The object of the study is the process of enzymatic hydrolysis of dietary fiber in flax meal, aimed at the bioconversion of cellulose into soluble sugars. The work considers the use of cellulolytic enzymes and an antioxidant for the hydrolysis of cellulose in flax meal. This allows to increase the bioavailability of soluble sugars and other nutritional compounds, as well as to preserve polyunsaturated fatty acids (PUFA) of the lipid component of the meal, in particular alpha-linolenic acid (ALA), from oxidative destruction. The rational parameters of the enzymatic hydrolysis process are determined: pH 4.5 and temperature 50 °C, which ensure the maximum yield of soluble sugars (11.4 %) with minimal losses of ALA (9.0 %). The use of an antioxidant – sodium salt of erythorbic acid (E 316) to protect PUFA from oxidative damage during enzymatic hydrolysis is also considered. The most effective concentration of sodium erythorbate was 0.03–0.035 %, which minimizes ALA losses to 1.4 %. The results of the research are important for the development of new technologies for processing flaxseed meal, which will contribute to improving the quality of products and their preservation for a long period. The results obtained are explained by biochemical and chemical interactions between the components of the reaction mixture (enzyme, buffer, antioxidant) and the components of flaxseed meal (dietary fiber, lipid complexes). This leads to an increase in the efficiency of cellulose hydrolysis and the preservation of PUFA from oxidation. The results obtained allow to consider flaxseed meal with hydrolyzed cellulose as a promising product for the food industry and feed production

Keywords: cellulolytic enzymes, dietary fiber, flaxseed meal, α-linolenic acid, antioxidants

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DEVELOPMENT OF APPROACHES FOR THE BIOCONVERSION OF DIETARY FIBERS IN FLAX MEAL USING CELLULOLYTIC ENZYMES

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1. Introduction

Scientific research in the field of bioconversion of dietary fiber from plant raw materials is becoming increasingly important in the context of the global transition to sustainable and resource-saving technologies [1]. The study and optimization of the processes of enzymatic hydrolysis of cellulose-containing materials opens up opportunities for increasing their bioavailability and expanding the scope of applications in the food industry, dietary nutrition and feed

production. In the context of the development of specialized nutrition, the issue of enriching products with essential nutrients, including polyunsaturated fatty acids (PUFA), which play a critically important role in maintaining human and animal health, is becoming relevant [2, 3].

The annual global production of linseed oil is approximately 650 thousand tons, which is accompanied by the formation of significant volumes of cake – about 1.2–1.3 million tons. In Ukraine, in 2023, about 20 thousand tons of linseed oil were produced, which is equivalent to approximately 35 thousand tons of cake. This emphasizes the need to find effective methods for further processing of linseed cake to increase the economic efficiency of production [3]. Given the high content of valuable lipids, linseed cake is a promising raw material for expanded biotechnological use. However, the key problem remains the limited bioavailability of biologically valuable substances due to the significant content of insoluble dietary fiber, which forms a barrier to the absorption of lipid and protein components [4]. The use of cellulolytic enzymes for the hydrolysis of structural carbohydrates allows expanding the possibilities of using linseed cake, in particular, to create new products with increased nutritional value. On the other hand, enzymatic processes can initiate oxidative destruction of PUFA, primarily α-linolenic PUFA (ALA), which negatively affects their biological properties [5]. Therefore, an important aspect of research is the development of an antioxidant protection system that will ensure the stability of the lipid profile of flaxseed meal during the bioconversion process. Flaxseed meal is traditionally used as a valuable feed component in the diets of cattle, pigs and poultry, due to its high protein and ω-3 PUFA content. In addition, promising areas of its use in the food industry are the production of health-promoting ingredients enriched with proteins, flour mixtures, bars and other healthy food products [4]. The practical significance of research in this area is associated with the possibility of creating high-quality protein-fat products that can be used in both food and feed diets. Given the growing demand for functional ingredients derived from natural sources, biotechnological processing of flaxseed meal can contribute to the production of products enriched with bioavailable Omega-3 PUFAs, which will have a positive impact on human health and animal performance [6, 7]. In addition, the implementaI tion of rational enzymatic modification methods will minimize food waste, which is in line with modern principles of environmental sustainability and bioeconomy.

