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COMBINED METHOD OF THERMAL INACTIVATION OF ANTINUTRITIVE FACTORS IN SOY

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Abstract. Soybean is one of the most important agricultural crops in the world due to its versatility, it contains a record amount of vegetable protein (up to 40-50%), which is almost identical in amino acid composition to animal protein. Despite its high nutrient content, soy contains anti-nutritional factors: protease inhibitors, lectins, ureases, oligosaccharides. The leading antinutritional factors of soybeans are substances that exhibit trypsin-inhibitory activity in both animals and humans. Protease inhibitors account for about 5-10% of the total protein content in soybean seeds and belong to two main types: Kunitz inhibitor and Bowman-Birk inhibitor. These compounds block the activity of proteolytic enzymes in the digestive tract, reducing protein digestibility and amino acid bioavailability. Long-term consumption of raw soybeans causes pancreatic hypertrophy, reduced growth in animals, and impaired nutrient absorption. Therefore, inactivation of antinutritional factors is a critically important step in preparing soybean raw materials for use. One of the most common technological methods of processing soybeans is extrusion. The effect of different extrusion modes on the bioavailaility of nutrients in soybean meal was analyzed. Based on the data obtained, the optimal temperature range for processing soybeans was determined - 137-142°C. This range strikes a balance between sufficient inactivation of trypsin inhibitors (to a level of 7.9-8.5 mg/g) and maintaining high protein solubility (84-88%) and lysine availability (87-91%). Temperatures below 137°C result in insufficient inactivation of anti-nutritional factors, while temperatures above 142°C result in excessive protein denaturation and reduced nutrient bioavailability. A method of combined microwave-alkaline processing of soybeans has been proposed, which has several advantages: first, the processing time is 120–150 s, which is significantly less than autoclaving (15–20 min) or frying (20–30 min); second, lower energy consumption - at a power of 600 W and a duration of 150 s, the energy consumption is approximately 0.025 kWh per 100 g of raw material, which is a competitive indicator; third, the preservation of high protein solubility of 88.2% makes the processed raw material suitable for many technological applications.

Keywords: soy antinutrients, trypsin inhibitors, protein solubility, extrusion, microwave treatment, alkaline treatment, synergistic effect.

Introduction. Formulation of the problem

Soybean is a unique crop and the most important source of vegetable protein in the world. The high protein content (35–40%) and balanced amino acid composition make soybean an indispensable ingredient in the production of food products, compound feeds and protein concentrates. The soybean processing industry is a key and dynamically growing sector of the agro-industrial complex both in the world and in Ukraine, as it allows creating products with high added value (Fig. 1) [1-7].

The full use of soy protein is limited by the presence of anti-nutritional factors; these are protease inhibitors, urease, lectins, phytates, oligosaccharides, saponins, which reduce biological value, impair digestion and can cause metabolic disorders.

Analysis of recent research and publications

The problem of inactivation of antinutrients in legumes has been studied for several decades, and a lot of scientific data has been accumulated on the effectiveness of various processing methods. Traditional methods consist in the use of heat treatment to denature protein inhibitors. The intensity and duration of treatment significantly affect not only the inactivation of antinutrients, but also the preservation of the nutritional properties of the processed product.

