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INNOVATIONS IN THE PRODUCTION OF PASTA AND CEREAL PRODUCTS

S u m m a r y

Background. The growing demand for functional foods, together with the need to improve technological efficiency and competitiveness of cereal products, requires the development of innovative processing approaches. This study focused on improving pasta and cereal products through the use of functional ingredients (spirulina, isolated sunflower protein and inulin) combined with optimized extrusion, drying and cereal stabilization technologies based on Ukrainian raw materials. The research evaluated physicochemical, rheological, technological, microbiological and sensory properties to determine optimal processing conditions and product quality relationships.

Results and conclusions. The incorporation of 2 % spirulina significantly altered color characteristics ($\Delta E > 10$) and increased dough water absorption by 5.2 %, while the addition of 5 % sunflower protein increased dough viscosity by 18.3 % due to additional protein network formation. Inulin (3 %) enhanced water absorption by 7.5 % and contributed to smoother texture. A synergistic effect was identified for the spirulina-sunflower protein combination, increasing the elastic modulus (G′) by 25 % compared with the control. Extrusion temperature showed a strong negative correlation with product strength: increasing temperature from 45 °C to 60 °C reduced bending resistance from 32.5 to 27.8 N. Optimal extrusion parameters were established at 50 ± 2 °C, 90 ± 5 bar and 20 rpm. Three-phase drying (70 → 55 → 40 °C) ensured uniform moisture content (12.5 %) and preserved thermolabile components ($\Delta E < 1.5$). Infrared steaming of cereals reduced water activity to 0.62 ÷ 0.65, significantly improving storage stability. Consumer evaluation confirmed high acceptability, with 78 % willingness of respondents to purchase, and showed a strong correlation between the consistency and overall attractiveness of the product ($r = 0.87$).

Key words: Food industry, organoleptic evaluation, spirulina, inulin, extrusion parameters

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Introduction

The current stage of food industry development is characterized by the search for innovative solutions aimed at increasing the nutritional value of products, while maintaining their technological qualities [46]. Particular attention is paid to pasta and cereal products as key components of a diet; however, their production faces a number of systemic problems: technological gaps (degradation of biologically active substances during heat treatment, limited bioavailability of micronutrients in traditional formulations); environmental challenges (high energy consumption at the extrusion and drying stages, irrational use of local raw materials); and market restrictions (low competitiveness of Ukrainian products in European markets due to an insufficient level of innovation). Recent studies have indicated a growing interest in the introduction of functional ingredients into traditional grain products.

Hetman et al. [28] conducted an experimental study on the integration of functional ingredients into flour confectionery products using non-traditional types of raw materials: vegetable protein concentrates (lentil, pumpkin), prebiotic fibers (chicory, Jerusalem artichoke) for partial replacement of sugar and superfood powders (spirulina, chlorella). The authors developed technological stabilization parameters by optimizing temperature–time baking regimes, introducing the encapsulation of thermolabile components using the aerogel technology method and proving the effectiveness of hydrocolloid stabilizers in preventing delamination. The study by Porsiurova and Chuiko [47] revealed structural imbalances in the European pasta market, where Ukrainian products are inferior to EU analogues in price by 15 ÷ 30 %, which is directly related to the technological backwardness of production and the limited use of functional innovations. In parallel, the work of Makarova et al. [37] demonstrated the possibility of partial replacement (20 ÷ 40 %) of traditional wheat flour with alternative plant raw materials, in particular amaranth and sorghum, which opens up opportunities to increase the nutritional value of products. However, the authors noted significant difficulties in maintaining the optimal texture and consistency of finished products, especially after heat treatment.

An important theoretical basis for further research was established by Pivovarov et al. [45], who developed a comprehensive concept of innovative engineering for the food industry, emphasizing the critical need to adapt international technological solutions to the specifics of the Ukrainian raw material base, taking into account climatic conditions and the agrotechnical characteristics of local grain varieties. The practical aspect of the economic feasibility of such innovations is highlighted in the work of Sheludko [51], where, using the example of restaurant enterprises, it is demonstrated that expanding the range of in-house flour products with local ingredients increases the profitability of operational activities by 18 ÷ 25 %, which is especially relevant under the conditions of high market competition. The fundamental prerequisites for technological innovations are presented in the study of Kyrychenko et al. [35], who conducted an in-depth analysis of modern grain breeding strategies, substantiating the prospects of specialized varieties with a high protein content, such as "Dukat" wheat, as well as varieties adapted to the climatic changes in Ukraine, which creates a scientific basis for the development of new lines of functional products.

A review of traditional and innovative technologies for the production of grain products is presented in the work of Gómez and Pereira [25]. The study covers a wide range of issues, from classical methods of grain processing to the latest technological solutions. The authors particularly emphasize the importance of preserving the nutritional value of raw materials at all stages of processing. A comprehensive analysis of functional bakery products, breakfast cereals and pasta is presented in the work of Di Cairano et al. [14]. The study provides a detailed review of trends in the development of functional grain products. The authors highlight the importance of considering consumer preferences when creating new types of products. Of particular interest is the editorial article by De Arcangelis and Romano [13], dedicated to innovations in the production of pasta products. The authors focus on three key aspects: stability, nutritional value and product quality, and emphasize the need for an integrated approach to the modernization of production processes. The Italian experience in the production of dry pasta is described in detail in the work of Conte et al. [10]. The study covers both traditional and innovative ingredients and production technologies. The authors provide valuable examples of combining classic recipes with modern technological solutions.

