UDC 664.7:664.788:664.3:547.915
DOI: 10.15587/1729-4061.2025.330564

MODIFICATION OF STRUCTURAL AND MECHANICAL PROPERTIES OF THE EXTRUDATE BY ENRICHMENT WITH FOOD FIBERS AND LIPIDS

Ihor Petik
Corresponding author
PhD, Head of Laboratory
Department of Studies of Technology for Processing Oils And Fats
Ukrainian Scientific Research Institute of Oils and Fats of the National Academy of Agricultural Sciences of Ukraine
Dziuba ave., 2 A, Kharkiv, Ukraine, 61019
E-mail: petikigor1984@gmail.com

Serhii Stankevych
PhD, Associate Professor
Department of Zoology, Entomology, Phytopathology, Integrated Plant Protection and Quarantine named after B. M. Litvinova*

Volodymyr Panasenko
PhD, Senior Lecturer
Department of Engineering Mechanics and Technological Processes in the Agro-Industrial Complex
Vinnytsia National Agrarian University
Sonyachna str., 3, Vinnytsia, Ukraine, 21008

Kostiantyn Siedykh
PhD
Cyclical Commission of Food Technology and Hotel-Restaurant Business
A Separate Structural Unit "Kharkiv Trade and Economic Vocational College State University of Trade and Economics"
Otakara Yarosha lane, 8, Kharkiv, Ukraine, 61045

Maryna Ponomarova
PhD, Associate Professor
Department of UNESCO "Philosophy of Human Communication and Social and Humanitarian Disciplines"*

Olesia Filenko
PhD
Department of Chemical Engineering and Industrial Ecology
National Technical University "Kharkiv Polytechnic Institute"
Kyrpychova str., 2, Kharkiv, Ukraine, 61002

Iryna Balandina
PhD, Associate Professor**

Anton Ryabev
PhD
Department of Tourism and Hospitality**

Svitlana Zolotarova
PhD, Associate Professor
Department of UNESCO "Philosophy of Human Communication and Social and Humanitarian Disciplines"*

Viktoriia Novikova
PhD, Associate Professor
Department of Chemistry, Biochemistry, Microbiology and Food Hygiene*
*State Biotechnological University
Alchevskykh str., 44, Kharkiv, Ukraine, 61002
**Department of Tourism and Hospitality
O.M. Beketov National University of Urban Economy in Kharkiv
Marshala Bazhanova str., 17, Kharkiv, Ukraine, 61002

The object of the study is the composition of the feed extrudate modified by the addition of dietary fiber and lipid sources. The problem to be solved is the optimization of the structural and mechanical properties of the feed extrudate through the rationalization of the addition of components. Regression models have been developed to accurately predict the ratio of modifying additives that provides the specified water resistance and swelling index. It has been experimentally established that the rational ratio of components – 4.0±0.1% chicken fat and 6.0±0.2% wheat bran – provides water resistance of 190.0±7.5 min, swelling index of 55.0±2.1% and porosity of 60.0±2.2%. The results are achieved due to the complex interaction between the components, where lipids form a hydrophobic barrier, and dietary fibers create a stable porous matrix, which is confirmed by regression models. Comparative analysis with a commercial analogue ("Roycher™ AQUA Carp Finish") revealed competitive advantages of the developed extrudate: lower cost (310 USD/t versus 1050 USD/t). Structural and mechanical characteristics of the studied extrudates were similar. This makes the developed composition promising for industrial application. The results obtained are explained by the interaction of the protein-starch matrix with lipids and dietary fibers during extrusion, which is confirmed by statistically significant models. A distinctive feature of the study is a comprehensive approach to rationalizing the composition of the extrudate, which combines technological efficiency with economic feasibility. The extrudate of the developed composition can be used in the production of feed for aquaculture. Further research should be aimed at studying the long-term stability of product properties and adapting the technology to industrial conditions

Keywords: extrudate, dietary fiber, chicken fat, protein-starch matrix, structural and mechanical properties, swelling index

Received 07.03.2025
Received in revised form 25.04.2025
Accepted date 12.05.2025
Published date 17.06.2025

How to Cite: *Petik, I., Stankevych, S., Panasenko, V., Siedykh, K., Ponomarova, M., Filenko, O., Balandina, I., Ryabev, A., Zolotarova, S., Novikova, V. (2025). Modification of structural and mechanical properties of the extrudate by enrichment with food fibers and lipids. Eastern-European Journal of Enterprise Technologies, 3 (6 (135)), 15–21. https://doi.org/10.15587/1729-4061.2025.330564*