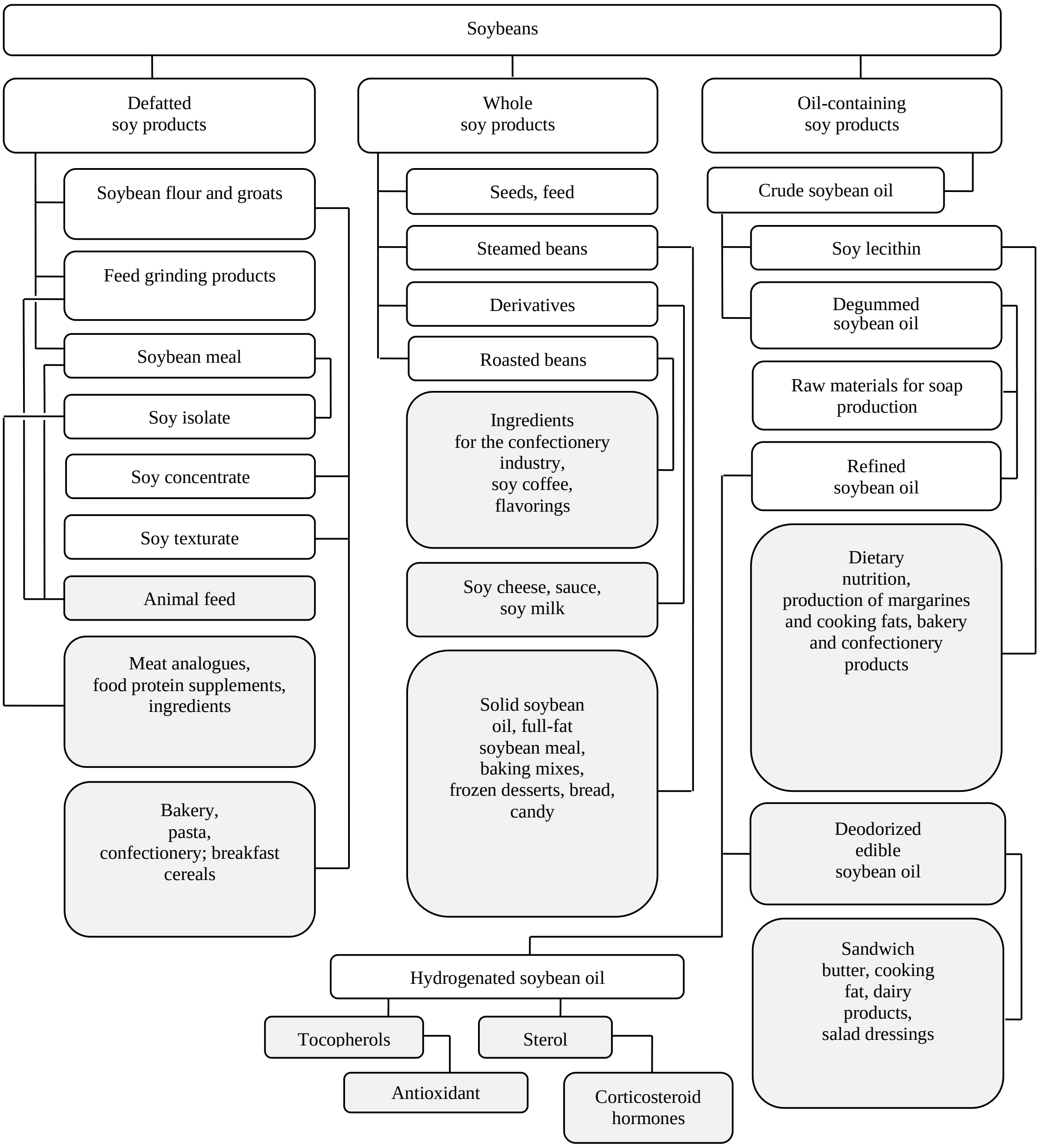


Fig. 1. Directions of processing and use of soybeans in industry

The chemical nature of soybean trypsin inhibitors includes disulfide bonds, which help maintain the spatial configuration of the molecule. The Kunitz inhibitor has two disulfide bridges, the Bowman-Birk inhibitor has seven bonds, due to which it is more heat-resistant [8, 9]. Thermal inactivation of these compounds occurs through the destruction of disulfide bonds and, consequently, denaturation of the protein structure, which leads to the loss of their activity.

Studies show that complete inactivation of trypsin inhibitors in raw soybeans requires prolonged boiling: 14 min provides 80% inactivation, and 30 min provides approximately 90% [10, 11]. Prolonged thermal exposure can negatively affect protein quality, reduce its solubility and bioavailability of amino acids. Therefore, the search for methods that provide effective inactivation at low temperatures and duration is relevant.

Studies have shown that pre-soaking soybeans before microwave processing provides a higher level of inactivation of trypsin inhibitors compared to dry raw materials [12]. The increased moisture content allows the soybeans to heat evenly and partially swell the proteins to increase the efficiency of thermal denaturation. However, the length of the soaking and subsequent drying process may be inefficient for industrial production.

Combined alkaline and heat treatment demonstrates a synergistic effect. Heating at pH 9 increases protein solubility compared to either treatment alone [13]. This is due to partial destruction of the buffering properties of proteins and a reduction in the effect of trypsin inhibitors on thermal denaturation.

The Institute of Feed and Agriculture of the Podillia NAAS developed a method for eliminating anti-nutritional factors in soybeans. Crushed soybean grains were treated in a calcium hydroxide solution with a concentration of 2.5% [14]. The technology consisted of soaking soybean flour in water at a ratio of 1:4 with the addition of 25 g/kg of alkali to achieve pH 7. The use of this method reduces the content of anti-nutritional substances and improves the digestibility of proteins, but requires a long processing time and subsequent washing of the raw materials.

A summary of the literature suggests that the most effective and promising approach is an integrated approach, namely a combination of different processing methods. The combination of microwave heating with pre-moistening and pH adjustment provides a synergistic effect of inactivation of antinutrients with lower energy costs and processing time.

