric structure	Warp knitted fabric
Content	73% polyamide and 27% elastin
Fabric mass (g/m^2)	98
Yarns density	5.5 tex. (50 denier)/24 filaments
Elasticity modulus in longitudinal direction, N/cm	11
Elasticity modulus in longitudinal direction, N/cm	4.3

Source: *developed by the author based on N. Kankariya (2022)*

The overpayment of the material (Fig. 1) provided the necessary elastic characteristics, in particular, the transformation of forced during stretching into pressure on the body. At the same time, the pressure parameters required from compression clothing were taken into account. These can be textile products of the first compression class (provide pressure from 2.4 kPa to 2.9 kPa), second class (pressure from 3 kPa to 4.3 kPa), third class (pressure from 4.4 kPa to 6 kPa) (Lee *et al.*, 2020).

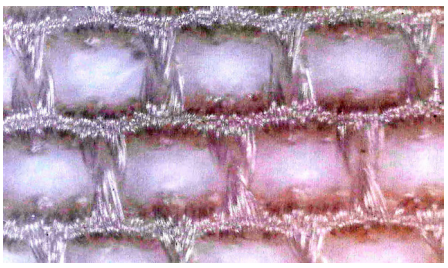

Figure 1. *Structure of compression textile material*

Source: *developed by the author*

The construction of a mathematical model was based on finite element approaches, which involved considering a conditionally continuous material as a complex of individual components. Such models more

often used linear models, which weren't always take into account the effect of changing the real geometry of the textile material, as well as its real physical characteristics. Such model was developed by H.F. Siddique *et al.* (2022). Meanwhile, any data on textile materials showed a pronounced deviation from the linear relationship of elongation and load, which can significantly affect the construction of a real model (Fig. 2).

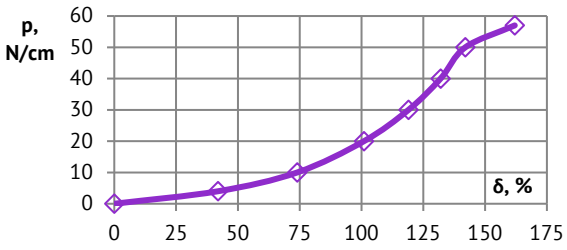

Figure 2. *The relationship between the specific force acting on the compression material, p, and its elongation, δ*
Source: *developed by the author based on H.F. Siddique et al. (2022)*

Deformations in different directions of the textile material caused different elastic forces, which made it necessary to take into account the effects of anisotropy. At the same time, standard characterisation experiments must be reorganised. The new approach should exclude marginal effects from the experiments and provide valid characteristics of the entire material (Fig. 3). This approach allowed to determine the elongation and narrowing of the material during testing it in two perpendicular directions. The main characteristics of the materials as a result of the experiment can be written in the form:

$$\begin{cases} p_x = K_{11}(\varepsilon_1 + \mu_{21} \cdot \varepsilon_2) \\ p_y = K_{22}(\mu_{12} \cdot \varepsilon_1 + \varepsilon_2), \end{cases} \quad (1)$$

where p_x, p_y – specific load per unit width of the material in the longitudinal and transverse directions, N/m; ε_1, ε_2 – relative deformation in the longitudinal and transverse directions; K_{11}, K_{12} – modules of elasticity for two directions; μ_{12}, μ_{21} – Poisson's ratios for two directions.

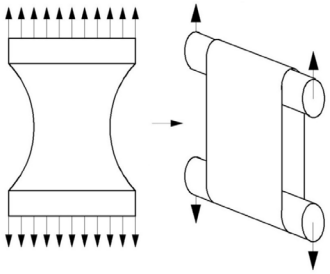

Figure 3. *Methods of determining the real characteristics of compression textile materials*
Source: *developed by the author*

The change in the geometry of the material cells indicated rather large deformations. As a rule, in models using finite element methods, the condition of small deformations was assumed. This fact, in particular, was implemented in the replacement of such trigonometric functions as sinus, and tangent with values of angles, which allowed for reducing the problem to a system of linear equations. Real compressions knitted materials in the process of deformation acquired noticeable deformations, which significantly affected the geometric characteristics of the cells (Fig. 4). At the same time, the rectangular cells significantly changed their geometry, which led to nonlinear dependencies.

