UDC 664.64:577.115.3
DOI: 10.15587/1729-4061.2024.315246

DEVELOPMENT OF AN EXTRUDED SYSTEM WITH ENHANCED CONTENT OF ALPHA-LINOLENIC POLYUNSATURATED FATTY ACID

Sergiy Bochkarev
Corresponding author
PhD, Associate Professor
Department of Physical Education*
E-mail: bockarevsergij@gmail.com
Tetiana Chaika
PhD
Department of Tourism and Hospitality Business*
Serhii Stankevych
PhD
Department of Zoology, Entomology, Phytopathology, Integrated Plant Protection and Quarantine B. M. Litvinova**
Inna Zabrodina
PhD
Department of Zoology, Entomology, Phytopathology, Integrated Plant Protection and Quarantine B. M. Litvinova**
Iryna Balandina
PhD
Department of Tourism and Hospitality***
Larysa Obolentseva
Doctor of Economic Sciences
Department of Tourism and Hospitality***
Tetiana Cheremska
PhD, Associate Professor
Department of Food Technology in the Restaurant Industry**
Myushfik Bakirov
PhD
Department of Meat Technology**
Oleg Kolontaievskyi
PhD
Department of Tourism and Hospitality***
Roman Voronov
PhD
Department of of Electric Transport***
*National Technical University "Kharkiv Polytechnic Institute"
Kyrpychova str., 2, Kharkiv, Ukraine, 61002
**State Biotechnological University
Alchevskykh str., 44, Kharkiv, Ukraine, 61002
***O. M. Beketov National University of Urban Economy in Kharkiv
Marshala Bazhanova str., 17, Kharkiv, Ukraine, 61002

The object of the study is the dependence of the technological indicators of the extruded system with an increased ALA content on the composition of the raw materials. The problem of the study is the need to increase the oxidative stability of the lipid component of extrudates, preserve their nutritional value and improve technological characteristics (in particular, porosity). An extruded system with an increased content of alpha-linolenic polyunsaturated fatty acid (ALA) based on a mixture of barley groats and flax seeds has been developed. The influence of flaxseed content on the technological parameters of model extruded systems, in particular porosity and oxidative stability of the lipid component, was studied. It was found that the rational content of flax seeds in the extrusion mixture is 7.0 %, providing the necessary porosity (80 %) and the induction period of accelerated oxidation at a temperature of 80 °C (10 hours). The proposed technological approach makes it possible to increase the shelf life of products while preserving nutritional value. The developed extruded system is promising for further implementation in the food industry, which will contribute to expanding the range of extruded products and increasing their market competitiveness. The effect of antioxidants – ascorbic and ferulic acids on the oxidative stability of lipids of the extruded system was studied: the content of ascorbic acid – 0.06...0.09 %, the content of ferulic acid – 0.10...0.15 %. The lipid component of the extruded system of the developed composition demonstrates a high level of oxidative stability (oxidation induction period – up to 22 hours). The obtained results indicate the possibility of using extruded systems with an increased ALA content to create specialized products with extended shelf life and reduced raw material costs

Keywords: extruded system, alpha-linolenic acid, flax seeds, barley groats, technological indicators

Received 04.09.2024
Received in revised form 22.10.2024
Accepted 15.11.2024
Published 27.12.2024

How to Cite: *Bochkarev, S., Chaika, T., Stankevych, S., Zabrodina, I., Balandina, I., Obolentseva, L., Cheremska, T., Bakirov, M., Kolontaievskyi, O., Voronov, R. (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*

1. Introduction

Plant raw materials contain proteins, carbohydrates, lipids, minerals, vitamins, organic acids, and also have high nutritional, taste and biologically active properties. The main task of the industry is to preserve and improve the nutritional value and consumer qualities of plant raw materials in the process of technological processing [1, 2].

Extrusion technology is gaining more and more popularity for processing food raw materials. Extrusion makes it possible to increase the digestibility of components of plant raw materials, in particular protein and starch [3]. In addition, the selection of rational parameters for the extrusion process can solve two important tasks: the destruction of antinutrients (protease inhibitors, etc.) contained in some types of plant raw materials and the destruction of pathogenic microorganisms.

The extrusion process is widely used in industry [3, 4]. The advantage of this technology is a radical change in the structure of the raw material, its physical properties and nutritional value, as well as the chemical composition during processing. A wide range of plant raw materials are subjected to extrusion: grain, beans, fruits, vegetables, tubers, leaves and stems of plants, as well as their mixtures [5]. An important advantage of extrusion technology is the possibility of processing food industry waste, such as oilseed meal and cake, fruit pomace, fruit peel, etc., for their further use [5, 6]. By varying the parameters of the extrusion process of plant raw materials, it is possible to obtain a product with the necessary properties and ensure a minimum decrease in nutritional value due to the destruction of useful substances. In improving this technology, the main direction is the development of new recipes for raw material mixtures and extrusion process parameters [5].

The presence of lipids in raw materials for extrusion has a positive effect on the extrusion process, helping to reduce friction, plasticizing the product and gluing its components. However, the processes of oxidative deterioration of lipids, especially polyunsaturated fatty acids (PUFAs), during processing degrade product properties. There are known scientific data that during extrusion, enzymes that accelerate oxidation are destroyed, and during the Maillard reaction, protein-carbohydrate complexes are formed, which are antioxidants [7]. However, the presence and quantitative content of PUFAs is a significant factor that affects the porosity and stability of extruded lipid-containing systems during storage [8].