The purpose of the study

The purpose of the study: to investigate different methods of heat treatment of soybeans to inactivate antinutrients while preserving the nutritional value of proteins.

To achieve this goal, it is necessary to solve the following tasks:

– determine the quality indicators of soybeans;

– characterize antinutrients of soybeans;

– analyze the methods of heat treatment of soybeans;

– determine the activity of trypsin inhibitors and the solubility of soybean protein under different processing methods.

Research materials and methods

All experiments to determine the physical properties of feed were conducted at the Department of Grain and Feed Technology of the Odesa National University of Technology, in accordance with standard methods accepted for soy according to DSTU 4964-2008. Soy was assessed by the following physical properties: mass fraction of moisture, flowability, angle of repose.

Characteristics of raw materials and reagents

For experimental studies, soybeans grown in Ukraine, harvest 2024, were used. The raw materials were stored in paper bags at a temperature of 18–20°C and a relative humidity of 30–40%. The initial moisture content of the beans was 9%, which corresponds to standard storage conditions for oilseeds. The crude protein content in the control samples was 33.7%, and crude fat was 21.5%.

Baking soda (sodium bicarbonate, $NaHCO_3$ with a mass fraction of the basic substance of at least 99.9%) was used as an alkaline reagent. The choice of soda as an alkaline agent is due to its wide application in the food industry, safety of use, and the ability to effectively regulate the pH level without introducing toxic components or heavy metals. Distilled water with a specific electrical conductivity of no more than 5 μS/cm was used to prepare the solutions.

Alkaline treatment

The experimental samples were treated with a solution of baking soda to achieve a pH of 8. Based on the data from the buffer capacity determination, it was found that to achieve this pH level, it was necessary to add 1.0% of soda by weight of the raw material (1.0 g per 100 g of soybeans). The soda was dissolved in the calculated volume of distilled water (7.06 ml).

The obtained alkaline solution was used to moisten the soybean samples similarly to the control group using a spray gun. After moistening, the samples were kept in sealed bags for 60 min to evenly distribute the alkali and establish an equilibrium pH value. The pH control was carried out on water extracts (sample:water ratio = 1:10) 60 min after treatment. The actual pH value of the extracts was 7.9±0.1, which confirms that the target alkalinity level was achieved.

Microwave treatment

Microwave treatment was performed in a household microwave oven with a nominal power of 800 W. To ensure the same processing conditions for all samples, a 600 W mode (75% power) was used, which provides more controlled heating conditions and reduces the risk of local overheating.

Samples weighing 100 g were placed in plastic containers and distributed in a uniform layer 8–10 mm thick to ensure uniform heating. The containers were placed in the center of the rotating plate of the microwave oven. The duration of treatment varied from 30 to 150 s in 30 s increments, which allows us to evaluate the kinetics of trypsin inhibitor inactivation and changes in protein solubility depending on the exposure time.

After microwave treatment, the samples were cooled to room temperature in air for 30 minutes, after which the mass loss due to moisture evaporation was determined. The treated samples were ground to a fraction of 0.5 mm and stored in sealed plastic containers at a temperature of 4±2°C until analytical studies were performed, but not more than 24 hours.

Extrusion

Soybeans were extruded on a grain extruder EZ-150 (Fig. 2) at a pressure of 2…3 MPa and a temperature of 132-151°C. Then they were cooled to a temperature that did not exceed the ambient temperature by more than 10°C. They were crushed in a crusher equipped with a sieve Ø 3 mm to obtain a crushed extruded product size of 3 mm. The size of the crushed grain is such that it could later be used for young farm animals;

according to DSTU, the exit from a sieve with a diameter of 3 mm should not exceed 5%.

Fig. 2. Grain extruder EZ-150

Methods of analysis

To assess the quality indicators of soybean samples, a Bruker TANGO infrared spectrometer (Germany) with Evonik calibration was used (Fig. 3), which provides a fast and non-destructive determination of quality indicators. The device operates in the near-infrared spectrum (850–1050 nm) and uses chemometric models to calculate component concentrations based on spectral characteristics.

Fig. 3. Bruker TANGO infrared spectrometer

Determination of trypsin inhibitor activity and protein solubility in KOH solution was carried out by spectrometric method using a calibration model developed for soy products. The results were expressed in milligrams of trypsin inhibitors per gram of dry matter (mg/g) and as a percentage of total protein content, respectively. The relative error of determination was no more than 1%.

Five parallel samples were prepared for each treatment option, which ensures high statistical reliability of the results.

The mass fraction of moisture was determined by drying the sample of the product in the weighing cup in the drying oven at 130 °C for 40 min, and was calculated using the formula [15]:

$$W = \frac{q_1 - q_2}{q_1 - q_0} \times 100, \% \qquad (1)$$

where q_0 – weight of the empty weighing cup, g;

q_1 – weight of the weighing cup with a sample before drying, g;

q_2 – weight of the weighing cup with a sample after drying, g.