While prior research has focused on the separate applications of dietary fibers, plant proteins or spirulina in cereal-based goods, less focus has been placed on their combined sensory and technical benefits in a single formulation. Specifically, the combined effects of spirulina, sunflower protein and inulin on the creation of dough structure, cooking quality and consumer perception are still not well understood. By offering a thorough assessment of physicochemical, rheological, microbiological and sensory parameters, the current study fills this knowledge gap and advances the comprehension of how multi-component functional enrichment affects pasta product quality indicators that are focused on the market, as well as technological performance.

The purpose of this study was to develop scientifically based technological parameters for the production of pasta and cereal products using innovative combinations of functional ingredients. The study aimed to address the following key tasks: to determine the optimal extrusion parameters for products with functional additives; to develop effective drying modes, ensuring the preservation of product quality; and to assess the impact of the proposed technologies on the structural and mechanical properties of finished products.

Materials and methods

Research design and materials

The research into pasta and cereal production technologies was conducted at the National University of Food Technologies (Kyiv) from October 2024 to March 2025, focusing on three key innovations: the combination of functional ingredients (spirulina, sunflower protein, inulin) with Ukrainian raw material varieties (“Dukat”, “Diana”, “Helios”); the optimization of extrusion parameters to preserve nutrients; and the implementation of combined cereal processing (infrared steaming with instant cooling). The experimental part of the work included the development and testing of new formulations, the assessment of the impact of innovative technological parameters on the quality of raw materials and finished products, and consumer testing of the samples.

The main raw material for pasta production was high-quality flour from durum wheat (*Triticum durum*) of the “Dukat” variety, produced under the trademark (TM) “Yaroslav”, in accordance with GSTU 46.004-99 [27]. It was characterized by a high gluten content (not less than 28 %) and increased pigmentation. For cereal products, buckwheat groats (*Fagopyrum esculentum*) of the “Diana” variety and polished pearl barley groats (*Hordeum vulgare*) of the “Helios” variety were used. Buckwheat and barley grains were cleaned using a combined separation method, which included preliminary calibration, removal of impurities using an air-sieve separator SAD-5 (Limited Liability Company (LLC) “Khorolsky Mechanical Plant”, Ukraine), and final grinding on an abrasive grinding machine SMH-4 (PETKUS Technologie GmbH, Germany).

Cereal processing methodology

For cereal products, an innovative technology of thermal stabilization was employed to increase storage stability. The process included the following sequential operations: first, the grain was subjected to infrared steaming on a Satake IRS-150 installation (Satake Corporation, Japan) with a radiation intensity of $0.8 \div 1.2$ kW/m², an exposure duration of $90 \div 120$ seconds and a wavelength of $2.5 \div 3.5$ µm, which ensured deep inactivation of enzymes (lipases, peroxidases) and microflora with minimal impact on the structural integrity of the grain. The selected wavelength range was optimally absorbed by moisture in the grain, ensuring efficient energy transfer, while the intensity and duration of the treatment were chosen to achieve uniform heating without surface overheating. Immediately after steaming, the grain was transferred to the CoolBelt CB-100 belt cooler (Satake Corporation, Japan), where it was rapidly cooled to a temperature of 25 ± 2 °C, which made it possible to halt the thermal effect, fix the achieved state and prevent damage to the grain structure due to residual heating. To objectively assess the effectiveness of stabilization and predict a shelf life, water activity (AW) was determined in the finished samples using a specialized water activity analyzer LabMaster-aw (Novasina AG, Switzerland). The determination method corresponded to standard procedures for food products according to DSTU ISO 21807:2007 [19]. This indicator is key to assessing the risk of microorganism development and hydrolytic enzymatic processes during storage. In this study, a shelf life was not monitored through long-term storage trials. Stability was predicted based on experimentally determined AW values and established microbiological thresholds. Thus, the conclusions regarding storage stability are based on theoretical prediction supported by AW measurements rather than time-based shelf-life testing.

For the study of cereal products, four sample variants were prepared (two for buckwheat “Diana” and barley “Helios” – control and experimental), each weighing 2 kg after processing. Each variant was produced in three independent replicates, ensuring the statistical reliability of the results. Samples obtained after infrared steaming and rapid cooling were used to determine AW and for further analysis of storage stability.