Therefore, research aimed at substantiating the component composition of the extruded lipid-containing system enriched with PUFAs, as well as determining the dependence of its technological indicators on the PUFA content, are relevant. The results of such research will provide an opportunity to expand the range of special-purpose extrudates, in particular in the oil and fat industry, and improve the quality of finished products with health-improving properties.

2. Literature review and problem statement

It is known that the oxidation of fats during processing deteriorates product properties. In the study [9], the influence of raw material moisture and lipid content on the technological properties of extruded protein-fat systems was analyzed in detail. The authors concluded that the selection of rational parameters of lipid and moisture content is critical for preserving the technological characteristics of the product, in particular porosity and texture. In the study [10], a thorough analysis of the influence of cellulose- and lipid-containing components on the technological parameters of extrudates was carried out. The authors determined that such components have a significant effect on the porosity, water absorption capacity and swelling degree of extruded products, which makes them promising for use in the production of products with improved texture characteristics. But studies [9, 10] did not consider in detail the stability of PUFAs, in particular alpha-linolenic acid (ALA), during the extrusion process and during storage of the obtained extrudates. However, the effect of different types of polyunsaturated fatty acids, particularly alpha-linolenic acid (ALA), on the stability and oxidative properties of the finished product during storage was not sufficiently covered in the study. This issue is partially considered in [11], showing that during extrusion this phenomenon is not observed due to the short duration of the process. Although studies [11] confirm that the short duration of the extrusion process minimizes fat oxidation, the long-term stability of PUFAs, in particular alpha-linolenic acid (ALA), after processing and during storage of the finished product remains an unresolved issue. Studies do not address the impact of storage conditions, such as temperature, humidity and oxygen exposure, on the stability of PUFAs in finished extruded systems. These factors can significantly affect the level of fat oxidation, in particular under long-term storage conditions, which can lead to deterioration of the organoleptic properties and nutritional value of the product. One of the objective reasons why this issue has not been resolved is the difficulty of long-term studies aimed at studying the stability of fatty acids after processing. This requires systematic research, including long experimental periods, as well as analysis at different stages of product storage.

At the same time, the process of extruding plant raw materials leads to fat reduction in the finished product [12]. However, questions regarding the preservation of specific polyunsaturated fatty acids, such as alpha-linolenic acid (ALA), during extrusion remain unresolved in the study. The main reason for this is the difficulty in controlling the chemical changes that occur with lipids under the influence of high temperatures and pressures during extrusion.

In [13], scientists associate fat reduction with low raw material moisture and high extrusion temperature. However, in this work, the question of the specific mechanisms that cause such fat loss, in particular the interaction of lipids with other components during extrusion, remained unresolved. One of the reasons for this is the difficulty of studying chemical changes in lipids during high-temperature processing. At the same time, the work [14] determined that fat reduction increased at the moisture content of the raw material (a mixture of wheat and almond flour) from 26 to 30 %, but decreased at the moisture content from 30 to 36 %. The reason for this discrepancy has not been found. Although the study showed some association between moisture content and fat fraction loss, the mechanisms explaining this behavior remained unclear. One of the objective reasons for this is the complexity of the extrusion process, where many physical and chemical changes occur simultaneously, such as temperature, pressure, mechanical mixing and reactions of the raw material components. Probably, other process parameters had an impact, including the viscosity of the raw material, as shown in studies [12], which examined in detail the influence of extrusion parameters, such as temperature, moisture content, and screw speed, on the final properties of extruded products. However, the relationship between the composition of lipids, especially PUFAs, and their stability during the extrusion process was not sufficiently investigated in the work.

It was found that the formation of a lipid-amylose complex during corn starch extrusion occurs at a temperature of 110...140 °C and low moisture content of plant material [15]. The results of the analyzed experimental studies confirm that a low fat content in the raw material contributes to the efficient implementation of the extrusion process and prevents oxidation of the finished product, while a high fat content worsens the course of the extrusion process and product quality. But the effect of different polyunsaturated fatty acids, such as ALA, on the extrusion process and the stability of the final product has not been sufficiently investigated. In particular, ALA has a high tendency to oxidation, which can deteriorate the quality of extruded products and shorten their shelf life. Despite the available data on the oxidative stability of total lipids, no specific studies on the effect of ALA on this process have yet been conducted. The reasons for this can be both objective and subjective. In particular, the oxidative instability of PUFAs such as ALA complicates the development of sustainable systems, and this issue requires additional research taking into account technological features and storage conditions. This requires the development of more specialized approaches to the extrusion of lipid-containing raw materials, in particular systems with a high PUFA content, which may also be one of the reasons why this issue has not yet been fully resolved.