The flowability was determined by pouring the product through a hole of a certain size (4 cm in diameter) [13]. The product was poured into a box with an outlet closed with a latch. To determine the product's flowability, the latch was opened and the time of pouring of the product through the outlet onto a horizontal surface was noted. The volume of the product poured was measured with a cylinder. The flowability was determined from the formula:

$$W = \frac{q}{S \times t}, cm/s \qquad (2)$$

where q – volume of the product that passed through the hopper outlet, cm^3;

t – duration of pouring of the product, s;

S – cross-section area of the outlet, cm^2.

The angle of repose was determined by pouring the product out of the filler onto a horizontal surface. The product was poured through a metal funnel that had the cone angle 60°, until the top of the pile reached the height of the vertical walls of the device. The angle was measured with a protractor. To this end, the protractor was applied to the cone generatrix, and the angle β was determined with a plumb bob. Then the angle of repose α was calculated as: α = 90–β [15].

Results of the research and their discussion

For experimental studies, soybeans grown in Ukraine of the 2024 harvest were used. The raw materials were stored in paper bags at a temperature of 18–20°C and a relative humidity of 30–40%. The initial moisture content of the beans was 9%, which corresponds to the standard storage conditions for oilseeds according to DSTU 4964:2008 (Table 1). The crude protein content in the control samples was 35.8%, and crude fat was 21.5%.

Table 1 – Quality indicators of soybeans

Name of indicators	Experimental data	DSTU 4964-2008
Organoleptic		
Shape	Spherical	Spherical
Colour	Light yellow	Light yellow
Odour	Neutral	Neutral
Physical		
Humidity, not more than, %	9	12
Volumetric mass, not less than, kg/m^3	776	750
Natural slope angle, not less than, deg	30	25
Chemical		
Crude protein on dry matter, not less, %	35,8	35
Crude fat on dry matter, not less, %	21,5	12
Urease activity, pH units	1,91	-
Soluble protein, %	97,68	-
Digestible protein, %	25,4	-

The leading antinutritional factors of soybeans are substances that exhibit trypsin-inhibitory activity in both animals and humans. Protease inhibitors account for about 5-10% of the total protein content in soybean seeds (Fig. 4).

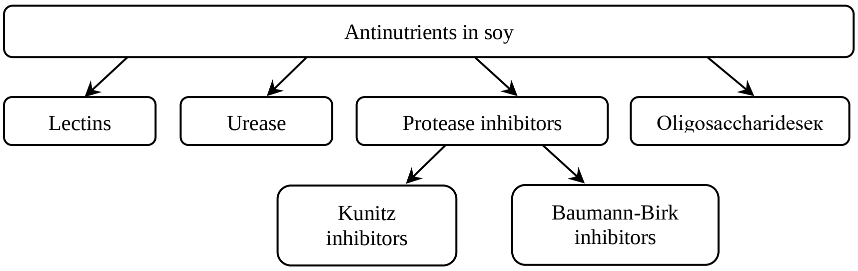


Fig. 4. Antinutrients in soy

A distinctive feature of soy antinutrients is their ability to form stable complexes with digestive enzymes of the gastrointestinal tract. This leads to a decrease in the absorption of dietary protein. Although some of the inhibitors (30-40%) are deactivated in the stomach, the most stable ones reach the duodenum in an active form and inhibit pancreatic enzymes. The body's compensatory reaction - increased enzyme production - can ultimately cause pancreatic hypertrophy [16].

Two types of inhibitors are present in soybeans – Kunitz inhibitor (Fig. 5) and Bowman-Birk inhibitor (Fig. 6), which are proteinaceous substances. Kunitz inhibitor is water-soluble, consists of 181 amino acid residues, has one disulfide bridge and a molecular weight of approximately 25,000 Da, and exhibits high inhibitory activity against trypsin [16].

In the Bowman-Birk inhibitor, the polypeptide chain consists of 71 amino acid residues and includes 7 disulfide bonds (Fig. 6). The study of the domain structure of this protein showed that it has a stable conformation even after the disulfide bonds are broken. Therefore, the Bowman-Birk inhibitor is more resistant to heat treatment, acids and bases. Molecular weight 6000-10000 Da. In untreated soybeans, about 14% of Kunitzat inhibitors and 0.6% of Bowman-Birk inhibitors [16].

The problem of inactivation of anti-nutritional factors in legumes has been studied for several decades, and a significant amount of scientific data has been accumulated on the effectiveness of various processing methods. Traditional approaches are based on thermal denaturation of protein inhibitors, however, the intensity and duration of processing significantly affect not only the inactivation of anti-nutritional factors, but also the preservation of the nutritional properties of the final product.