For cereal products, a step-by-step technology for heat treatment and stabilization of buckwheat grains of the “Diana” variety and barley of the “Helios” variety was used. In the first stage, the grain was subjected to infrared steaming on an IRS-150 installation (Satake Corporation, Japan) with a radiation intensity of $0.8 \div 1.2$ kW/m², a wavelength of $2.5 \div 3.5$ μm, and an exposure of 90 ± 5 s for buckwheat and 120 ± 5 s for barley, which ensured deep inactivation of enzymes (lipases, peroxidases) and microflora. Preliminary optimization experiments that took into account structural and compositional variations between barley and buckwheat grains were used to choose various exposure times. Buckwheat achieved the desired technical result with a shorter exposure (90 ± 5 s), while barley needed a somewhat longer treatment (120 ± 5 s) to achieve effective enzyme inactivation and microbiological stabilization because of its denser husk structure and greater β-glucan content. The grain temperature at the outlet of the steaming chamber was 95 ± 3 °C. The second stage involved instant cooling of the treated grain on a CoolBelt CB-100 belt cooler (Satake Corporation, Japan) to a temperature of 25 ± 2 °C for 90 ± 10 s, which prevented residual heating and structural damage to the grain. The third stage included the selection of samples weighing 2 kg in three replicates for each type of cereal (control and experimental) and the determination of AW using the LabMaster-aw analyzer (Novasina AG, Switzerland) in accordance with DSTU ISO 21807:2007 [19].

Pasta preparing and processing methodology

The water used for dough preparation met the requirements of DSTU 7525:2014 [16] for drinking water, with total mineralization not exceeding 250 mg/dm^3 and a hardness of up to 3.0 mg-eq/dm^3. For pasta products, five recipe options (control + four combinations of additives) were studied, each comprising 3 kg of sample (after extrusion). Each option was prepared in triplicate. In a series of experiments with additives, the following functional ingredients were used: spirulina leaf powder (Spirulina platensis) produced by "AlgaeHealth Solutions" (China); isolated sunflower protein ("SunPro Isolate", Sunflower Ingredients Group, the Netherlands); and prebiotic inulin ("Frutafit TEX", Sensus, the Netherlands). The selection of these functional ingredients was based on their ability to purposefully enhance the nutritional value and technological properties of the finished product. Spirulina platensis leaf powder is a concentrated source of high-value proteins (approximately 60 ÷ 65 %), phycocyanin and micronutrients, which allows both an increase in biological value and the attainment of an attractive natural green hue in products. Isolated sunflower protein is characterized by a balanced amino acid profile and a high ability to form disulphide bonds with gluten, thereby improving the structure and elasticity of the dough. The prebiotic inulin, as a high-molecular-weight fructan, exhibits hydrocolloid and texture-forming properties, contributes to a smooth consistency, reduces the glycaemic index of products and acts as dietary fiber, positively affecting the intestinal microbiome. The following application levels were used in the study: spirulina – 2 % of the flour mass; isolated sunflower protein – 5 %; inulin – 3 %. These concentrations were selected based on the results of previous trials and literature data to achieve a noticeable functional effect without impairing the rheological properties of the dough or the consumer characteristics of the finished products. In particular, a spirulina content exceeding 2 % results in excessive intensity of the green hue and a specific aftertaste; the addition of sunflower protein above 5 % significantly increases viscosity and complicates extrusion; and inulin levels above 3 % lead to the excessive softening of the dough matrix and deterioration of the strength of dry products.

The technological process of pasta production included the following operations. Dough preparation was carried out in a twin-screw dough mixer Diosna W 240 A (Diosna Dierks & Söhne GmbH, Germany), where a mixture of flour, water, functional ingredients (according to the recipe) and a small amount of citric acid solution (to stabilize the spirulina pigment) was kneaded until a homogeneous consistency was obtained at a temperature of 40 ± 2 °C for 10 minutes. For each experimental variant, 3 kg of dough was prepared in three independent replicates. The recipes (calculated per 1 kg of durum wheat flour of the "Dukat" variety) were as follows: control (without additives): flour 1,000 g; drinking water 300 ± 5 cm^3; citric acid solution 0.1 % – 10 cm^3. Spirulina 2 %: flour 980 g; Spirulina platensis leaf powder 20 g; drinking water 305 ± 5 cm^3; citric acid solution 0.1 % – 10 cm^3. Sunflower protein 5 %: flour 950 g; isolated sunflower protein 50 g; drinking water 310 ± 5 cm^3; citric acid solution 0.1 % – 10 cm^3. Inulin 3 %: flour 970 g; inulin 30 g; drinking water 315 ± 5 cm^3; citric acid solution 0.1 % – 10 cm^3. Combination (spirulina 2 % + sunflower protein 5 %): flour

930 g; Spirulina platensis leaf powder 20 g; isolated sunflower protein 50 g; drinking water 320 ± 5 cm^3; citric acid solution 0.1 % – 10 cm^3. The amount of water was adjusted within ±5 cm^3 depending on the water absorption capacity of the raw material to ensure the target dough consistency suitable for extrusion.

The dough was then fed into a PastaPress PPX-45 single-screw extruder (Bühler AG, Switzerland) equipped with a bronze die for spaghetti production with a diameter of 1.8 mm. Extrusion was performed using six combinations of parameters formed by varying three temperature levels in the pressing zone (45 °C, 50 °C, 60 °C) and two pressure levels (90 and 100 bar) at screw speeds of 15, 20 or 25 rpm. In total, a full factorial design was implemented, allowing the evaluation of the influence of each parameter and their interactions on the structure formation of the dough and the physical and mechanical properties of the finished products. The optimal mode was determined based on an integral assessment, which included bending strength, color stability (ΔE), the absence of shape defects after drying and the preservation of functional components (minimum losses of phycocyanin and protein). The best results were recorded for the combination of temperature 50 ± 2 °C, pressure 90 ± 5 bar and a screw speed of 20 rpm, which provided a balance between technological process stability and high product quality. The extruded product was cut, after which the samples were dried in a modern convective dryer Multidry™ MD-300 (SACMI Imola S.C., Italy), using an innovative three-phase drying mode with a smooth change in temperature (70 °C → 55 °C → 40 °C) and relative humidity for a total duration of six hours.