The study [16] proved the value of flaxseed as part of protein-fat systems, which is due to the high content of PUFAs, in particular ALA, dietary fiber, lignans, etc., making it a promising ingredient for extrusion systems. But the work did not address the impact of temperature and mechanical extrusion loads on the stability of ALA, as well as the influence of these factors on the texture and nutritional value of the final product. Using flaxseed in extrusion processes is complicated by the high tendency to fat oxidation, especially at high temperatures. Compared to flaxseed, barley is a more stable raw material that contains a significant amount of β-glucans and other biologically active compounds [17]. Barley is characterized by a balanced amino acid composition, however, the dominance of prolamins and glutelins in its protein composition reduces its suitability for the formation of strong protein structures in extruded products. However, in the study [17], issues on determining the rational composition of lipid-containing and protein-containing raw materials to preserve biologically active components, in particular PUFAs, in extruded systems remained unresolved.

Analysis of literature sources showed that the extrusion process is extremely important for obtaining food products with altered structure and improved properties, but the stability of PUFAs, in particular ALA, during extrusion remains insufficiently studied. On the one hand, the works [13, 14] found that the loss of fat fraction during extrusion depends on humidity and temperature, but no studies were conducted that would reveal the mechanisms of influence on ALA stability. This is due to the chemical complexity of the processes occurring during extrusion, and requires additional research to clarify the impact of various technological parameters on PUFAs.

On the other hand, the results of [15] confirmed the formation of lipid-amylose complexes during extrusion under certain conditions, however, the effect of ALA as the main PUFA on the stability of the final extruded products remains unexplored. This may be due to the high tendency of ALA to oxidize in the extrusion process, which degrades product quality and shortens its shelf life.

Studies [16, 17] show the value of flax as a rich source of PUFAs, but insufficient attention has been paid to the effect of mechanical and temperature loads during extrusion on lipid stability. It was found that barley can serve as a more stable raw material, but its protein composition does not contribute to the formation of strong structures. Despite this, the issue of preserving biologically active components, in particular ALA, in extruded systems remains unresolved. Therefore, on the basis of a critical analysis, it can be argued that it is appropriate to conduct a study on developing extruded systems with an increased ALA content, in order to find out its impact on the technological parameters of the extrusion process and the stability of the final product during storage.

3. The aim and objectives of the study

The aim of the study is to develop an extruded system with enhanced ALA (alpha-linolenic acid) content, enabling the examination of extrusion parameters effect on ALA stability and the technological properties of the final product. This will facilitate the creation of an oxidation-resistant extruded system with a high ALA content, thereby extending its shelf life while meeting the growing demand for omega-3 PUFA-enriched products.

To achieve the aim, the following objectives were accomplished:

– to determine the chemical composition of raw materials for the extruded system with enhanced ALA content;

– to analyze changes in the technological properties of the extruded system, specifically porosity and oxidative stability of the lipid component, depending on ALA content;

– to study the impact of antioxidants on the oxidative stability of the extruded system.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of the study is the technological parameters of an extruded system with an increased ALA content, based on lipid-containing and protein-containing raw materials of plant origin. The primary hypothesis of the study is the potential stabilization of ALA against oxidative degradation in the extruded system by rationalizing the component ratio. This approach aims to minimize lipid oxidation while preserving the high nutritional and technological properties of the resulting products. Additionally, stabilization of the lipid component in the ALA-enriched extrudate against oxidative damage can be achieved through the use of an antioxidant complex.

Assumptions adopted in the study:

– there exists an optimal ALA content in the composition of the extruded system that enhances its nutritional value without compromising the technological characteristics of the extrudate during production and storage;

– within the antioxidant complex of ascorbic and ferulic acids, a specific ratio may exhibit a non-additive effect on inhibiting the oxidative degradation of the lipid component in the ALA-enriched extrudate;

– the induction period of accelerated oxidation of the lipid component in the extruded system samples is proportional to their induction period under recommended storage conditions (absence of oxygen and light, temperature range from +5 °C to +25 °C).

Simplifications accepted in the study:

– for analyzing the oxidative stability of the lipid component in the extruded system, ALA, representing the class of polyunsaturated fatty acids (PUFAs), was selected as the primary indicator. Other components of the lipid profile, such as monounsaturated and saturated fatty acids, are not considered in detail due to their significantly higher stability compared to ALA;

– microbiological aspects and enzymatic reactions were also excluded from consideration, as the study focuses on the physicochemical and technological parameters of extrusion and the stability of fatty acids in the final product.

4. 2. Materials and equipment used in the experiment

The following materials and reagents were used in the studies:

– flax seeds (produced in Ukraine), compliant with DSTU 4967 (CAS 8001-26-1);

– barley groats (produced in Ukraine), compliant with DSTU 7700 (Regulation (EC) No. 178/2002);

– ascorbic acid (produced in Ukraine), compliant with CAS 50-81-7;

– ferulic acid (produced in China), compliant with CAS 1135-24-6.

4. 3. Methodology for producing extrudates

The extrusion of raw material components was performed using a PE-20 extruder, specifically designed for the production of expanded extruded products. Ascorbic acid and ferulic acid were incorporated into the raw material mixture in the form of powders, which were evenly blended with a small portion of the mixture prior to extrusion. The extrusion temperature in the area in front of the die did not exceed 135 °C, and the screw rotation speed was set at 250 rpm.