Currently, there are two main ways to reduce the content of antinutrients in soybeans:

1. Breeding - selection and cultivation of soybean varieties with a genetically low TIA (trypsin inhibitory activity) index.

2. Technological - processing of raw materials by various physical and chemical methods (Fig. 7) [17].

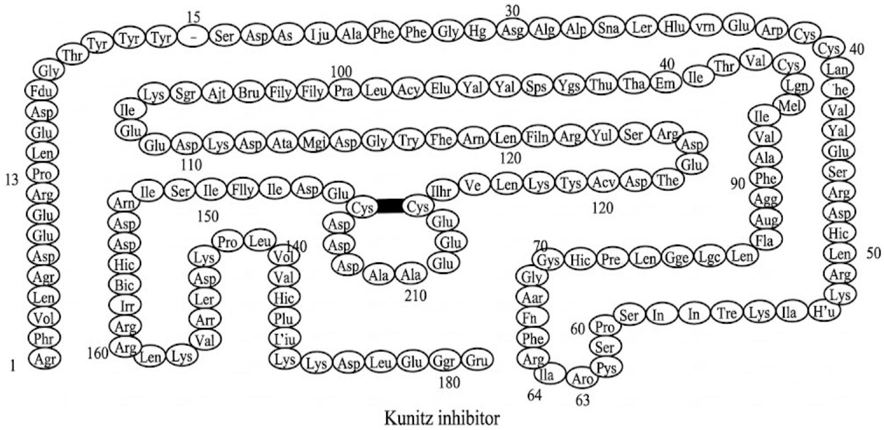
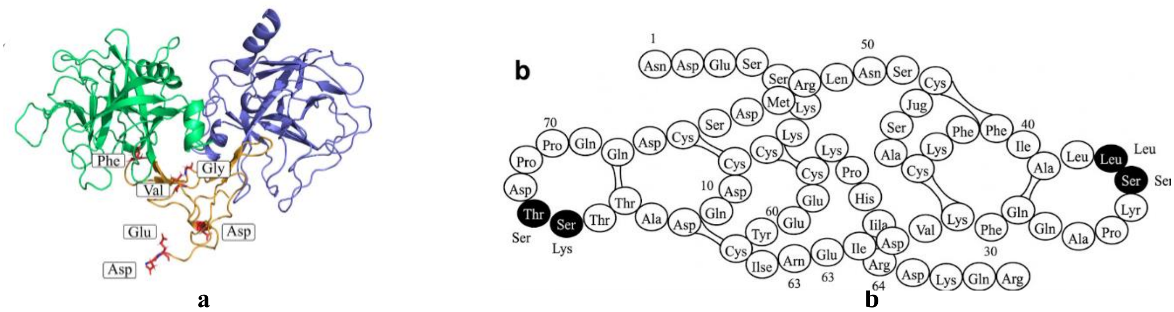


Fig. 5. Structure of Kunitz inhibitor



a b

Fig. 6. Spatial structure (a) and structure of the Bowman-Birk inhibitor (b)

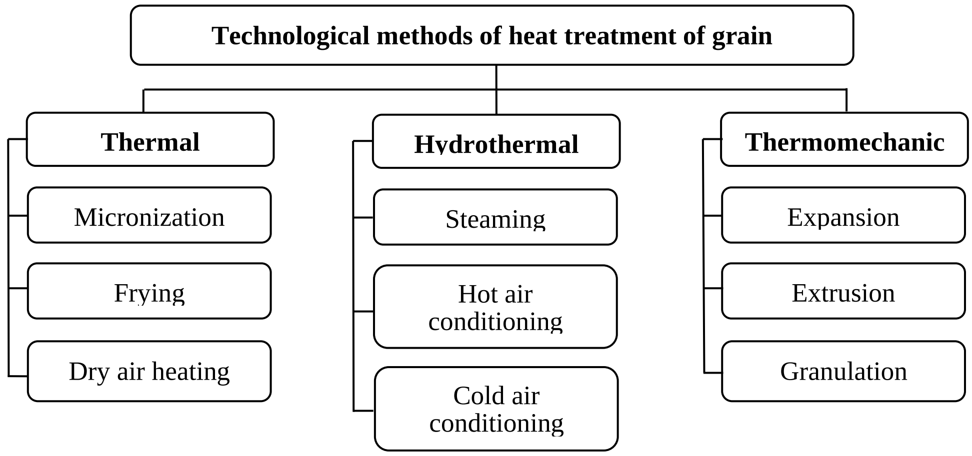


Fig. 7. Classification of technological methods of heat treatment of grain

One of the most common technological methods of processing soybeans into feed is dry extrusion. Extrusion has almost the same productivity as wet-heat processing, but is inferior in high specific electricity consumption (Table 2) [17, 18].