1. Introduction

The widespread use of thermoplastic extrusion methods in processing technologies is explained primarily by the possibility of effective influence on polysaccharides and proteins of the processed raw materials. Almost all issues related to the transformations of these ingredients that are part of raw materials of plant origin have been studied quite comprehensively. The most significant factors influencing this process have been identified, and their rational numerical values have been substantiated [1]. A more complex task of obtaining extrudates with the planned properties is the processing of carbohydrate-protein-lipid raw materials. Solving this task is complicated by the peculiar behavior of lipids in the extrusion process. When a certain lipid concentration is exceeded, the dissipative system of the extruder operates unstably, since the mechanical energy of the working bodies is inefficiently converted into heat [2]. In other words, the increased lipid content reduces friction between the material particles and the working surfaces of the extruder. This leads to a decrease in the temperature and pressure of the product at the outlet of the equipment. As a rule, this inhibits the process of pore formation and allows obtaining extrudates with high values of the expansion coefficient [3]. Even more complex technical and technological problems must be solved in the process of processing raw materials containing, in addition to the above ingredients, soluble (pectin, gums, mucus) and insoluble dietary fibers (fiber, lignin) [4]. Some types of such raw materials have unique properties, having in their composition relatively many proteins, lipids and dietary fibers and relatively few carbohydrates. Such raw materials include milk thistle seeds, pumpkin (with shell), flax, sesame, etc. [5, 6]. It is known that with a high fiber content in the raw material, the activity of starch as an initiator of the pore formation process in extrudates decreases. On the other hand, the use of extrudates obtained from plant starch-containing raw materials indicates a significant influence of their porosity on swelling, water and lipid-holding capacity, solubility, expansion coefficient, as well as texture and digestibility of finished products [7]. These properties of extrudates depend to a decisive extent on the starch content and mass fraction of moisture in the raw materials [8]. Taking into account the described patterns, it is logical to assume a significant deterioration of the pore formation process during the processing of raw materials with a high content of dietary fiber [9].

Thus, research aimed at enriching extruded products with dietary fiber and lipids is not only important from a scientific point of view, but also necessary for the further development of innovations in the processing industry. The obtained scientific results should contribute to the improvement of modern extrusion technologies and the expansion of the range of competitive products.

2. Literature review and problem statement

In the study [10], it was found that a decrease in moisture content from 33 to 14% changes the nature of starch transformations from gelatinization to dextrinization, with a peak of gelatinization at 28–29% moisture content. However, the authors did not investigate the effect of extruder pressure on these processes, which may be key for industrial scaling. This is due to the fact that the work is focused on laboratory conditions with fixed screw parameters, while in real production the pressure fluctuates due to the uneven supply of raw materials. The results of the study [11] confirm the increase in the content of dextrins at low moisture content, but do not take into account the role of lipids in these transformations. This is due to the limitation of the study: the authors used pure starches without additives, while in food compositions the presence of fats can change the kinetics of degradation. Thus, the question of the complex influence of technological parameters, in particular moisture content, lipid content and the dynamics of dextrinization remains open. In contrast, the results of [12] deny significant degradation of starch during extrusion, emphasizing the preservation of its structure. However, their conclusions are based on the analysis of only two types of starch (corn and sorghum), while to generalize the thesis it is necessary to include a more diverse range of raw materials (e.g., high-amylose starches). This limitation is explained by the narrow goal of the study – the assessment of technological properties of specific products, rather than the fundamental study of transformation mechanisms. Despite significant progress in understanding starch transformations, gaps remain in the study of complex interactions between extrusion parameters, raw material composition and functional additives. Overcoming these limitations requires interdisciplinary research involving mathematical modeling methods and advanced rheological characterization.

As shown in [13], the presence of lipids, in particular oleic acid, promotes the formation of amylose-lipid complexes, which reduce the hydrophilicity of starch and inhibit gelatinization. Extrusion with 5–10% lipids at 100°C allows to obtain resistant starch [14]. However, these studies do not take into account the dynamics of complex formation with variable extrusion parameters (screw speed, compression ratio), which limits the possibility of optimizing the process. This is due to the fact that the works are focused mainly on fixed processing modes, without taking into account the industrial variability of conditions. As shown in [10], a decrease in moisture content from 33 to 14% changes the nature of starch transformations from gelatinization to dextrinization. This trend is confirmed by data [11], where extrusion at low moisture content contributed to an increase in the content of dextrins. However, none of these studies analyzed how the presence of lipids affects these transformations at different moisture levels. This is a significant omission, since in real food systems starch, lipids and water interact in a complex way. In contrast, the authors of [12] deny significant starch degradation during extrusion. However, this study is limited to the analysis of only two types of starch without taking into account their lipid environment. Such a discrepancy in results may be due to the lack of standardization of experimental conditions regarding lipid composition.