4. 4. Methods for determining the characteristics of raw materials for an extruded system

The following parameters were determined for raw material components used in the extruded system:

– moisture and volatile substances content – in accordance with DSTU 7621;

– crude protein content – in accordance with DSTU 7169;

– lipid content – in accordance with DSTU 7491;

– carbohydrate content – in accordance with DSTU ISO 6493;

– ash content – in accordance with DSTU ISO 5984;

– fatty acid composition of the lipid fraction – in accordance with DSTU ISO 5508.

For the samples of the extruded system, the following parameters were determined:

– porosity – in accordance with [10];

– induction period of accelerated lipid oxidation – in accordance with DSTU ISO 6886.

4. 5. Planning research and processing results

In studies examining dependencies (2) and (3) of the porosity of an extruded system and the induction period of lipid oxidation at 80 °C based on flaxseed content, single-factor experiments were employed. For investigating dependency (4), which relates the induction period of accelerated oxidation of the extruded system to the antioxidant content in the raw materials, two-factor experiments were conducted. Each experiment was repeated three times. The equations for these dependencies were calculated by approximating experimental data through trendline construction. Experimental data processing and the creation of graphical dependencies were performed using Microsoft Excel (USA) and Stat Soft Statistica v 6.0 (USA).

The significance of the coefficients in the approximating equation for dependency (4), describing the induction period of accelerated oxidation of the extruded system in relation to the antioxidant content in the raw materials, was validated by testing the hypothesis of null parameter equality. The degree of influence of the antioxidant content in the raw materials on the induction period of accelerated lipid oxidation in the system was assessed through the coefficient of determination R^2. A value of R^2=0.983 indicates that over 98 % of the variations in the induction period of accelerated lipid oxidation in the extrudate's lipid component are attributable to variations in antioxidant content.

The significance of the developed approximating model (4) was determined by comparing the calculated Fisher criterion with its critical tabulated value at a significance level of p=0.05 and the corresponding degrees of freedom. The results confirm that the calculated coefficients of determination for the approximating dependency (4) are substantial, and the equation is statistically significant with a confidence level exceeding 95 %.

4. 6. Method of comparative analysis of raw material costs for various extruded systems

The difference in the cost of raw material components ($E_{c.r.}$) represents a reduction in production cost when comparing the cost of components in extruded systems with an analogous development. It is calculated using formula (1):

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

where P_i, P_j represent the cost of raw material components in the extruded systems of the analogous development and the proposed composition, respectively, \$/kg; C_i, C_j represent the content of raw material components in the extruded systems of the analogous development and the proposed composition, respectively, kg/ton.

5. Results of developing an extruded system with increased alpha-linolenic polyunsaturated fatty acid content

5. 1. Determination of the chemical composition of raw materials for the extruded system

To develop an extruded system with an enhanced ALA content, two raw materials were selected: flaxseed and barley groats. These components were chosen due to the high ALA content in flaxseed and the presence of specific carbohydrates in barley, including glycans, arabinoxylans, and hemicellulose. The chemical composition of the raw materials is presented in Fig. 1.

The fatty acid composition of flaxseed oil, extracted from flax seeds, and the lipids extracted from barley groats has been determined (Fig. 2).

Significant differences in the composition of raw material components necessitate precise optimization of their ratios to achieve stability in the extruded product, target porosity, and resistance to lipid oxidation.

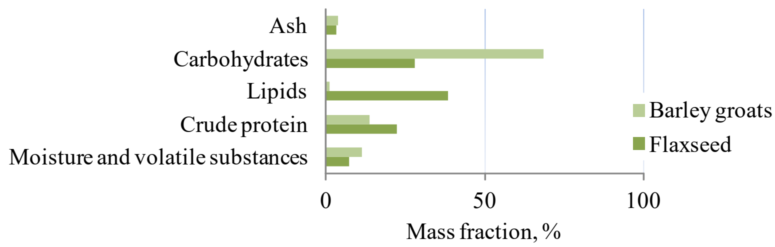


Fig. 1. Chemical composition of raw components for the extruded system

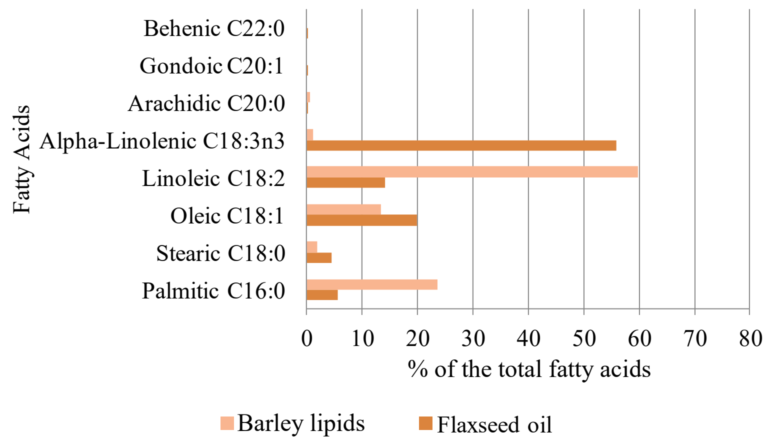
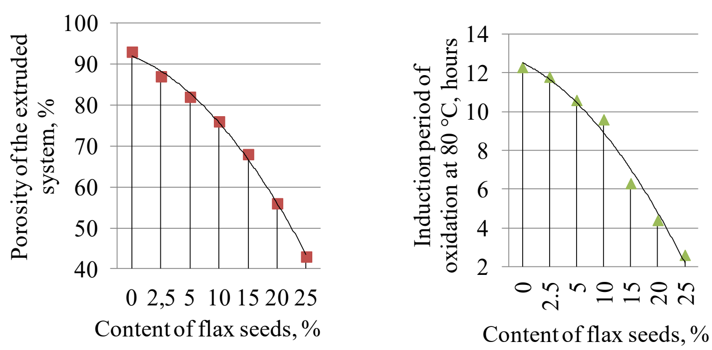