Table 2 – Comparative characteristics of methods of heat treatment of grain raw materials

Processing methods	Productivity, t/h	Specific electricity consumption, kWh/t
Extrusion	12-15	70-140
Moisture-heat treatment with steam	8-10	18-25
Micronization	2	-
Microwave treatment	0,5	-

The effect of different extrusion modes on the bioavailability of nutrients in soybean meal was analyzed. A comparative analysis of the average values of soybean and soybean meal quality indicators for 2024 is presented in Table 3.

Table 3 – Comparison of soybean and soybean meal quality indicators

Raw materials	Raw soybeans	Soybean meal
Moisture, %	7,83	6,14
Crude protein, %	35,39	44
Oil content, %	22,1	9
Protein solubility, %	92,64	84
Lysine content, %	2,25	2,72
Reactive lysine, %	1,98	2,39
Lysine availability, %	90,12	88,46
Trypsin inhibitor content, mg/g	31,05	7,2

Analysis of the data in Table 3 demonstrates significant changes in soybean quality parameters after the processing process. Extrusion followed by pressing leads to a significant decrease in trypsin inhibitor content - from 31.05 mg/g in raw soybeans to 7.2 mg/g in soybean meal, which is a decrease of 76.8%. This is critically important for increasing feed digestibility by animals, since trypsin inhibitors block the work of enzymes necessary for protein breakdown.

At the same time, there is an increase in the crude protein content from 35.39% to 44%, which is associated with the removal of part of the oil (decrease in oil content from 22.1% to 9%) and the concentration of the protein fraction. It is important to note that although the lysine content increased from 2.25% to 2.72%, its availability decreased slightly - from 90.12% to 88.46%. This confirms that excessive heat treatment can negatively affect the availability of amino acids, especially lysine, which is thermolabile.

Protein solubility, which is an important indicator of its bioavailability, decreased from 92.64% to 84%. This decrease is moderate and is within the optimal range for soybean meal, as too high solubility (>90%) may indicate insufficient inactivation of anti-nutritional factors, and too low (<75%) may indicate excessive protein denaturation and reduced digestibility.

The study showed that as the processing temperature increased, trypsin inhibitor (TIA) levels, protein solubility, and reactive lysine content decreased. The results of processing in the temperature range of 132 to 151 degrees are presented in Table 4.

Analysis of the data in Table 4 reveals a clear relationship between processing temperature and key quality parameters of soybean meal. As the temperature increases from 132°C to 151°C, there is a progressive decrease in trypsin inhibitor content from 9.1 mg/g to 3 mg/g. This confirms the effectiveness of high-temperature processing in inactivating anti-nutritional factors.

Table 4 – Effect of processing temperature on soybean meal quality indicators

Temperature, °C	Protein solubility in KOH, %	Trypsin inhibitor content, mg/g	Reactive lysine content, %	Lysine content, %	Lysine availability, %
132	91,2	9,1	1,949	2,141	89,074
134	88,7	8,4	2,578	2,817	90,418
137	87,9	8,3	2,534	2,798	91,764
139	86,4	8,1	2,395	2,653	90,572
140	86,7	8,1	2,306	2,638	90,961
142	84	7,9	2,388	2,793	87,143
146	75	5,1	2,01	2,469	83,156
148	74,8	4,5	2,077	2,486	83,225
151	67	3	1,966	2,506	80,41

However, in parallel with this, there is a significant decrease in the solubility of the protein in KOH - from 91.2% to 67%, which indicates a significant denaturation of the protein at high temperatures. A particularly sharp drop in solubility is observed at temperatures above 142°C, when the indicator reaches below 84%, which is a critical limit for optimal protein digestibility by pigs. Lysine availability indicators also show negative dynamics with increasing processing temperature.

Based on the data analysis, it is possible to determine the optimal temperature range for soybean processing - 137-142°C. In this range, a balance is achieved between sufficient inactivation of trypsin inhibitors (to the level of 7.9-8.5 mg/g) and preservation of high protein solubility (84-88%) and lysine availability (87-91%). At temperatures below 137°C, anti-nutritional factors are insufficiently inactivated, and at temperatures above 142°C, excessive protein denaturation and a decrease in the bioavailability of nutrients occur.

To further reduce the impact of anti-nutritional factors, it is recommended to carry out additional processing of the finished product by fermentation, enzymatic treatment or a combination thereof. The most effective is the combined method, which allows to break down both protein inhibitors and phytate compounds. Also promising is the use of microwave technology for pre-treatment of the input raw materials, which is characterized by speed, economy and ease of integration into the production process.