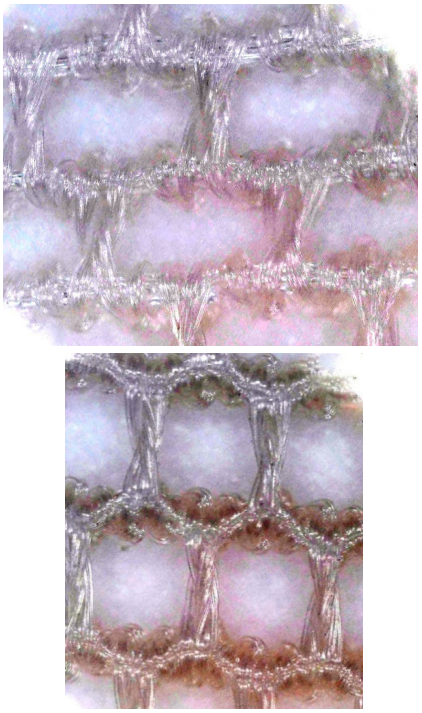

Figure 4. *Deformation of the compression material in the longitudinal and transverse directions*
Source: *developed by the author*

These facts demonstrated the need to improve existing models in the direction of taking into account their real structural, geometric, and physical characteristics. The main requirement, in this case, was to ensure the necessary pressure of compression clothing. It was desirable to take this requirement into account at the stage of pattern making, bearing in mind the real physical and geometric parameters of compression textile materials. At the same time, as mentioned by W. Xi *et al.* (2020), constant pressure over the entire surface of the compression product may be required, as well as variable pressure to help the body to move blood properly. Together with the constructed deformation model and real pattern-making methods, experiments were used by M. Riabchykov *et al.* (2023) to determine the pressure between the human body and

compression clothing to assess the adequacy of the developed methods. Body-garment pressure measurements using pressure sensors provided the full range of data-predicted values required of compression garments.

Mathematical modelling methods allowed determining the deformations of compression clothing elements under conditions of nonlinear physical and geometric processes. This led to the need to solve systems of nonlinear equations. Iteration methods were used to solve them. As a first approximation, solutions of a linear problem for a square cell were chosen.

Results and Discussion

It worth to start with the real problem of designing compression medical clothes to provide constant pressure for an individual case. The real structure of the compression textile material (Fig. 1) showed undoubted discreteness. This confirmed the possibility of creating a model in the form of discrete elements with the possibility of determining real deformations.

A deeper analysis, meanwhile, demonstrated certain limitations of using a direct geometric interpretation in the form of rectangular cells with a hinged combination (Fig. 5, a). At the same time, the stiffness parameters of elements 1 and 2 should be chosen based on the real characteristics of the material. Such a model cannot take into account the behaviour of the material in the case of complex loading, in particular, the resistance of the material to shear deformations.

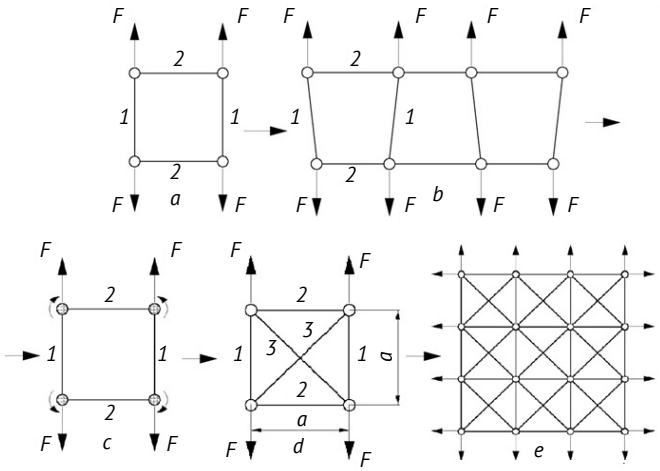

Figure 5. *A discrete model of compression textile material*

Note: *a – rectangular cells with a hinged combination; b – trapezoid element; c – replacement od hinged models with the ability to perceive moments; d – diagonal element conditionally added to the cells; e – replacement of textile material with a system of cells*
Source: *developed by the author*