Fig. 2. Fatty acid composition of the lipid fraction in raw material components for the extruded system

5. 2. Analysis of changes in the technological properties of the extruded system depending on the content of alpha-linolenic polyunsaturated fatty acid

The dependence of porosity and the induction period of lipid oxidation in model samples of the extruded system containing varying amounts of flaxseed – a source of ALA – was investigated (Fig. 3).



a *b*

Fig. 3. Technological properties of model samples of the extruded system with varying ALA content: *a* – dependence of the porosity of the extruded system on the flaxseed content; *b* – dependence of the oxidation induction period of the lipid component of the extruded system on the flaxseed content

Equations (2) and (3) describe the approximative dependencies of the porosity of the extruded system and the oxidation induction period of its lipid component at 80 °C on the flaxseed content:

$$S(C_{ls}) = -0.0253 \cdot C_{ls}^2 - 1.2689 \cdot C_{ls} + 91.1800; \quad (2)$$

$$IP(C_{ls}) = -0.00275 \cdot C_{ls}^2 - 0.3372 \cdot C_{ls} + 12.5000; \quad (3)$$

where $S(C_{ls})$ represents the porosity of the extruded system, %,

$IP(C_{ls})$ is the induction period of oxidation at 80 °C for the lipid component of the extruded system, hours;

C_{ls} denotes the flaxseed oil content, %.

It should be noted that the approximation dependencies (2) and (3) adequately describe the porosity of the extruded system and the induction period of lipid oxidation at 80 °C within the flaxseed content range of 0–25 %. Therefore, to ensure an induction period of lipid oxidation in the extruded system at 80 °C within the range of 8–10 hours, the flaxseed content in the system should be between 3.5 % and 7.0 %. The predicted porosity of the extruded system within this flaxseed content range is 81–86 %. Consequently, it was decided to produce an extrudate sample containing 93 % barley groats and 7 % flaxseed. The technological parameters of the resulting extrudate, determined experimentally, are as follows: porosity of 80 % and an induction period of 10.0 hours, which are practically identical to the calculated values (81.06 % and 10.0 hours, respectively).

5. 3. Study of the impact of antioxidants on the oxidative stability of the extruded system

Selected antioxidants were used to inhibit oxidative spoilage of the lipid component in the proposed extruded system formulation: ascorbic acid and ferulic acid. Ascorbic acid is an effective water-soluble antioxidant that readily donates electrons to neutralize free radicals, preventing the initiation and propagation of oxidative processes in lipids. Ferulic acid, in turn, is a fat-soluble antioxidant capable of neutralizing free radicals in lipophilic environments, particularly under high-temperature extrusion conditions.

The mutual effects of the selected antioxidants on the induction period of accelerated oxidation (at 80 °C) of the lipid component in the extruded system were investigated. The ascorbic acid content in the raw material was varied within the range of 0.00–0.09 % (based on the total mass of the extrusion mixture) in increments of 0.03 %. The ferulic acid content in the raw material was varied within the range of 0.00–0.15 % (based on the total mass of the mixture) in increments of 0.05 %. The obtained induction period values for the accelerated oxidation of the extruded system ranged from 10 to 25 hours.

The approximation dependence of the induction period of accelerated oxidation of the extruded system on the antioxidant content in the raw material is presented in equation (4):

$$IP\left(c_{aa},c_{fa}\right)=8.1535+122.7429\cdot c_a+91.4239\cdot c_{fa}-$$
$$-1,027.5288\cdot c_a^2+395.6522\cdot c_a\cdot c_{fa}-275.0000\cdot c_{fa}^2; \quad (4)$$

where $IP(c_{aa}, c_{fa})$ – the induction period of accelerated oxidation (at 80 °C) for the extruded system, measured in hours;

c_{aa} – ascorbic acid content in the extrusion mixture, %;

c_{fa} – ferulic acid content in the extrusion mixture, %.

The presented approximation model adequately describes the actual oxidation potential of the lipid component in the extruded system within the specified antioxidant content intervals.

The surface of the obtained dependence is illustrated in Fig. 4.

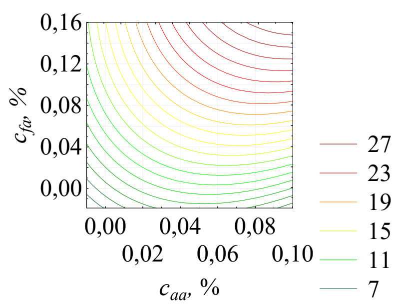


Fig. 4. Dependency of the induction period of accelerated oxidation ($IP(c_{aa},c_{fa})$) of the lipid component in the extruded system on the content of ascorbic acid (c_{aa}) and ferulic acid (c_{fa}) in the initial raw material mixture

Based on the experimental results and their statistical analysis, the content of antioxidants in the selected raw material for extrusion was adjusted. From both a technological perspective (oxidative stability) and an economic perspective (cost efficiency), an optimal range of antioxidant content was determined for producing an extruded system, as follows:

– ascorbic acid content: 0.06–0.09 %;

– ferulic acid content: 0.10–0.15 %.