Therefore, research into the development of an effective method for enzymatic bioconversion of dietary fiber from flax meal is relevant both from a scientific and practical point of view. They contribute to the development of advanced processing technologies for plant raw materials, increasing the bioavailability of nutritional components, and developing innovative products for the food and feed industry, animal husbandry, and the production of dietary supplements. In addition, such research contributes to increasing the efficiency of using secondary plant raw materials, enriching the diet of humans and animals with biologically valuable components, and improving the quality characteristics of final products. The results of the research should contribute to the development of innovative technologies for processing flax meal, ensuring the stability of omega-3 PUFA in the products of its bioconversion, and reducing the loss of valuable nutrients during production and storage. Such technologies contribute to the sustainable development of the biotechnology industry through the introduction of environmentally friendly methods for processing plant raw materials.

2. Literature review and problem statement

In work [8], the use of carbohydrases and proteolytic enzyme preparations for the processing of sunflower meal was investigated, which allowed obtaining hydrolysates with improved technological and nutritional properties. However, the issue of using cellulolytic enzymes for the bioconversion of dietary fibers was not considered. The main reason for this is the focus of research on the protein component of the raw material, while the mechanisms of transformation of non-starch polysaccharides remain poorly understood.

In the study [9], it was shown that mechanical grinding of raw materials is an effective way to prepare the substrate for further processing, as it reduces the particle size and increases the specific surface area of the substrate. It was also found that extrusion provides additional technological advantages, such as texturization, stabilization and sterilization of raw materials. However, this work did not consider the specific conditions of extrusion processing of flax cake, which could contribute to the effective subsequent enzymatic hydrolysis of its dietary fibers. This is explained by the fact that most studies are focused on correcting the content of dietary fiber by physical and mechanical methods, and not by bioconversion. Researchers behaved similarly in work [10], which presents the results of studies on the creation of a rational composition of extruded feed using sunflower and soybean meal, as well as oat groats. Although the study covers a wide range of secondary plant raw materials, oilseed cake is not considered as a separate component subject to targeted bioconversion. The reason for this may be the insufficient amount of data on the specific effect of enzymatic hydrolysis on the structure and nutritional properties of the lipid component of the cake. In work [11], the technology of extrusion of flax seeds in mixtures with other components was investigated. It was found that the introduction of up to 7 % of flax seeds into the extruded mixture contributes to the preservation of biologically active lipids, in particular ALA, and the inhibition of oxidative destruction. An unresolved issue in the works [9–11] is the influence of extrusion processing on the subsequent enzymatic bioconversion of secondary products of oil and fat production. In the work [12], such an aspect of the bioconversion of oil raw materials as the inactivation of lipoxygenases in flax seeds using chemical reagents was considered, which allows reducing the oxidative damage of lipids during storage. At the same time, the possibility of combined use of chemical and enzymatic processing for the preservation of PUFAs was not investigated. This can be explained by the fact that the main emphasis of the works [12, 13] was made on the stabilization of the lipid component from oxidative destruction, and not on improving the bioavailability of other nutritional components.

In the study [13], the possibility of using the microfungus *Pleurotus ostreatus* for the bioconversion of sunflower meal was considered. However, the effect of the producer enzymes on the degree of preservation of the lipid component of the substrate was not taken into account. This can be explained by the specificity of the finished product used as livestock feed.

The work [14] is devoted to the analysis of the nutrient profile of flaxseed meal and methods of its processing, in-

cluding fermentation. A number of anti-nutritional factors that interfere with the absorption of nutrients were identified, and various methods for their elimination were proposed. However, the specificity of the effect of cellulolytic enzymes on the destruction of the fibrous structure of flaxseed meal was not studied, which is an important step in increasing the bioavailability of nutrients.

The work [15] investigated aspects of the bioconversion of oilseed meal for use as an organic fertilizer. However, the potential of enzymatic bioconversion of flaxseed meal for food use remained beyond the scope of the study. The main reason for this is the focus of research on the agronomic aspects of the use of meal, rather than on food technologies.

Thus, the results of existing scientific research leave open the question of rationalizing the conditions of enzymatic hydrolysis of dietary fiber of flax meal in order to increase the bioavailability of its nutritional components. It is also necessary to develop an effective method for protecting PUFA from oxidative damage in the process of enzymatic bioconversion. Solving these issues will not only increase the shelf life of food products based on flax meal, but also expand their application in the food industry, which is of significant scientific and practical interest. Based on the analysis of the literature, it was determined that the study of the influence of cellulolytic enzymes on the structure and nutritional characteristics of flax meal is relevant.