The ability to catch shear deformations can be taken into account by changing the geometry of the cells, for example by changing the shape of a rectangle to a trapezoid (Fig. 5, b). Such a proposal excluded the unification of elements and complicated the consideration of geometric characteristics. Another way to take into account the shift factor can be to replace hinged models with the ability to perceive moments (Fig. 5, c). Such a scheme corresponded most closely to the real structure of the material, but it required taking into account additional components, when determining deformations and adding unknowns during mathematical modelling. As a result, the complexity of calculations increased significantly. In this study, an artificial step was proposed. To take into account the possibilities of displacement, element 3 was conditionally added to the cells, which ensured the perception of arbitrary deformations. At the same time, the compression textile material was replaced by a system of cells (Fig. 5, e). At the same time, the real characteristics of cell elements were determined from real macro-experiments for textile materials.

The first step in creating the model was the case of a linear isotropic material that has the same elastic characteristics in all directions. The modelling condition should be to ensure the same characteristics for the macro experiments and the calculated discrete model. In the case of an isotropic structure, such requirements lead to the conditions for determining the stiffness indicators of structural elements:

$$g1 = g2 = \frac{\sqrt{2}\cdot E\cdot a}{1+\mu};$$
$$g3 = \frac{\sqrt{2}\mu\cdot E\cdot a}{1-\mu^2}, \quad (2)$$

where E – modulus of elasticity; μ – Poisson's ratio; a – sell dimension; $g1$ – stiffness of horizontal element; $g2$ – stiffness of horizontal element; $g3$ – stiffness of diagonal element.

The structure for simulating anisotropy replaces square cells with rectangular ones as shown in Figure 6.

Anisotropy will be provided by the correct choice of the ratio of longitudinal and transverse elements. Taking into account the data of the experiments according to the scheme of Figure 3, the diagonal angle of the rectangular element, which provided the necessary anisotropy indicators, should be determined from the condition:

$$tg\alpha = \frac{0{,}77-0{,}35\cdot\mu_{12}+0{,}35\cdot\mu_{21}-0{,}2\cdot\mu_{12}\cdot\mu_{21}}{\varsigma^{0{,}4+0{,}1\cdot\mu_{12}+0{,}9\cdot\mu_{12}\cdot\mu_{21}}}. \quad (3)$$

The formula defined μ_{12} – Poisson's (compression) ratio in the transverse direction stretched in the longitudinal direction; μ_{21} – Poisson's ratio in the longitudinal direction stretched in the transverse direction; $\varsigma = E1/E2$, $E1$ – modulus of elasticity in the longitudinal direction; $E2$ – modulus of elasticity in the transverse direction.

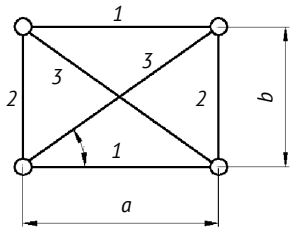

Figure 6. *Rectangular element for modelling anisotropic structure*

Note: *1 – longitudinal member; 2 – transverse member; 3 – diagonal member; a – longitudinal member length; b – transverse member length*
Source: *developed by the author*

The physical characteristics of the stiffness of the elements were determined based on real experimental data. The proposed structure can take into account the effects of geometric nonlinearity. In the case of deformations, the values of which were comparable to the cell sizes, the equilibrium equations must take this fact into account. The rationale for the methods of determining nonlinear effects was shown in Figure 7. At the same time, the cell acquired longitudinal Δx and Δy transverse deformations, the magnitudes of which were comparable to the cell sizes. The angle of inclination of the diagonal varies significantly and this must be taken into account, when constructing the equilibrium equations.

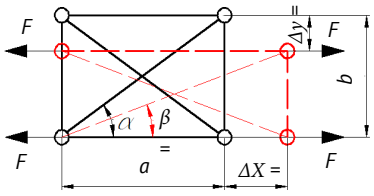

Figure 7. *Taking into account the effects of geometric nonlinearity*

Note: *a – longitudinal member length; b – transverse member length; F – strength in the element*
Source: *developed by the author*