Quality and safety assessment

The quality analysis of raw materials and finished products included the determination of moisture content (thermogravimetric method using a Memmert UN110 drying oven, Germany), ash content (Nabertherm L5/11 muffle furnace, Germany), and protein content (Kjeldahl method using a Kjeltec 8400 nitrogen analyzer, Foss Analytical, Denmark). Color characteristics were measured with a ColorFlex EZ colorimeter (HunterLab, USA), which automatically records color parameters in the CIE L*a*b* (CIE L*a*b*) color space. The CIE L*a*b* system is an international standard for instrumental color evaluation and expresses color in three coordinates. Strength and deformation parameters during bending were assessed using a TA.XTplusC texturometer (Stable Micro Systems, Great Britain) equipped with a three-point bending module. Cooking properties (cooking time, mass gain and dry matter loss in broth) were determined according to the requirements of DSTU ISO 7304:2005 [20], which serves as an interstate standard. The viscosity properties of dough semi-finished products during extrusion were measured using a capillary rheometer RH7 (Bohlin Instruments, Great Britain). The determination of gluten elasticity (gas resistance index of deformed dough, GD) was carried out on a Chopin NG alveograph (Française des Instruments de

Contrôle et d'Analyse, France) in accordance with the standard method of the American Association of Cereal Chemists (AACC) 54-30 [1]. The test consisted of measuring the resistance of gluten to swelling under air pressure, which enabled the assessment of its elastic properties and ability to form a stable dough matrix. Gluten water absorption was determined using the standard method AACC 56-11.02 (ICC 137/1) [8] with a Glutomatic 2200 device (Perten Instruments, Sweden).

Microbiological indicators were examined in accordance with the requirements of DSTU EN ISO 4833-1:2014 [18] (the determination of total microbial count) and DSTU EN ISO 21528-2:2022 [17] (the determination of enterobacteria count). The choice of these indicators was due to their relevance for assessing the sanitary and hygienic safety of dry food products. The total microbial count (DSTU EN ISO 4833-1:2014) reflects the level of microbiological purity and possible secondary contamination, while the number of enterobacteria (DSTU EN ISO 21528-2:2022) serves as a sanitary indicator of potential foodborne pathogen presence.

Consumer sensory analysis

Organoleptic consumer evaluation of pasta samples was conducted with the participation of 100 non-expert consumers (50 men and 50 women) aged 20 to 65 years (mean age of 42 ± 5 years), all of whom permanently resided in Kyiv or the Kyiv region. The inclusion criteria included regular consumption of pasta (at least once per week during the past six months), absence of allergies to sample components and no chronic diseases affecting sensory perception. The exclusion criterion was a professional activity related to the food industry or a sensory analysis. The sample was formed through random sampling with subsequent stratification by gender and age groups (20 ÷ 35, 36 ÷ 50 and 51 ÷ 65 years). The purpose of this stratification was to evaluate possible variations in sensory perception and purchase intention among various demographic groups. By enabling the confirmation of whether the noted preferences were universal or reliant on certain customer segments, it improved the dependability of the conclusions. The tasting was conducted in the sensory laboratory of the Institute of Food Technologies (Kyiv), adapted to the requirements of DSTU ISO 8589:2013 [21], under controlled microclimate and lighting conditions. The organoleptic characteristics of the finished samples were evaluated on a five-point scale using a sensory analysis. Each parameter – appearance, color, consistency, smell and taste – was assessed separately. A score of 5 points was assigned to samples with optimal, typical properties without defects. A score of 4 points corresponded to minor deviations not affecting overall quality, while 3 points or below reflected significant shortcomings that reduced consumer appeal. To assess overall product attractiveness, a five-point scale of purchase intent was applied: 5 points denoted full willingness to purchase without reservation, and 1 point indicated categorical unwillingness to purchase due to significant shortcomings. Intermediate scores (2 ÷ 4 points) reflected varying degrees of hesitation or conditional willingness to purchase depending on sensory perception. All participants were informed about the purpose and conditions of the study and provided written informed consent. The evaluation process complied with the ethical principles of the WMA Declaration of Helsinki [58].

Statistical analysis

Statistical processing of the obtained experimental data was performed using the Statistica 14.0 software package (TIBCO Software Inc., USA). To identify statistically significant differences between the mean values of quality indicators for samples obtained under different technological parameters, a one-way analysis of variance (ANOVA) was applied, followed by comparison using the Tukey (HSD) criterion at a significance level of $p < 0.05$. Pearson correlation analysis was used to identify relationships between process parameters and the quality indicators of the finished products. Consumer evaluation results were analyzed using the non-parametric Mann-Whitney U-test to compare scores between sample groups. Data are presented as mean ± standard deviation (M±SD).