3. The aim and objectives of the study

The aim of the study is to develop an effective method for bioconversion of dietary fiber in flax meal using cellulolytic enzymes to increase its nutritional value. At the same time, it is important to minimize oxidative damage to polyunsaturated fatty acids (PUFA), in particular omega-3 (alpha-linolenic acid), contained in flax meal. This will allow creating a product with increased bioavailability of nutrients and a stable lipid profile, which can be used in functional nutrition, dietary supplements and feed mixtures to enrich the diet with PUFA.

To achieve this aim, it is necessary to solve the following objectives:

– to rationalize the conditions of enzymatic hydrolysis of dietary fiber in flax meal by adjusting the process parameters to achieve maximum bioavailability of nutrients;

– to propose a system of antioxidant protection for prer serving flaxseed meal PUFAs during enzymatic bioconversion by determining the rational concentration of a natural antioxidant.

4. Materials and methods of the study

4. 1. Object and hypothesis of the study

The object of the study is the process of enzymatic hydrolysis of dietary fibers in flax meal, aimed at the bioconversion of cellulose into soluble sugars. The main hypothesis is that the use of cellulolytic enzymes with reasonable rational process parameters, such as temperature and pH of the reaction, allows to maximize the bioavailability of nutrients, in particular polysaccharides, in the final product. At the same time, enzymatic hydrolysis will not initiate oxidative destruction of PUFA of the lipid phase of flax meal if antioxidants are used in the reaction mixture. Such studies are important for the food industry and feed production.

The study assumes that flax meal has a homogeneous chemical composition, which allows to generalize the results of enzymatic hydrolysis of cellulose in a certain way. In addition, it is assumed that the selected enzymatic hydrolysis parameters (temperature and pH) are rational for achieving the maximum yield of soluble sugars and preserving the bioactive components of flaxseed meal. It is also believed that the use of antioxidants, in particular sodium salt of erythorbic acid, has a predictable effect on the stability of PUFA during hydrolysis.

The study adopted a simplification that all process conditions (pH, temperature, enzyme and antioxidant concentrations) are the same for all experimental samples and do not depend on changes in the chemical composition of a particular batch of flaxseed meal. This simplifies the interpretation of the results and allows analyzing the effect of changes in process parameters without taking into account individual differences between samples from different production batches.

4. 2. Materials used in the experiment

The following materials were used during the research:

– flaxseed cake (*Linum usitatissimum*), obtained after industrial pressing of flaxseed oil (produced in Ukraine), according to DSTU 8241/Regulation (EC) No. 183/2005;

– enzyme preparation of cellulase (activity 10,000 units/g, pH-optimum 3.5–4.5, temperature optimum 50–65 °C, produced in Ukraine), according to CAS 9012-54-8;

– sodium erythorbate E 316 (produced in China), according to CAS 6381-77-7.

The choice of antioxidant for the protection of PUFA in the process of enzymatic hydrolysis of flaxseed cake was based on its effectiveness, safety and compatibility with the reaction medium. Among a wide range of potential antioxidants, ascorbic acid, tocopherols, gallates and sodium erythorbate (E 316) were considered. Sodium erythorbate was chosen due to its stability in acidic media, ability to effectively inhibit lipid oxidation and high compatibility with enzymatic systems.

4. 3. Method of enzymatic treatment of flax cake with cellulolytic enzymes

The cake is ground to particles of 0.5–1 mm in size to increase the accessibility of the substrate to enzymes. To ensure a stable pH within 3.5–4.5, a citrate buffer was used. Sodium isoascorbate, a cellulase complex (at a concentration of 1000 units/g of substrate), a solid-liquid phase ratio of 1:4 are added to the buffer solution, which ensures effective bioconversion and minimizes the cost of subsequent drying. Hydrolysis is carried out at a temperature of 45±1 °C for 12 hours with constant stirring (100 rpm). After completion of the enzymatic process, the mixture is cooled to 4 °C, dried in a Heidolph Hei-VAP Core rotary vacuum dryer (Germany) at a temperature of 40 °C to minimize PUFA losses. The methodology was developed by the authors based on modified approaches to enzymatic processing of plant materials.