Under which the induction period of accelerated oxidation in the extrudate ranges from 20 to 22 hours.

Analysis of the obtained dependency (Fig. 4) demonstrates that increasing the ascorbic and ferulic acid content in the extrusion mixture significantly enhances the stability of the lipid component in the extruded system. Specifically, with an increase in ascorbic acid above 0.09 % and ferulic acid above 0.15 %, the induction period extends to 23.74 hours, indicating a substantial improvement in the system's antioxidant protection. However, excessive concentrations of antioxidants may have undesirable consequences. Notably, high levels of ascorbic acid can accelerate oxidative processes in the presence of transition metal ions and alter the product's flavor profile. Conversely, elevated ferulic acid content can affect the extrudate's texture. This antioxidant interacts with proteins and carbohydrates, forming cross-links that reduce the porosity of the final product.

6. Discussion of the development results of an extruded system with enhanced alpha-linolenic polyunsaturated fatty acid content

The possibility of developing an extruded system with an increased content of alpha-linolenic acid (ALA) based on barley groats and flaxseed was explored. The primary objective was to achieve lipid stability during the extrusion process, given ALA's high susceptibility to oxidation. Ascorbic acid and ferulic acid were used as antioxidants, justified by their proven efficacy in stabilizing PUFAs.

An analysis of the obtained results (Fig. 1) reveals significant differences in the composition of flaxseed and barley groats. Flaxseed contains relatively low moisture levels (7.3 %) compared to barley groats (11.2 %). This factor may influence the technological parameters of the extrusion process, such as processing temperature and product stability during extrusion. The lower moisture content of flaxseed contributes to achieving a denser texture in the final product. Flaxseed has a higher protein content (22.4 %) compared to barley groats (13.8 %). The elevated protein level can enhance the nutritional value of the extruded product and promote the formation of a more stable structure during extrusion. Flaxseed also contains a significant amount of lipids (38.4 %) compared to barley groats (1.2 %). This high fat content may considerably impact technological processes like extrusion and thermal stability, especially since lipids are prone to oxidation during high-temperature processing. It is also important to consider that the high lipid content in the extruded system may require the use of antioxidants or specific storage conditions to prevent oxidation. Barley groats have a significantly higher carbohydrate content (68.6 %) compared to flaxseed (28.1 %). This carbohydrate richness can promote the formation of a more porous product structure, as carbohydrates, particularly starch, tend to expand during extrusion. Higher carbohydrate content can also improve the sensory properties of the final product. The ash content in both components (3.2 % in flaxseed and 3.7 % in barley groats) indicates a similar mineral composition, which may influence the nutritional value of the final product but is not a critical factor for the extrusion process.

The fatty acid composition of the lipid component of raw materials (Fig. 2) indicates that flaxseed provides a high content of ALA, while barley groats contribute structural and stabilizing carbohydrate components that enhance the technological properties of the extruded system.

Studies on the technological properties of the extruded system, particularly porosity and the stability of the lipid component (Fig. 3), revealed a significant dependence of these parameters on the flaxseed content – the primary source of ALA. As the flaxseed content increases, system porosity decreases, as confirmed by the approximated dependency (2), which describes a negative correlation between the amount of flaxseed and the product's porosity. Porosity measurements of extruded samples demonstrated that the predicted porosity of the extruded system within the specified flaxseed content ranges from 81 % to 86 %, ensuring adequate lightness and a pleasant texture of the product.

It was shown that a flaxseed content of 3.5–7.0 % allows achieving an oxidation induction period of the lipid components at 80 °C within 8–10 hours, which is optimal for maintaining product quality during storage. Dependency (3) confirms this pattern, demonstrating that an increase in ALA content leads to a reduction in the stability of the lipid component. However, with a controlled flaxseed content, a rational balance is maintained between the beneficial properties of ALA and the oxidative stability of the extruded system.

The study confirmed the critical importance of selecting appropriate antioxidants to prevent oxidative spoilage. Ascorbic and ferulic acids were identified as effective antioxidants for protecting lipids in a system containing flaxseed, which is a primary source of alpha-linolenic acid (ALA). Ascorbic acid, due to its water-soluble properties, acts as an antioxidant in polar environments, while ferulic acid, a fat-soluble antioxidant, effectively neutralizes free radicals in the lipophilic phase. Experiments demonstrated that combining these two antioxidants significantly extends the induction period for lipid oxidation in the extruded system.

It was found that the antioxidant content within the ranges of 0.06–0.09 % for ascorbic acid and 0.10–0.15 % for ferulic acid is optimal for efficiently inhibiting lipid oxidation. At a temperature of 80 °C and with the recommended antioxidant concentrations, the induction period can reach 20–22 hours (dependency (4)). This level of oxidative stability is crucial for extending the shelf life of the extruded system and preserving the beneficial properties of ALA. Further increases in antioxidant concentrations slightly improve the lipid stability of the extruded system. However, excessive use of antioxidants may have negative consequences, such as affecting the flavor and texture of the product due to interactions with other components of the mixture.