Results

Detailed analysis of the physicochemical characteristics of raw materials and semi-finished products

Durum wheat flour of the "Dukat" variety underwent a comprehensive assessment for compliance with the requirements of GSTU 46.004-99 [27]. In addition to the high content of raw gluten (28.7 ± 0.4 %), which exceeds the minimum standard (28 %), the analysis revealed optimal rheological properties: gluten water absorption was 62.5 ± 1.2 %, and its elasticity (GD index, determined on the Chopin NG alveograph) was 82 ± 3 %. This indicates the ability to form a strong, elastic dough matrix, which is critically important for the quality of pasta products. A colorimetric analysis confirmed the intense yellow pigmentation characteristic of durum wheat: the b* coordinate in the CIE L*a*b* system reached 33.5 ± 0.5, which is significantly higher than that of common wheat flour (b* ≈ 20 ÷ 25). The brightness value L* was 84.2 ± 0.3, and the red hue a* = -1.0 ± 0.1, corresponding to the classic color profile of high-quality pasta products. Table 1 summarizes the relative impacts of each functional ingredient (inulin, sunflower protein and spirulina) and their combination on the dough's rheological and physicochemical characteristics in comparison to the additive-free control sample. A systematic evaluation of the individual and combined effects of the tested formulations is made possible by the presentation of important indicators in the table.

Table 1. The influence of functional ingredients on the properties of dough and semi-finished products

Parameter		Control (without additives)	Spirulina 2 %	Sunflower protein 5 %	Inulin 3 %	Combination (spirulina 2 % + protein 5 %)
Gluten content [%]		28.7 ± 0.4	28.5 ± 0.5	30.2 ± 0.6	28.3 ± 0.4	30.0 ± 0.5
Color (L*a*b*)	L*	84.2 ± 0.3	78.5 ± 0.6	83.5 ± 0.4	83.8 ± 0.3	78.0 ± 0.5
	a*	-1.2 ± 0.1	-4.8 ± 0.3	-1.0 ± 0.1	-1.1 ± 0.1	-4.5 ± 0.2
	b*	33.5 ± 0.5	28.1 ± 0.7	32.8 ± 0.4	33.2 ± 0.5	27.8 ± 0.6
Water absorption [%]		Basic	+5.2 ± 0.6	+3.8 ± 0.4	+7.5 ± 0.8	+6.0 ± 0.7
Viscosity at 50 s^{-1} [Pa·s]		1057 ± 38	1120 ± 42	1250 ± 45	980 ± 35	1320 ± 50
Modulus of elasticity G' [kPa]		15.2 ± 0.8	16.0 ± 0.9	18.5 ± 1.0	13.0 ± 0.7	19.0 ± 1.1

Explanatory notes: L* – lightness; a* – red-green axis; b* – yellow-blue axis; Sources: compiled by the authors

The introduction of spirulina powder at 2 % of the flour mass led to a radical change in the colorimetric characteristics of the dough. The intensive phycocyanin complex of spirulina caused a sharp increase in the negative values of the a* coordinate (green tint) to -4.8 ± 0.3 (versus -1.2 ± 0.1 in the control) and a significant decrease in the b* value (yellow tint) to 28.1 ± 0.7 (versus 33.5 ± 0.5 in the control). The brightness L* also decreased to 78.5 ± 0.6. This effect ($\Delta E > 10$ relative to the control) was visually perceived as a pronounced green color. Additionally, spirulina exhibited hydrocolloid properties: the water absorption of the dough mixture increased by 5.2 ± 0.6 % compared with the control due to the high hygroscopicity of the proteins and polysaccharides of the microalgae.

The addition of isolated sunflower protein at 5 % of the flour mass significantly affected the rheological properties of the dough. Capillary rheometry revealed a clear dependence of viscosity on shear rate and protein concentration. At a shear rate of 50 s^{-1}, representative of extrusion conditions, the effective viscosity of the sample with sunflower protein was 1250 ± 45 Pa·s, which is 18.3 ± 2.1 % higher than that of the control sample (1057 ± 38 Pa·s). This is explained by the ability of sunflower proteins to form disulphide bonds with the gluten matrix, as well as by their high water-holding capacity. The flow curve exhibited pseudoplastic behavior, but with a more pronounced thixotropic effect in the protein-enriched sample, indicating the formation of a stronger internal network structure capable of partial recovery after mechanical loading. This has a direct effect on the formation of a denser pasta structure during extrusion.

The introduction of the prebiotic inulin at a concentration of 3 % revealed pronounced hydrophilicity. The water absorption capacity of the flour mixture containing inulin increased by 7.5 ± 0.8 % compared with the control. This effect is due to the ability of inulin, as a high-molecular fructose polymer, to bind a significant amount of water through the formation of a hydrogel phase. A dynamic rheological analysis revealed a decrease in the elastic modulus (G′) and the viscosity modulus (G″) of the dough with inulin by 12 ÷ 15 % compared with the control across the entire range of deformations, indicating a slightly lower stiffness of the dough matrix. However, this change did not have a negative effect on the stability of the dough during extrusion. It was also noted that inulin acted as a texturizer, contributing to the formation of a smoother consistency in the finished products after cooking. Studies of mixtures of functional ingredients (e.g. spirulina + sunflower protein) revealed nonlinear interactions. Thus, the combination of 2 % spirulina and 5 % sunflower protein led to a significant increase in viscoelastic properties (an increase in G′ by 25 % compared with the control), which exceeded the sum of the effects of the individual components. This is explained by the potential formation of complexes between spirulina and sunflower proteins and gluten. This interaction strengthens the overall protein-gluten network in the dough through additional intermolecular bonds. This results in a denser and more cohesive structure, leading to improved firmness and elasticity of the pasta after cooking, while maintaining a desirable “al dente” texture without excessive hardness. At the same time, inulin in combination with proteins demonstrated the ability to reduce excessive viscosity growth, contributing to better dough workability. These complex interactions emphasize the importance of careful selection of concentrations and combinations of functional ingredients to achieve the desired technological properties of semi-finished products and the quality of the final product.