For this case, the force-dependent deformations were determined by a system of nonlinear equations based on the methods that have been developed and were indicated as used in this study:

$$\begin{cases} \Delta x = \dfrac{F}{g1} - \dfrac{g3}{g1}\dfrac{\sqrt{(a+\Delta x)^2+(b-\Delta y)^2}-\sqrt{a^2+b^2}}{\sqrt{1+\left(\frac{a+\Delta x}{b-\Delta y}\right)^2}} \\ \Delta y = \dfrac{g3}{g2}\dfrac{\sqrt{(a+\Delta x)^2+(b-\Delta y)^2}-\sqrt{a^2+b^2}}{\sqrt{1+\left(\frac{b-\Delta y}{a+\Delta x}\right)^2}}, \end{cases} \quad (4)$$

where a – longitudinal size of the cell; b – transverse size; $g1$, $g2$, $g3$ – stiffness parameters determined by formula (2).

This formula allowed, based on iterative approaches, to determine the real deformations of elements along the abscissa axis Δx, and along the ordinate axis Δy of compression clothing under the action of load F. It can be seen from the system that the values of the deformations depending on the applied forces were from both parts of the equation in the transcendental form. The real deformations for this case were determined by solving these equations using the iteration method.

To achieve the greatest effect, compression clothing should provide individual characteristics of a person (Richards *et al.*, 2020). The real geometric characteristics of the body element can be obtained by 3D scanning methods (Fig. 8, a). The resulting digital model allowed to determine the coordinates of individual points of clothing elements, in particular, the structure in the form of separate sections (Fig. 8, b).

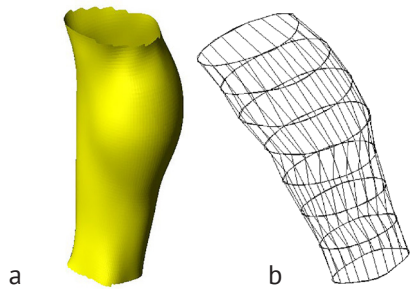

Figure 8. *3D surface for designing compression clothing*

Note: *a – real geometric characteristics of the body element; b – digital model of the body element*
Source: *developed by the author*

Determining the lengths of the cross-section lines and taking into account the distances between them allowed the creation of the scan of the surface of an element of the human body. At the same time, linear models of deformation allowed for determining negative allowances during pattern creation. The task was to build a pattern of compression clothing that provided the necessary pressure, taking into account the real physical characteristics of materials and real nonlinear characteristics of deformations. Such a problem can be

solved within the framework of the proposed model. At the same time, the forces in the elements of the cells were transformed into the effect of pressure as shown in Figure 9. The initial sizes of the material cells were increased to the size of the human body in a separate section. Efforts were determined based on equilibrium equations taking into account nonlinear physical and geometric effects. Efforts were listed in the pressure parameter. If the pressure parameters wasn't match the required values, corrections were made to the geometry of the proposed structure.

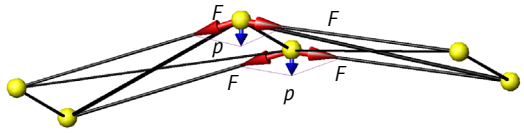

Figure 9. *Dependence of pressure on forces in the cells*

Note: *F – force in the element; p – pressure on the limb*
Source: *developed by the author*

The proposed technique was tested for the task of ensuring constant pressure over the entire surface. The results of building patterns for such conditions were shown in Figure 10. At the same time, the figure showed the difference between the initial sweeps of the surface of the body element, the proposed pattern on the base of the linear arrangement, and the required geometry taking into account nonlinear and anisotropic effects.

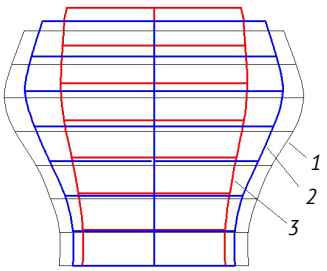

Figure 10. *Patterns to ensure constant pressure of compression clothing*

Note: *1 – stretching of the surface of the limb; 2 – the required geometry of the knitted fabric based on the linear arrangement; 3 – the required geometry of the knitted fabric taking into account nonlinear and anisotropic effects*
Source: *developed by the author*

These results determined the necessary geometric parameters of compression clothing, which provided the necessary pressure for an individual consumer. The requirements of the variable pressure length can be taken into account by the corresponding changes as a result of calculations according to the proposed model. The experiment used a conical rubber element 1, which imitated an element of the human body (Fig. 11). Compression product 2, designed according to the developed methods, was put on the conical element. Wires to pressure sensors 3, which were located on the surface of the rubber element, were passed through the holes in the rubber element. Eight sensors were located evenly around the circle in two cross-sections. For the pressure measurement sensor with limits up to 10 kPa was used in experiments. Pressure-sensing elements based on piezo resistive effect had sensitivity ±0.07 kPa^{-1}.