The study of the interaction of starch with proteins [15] demonstrates the mechanism of modification of the starch structure, but does not take into account the competitive influence of all components in complex multicomponent systems. This limits the possibility of predicting the structural and mechanical properties of the final product. Of particular interest is the dynamics of modification of dietary fibers during extrusion. Although numerous studies [16, 17] confirm the increase in the solubility of dietary fibers under the influence of thermomechanical processing, their potential interaction with the lipid phase remains practically unstudied. This creates scientific interest, since such interactions can significantly affect the formation of the microstructure of the extrudate and its functional properties. An important addition to these studies is the work [18], which established the optimal ratios of cellulose and lipid-containing components (sunflower husk 3–8% and phosphatide concentrate 3–6%) to achieve water resistance of 220–300 min. and swelling of 100–120%. However, even this work does not take into account the complex interaction between different types of dietary fibers and lipids. For example, studies of the effect of cellulose nanofibers [19] show the promise of their use for controlling the stability of the system, but there is no data on their complex effect in combination with other types of fibers and lipids. This limits the possibility of creating products with precisely specified mechanical characteristics.

The proposed study on the modification of the structural and mechanical properties of the extrudate by enriching it with dietary fibers and lipids aims to fill these scientific gaps by comprehensively studying the interaction of dietary fibers of different types with lipid components and protein additives under extrusion processing conditions. It is expected that the results obtained will allow developing scientifically sound approaches to the formulation of extruded products, optimizing the raw material composition to obtain products with specified structural and mechanical properties, and expanding the range of extruded products.

Thus, the analysis of the [10–19] demonstrates that despite significant progress in understanding individual aspects of extrusion processing of food systems, there are significant gaps in the study of complex interactions between components. This justifies the need for research into the modification of extrudate properties with dietary fibers and lipids.

3. The aim and objectives of the study

The aim of the study is to establish the patterns of influence of dietary fiber (wheat bran) and lipid components (chicken fat) on the structural and mechanical properties of the feed extrudate, which will allow developing scientifically based approaches to its modification. This will make it possible to create technological conditions for regulating the textural characteristics and increasing the nutritional value of feed extrudates based on protein- and starch-containing secondary products.

To achieve the aim, the following tasks were set:

– to determine the dependence of the structural and mechanical characteristics of the extrudate on the content of cellulose and lipid-containing components;

– to compare the structural and mechanical characteristics of the modified extrudate with a commercial analogue.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of the study is the chemical composition of the extrudate based on protein- and starch-containing raw materials, which is modified by adding sources of dietary fiber (wheat bran) and lipid components (chicken fat. The hypothesis of the study is that the introduction of wheat bran and chicken fat into the composition of the extrudate based on protein- and starch-containing raw materials will allow regulating its structural and mechanical properties. This should occur due to the complex interaction of dietary fiber and lipids with the protein-starch matrix, which affects the porosity, water resistance and swelling of the product. The main assumptions of the study: the optimal ratio of wheat bran and chicken fat in the composition of the extrudate will allow achieving a balance between its structural strength and functional characteristics. The interaction of lipids with dietary fiber during extrusion will contribute to the formation of a stable porous structure, which will affect the texture and technological properties of the finished product. product.

The main simplifications of the study: the chemical composition of wheat bran and chicken fat is considered stable for different batches of raw materials, which allows to generalize the results obtained without taking into account the natural variability of their properties. In addition, the influence of technological parameters of extrusion (temperature, pressure) on the formation of the structure of the extrudate is considered as a secondary factor compared to the influence of the compositional composition.

The specified assumptions and simplifications will allow to focus on the study of key patterns of modification of the structure of the extrudate and will ensure the reproducibility of the results for further scaling up the technology.