4. 4. Methodology for the analysis of flaxseed meal after hydrolysis

To determine the content of soluble sugars (glucose, fructose, maltose) in flaxseed meal dried after enzymatic hydrolysis, a 3,5-dinitrosalicylic test (DNS-test) is used, based on the colorimetric determination of soluble sugars. The optical density is measured on a Milton Roy Spectronic

20 spectrophotometer at 540 nm, comparing with a standard calibration curve constructed for glucose.

The content of PUFA in the lipid fraction of flaxseed meal dried after enzymatic hydrolysis is determined by gas-liquid chromatography. First, low-temperature extraction of lipids is carried out according to the Bly and Dyer method, using a cold chloroform:methanol mixture at 4 °C, which minimizes the oxidation of PUFA. After extraction, the organic phase is separated by centrifugation (5000 rpm, 10 min, 4 °C), and the solvent is evaporated in vacuo. Lipids are esterified into fatty acid methyl esters. Analysis is performed on a gas chromatograph with a flame ionization detector. A nitrogen atmosphere is used to prevent oxidation at all stages. This technique is a modified version of the classical approaches to the PUFA analysis in lipid extracts.

4. 5. Research planning and results processing

Two- and one-factor experiments were used in the research on the development of a method for bioconversion of dietary fibers in flax meal using cellulolytic enzymes. In each of the experiments, three repetitions were carried out to ensure statistical reliability of the results. Statistical models of dependencies (1) and (2) were calculated by approximating experimental data by constructing a trend surface. The significance of the equations of these dependencies was established by calculating the Fisher criterion (F), based on the assumption (null hypothesis) that the equation is statistically insignificant. The calculated values of the Fisher criterion for dependency (1): F (2.7)=12.491; for dependency (2): F (2.7)=9.562. These values of the Fisher criterion are greater than its critical tabular value F_{tab}(2.7)=4.74 (p=0.05). The obtained result allows to reject the null hypothesis and, with a probability of 95 %, to recognize the values of the coefficients of determination R^2=0.935 for dependence (1) and R^2=0.972 for dependence (2) as significant. In turn, the equations of approximation dependences (1) and (2) are significant. The processing of experimental data and the construction of graphical dependences were performed using the Stat Soft Statistica v 6.0 package (USA).

5. Results of studies on the inactivation of flaxseed lipoxygenases using chemical reagents

5. 1. Rationalization of conditions for enzymatic hydrolysis of dietary fiber from flaxseed meal

Enzymatic hydrolysis of flaxseed meal cellulose was carried out under conditions that varied according to the following parameters: pH of the medium – from 3.5 to 4.5 (variation interval – 0.5); reaction temperature – from 45 °C to 55 °C (variation interval – 5 °C). Rational conditions for the maximum possible hydrolysis of cellulose were determined by the highest yield of soluble sugars and the lowest losses of ALA ($C_{18:3}$, ω-3). Analysis of the influence of pH and temperature on the enzymatic reaction allows to establish rational parameters for the enzymatic bioconversion of flaxseed meal cellulose. It should be noted that in the original sample the content of soluble sugars was 1.8 %, and the content of ALA in the lipid component was 7.2 %.

The approximate dependences of the content of soluble sugars in flax meal and ALA in its lipid component after enzymatic hydrolysis on the process factors are presented using equations (1) and (2):

$$C_{SC}(pH, T)=-184.9111+25.7\cdot pH+5.1533\cdot T-2.1333\cdot pH^2-0.05\cdot pH\cdot T-0.0493\cdot T^2, \quad (1)$$

$$C_{ALA}(pH, T)=4.7067+1.6933\cdot pH-0.1153\cdot T, \quad (2)$$

where C_{SC} – content of soluble sugars, %;

C_{ALA} – content of α-linolenic polyunsaturated fatty acid, %;

pH – pH of the solution where enzymatic hydrolysis is carried out, units;

T – temperature of the solution where enzymatic hydrolysis is carried out, °C.

Fig. 1, *a*, *b* show graphical dependences of the content of soluble sugars in flax meal and ALA, its lipid component, after enzymatic hydrolysis, on the pH and temperature of the solution where enzymatic hydrolysis is carried out.