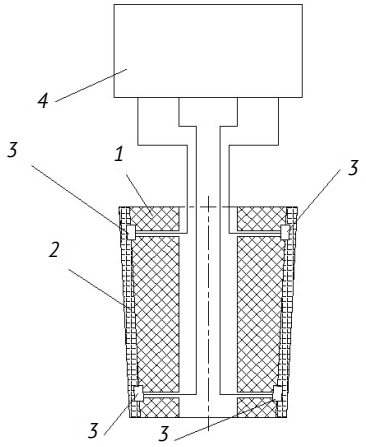

Figure 11. *Experimental studies of compression clothing*

Note: *1 – rubber element; 2 – compression product; 3 – pressure sensors; 4 – measuring console*
Source: *developed by the author*

The developed pattern according to the conical shape of the element imitating the limb of the body was made of compression material. Pressure values were taken from eight elements. After that, the compression textile was removed and unloading was carried out. The process was repeated four times, thus thirty-two pressure readings were obtained. The average value, variance, and root mean square deviation was determined. A total of three samples of compression garments were produced to provide different levels of pressure. The values obtained as a result of using the theoretical model, as well as the experimental data were given in Table 2.

Table 2. *Obtained pressure parameters for different samples of compression clothing*

Sample number	Theoretical pressure value, kPa	The average value of experimental data, kPa	Root mean square deviation, kPa	Real pressure values, kPa
1	2.8	2.97	0.08	from 2.73 to 3.21
2	3.6	3.86	0.11	from 3.53 to 4.19
3	4.5	4.64	0.13	from 4.25 to 5.03

Source: *developed by the author*

The results of the study proved the adequacy of the obtained calculation models and the possibility of their use in the processes of real pattern-making of elements of compression clothing. This study provided new results that can improve the consumer characteristics of compression garments. Comparison with known results demonstrated certain advantages of the proposed approaches and methods. It was possible to note the insufficient level of scientific substantiation of the parameters of compression clothing, taking into account the real values of the mechanical characteristics. The study of J. Lee & W. Do (2023) attempted numerical modelling of elastic clothing using the finite element method. In this study, an analysis of the influence of different pressure levels during wearing compression clothing was carried out. In contrast to this study, the proposed approaches allowed to take into account the effects of geometric and physical nonlinearity, which increased the accuracy of the modelling.

The structural-rod model of the textile material was developed in study of T. Yelina *et al.* (2022). Analysis of the proposed structure proved the possibility of its use in limited cases. Taking into account nonlinear and anisotropic properties in such a model caused great complications. This study used more precise approaches, which allowed for improved product characteristics. Attempts to take into account the anisotropic properties of textile materials were demonstrated in article of D. Wijesinghe & B.J. Roth (2022). In contrast to the results obtained in this study, these works weren't provide clear answers to the question of the correctness of using data from macro experiments to determine the mechanical characteristics of textile materials.

As noted by A. Tomaszewska & D. Reznikov (2025) attempts to analytically model the behaviour of textile materials in models of continuous environments can provide only separate solutions; they were quite difficult to apply to real problems. Modelling of structural and mechanical characteristics of knitted networks, taking into account morphological operations, was substantiated in the study of X. Li *et al.* (2022). The prospects for the development of such models were related to their connection to ensuring the mechanical characteristics of real textile products. Z. Jing & Z.M. Hua (2021) emphasised that the proposed models can be extended to design real clothing elements. Existing models of the mathematical design of clothing imply only geometric solutions without significant consideration of mechanical properties and deformations of textile materials, which were necessarily required in the design of compression textile products. The problems of real pattern computation taking into account mechanical and geometric parameters were solved in the study of W. Long *et al.* (2021). Researchers M. Riabchykov *et al.* (2023) developed a mathematical model of the surface with the determination of triangulation parameters and established that the accuracy of creating unfolding for further pattern making depends on the direction and number of geometric elements. In the context of medical research on bone prosthetics, the authors O. Zubkov & V. Torchynskyi (2024) noted the use of medical materials made of plastic. Overall, researchers noted that the use of such materials was reliable and durable. Real methods of designing a compression beam required consideration of nonlinear deformations, which weren't provided by the proposed methods. The real result of this study was developing methods for designing compression products to ensure a given pressure, taking into account anisotropy and nonlinear deformation effects.