The chemical composition, technological, and economic indicators of the extruded system of the proposed formulation were analyzed and compared to a similar development [18] – an extruded mixture of flaxseed and a bean-corn flour blend in a ratio of 10:45:45, which was selected as the benchmark. The raw material cost for the benchmark system is approximately $757.5 per ton, while the cost of the developed extruded system is approximately $295.0 per ton.

The reduced cost of the developed extruded system is attributed to a lower proportion of high-cost components, such as flaxseed (7 % compared to 10 % in the comparable system), and the use of a more affordable ingredient – barley groats, which represent a more economically viable raw material. This also positively impacts the overall production cost, enabling the manufacturer to offer the final product at a lower price, potentially attracting a broader consumer audience.

Analysis of the economic feasibility of using the developed extruded system highlights its significant advantages over similar systems. The raw material cost for the developed extruded system is approximately $295.00 per ton, which is considerably lower compared to a similar extruded mixture of flaxseed and bean-corn flour ($757.50/ton). This cost difference nearly halves production expenses, making the new system more competitive. Furthermore, using antioxidants, such as ascorbic acid and ferulic acid, is an economically advantageous step to extend the product's shelf life and reduce the risk of lipid oxidation. This prevents quality degradation during storage, significantly enhancing the product's market competitiveness. Unlike the comparable system, which does not include antioxidants, the stabilization of the lipid component in the developed system allows it to maintain its nutritional value and organoleptic properties over a longer period, minimizing losses due to spoilage.

The development of an extruded system with increased ALA (alpha-linolenic acid) content exhibits certain distinctions from previous studies, such as [13], which examined the reduction of ALA content due to low moisture and high extrusion temperatures. However, this research focuses on stabilizing ALA against oxidative deterioration, which is critical for achieving an extended product shelf life, particularly under accelerated oxidation conditions. Previous studies have not proposed viable solutions to prevent lipid losses during high-temperature processing, primarily due to the complexity of analyzing chemical changes in lipids under such conditions. Similarly, [14] reports test results on fat fraction losses under various moisture conditions, further highlighting the complexity of physicochemical processes during extrusion.

In this development, attention is paid to balancing antioxidant and lipid content, which mitigates the adverse effects of oxidative degradation on the lipid component, particularly ALA. A comparison with [16] highlights differing approaches to flaxseed use in extruded systems. While [16] demonstrated that flaxseed solutions are a promising source for protein-lipid systems due to their high ALA content, it did not address the impact of extrusion parameters, such as temperature and mechanical stress, on ALA stability. Additionally, issues of oxidative stability during high-temperature processing were not explored.

A critical area of this research is refining the conditions for applying the obtained results to the development of extruded systems with increased ALA content. Given the enhanced stability of the lipid component through the use of antioxidants such as ascorbic and ferulic acids, the findings can be effectively implemented in manufacturing processes specializing in the extrusion of high-lipid products. This not only extends product shelf life but also improves quality in terms of nutritional value and oxidative stability. Furthermore, the results are compatible with existing technological processes, enabling seamless integration of the new systems into already operational extrusion lines.

A limitation of utilizing the research results lies in the fact that when scaling the production method of extruded products with different raw materials or under conditions of altered chemical composition of components, adjustments to the technological process parameters may be required. Moreover, porosity, oxidative stability, water absorption capacity, and other technological indicators can significantly vary depending on the initial composition of the raw materials.

At the same time, it is worth noting certain shortcomings of this study, in particular, the lack of exploration of how changes in temperature or screw rotation speed of the extruder influence the final product indicators when these antioxidants are used. Fixing these parameters at specific values during the experiment may have limited the identification of optimal conditions to maximize both the product's porosity and ALA stability. In the future, expanding experimental research to investigate the effects of technological parameters on the efficiency of the extrusion process would be beneficial.

The prospects for applying this approach to developing extruded systems with increased ALA content in various sectors of the food industry include the formulation of extrudates for sports nutrition and specialized purposes, particularly dietary nutrition and nutrition for individuals with increased demand for ω-3 PUFA.

7. Conclusions

1. The chemical composition of raw materials for the extruded system – flaxseed and barley groats – was analyzed. It was determined that the lipid content in flaxseed constitutes 38.4 %, with a significant portion represented by alpha-linolenic polyunsaturated fatty acid (55.8 % of the total fatty acids). Additionally, flaxseed contains a considerable amount of protein (22.4 %) and dietary fiber (28.1 %). Barley groats, serving as the base component of the extruded system, contain 11.2 % moisture, 13.8 % protein, 1.2 % lipids, and 68.6 % carbohydrates. The combined use of these components allows for optimizing the nutritional value of the extruded system based on them.

2. The optimal flaxseed content in the extruded system was determined using approximative dependencies of extrudate porosity and the oxidative stability of the lipid component on its content. A flaxseed content of 7 % in the extruded system ensures rational technological properties of the extrudate. The porosity of the finished product is 80 %, and the induction period for accelerated oxidation at 80 °C reaches 10 hours.