Analysis of the influence of extrusion and drying parameters on the quality of pasta products

An experimental study on an extruder clearly demonstrated the critical dependence of the key strength indicator – the bending resistance of dry products – on the temperature in the pressing zone. Increasing the temperature from 45 °C to 60 °C at a fixed pressure of 100 bar and a screw speed of 20 rpm led to a statistically significant ($p < 0.05$) decrease in strength from 32.5 ± 1.2 N to 27.8 ± 1.0 N (Table 2). This phenomenon is explained by the increased thermal denaturation of proteins (gluten and added sunflower protein) and the partial gelatinization of starch at elevated temperatures. Denaturation disrupts the formation of the optimal gluten network, which forms the basis of the pasta structure, making it more fragile [29]. In parallel, elevated temperature can contribute to the degradation of thermolabile components, in particular spirulina pigments, although this effect within the studied range did not yet become critical for color, provided that subsequent drying was optimal.

Table 2. Comparative analysis of the impact of temperature regimes

Parameter	Temperature		
	45 °C	50 °C	60 °C
Bending strength [N]	32.5 ± 1.2	31.8 ± 1.1	27.8 ± 1.0
Color stability, ΔE	0.8 ± 0.2	1.2 ± 0.3	2.5 ± 0.4
Drying time [hours]	6.5	6.0	5.5

Explanatory notes: compiled by the authors.

It was found that the use of functional ingredients (spirulina, sunflower protein) requires the adjustment of standard extrusion modes. For the studied formulations, the optimal mode was determined to be a temperature of 50 ± 2 °C and a pressure of 90 ± 5 bar at a screw speed of 20 rpm. This combination ensured sufficient plasticization of the dough mass for the effective molding of products using a spaghetti die (Ø 1.8 mm) without excessive thermal load. Pressure within the range of 90 ± 5 bar contributed to the compaction of the product structure during molding, which positively affected its strength, while avoiding excessively high pressure (over 100 bar) prevented mechanical damage to the structure and excessive heating due to friction. The screw speed of 20 rpm ensured a stable flow of the mass into the die without the risk of delamination or overloading the equipment. This optimized regime made it possible to achieve a balance between favorable technological characteristics of the process (extrusion stability, the absence of shape defects) and the preservation of the functional properties of the ingredients added and the strength of the finished dry product.

The use of a specially developed three-phase drying regime (70 °C → 55 °C → 40 °C) proved to be a decisive factor for the final quality of the product, especially in the presence of temperature-sensitive spirulina. This gradient approach ensured uniform moisture removal across the entire cross-section of the product to a final moisture content of 12.5 ± 0.3 %, thereby preventing the occurrence of internal stresses and, consequently, warping or cracking of the products. The initial phase at 70 °C allowed for the rapid removal of surface moisture, while preventing the formation of a closed crust that would hinder further moisture evaporation from the deeper layers. The sequential temperature reduction to 55 °C and then to 40 °C ensured a gentler and more controlled removal of bound moisture from the core of the product. An important outcome of this carefully controlled thermal regime was the minimal degradation of thermolabile components, particularly phycocyanin in spirulina. This was objectively confirmed by the stability of the color characteristics of the finished product: the color change (ΔE) compared with the state of the product immediately after extrusion was less than 1.5 units according to the CIE L*a*b* system. Such a small color change indicates the effective protection of the pigment from the destructive effects of high temperature during the prolonged drying process. The total drying time was 6 hours, which is acceptable for an industrial process, while ensuring high product quality.

Detailed analysis of the quality of finished pasta and cereal products

The cooking properties of pasta containing functional ingredients, studied according to DSTU ISO 7304:2005 [20], demonstrated high technological efficiency of the developed formulations. The cooking duration of 7.5 ± 0.5 minutes indicates the optimal density of the structure, ensuring the rapid and uniform heating of the product without the risk of overcooking. The mass gain indicator (2.3 ± 0.1 g/g) reflects the ability of the pasta to effectively absorb water during heat treatment, which is directly related to preserving the integrity of the protein–carbohydrate complex and forming the desired texture in the finished product. Low losses of dry matter in the broth (5.8 ± 0.3 %) confirm the strength of the internal structure and the effective formation of cross-links in the gluten matrix, which prevents the leaching of nutrients. This set of parameters illustrates the ability of functional ingredients (spirulina, sunflower protein, inulin) to positively influence structure formation without impairing technological characteristics.