4. 2. Research materials and equipment used in the experiment

The following materials and reagents were used during the study:

– sunflower meal (produced in Ukraine), according to DSTU 4638 (CAS 68937-99-5);

– soybean meal (produced in Ukraine), according to DSTU 4230 (CAS 68308-36-1);

– crushed oat groats (produced in Ukraine), according to DSTU 7698 (CAS 97-56-3);

– wheat bran (produced in Ukraine), according to DSTU 3016 (CAS 9004-34-6);

– chicken fat (produced in Ukraine), according to DSTU 4827 (CAS 8023-79-8).

4. 3. Extrusion technique

Extrusion of a pre-crushed and homogenized mixture of oilseed meal, oat groats, wheat bran, and chicken fat was carried out on a PE-20 press extruder (Ukraine) according to previous experimental studies described in [2].

4. 4. Methods for determining the chemical composition and technological parameters of raw materials for extruded feed

The following indicators were determined in additives for modifying the technological properties of extruded feed and in the finished product:

– mass fraction of lipids and fiber – according to DSTU 7491;

– porosity – according to [2];

– water resistance and swelling index – according to DSTU 3526.

4. 5. Research planning and results processing

To study the influence of the content of wheat bran and chicken fat on the structural and mechanical properties of the extrudate, the method of multifactor experimental planning was used. The research was conducted with three repetitions for each combination of factors. Mathematical processing of the obtained data was performed using the Stat Soft Statistica v 6.0 software package (USA). Approximation of the experimental results was carried out by constructing second-order polynomial regression models. The statistical significance of the coefficients of the regression equations was assessed using the Student's *t*-test at a significance level of $p < 0.05$. The adequacy of the constructed models was confirmed by the values of the coefficients of determination ($R^2 = 0.958$ and $R^2 = 0.972$ for the equations of the dependences of water resistance and extrudate swelling index on the content of modifying additives, respectively) which indicates the ability of the specified regression models to explain more than 95% of the variation in the results.

The significance of the obtained regression models was checked using the Fisher criterion. The calculated values of the F-criterion (18.74 and 24.15 for the equations of the dependences of water resistance and extrudate swelling index on the content of modifying additives, respectively) significantly exceeded the critical tabular value ($F_{tab}(2,12)=3.88$ at $p=0.05$), which confirms the statistical reliability of the obtained dependencies.

4. 6. Method of analyzing the economic feasibility of using the proposed raw material components

Economic efficiency ($E_{c.r.}$) of the studied solution is expressed in the reduction of production costs when replacing commonly used components with the proposed ones. To quantify this effect, a calculation formula (1) is proposed, which allows for a comparative analysis of the cost between innovative and standard production technologies. This approach allows to justify the feasibility of introducing a new formulation in industrial conditions

$$E_e = \sum_{i=1}^{n} P_i \cdot C_i - \sum_{j=1}^{m} P_j \cdot C_j, \quad (1)$$

where P_i, P_j – cost of components of extruded protein-fat systems in the composition of a commercial analogue and proposed respectively, USD/kg; C_i, C_j – content of components of extruded protein-fat systems in the composition of a commercial analogue and proposed respectively, kg/t.

5. Results of determining the influence of cellulose and lipid-containing components on the technological parameters of the extruded mixture

5. 1. Determination of the dependence of the structural and mechanical characteristics of the extrudate on the content of cellulose and lipid-containing components

The possibility of modifying the structural and mechanical properties of the extrudate of the composition developed in previous studies [2] was investigated. The specified structural and mechanical indicators are water resistance (within 180–210 min.), swelling index (within 45–70%).

The influence of dietary fibers and lipids selected for modification of raw material components – wheat bran and chicken fat – on the structural and mechanical characteristics of the extruded mass (water resistance and swelling index) was determined.

The obtained empirical relationships are described by regression equations:

$$WR\left(C_{ch.f.}, C_{wh.b.}\right) = 17.0435 + 4.4679 \cdot C_{ch.f.} - 4.0363 \cdot C_{wh.b.} - 0.0502 \cdot C^2_{ch.f.} + 3.5364 \cdot C_{ch.f.} \cdot C_{wh.b.} + 1.7604 \cdot C^2_{wh.b.}, \quad (2)$$

$$SI\left(C_{ch.f.}, C_{wh.b.}\right) = 165.0509 - 10.0394 \cdot C_{ch.f.} - 8.3726 \cdot C_{wh.b.} + 0.5307 \cdot C^2_{ch.f.} - 0.0421 \cdot C_{ch.f.} \cdot C_{wh.b.} - 0.4062 \cdot C^2_{wh.b.}, \quad (3)$$

where WR ($C_{ch.f.}$, $C_{wh.b.}$) – water resistance of the extrudate, min;

SI ($C_{ch.f.}$, $C_{wh.b.}$) – swelling index,%;

$C_{ch.f.}$ – chicken fat content in the extrudate,%;

$C_{wh.b.}$ – wheat bran content in the extrudate,%.