Microwave treatment was performed in a household microwave oven with a nominal power of 800 W. To ensure the same processing conditions for all samples, a 600 W mode (75% power) was used, which provides more controlled heating conditions and reduces the risk of local overheating.

Samples weighing 100 g were placed in plastic containers and distributed in a uniform layer with a thickness of 8–10 mm to ensure uniform heating. The containers were placed in the center of the rotating plate of the microwave oven. The treatment duration varied from 30 to 150 seconds in 30-second increments, which allows us to evaluate the kinetics of trypsin inhibitor inactivation and changes in protein solubility depending on the exposure time.

The untreated control sample was characterized by a trypsin inhibitor activity of 29.8±1.2 mg/g, which is a typical value for raw soybeans.

Table 5 – Effect of duration and type of retort on the activity of trypsin inhibitors

Processing duration, s	Processing type	
	Microwave processing	Microwave alkaline processing
30	25,6	23,9
60	15,5	12,6
90	10,8	9,1
120	10,2	7,2
150	7,1	4,7

During microwave treatment, a gradual decrease in the activity of trypsin inhibitors is observed with increasing heating duration (Table 5). Treatment for 30 s provides a decrease in activity to 25.6 mg/g (by 14.1% compared to the control), i.e. to the level reached at a temperature of 62°C - the beginning of denaturation of the most heat-sensitive protein fractions. An intensive decrease in activity occurs between the intervals of 30–60 s (from 25.6 to 15.5 mg/g), when the sample temperature is 83°C, denaturation of the Kunitz inhibitor occurs, which is less heat-resistant compared to the Bowman-Birk inhibitor [8].

With a further increase in the treatment time to 90–120 s, the rate of decrease in the activity of trypsin inhibitors decreases (from 15.5 to 10.2 mg/g), indicating a higher thermal stability of the Bowman-Birk inhibitor with seven disulfide bonds, as well as the fact that a longer thermal exposure is required for complete denaturation [19]. During treatment for 150 s (125°C), the activity decreases to only 7.1 mg/g, which corresponds to a 76.2% decrease compared to the control sample.

Optimal microwave-alkaline treatment of soybeans shows significantly higher efficiency of inactivation of trypsin inhibitors in all studied time intervals. Within 30 s of microwave-alkaline treatment, the activity decreases to 23.9 mg/g, which is 6.6% less, compared to pure microwave treatment for the same duration. The greatest effect is observed at treatment for 120–150 s, when the combined treatment reduces the activity to 7.2 and 4.7 mg/g, which is 29.4% and 33.8% more effective, respectively, than pure microwave treatment.

At a duration of 150 s, the combined treatment reduces the activity of trypsin inhibitors by 84.2% to 4.7 mg/g, which corresponds to the limit level accepted as safe for use in feed purposes (<5 mg/g) [20]. This confirms that the combination of alkaline and heat treatment has a synergistic effect. Increasing the pH to 8 leads to partial ionization of carboxyl and amino groups of protein molecules, which leads to electrostatic repulsion and unfolding of the tertiary structure of the protein. This makes disulfide bonds more accessible for destruction, which accelerates the rate of denaturation of trypsin inhibitors.

It is worth noting that even with the longest processing time (150 s), the protein solubility remains quite high – 87.4% for microwave processing and 88.2% for microwave-alkaline processing of soybeans. This indicates a relatively mild nature of the thermal effect, which allows for effective restoration of trypsin activity without excessive denaturation of protein structures, which is important for preserving the technological properties of soybean raw materials.

Analysis of the kinetics of inactivation of trypsin inhibitors shows that the most intense decrease in their activity occurs at 30–90 s of treatment when the temperature of the samples increases from 60°C to 100°C. This corresponds to the denaturation temperature of the main soybean proteins: β-conglycinin (75–80°C) and glycinin (85–95°C). In this temperature range, protein structures unfold and the processes of destruction of the active centers of trypsin inhibitors occur.

With a treatment duration of more than 120 s, the inactivation rate slows down, which may be due to several factors:

- firstly, by this point the most thermolabile fraction of inhibitors has already been inactivated, and the predominantly thermostable Bowman-Birk inhibitor remains;

- secondly, at temperatures above 110 °C, intensive moisture evaporation begins, which reduces the efficiency of heat transfer and can lead to local overheating instead of uniform heating.

From the point of view of practical application, the most optimal time for combined microwave-alkali treatment is the interval of 120–150 s. At this time, the activity of trypsin inhibitors is 4.7–7.2 mg/g, and the protein solubility is 87.8–88.2%. This indicator is close to the results obtained when processing soybean meal by traditional methods, such as autoclaving or extrusion, where the residual activity of trypsin inhibitors is usually 3–5 mg/g.