The microbiological safety of the products, determined according to DSTU EN ISO 4833-1:2014 [18] (total microbial count) and DSTU EN ISO 21528-2:2022 [17] (enterobacteria), confirms the effectiveness of the thermal treatment regimes. The indicator KMAFAnM$<1\times10^3$ CFU/g is significantly lower than the regulatory threshold established for dry cereal and pasta products ($\leq 5\times10^4$ CFU/g), indicating a high level of microbiological safety. This significant margin confirms the proper sanitary and hygienic condition of the raw materials, the effectiveness of the applied thermal treatments and the absence of secondary contamination during production. The complete absence of *E. coli* bacteria in all tested samples emphasizes the effectiveness of the thermal drying stage, which is critically important for functional products.

For cereal products, the key result was a significant improvement in storage stability due to the use of a combined processing technology on the Satake IRS-150 infrared steaming unit with subsequent instant cooling on the CoolBelt CB-100 belt cooler. This process ensured deep inactivation of enzymes (lipases, peroxidases) and microflora without destroying the grain structure. Measurement of AW on a water activity analyzer (a method prescribed by food standards) revealed critically low values: 0.62 ± 0.02 for buckwheat “Diana” and 0.65 ± 0.02 for barley “Helios”. These indicators are crucial for predicting product stability, as they are well below the critical threshold AW > 0.7, required for the development of most bacteria, yeast and mold. This level of AW also effectively inhibits hydrolytic enzymatic processes (in particular, rancidity of fats in buckwheat), which is the main cause of cereal spoilage during storage. This processing technology makes it possible to significantly increase the shelf life of products without the use of preservatives.

Detailed results of organoleptic evaluation and statistical analysis

The samples with the addition of 2 % spirulina powder proved to be particularly attractive in terms of external characteristics, receiving an average score of 4.3 ± 0.4 points. The difference in color perception between different age groups was insignificant ($p > 0.05$), indicating the universal attractiveness of the green shade. In their open comments, the study participants associated this color with such aspects as the naturalness and environmental friendliness of the product, the high content of nutrients and the original design, which favorably distinguishes this product from traditional analogues on the market. The taste qualities of the samples with spirulina received an average score of 4.1 ± 0.5 points. An analysis of individual ratings showed that 72 % of tasters noted a harmonious combination of flavors, 18 % mentioned barely noticeable “marine” notes, and only 10 % of participants perceived a pronounced specific aftertaste.

The products with 5 % isolated sunflower protein were distinguished by exceptional textural characteristics (4.4 ± 0.3 points). During cooking, these samples demonstrated optimal density (no disintegration), pronounced elasticity (“al dente” effect), the absence of sliminess and a uniform structure without hard inclusions. These qualities were especially appreciated by participants aged $36 \div 50$, who are traditionally the main target audience for premium pasta products. Open comments from participants emphasized that consistency was the decisive factor in forming the overall impression of the product.

The addition of spirulina and isolated sunflower protein broadens the product's protein profile and may help consumers looking for plant-based substitutes from a nutritional and safety standpoint, but it also necessitates taking into account any individual sensitivities [3, 15, 40]. In contrast to soy, sunflower protein is generally thought to be hypoallergenic; nonetheless, in people who have seed allergies, cross-reactivity cannot be completely ruled out. Despite not being one of the main known allergens, the usage of spirulina requires stringent quality control to guarantee purity and avoid contamination. These ingredients may help form protein structures in gluten-free or allergy-sensitive formulations without gluten. However, their interactions with other starch matrices (like rice or corn flour) may differ from those in wheat-based systems and necessitate separate optimization to preserve texture and digestibility while guaranteeing consumer safety.

The use of infrared steaming technology for cereal grains significantly affected their organoleptic properties [33, 36]. After thermal stabilization, the preservation of the natural color and gloss of the grain was observed, indicating the absence of thermal damage to the surface layers. An aroma evaluation showed that the processing did not lead to the appearance of foreign odors, preserving the characteristic odor of the raw material. The taste characteristics of the samples remained natural, without signs of bitterness or other unpleasant notes, which can usually occur due to enzymatic processes during long-term storage. The organoleptic stability of the grain ensures the attractiveness of the final product for consumers and indicates the effectiveness of the selected processing mode [2, 31, 34]. The grain exhibited uniform density, without signs of excessive softening or brittleness, which could negatively affect the technological parameters of cereal product manufacture. Such textural stability is important for further processing, as it ensures the preservation of shape during cooking or other culinary operations. In addition, rapid cooling after steaming prevented the development of internal stresses in the grain structure, positively influencing the maintenance of integrity during storage. The results obtained confirm that the proposed technology is an effective means of improving the quality and durability of cereal products.

A statistical analysis (Mann-Whitney U-test, $p < 0.05$) confirmed that the overall consumer attractiveness of the innovative samples (with any of the studied additives) significantly exceeded that of the control samples (without additives) by 15.7 %. This advantage was directly reflected in the indicator of purchase readiness: 78 % of participants rated the innovative samples at 4 or 5 points (corresponding to conditional or full readiness to buy the product), while for traditional pasta this indicator was only 65 %. This clearly indicates the commercial potential of the new products. Pearson correlation analysis revealed a very strong positive relationship ($r = 0.87$, $p < 0.01$) between the assessment of the consistency of the finished product and overall consumer attractiveness. This emphasizes the crucial role of this parameter (texture) in forming a positive consumer impression for this product category – an influence even greater than that of color or taste.