The graphical representation of the obtained dependencies (2), (3) is shown in Fig. 1, 2.

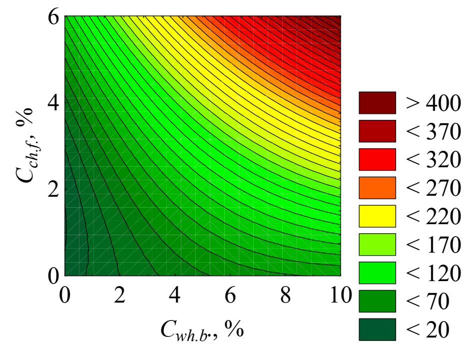

Fig. 1. Dependence of the water resistance of the extrudate on the content of wheat bran and chicken fat in the raw materials

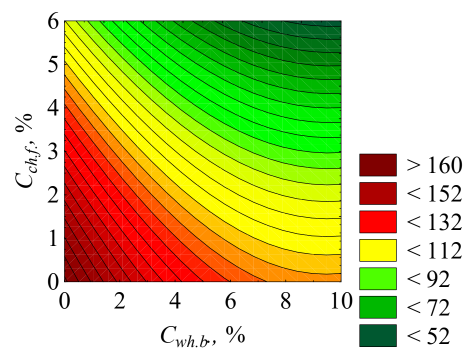

Fig. 2. Dependence of the extrudate swelling index on the content of wheat bran and chicken fat in the raw materials

Regression dependencies (2), (3) demonstrate high predictive ability for assessing the water resistance and swelling of the extruded product within the studied concentrations:

– chicken fat – 0.0 – 6.0%;

– wheat bran – 0.0 – 10.0%.

Based on the conducted studies, a rational extrudate formulation with modified technological properties was developed, containing:

– chicken fat – 4.0 ± 0.1%;

– wheat bran – 6.0 ± 0.2%.

These parameters provide a given balance between the structural characteristics and functional properties of the finished product. The obtained results confirm the effectiveness of using cellulose and lipid-containing additives for targeted modification of the properties of extruded products. The obtained structural and mechanical characteristics of the extruded mass, in particular water resistance (190.0 ± 7.5 min.) and swelling index (55.0 ± 2.1%) meet the requirements for aquaculture feeds.

5. 2. Comparison of structural and mechanical characteristics of the modified extrudate with an analogue

To objectively assess the quality of the developed extrudate, a comparative analysis of the structural and mechanical characteristics of the modified extrudate with the commercial fish feed of the trademark "Roycher ™ AQUA Carp Finish" [20] was carried out, which was chosen as a reference sample [18] due to its application in aquaculture. According to the manufacturer, the main components of the commercial feed are: dehydrated chicken meat meal, fish meal, dry chicken blood, animal fats, fish oil, feed yeast, grain components (wheat, corn), soybean meal and a complex of vitamins and minerals. The cost of the analogue is approximately 1050 USD/t [20].

The structural and mechanical characteristics of the studied extrudate samples are given in Table 1.

Table 1

Structural and mechanical characteristics of the developed extrudate and commercial analogue

Composition	Extrudates	
	Designed	Commercial analogue: «Roycher ™ AQUA Carp Finish»
Lipid mass fraction,%	7.58 ± 0.31	7.95 ± 0.20
Fiber mass fraction,%	11.94 ± 0.48	8.35 ± 0.65
Porosity,%	60.00 ± 2.20	62.00 ± 1.80
Water resistance, min.	190.00 ± 7.50	195.00 ± 6.80
Swelling index,%	55.00 ± 2.10	62.00 ± 1.70

Experimental data show that the developed plant extrudate is competitive with commercial fish feed based on animal raw materials in terms of chemical composition and technological properties. At the same time, the cost of the resulting product is only 310 USD/t, which makes it an economically viable analogue.