Conclusions

This study provided a comprehensive approach to improving the design of compression clothing by integrating advanced modelling techniques that accounted for the real mechanical characteristics of textile materials. A significant contribution of this research lay in the development of a model that considered the anisotropic and nonlinear deformation properties of compression fabrics, addressing gaps in previous studies that primarily relied on simplified geometric or linear models.

By incorporating finite element methods and discrete structural modelling, the study successfully refined the accuracy of pressure distribution predictions in compression garments. Experimental validation using pressure sensors confirmed the reliability of the proposed model, demonstrating its applicability in real-world pattern-making for medical and athletic compression wear. The findings highlighted the necessity of tailoring compression clothing to individual anatomical characteristics, emphasising the role of 3D scanning in achieving a precise fit and optimal pressure distribution.

This study bridged the gap between theoretical modelling and practical garment design by integrating real material behaviours into the construction process. The ability to accurately simulate the effects of geometric deformations on pressure distribution allowed for the creation of garments that provided the necessary support, while maintaining comfort and functionality. The developed methodology has broad implications for both medical and sports applications, offering a pathway toward more effective, customised compression wear.

Future research could further refine these models by incorporating additional biomechanical factors, such as dynamic movement analysis, to enhance the adaptability of compression garments in varying conditions. The results of this study paved the way for innovations in smart textile applications, where compression clothing can be designed with embedded sensors to provide real-time physiological feedback for medical and performance-enhancing purposes.

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Conflict of Interest

None.

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Покращення споживних властивостей компресійного трикотажу із заданим тиском на основі моделювання нелінійних деформацій

Микола Рябчиков

Доктор технічних наук, професор
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-9382-7562

Анотація. Стаття присвячена актуальній проблемі забезпечення раціональних параметрів компресійних текстильних виробів, які впливають на якісні характеристики їх функціонування. Метою даної роботи було обґрунтування методів конструювання компресійного одягу з урахуванням індивідуальних особливостей будови тіла людини, анізотропії матеріалів, відхилень від лінійних законів деформації та великих деформацій, значення яких є порівняними з геометричними розмірами. Було розроблено дискретно-неперервну модель, яка представляє умовно неперервний компресійний текстильний матеріал у вигляді комірок, елементи яких мають певні характеристики, визначені на основі макроекспериментів. Індивідуальна геометрія тіла людини визначалася методами 3D-сканування. Використання структурної моделі дозволило створити лекало, що забезпечує заданий тиск на тіло людини. Запропонований підхід дозволив створювати викрійки компресійного одягу з урахуванням заданого тиску на тіло людини. Створена дискретна модель для моделювання текстилю використовувала додаткові структурні елементи, які дозволили враховувати опір матеріалу до зсувних напружень та анізотропію текстильного матеріалу. Відхилення від лінійного закону деформації текстильного матеріалу забезпечувалося характеристиками структурних елементів. Значні деформації виробу враховувалися при складанні системи нелінійних рівнянь. Експериментальні дослідження підтвердили адекватність отриманих результатів. Запропонована модель вперше дозволила врахувати всі реальні ефекти при деформації текстильних матеріалів, що забезпечило адекватність результатів у процесі створення компресійного одягу. Отримані результати дозволяють створювати компресійні текстильні вироби із заданими параметрами тиску вздовж довжини

Ключові слова: медичні текстильні матеріали; компресійний текстиль; дискретна модель; конструювання лекал; 3D-поверхня

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Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
Тел.: (0332) 746 103
E-mail: info@c-bulletin.com.ua
https://c-bulletin.com.ua/uk

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Address for contacts:
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
Tel.: (0332) 746 103
E-mail: info@c-bulletin.com.ua
https://c-bulletin.com.ua/en