3. The optimal content of ascorbic and ferulic acids in the extruded system enriched with alpha-linolenic acid was determined to enhance the oxidative stability of the lipid component. An approximative model was proposed to describe the mutual non-additive effects of antioxidants on the oxidation induction period of the extrudate at 80 °C. The rational concentrations of antioxidants in the extruded system were substantiated as follows: ascorbic acid – 0.06–0.09 %, ferulic acid – 0.10–0.15 %. It was found that within these concentrations, the induction period for accelerated oxidation increases by 2.2 times compared to the control.

Conflict of interest

The authors declare no conflict of interest regarding this study, including financial, personal, authorship-related, or any other type of conflict that could influence the research and its outcomes as presented in this paper.

Funding

The research was conducted without financial support.

Data availability

The manuscript does not contain any associated data.

Use of artificial intelligence tools

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

References

1. 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
2. Belinska, A., Bliznjuk, O., Shcherbak, O., Masalitina, N., Myronenko, L., Varankina, O. et al. (2022). Improvement of fatty systems biotechnological interesterification with immobilized enzyme preparation usage. Eastern-European Journal of Enterprise Technologies, 6 (6 (120)), 6–13. https://doi.org/10.15587/1729-4061.2022.268373
3. Bajaj, S. R., Singhal, R. S. (2019). Effect of extrusion processing and hydrocolloids on the stability of added vitamin B12 and physico-functional properties of the fortified puffed extrudates. LWT, 101, 32–39. https://doi.org/10.1016/j.lwt.2018.11.011
4. Zhang, B., Liu, G., Ying, D., Sanguansri, L., Augustin, M. A. (2017). Effect of extrusion conditions on the physico-chemical properties and in vitro protein digestibility of canola meal. Food Research International, 100, 658–664. https://doi.org/10.1016/j.foodres.2017.07.060
5. 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
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. Technology Organic and Inorganic Substances, 4 (6 (130)), 14–21. https://doi.org/10.15587/1729-4061.2024.309079
7. Singh, R., Sá, A. G. A., Sharma, S., Nadimi, M., Paliwal, J., House, J. D., Koksel, F. (2023). Effects of Feed Moisture Content on the Physical and Nutritional Quality Attributes of Sunflower Meal-based High-Moisture Meat Analogues. Food and Bioprocess Technology, 17 (7), 1897–1913. https://doi.org/10.1007/s11947-023-03225-8
8. Flôres, I. G., Salles, C., Conti, A. C. (2024). Effects of the extrusion conditions, the addition of oil and the food matrix on the physical and sensory characteristics of pre-extrusion flavored products. Journal of Food Science and Technology, 61 (11), 2145–2156. https://doi.org/10.1007/s13197-024-05985-3

9. Papchenko, V., Stepankova, G., Karatieieva, O., Balandina, I., Shapovalenko, D., Kariuk, A. et al. (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
10. 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
11. 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
12. Leonard, W., Zhang, P., Ying, D., Fang, Z. (2019). Application of extrusion technology in plant food processing byproducts: An overview. Comprehensive Reviews in Food Science and Food Safety, 19 (1), 218–246. https://doi.org/10.1111/1541-4337.12514
13. Tumuluru, J. S., Sokhansanj, S., Bandyopadhyay, S., Bawa, A. S. (2012). Changes in Moisture, Protein, and Fat Content of Fish and Rice Flour Coextrudates during Single-Screw Extrusion Cooking. Food and Bioprocess Technology, 6 (2), 403–415. https://doi.org/10.1007/s11947-011-0764-7
14. Yousf, N., Nazir, F., Salim, R., Ahsan, H., Sirwal, A. (2017). Water solubility index and water absorption index of extruded product from rice and carrot blend. Journal of Pharmacognosy and Phytochemistry, 6 (6), 2165–2168. Available at: https://www.academia.edu/65515809
15. Arêas, J. A. G., Rocha-Olivieri, C. M., Marques, M. R. (2016). Extrusion Cooking: Chemical and Nutritional Changes. Encyclopedia of Food and Health, 569–575. https://doi.org/10.1016/b978-0-12-384947-2.00266-x
16. Belinska, A., Bochkarev, S., Varankina, O., Rudniev, V., Zviahintseva, O., Rudnieva, K. et al. (2019). Research on oxidative stability of protein-fat mixture based on sesame and flax seeds for use in halva technology. Eastern-European Journal of Enterprise Technologies, 5 (11 (101)), 6–14. https://doi.org/10.15587/1729-4061.2019.178908
17. Papchenko, V., Matveeva, T., Bochkarev, S., Belinska, A., Kunitsia, E., Chernukha, A. et al. (2020). Development of amino acid balanced food systems based on wheat flour and oilseed meal. Eastern-European Journal of Enterprise Technologies, 3 (11 (105)), 66–76. https://doi.org/10.15587/1729-4061.2020.203664
18. Vadukapuram, N., Hall, C., Tulbek, M., Niehaus, M. (2014). Physicochemical Properties of Flaxseed Fortified Extruded Bean Snack. International Journal of Food Science, 2014, 1–8. https://doi.org/10.1155/2014/478018