6. Discussion of the patterns of influence of dietary fibers and lipids on the structural and mechanical properties of the extrudate

The introduction of wheat bran (6.0 ± 0.2%) and chicken fat (4.0 ± 0.1%) into the composition of the extrudate is a key factor in modifying its structural and mechanical properties. This contributes to the formation of a given porosity (60.0 ± 2.2%), provides controlled water resistance (190.0 ± 7.5 min.) and a swelling index of 55.00 ± 2.10% due to the complex interaction of dietary fibers with lipid components during extrusion. Analysis of the obtained regression relationships (2), (3) and graphical data (Fig. 1, 2) allows to determine the rational ratios of raw materials rich in dietary fibers and lipids. This allows to ensure a certain balance between such structural and mechanical characteristics of the extrudate as water resistance and swelling index. The least favorable conditions for the formation of a stable structure are observed at a chicken fat content below 2%, where water resistance does not exceed 26 min, and the swelling index increases to 147%. This is explained by the insufficient hydrophobic effect of lipids, which leads to excessive swelling of the matrix. When the wheat bran content increases to 10%, a critical decrease in water resistance (up to 34 min) is observed, associated with excessive compaction of the fibrous structure.

Rational indicators are achieved with the content of modifying additives: chicken fat – 4.0 ± 0.1%; wheat bran – 6.0 ± 0.2%. This indicates the formation of a stable protein-lipid-fibrous matrix, where lipids play the role of a hydrophobic barrier, i.e. water resistance (190.0 ± 7.5 min), dietary fibers participate in the formation of the specified porosity (60 ± 2.2%) and swelling index (55.0 ± 2.1%). With a further increase in the chicken fat content above 6%, a decrease in product quality is observed, because the excess lipids disrupt the structure (the coefficient of equation (3) is $0.0502 \cdot \tilde{N}^2_{ch.f.}$). In addition, the stickiness of the mass increases, and the swelling index of the extrudate critically decreases. The parameters of the extruded system of a reasonable composition (Table 1) provide technological and economic advantages compared to the commercial analogue, in particular, lower cost (310 USD/t) while maintaining key structural and mechanical characteristics.

The difference in the results obtained in the study lies in the integrated approach to modifying the structural and mechanical properties of the extrudate through the simultaneous use of a source of dietary fiber (wheat bran) and lipids (chicken fat). In works [8–12], the main attention was paid to individual aspects of the influence of fibers or lipids, while their complex effect remained insufficiently studied. The obtained regression relationships (2), (3) demonstrate that a rational ratio of components – 4.0 ± 0.1% chicken fat and 6.0 ± 0.2% wheat bran – provides: water resistance 190 ± 7.5 min., swelling index 55 ± 2.1%, porosity 60 ± 2.2% (Table 1). These indicators are the result of a complex interaction between the components of the extruded system: lipids form a hydrophobic barrier, and fibers create a frame structure. In contrast, in [13], the effect of only fibrous components on water resistance was studied, without taking into account their combination with lipids. The authors of [14] studied the effect of lipids separately, but did not analyze the role of dietary fibers in the formation of the porous structure. The key advantage of the approach proposed in the article is the modeling of the ratios of modifying components, which allows to simultaneously control the water resistance and swelling index indicators. For example, the results of the study [15] showed that adding wheat bran to the extruded system reduces the water absorption coefficient, but did not take into account their combination with lipids to stabilize the product structure. In [16], the optimal fat content (5.0–7.0%), but without analyzing its interaction with fibers, was established.

An important aspect of this study is the comparison of the development with a commercial analogue (Table 1). The developed extrudate has a higher fiber content (11.94 ± 0.48% versus 2.35 ± 0.05% in the analogue), which improves its technological properties. However, unlike works [17, 18], where the emphasis was on individual technological parameters, this study integrates the chemical composition of the extrudate with structural and mechanical characteristics. Thus, the results obtained allow to consider the developed extrudate as a promising feed product for aquaculture, where the combination of water resistance, controlled swelling and economic indicators are decisive factors.

The results obtained on the influence of dietary fibers and lipids on the structural and mechanical properties of the extrudate have certain limitations related to the specifics of the raw materials used. These studies were conducted on specific samples of wheat bran and chicken fat with clearly defined characteristics. However, the variability of the chemical composition of the proposed components depending on the wheat variety, grain grinding technology, chicken fat production technology and its storage conditions may affect the reproducibility of the results. In particular, the following factors may limit the application of the developed models:

– the difference in the fractional composition of bran: the content of cellulose, hemicellulose and lignin may vary, which affects their interaction with the extrudate matrix;

– qualitative indicators of chicken fat: peroxide and acid values may change its hydrophobic properties;

– technological parameters of extrusion (temperature, pressure, screw speed) in industrial conditions may differ from laboratory ones, which requires additional research to adapt the obtained results to production conditions.