Modern soybean processing technologies use methods such as autoclaving (121°C, 15–20 min), extrusion (130–150°C, 30–60 s), and toaster oven roasting (110–120°C, 20–30 min). Autoclaving provides complete inactivation of trypsin inhibitors, but requires a long processing time and significant energy consumption. Extrusion is more energy efficient, but requires special equipment and can lead to excessive protein denaturation with a loss of solubility of up to 70–75%.

Conclusion

Soybean meal is an effective source of protein for the production of animal feed. Soybean meal has a high crude protein content, a balanced amino acid profile, and lysine availability, making it an economical alternative to other protein supplements. However, heat treatment control is important to achieve a balance between reducing anti-nutritional factors and maintaining the bioavailability of nutrients.

Extrusion effectively reduces the activity of trypsin inhibitors in raw materials at temperatures from 110 to 140 °C. However, this method has a significant drawback: at a temperature of 110 °C, a loss of essential amino acids occurs in the amount of 7%, and at a temperature of 140 °C the loss increases to 15.5%. Therefore, it is urgent to search for methods that would ensure effective inactivation with lower temperature and time parameters.

The proposed method of combined microwave-alkaline processing of soybeans has several advantages:

– the processing time is 120–150 s, which is significantly less than autoclaving (15–20 min) or frying (20–30 min);

– lower energy consumption – at a power of 600 W and a duration of 150 seconds, the energy consumption is approximately 0.025 kWh per 100 g of raw material, which is a competitive indicator.

– the preservation of high protein solubility of 88.2% makes the processed raw material suitable for many technological applications.

An additional advantage is the possibility of continuous processing in industrial conditions. Conveyor-type microwave plants allow for a continuous process with precise control of processing parameters, which is more difficult for batch autoclave plants. Alkaline pre-wetting can be integrated into the process line as a preparation stage before microwave heating, which does not require additional equipment and does not significantly complicate the process.

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КОМБІНОВАНИЙ МЕТОД ТЕРМІЧНОЇ ІНАКТИВАЦІЇ АНТИПОЖИВНИХ ФАКТОРІВ СОЇ

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Анотація. Соя є однією з найважливіших сільськогосподарських культур у світі завдяки своїй універсальності, вона містить рекордну кількість рослинного білка (до 40-50%), який за складом амінокислот майже ідентичний тваринному. Попри високий вміст поживних речовин, соя містить антипоживні фактори: інгібітори протеаз, лектини, уреази, олігосахариди. Провідне місце серед антипоживних факторів сої посідають речовини, що виявляють трипсин-інгібуючу активність як у тварин, так і в людини. Інгібітори протеаз становлять близько 5-10% від загального вмісту білка в насінні сої та належать до двох основних типів: інгібітор Кунітца та інгібітор Боумена-Бірка. Ці сполуки блокують активність протеолітичних ферментів травного каналу, знижуючи перетравність білків та біологічну доступність амінокислот. Тривале споживання сирої сої викликає гіпертрофію підшлункової залози, зниження приростів у тварин та погіршення засвоюваності поживних речовин. Тому інактивація антипоживних факторів є критично важливим етапом підготовки соєвої сировини до використання. Одним із найбільш поширених технологічних способів обробки сої є екструдування. Проаналізовано вплив різних режимів екструдування на біологічну доступність поживних речовин у соєвій макусі. На основі отриманих даних визначено оптимальний температурний діапазон для обробки сої – 137-142°С. У цьому діапазоні досягається баланс між достатньою інактивацією інгібіторів трипсину (до рівня 7,9-8,5 мг/г) та збереженням високої розчинності протеїну (84-88%) та доступності лізину (87-91%). При температурах нижче 137°С недостатньо інактивуються антипоживні фактори, а при температурах вище 142°С відбувається надмірна денатурація білка та зниження біологічної доступності поживних речовин. Запропоновано метод комбінованої СВЧ-лужної обробки сої, яка має кілька переваг: по-перше, тривалість обробки становить 120–150 с, що значно менше, ніж автоклавування (15–20 хв) або обсмажування (20–30 хв); по друге, менші енергетичні витрати – при потужності 600 Вт та тривалості 150 с енергоспоживання становить приблизно 0,025 кВт·год на 100 г сировини, що є конкурентоспроможним показником; по третє, збереження високої розчинності білка 88,2% робить оброблену сировину придатною для багатьох технологічних застосувань.

Ключові слова: антипоживні речовини сої, інгібітори трипсину, розчинність білка, екструдування, СВЧ-обробка, лужна обробка, синергічний ефект.

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