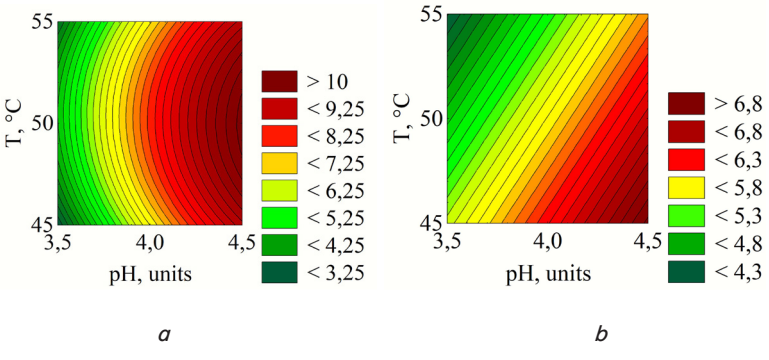

Fig. 1. Dependence of quality indicators of processed flaxseed meal after enzymatic hydrolysis on pH and temperature of the solution: *a* — dynamics of changes in the content of soluble sugars; *b* — dynamics of changes in the content of ALA in its lipid component

Based on the results of experimental studies, the most rational parameters of enzymatic hydrolysis of flaxseed meal cellulose are pH 4.5 and temperature 50 °C, which provides the highest yield of soluble sugars (11.4 %) with minimal permissible losses of ALA (9.0 %). To further improve the stability of PUFA in the lipid fraction of the meal, it is advisable to use antioxidants.

5. 2. Development of antioxidant protection for the preservation of polyunsaturated fatty acids of flaxseed meal during enzymatic bioconversion

PUFA, in particular ALA, contained in flaxseed meal, are sensitive to oxidative damage due to the influence of temperature, oxygen and metal ions during enzymatic bioconversion of dietary fibers. In order to minimize oxidation in the reaction mixture, antioxidant protection based on the sodium salt of erythorbic acid (sodium erythorbate, E 316) was used.

To determine the rational content of sodium erythorbate in the reaction mixture, a series of experiments were conducted in the concentration range of 0.01–0.05 % (wt.). The results of studies on the dependence of the ALA content in the lipid fraction of flaxseed meal treated with cellulolytic enzymes on the content of sodium erythorbate in the reaction mixture are shown in the graph (Fig. 2).

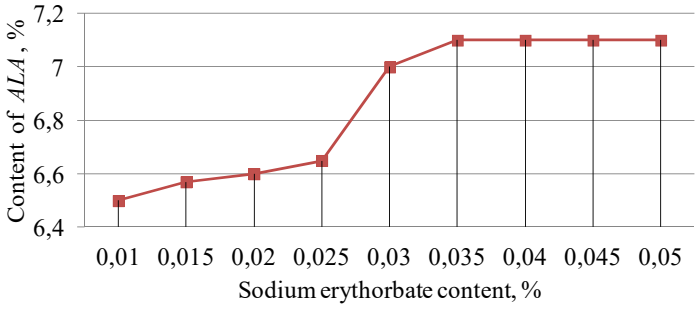

Fig. 2. Dependence of ALA content in lipid fraction of flaxseed meal treated with cellulolytic enzymes on sodium erythorbate content in the reaction mixture

The experimental results indicate that the use of sodium salt of erythorbic acid at a concentration of 0.03–0.035 % is rational. Such antioxidant content allows minimizing ALA losses during enzymatic hydrolysis of cellulose (1.4 %), ensuru ing the stability of the lipid fraction of flaxseed meal, thereby improving the quality of the final product.

6. Discussion of the results of using cellulolytic enzymes for the bioconversion of dietary fiber in flax meal

The process of enzymatic hydrolysis of cellulose using cellulolytic enzymes is an important stage in the bioconversion of dietary fiber of flaxseed meal. The use of a substantiated method allows not only to reduce the content of insoluble fiber, but also to significantly improve the bioavailability of nutrients, such as soluble sugars, proteins, lipids, etc.