The disadvantage of the conducted study is the lack of a comprehensive analysis of the influence of technological parameters of extrusion (temperature, pressure, screw speed) on the formation of the structure of the modified extrudate. Although a rational ratio of dietary fibers and lipids in the extrudate has been established, the influence of extrusion modes on the stability of the resulting porous structure remains unclear.

A promising direction for further research is the study of the complex interaction between different types of fibers and lipids, as well as the development of antioxidant systems to increase the stability of the lipid fraction. This will allow developing universal approaches to modifying the structural and mechanical properties of extruded products for various industries.

7. Conclusions

1. The dependence of the structural and mechanical characteristics of the extrudate on the content of wheat bran (source of dietary fiber) and chicken fat (source of lipids) was established. The obtained regression models demonstrate that the rational ratio of components is 4 ± 0.1% chicken fat and 6 ± 0.2% wheat bran. This content of modifying additives provides water resistance of the extrudate 190 ± 7.5 min, swelling index 55 ± 2.1%, porosity 60 ± 2.2%. This indicates the effective interaction of lipids with fibers, which forms a stable structure with controlled technological properties.

2. Comparative analysis with a commercial analogue (“Roycher™ AQUA Carp Finish”) revealed competitive indicators of water resistance of the developed extrudate (190 ± 7.5 min vs. 205 ± 7.8 min), porosity (60.00 ± 2.20% vs. 62.00 ± 1.80%) and swelling index (55.00 ± 2.10% vs. 62.00 ± 1.70%) at a significantly lower cost (310 USD/t vs. 1050 USD/t).

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship, or any other type that could influence the study and its results presented in this article.

Funding

The research was conducted without financial support.

Data availability

This manuscript does not have any associated data.

Use of artificial intelligence tools

The authors confirm that no artificial intelligence technologies were used in the creation of this work.

References

1. Aschemann-Witzel, J., Gantriis, R. F., Fraga, P., Perez-Cueto, F. J. A. (2020). Plant-based food and protein trend from a business perspective: markets, consumers, and the challenges and opportunities in the future. Critical Reviews in Food Science and Nutrition, 61 (18), 3119–3128. https://doi.org/10.1080/10408398.2020.1793730
2. Petik, I., Litvinenko, O., Kalyna, V., Ilinska, O., Raiko, V., Filenko, O. et al. (2023). Development of extruded animal feed based on fat and oil industry waste. Eastern-European Journal of Enterprise Technologies, 2 (11 (122)), 112–120. https://doi.org/10.15587/1729-4061.2023.275509
3. Singh, J. P., Kaur, A., Singh, B., Singh, N., Singh, B. (2019). Physicochemical evaluation of corn extrudates containing varying buckwheat flour levels prepared at various extrusion temperatures. Journal of Food Science and Technology, 56 (4), 2205–2212. https://doi.org/10.1007/s13197-019-03703-y
4. Bochkarev, S., Chaika, T., Stankevych, S., Zabrodina, I., Balandina, I., Obolentseva, L. et al. (2024). Development of an extruded system with enhanced content of alpha-linolenic polyunsaturated fatty acid. Eastern-European Journal of Enterprise Technologies, 6 (11 (132)), 15–23. https://doi.org/10.15587/1729-4061.2024.315246
5. Stankevych, S., Gorbunov, K., Zabrodina, I., Popov, M., Kalyna, V., Novozhylova, T. et al. (2024). Identification of the oxidation and hydrolysis products content influence on the rapeseed oil oxidation induction period. Eastern-European Journal of Enterprise Technologies, 4 (6 (130)), 6–13. https://doi.org/10.15587/1729-4061.2024.308907
6. Belinska, A., Ryshchenko, I., Bliznjuk, O., Masalitina, N., Siedykh, K., Zolotarova, S. et al. (2024). Development of a method for inactivating lipoxygenases in linseed using chemical reagents. Eastern-European Journal of Enterprise Technologies, 4 (6 (130)), 14–21. https://doi.org/10.15587/1729-4061.2024.309079
7. Siddiqui, S. A., Kamran, F., Stankov, S., Rathod, N. B., Teixeira-Costa, B. E., Fidan, H. et al. (2024). Unveiling the Diversity of Non Conventional Proteins - From Sources, Extraction, Technofunctionality, Nutraceutical Potential to Advancement in Food Applications - A Systematic Review. Waste and Biomass Valorization, 16 (1), 29–51. https://doi.org/10.1007/s12649-024-02614-0
8. Papchenko, V., Stepankova, G., Karatieieva, O., Balandina, I., Shapovalenko, D., Kariuk, A., Statyvka, Y., Bakumenko, O., Melnyk, A., Horbas, S. (2023). Determining the effect of raw materials moisture and lipid content on the technological properties of the extruded protein-fat system. Eastern-European Journal of Enterprise Technologies, 4 (11 (124)), 37–46. https://doi.org/10.15587/1729-4061.2023.285132

9. Luthra, A., Kajla, P., Chhikara, N., Khatkar, B. S., Malik, M. (2025). Food and Dairy By-products Utilization. Engineering Solutions for Sustainable Food and Dairy Production, 331–344. https://doi.org/10.1007/978-3-031-75834-8_12
10. Gutierrez-Montiel, E., Ávila-Orta, C. A., Cabrera-Canales, Z. E., Covarrubias-Gordillo, C. A., Reyes-Rodríguez, P. Y., Rodríguez-Velázquez, J. G. et al. (2023). Effect of oxidized, maleate and dual chemical modification through extrusion on thermoplastic starch properties. Polymer Bulletin, 81 (3), 2525–2544. https://doi.org/10.1007/s00289-023-04857-8
11. Wang, B., Dong, Y., Fang, Y., Gao, W., Kang, X., Liu, P. et al. (2022). Effects of different moisture contents on the structure and properties of corn starch during extrusion. Food Chemistry, 368, 130804. https://doi.org/10.1016/j.foodchem.2021.130804
12. Gomes, K. S., Berwian, G. F., Batistella, V. M. C., Bender, L. E., Reinehr, C. O., Colla, L. M. (2022). Nutritional and Technological Aspects of the Production of Proteic Extruded Snacks Added of Novel Raw Materials. Food and Bioprocess Technology, 16 (2), 247–267. https://doi.org/10.1007/s11947-022-02887-0
13. Cervantes-Ramírez, J. E., Cabrera-Ramirez, A. H., Morales-Sánchez, E., Rodriguez-García, M. E., Reyes-Vega, M. de la L., Ramírez-Jiménez, A. K. et al. (2020). Amylose-lipid complex formation from extruded maize starch mixed with fatty acids. Carbohydrate Polymers, 246, 116555. https://doi.org/10.1016/j.carbpol.2020.116555
14. Cabrera-Ramírez, A. H., Cervantes-Ramírez, E., Morales-Sánchez, E., Rodriguez-García, M. E., Reyes-Vega, M. de la L., Gaytán-Martínez, M. (2021). Effect of Extrusion on the Crystalline Structure of Starch during RS5 Formation. Polysaccharides, 2 (1), 187–201. https://doi.org/10.3390/polysaccharides2010013
15. Qi, M., Jiang, L., Song, J., Han, F., Xu, M., Li, Y. et al. (2024). Investigating the Impact of Moisture Levels on Structural Alterations and Physicochemical Properties of Cassava Flour through Extrusion: A Comprehensive Study. Plant Foods for Human Nutrition, 79 (4), 909–914. https://doi.org/10.1007/s11130-024-01237-z
16. Tiwari, A., Jha, S. K. (2017). Extrusion cooking technology: Principal mechanism and effect on direct expanded snacks – An overview. International Journal of Food Studies, 6 (1), 113–128. https://doi.org/10.7455/ijfs/6.1.2017.a10
17. Banjac, V., Vukmirović, Đ., Pezo, L., Draganovic, V., Đuragić, O., Čolović, R. (2021). Impact of variability in protein content of sunflower meal on the extrusion process and physical quality of the extruded salmonid feed. Journal of Food Process Engineering, 44 (3). https://doi.org/10.1111/jfpe.13640
18. Petik, I., Litvinenko, O., Stankevych, S., Zabrodina, I., Ponomarova, M., Kotliar, O. et al. (2024). Determination of the cellulose- and lipid-containing components influence on the extrudate technological indicators. Eastern-European Journal of Enterprise Technologies, 2 (6 (128)), 6–13. https://doi.org/10.15587/1729-4061.2024.301843
19. Pennells, J., Bless, I., Juliano, P., Ying, D. (2024). Extrusion Processing of Biomass By-Products for Sustainable Food Production. From Biomass to Biobased Products. https://doi.org/10.5772/intechopen.111943
20. Roycher Aqua fish feed. Roycher Aqua. Available at: https://roycheraqua.com/ua/