Analysis of the obtained results of enzymatic hydrolysis of cellulose of flaxseed meal (dependencies (1), (2), Fig. 1) allows to determine rational process parameters that ensure the maximum yield of soluble sugars with minimal losses of ALA lipid fraction. The most unfavorable conditions for hydrolysis are observed at pH 3.5, where the content of soluble sugars does not exceed 3.9 %, and the content of ALA significantly decreases to 3.96–5.62 % depending on the temperature (ALA losses –22.0–50.0 %). This can be explained by the decrease in cellulase activity in an acidic environment, which limits the effectiveness of the cellulolytic enzyme preparation, as well as the increased sensitivity of ALA to destruction under acid catalysis. At pH 4.0, a significant improvement in the quality indicators of the finished product is observed:

– the content of soluble sugars increases to 6.7–7.9 %,

– the content of ALA in the lipid fraction decreases less critically and is 5.25–6.33 % (ALA losses are 12.1–27.1 %).

This indicates more favorable conditions for enzymatic cellulose cleavage, however, when the temperature is increased to 55 °C, partial destruction of omega-3 PUFA is still observed (ALA losses are about 15 %).

The most rational results of enzymatic hydrolysis were obtained at pH 4.5 of the reaction mixture, where the content of soluble sugars in flax meal after cellulose hydrolysis reaches a maximum of 11.4 % at 50 °C. This confirms the high efficiency of the enzymatic process under the specified conditions. At the same time, the ALA content in this hydrolysis mode decreases to 6.55 %, which is an acceptable compromise between the yield of sugars and the preservation of the lipid fraction in the processed product. At 45 °C, ALA losses in the lipid fraction are minimal (about 5 %), but the level of soluble sugars is lower (9.1 %). With a further increase in temperature to 55 °C, a decrease in the yield of sugars to 8.9 % is observed, which is probably due to partial thermal destruction of enzymes. Thus, pH 4.5 and a temperature of 50 °C are the most rational parameters for enzymatic hydrolysis of cellulose in flax meal, as they provide the maximum yield of soluble sugars (11.4 %) with moderate losses of ALA (about 9 %). Tem% peratures above 50 °C are undesirable due to active degradation of enzymes and ALA oxidation (loss of ALA about 15 %).

The results of experiments on the effect of sodium salt of erythorbic acid on the ALA preservation in flax meal during enzymatic hydrolysis of cellulose showed a positive relationship between the concentration of sodium erythorbate and the ALA content in the final product (Fig. 2). In the studied samples, a gradual increase in the content of alpha-linolenic acid was recorded from 6.5 % (loss 9.7 %) to 7.1 % (loss 1.4 %) with an increase in the concentration of sodium erythorbate from 0.010 % to 0.050 %. The increase in the ALA content after the introduction of sodium erythorbate at the level of 0.030 % is especially noticeable, when the ALA content reached a maximum value of 7 % (loss 2.8 %). With a further increase in the concentration of the antioxidant to 0.035 % and 0.050 %, the ALA level stabilized at 7.1 % (loss 1.4 %), which indicates the achievement of effective protection against destruction. These results indicate that the concentration of sodium salt of erythorbic acid in the range from 0.030 % to 0.050 % provides maximum PUFA protection of flaxseed meal from oxidation during enzymatic hydrolysis. Higher concentrations do not provide an additional increase in ALA content, which may indicate that the antioxidant saturation in the system has been achieved. The results obtained can be explained by several factors related to both the chemical and biochemical properties of sodium erythorbate and its interaction with PUFAs, in particular ALA, during enzymatic hydrolysis. Sodium erythorbate prevents the formation of free radicals and promotes the stability of lipids during enzymatic hydrolysis, preventing their oxidation. In addition, the introduction of sodium erythorbate into the reaction mixture may also have an indirect effect on the activity of enzymes involved in cellulose hydrolysis. Since sodium erythorbate stabilizes the structure of PUFAs, its introduction inhibits the oxidative destruction of lipids, thereby contributing to a more efficient enzymatic breakdown of fibers and the preservation of the lipid fraction.

The difference in the results obtained in the work lies in the focus of the enzymatic approach on dietary fiber, especially cellulose, which is one of the main components of flax meal. In works [8–12], existing studies are mainly focused on the correction of the composition of the raw material through physical and mechanical methods, and the mechanisms of enzymatic hydrolysis remain poorly understood. The results obtained show that rational parameters – pH 4.5 and temperature 50 °C provide the maximum yield of soluble sugars from the substrate (11.4 %) with minimal losses of PUFA, such as ALA, which is a key component of flax meal. In work [13], the process of bioconversion using a microorganism was studied, but the emphasis was on increasing the feed properties of the substrate without taking into account the influence of the producer enzymes on the preservation of the lipid component. The difference of the study is that specific cellulolytic enzymes were used to hydrolyze dietary fibers in flax meal, which contributes not only to improving

nutritional characteristics, but also to preserving ALA. In addition, in the work [15] there is no attention to the use of antioxidants to protect lipids from oxidative damage during enzymatic treatment, which is an important advantage of the study. The use of an antioxidant, in particular sodium salt of erythorbic acid (E 316), allows to significantly reduce ALA losses. This is a new approach compared to the methods used in the works [13, 14], where the issue of lipid stability during enzymatic treatment was not considered. The obtained results of bioconversion of dietary fibers of flax meal allow to consider them as a promising ingredient for various branches of the food industry. In particular, the increased bioavailability of soluble sugars and proteins contributes to the possibility of using the resulting product in the baking industry for the enrichment of functional bakery products, as well as in the production of gluten-free products. In addition, the improved solubility of fibers and their enzymatic modification may be useful in creating low-calorie fat substitutes in food products, which is important for dietary nutrition.

The limitation of using the obtained results of enzymatic hydrolysis of flax meal cellulose is that the work used samples of flax meal with specific physicochemical characteristics. Given the variability of the composition of lipids, dietary fiber and other components depending on the flax variety and its growing conditions, the results may differ when processing meal with different physicochemical properties. It is also important to take into account the specific composition of antioxidants in different samples of flax meal, since their level may affect the stability of the lipid fraction during enzymatic hydrolysis. In addition, depending on the storage conditions of flax meal before its processing, the level of lipid oxidation, in particular the peroxide value, may vary, which also requires adjusting the hydrolysis process and using antioxidant additives. Thus, to obtain stable and high-quality products, it is necessary to take into account variations in the composition of the starting material in order to fine-tune the parameters of the enzymatic process and rationally use antioxidants to preserve lipids and PUFA in the final product.

A drawback of the study is the lack of detailed data on the effect of different types of antioxidants on the stability of the lipid component of flaxseed meal during enzymatic hydrolysis. Despite the fact that sodium salt of erythorbic acid (E 316) was used in the experiments, it is necessary to further study the effectiveness of other natural and synthetic antioxidants, such as ascorbic acid or polyphenols. The question of the influence of storage conditions of the finished product after enzymatic bioconversion remains open, since even with rationalization of the cellulose hydrolysis process, further oxidation of the lipid component of flaxseed meal can occur during storage. Therefore, it is important to conduct additional studies on the effectiveness of antioxidant protection in the long term and under real storage conditions of finished products.

Based on the results obtained, several promising areas for further research in the field of bioconversion of dietary fibers in flax meal can be identified. One of the important areas is the study of the influence of different types of cellulolytic enzymes on the efficiency of hydrolysis of different types of fibers in flax meal. Additional research should also be conducted on the use of enzyme complexes for more effective cleavage of lignin and polysaccharides, which may be more resistant to hydrolysis. This will make it possible to significantly increase the nutritional value of the finished product. Another important area is the development and implementation of methods for preserving PUFA in flax meal after enzymatic hydrolysis.

7. Conclusions

1. The dependence of the efficiency of enzymatic hydrolysis of dietary fibers in flax meal on the process parameters, in particular the pH of the medium and the reaction temperature, was determined. Rational hydrolysis conditions were substantiated to achieve maximum bioavailability of nutrients, in particular soluble sugars. The rational parameters of the hydrolysis process are: pH of the reaction mixture – 4.0–4.5, reaction temperature – 50–55 °C. Under such conditions, the maximum yield of soluble sugars is achieved, which indicates effective cellulose cleavage and maximum bioavailability of nutritional components.

2. The use of sodium salt of erythorbic acid (E 316) allows to significantly reduce oxidative damage of PUFA, in particular ALA. The rational concentration of sodium erythorbate, which provides maximum protection against oxidation, is 0.03–0.035 %. This concentration allows to minimize the loss of ALA (1.4 %) in the lipid component of flaxseed meal during enzymatic hydrolysis of cellulose. Higher concentrations of the antioxidant did not lead to an additional reduction in oxidative damage.

Conflict of interest

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

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Data availability

The manuscript has no linked data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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