The possible existence of multicollinearity was suggested by further analysis that showed moderate intercorrelations across the three main sensory qualities (texture, taste, and appearance). Even after adjusting for the effects of taste and color, a partial correlation analysis showed that texture and overall appeal continued to have a statistically significant association. This suggests that consistency plays a role in the development of consumer preference on its own and is not just linked to other favorable sensory attributes. Therefore, it can be concluded that texture plays a major role in determining how the sample under study perceives the overall quality of the product.

No statistically significant differences ($p > 0.05$) were found in the average scores between gender groups (men vs women) and main age categories (20 ÷ 35, 36 ÷ 50, 51 ÷ 65 years). This indicates the universality of the positive perception of innovative pasta products among different target audience groups within the studied region (Kyiv city and the Kyiv region). The high evaluation of the consistency of the samples with sunflower protein was the same across all groups, and the attractiveness of the green color of the samples with spirulina did not depend on the gender or age of the respondents. The absence of significant differences between age groups may indicate a broader market potential for functional products.

Even though the tests were carried out in a lab setting, the technological parameters found are appropriate for industrial pasta manufacturing lines and, with a few minor modifications, can be applied to commercial-scale machinery. Large-scale implementation, however, might come with some difficulties, such as the requirement for exact dosage control and uniform dispersion of inulin and spirulina, possible variations in raw material quality and heightened susceptibility of the protein network to changes in moisture and temperature during high-throughput extrusion. Economic viability may also be impacted by the price and consistent availability of beneficial ingredients, especially spirulina. Therefore, before broad industrial adoption, pilot-scale validation and economic assessment are advised, even though the technology solutions show realistic scalability.

Discussion

The results obtained in the study demonstrate both similarities and differences with the data presented in the analyzed scientific works. The findings of Gopika et al. [26] on the influence of processing parameters on the quality of pasta products are largely confirmed in the present work, since a critical dependence of product strength on extrusion temperature was also identified. However, in contrast to the conclusions of those authors, the data obtained in this study indicate a narrower optimal temperature range (50 ± 2 °C) for products with functional additives.

The study by Panfilova et al. [42] presents the results of long-term field research aimed at optimizing the technology of growing winter wheat under the conditions of the Southern Steppe of Ukraine. The authors demonstrated that the combination of optimal sowing dates, moderate doses of mineral fertilizers and the use of biological products (Organic D2, Escort-bio) provides not only an increase in yield by 52.9 ÷ 55.0 %, but also an improvement in the qualitative characteristics of grain – an increase in protein content to 12.9 ÷ 15.0 % and crude gluten to 30.7 %. The results obtained confirm that innovative agrotechnological approaches to wheat cultivation have a direct impact on the formation of high-quality raw materials for the production of pasta and cereal products, since the high content of protein and gluten determines their technological properties and consumer characteristics.

The study by Gomes et al. [24] on the use of phenolic extracts in the production of pasta demonstrates a similar approach to the enrichment of products with biologically active substances. However, unlike the comparative work, in this study the focus was on thermostable components, which made it possible to preserve most of the nutrients during the technological process. The results of Sarkar and Fu [48] concerning the influence of flour quality on the final product are fully confirmed in the present study, as it was also found that the use of durum wheat flour of the "Dukat" variety with a high gluten content (28.7 ± 0.4 %) is a key factor in achieving optimal textural characteristics. Codină and Dabija [9] described innovative grain processing technologies, some of which were applied in this research. Of particular importance is their conclusion regarding the need for an individual approach to each type of raw material, which fully corresponds with the present findings on the necessity of adjusting technological parameters for products containing functional additives. Khemiri and Raymundo [32], in their review of new generations of grain products, emphasized the importance of consumer qualities, which is fully confirmed by the data of the organoleptic evaluation conducted in this study. However, in contrast to the authors' recommendations regarding the use of complex mixtures of additives, the results obtained indicate the effectiveness of relatively simple combinations of functional ingredients.

The work of Gamayunova et al. [22] presents the results of a study on the productivity of spring triticale under different fertilization schemes in the conditions of the Southern Steppe of Ukraine. The authors found that the combination of pre-sowing seed treatment with the biological preparation Escort-Bio, the application of mineral fertilizers (N30P30, N60P30) and foliar feeding with ammonium nitrate or urea provides an increase in yield up to 3.61 t/ha, as well as an improvement in grain quality indicators, in particular protein content and grain nature. Such innovative approaches to triticale cultivation technology contribute to the formation of grain with improved nutritional and technological characteristics, thereby increasing its suitability as a raw material for the production of cereal and flour products, including pasta.

The study by Pismennyi et al. [44] emphasizes that the development of innovative food industry products directly depends on the quality of raw materials, particularly wholegrain flour. The authors demonstrated that modern technologies for its production allow for the maximum preservation of nutrients (proteins, amino acids, minerals, antioxidants, fiber), while ensuring optimal physicochemical, flour-milling and baking properties. Of particular importance are such indicators as ash content, grinding fineness and gluten content and quality, which determine not only the quality of bread, but also the prospects for using this flour in the production of new-generation pasta and cereal products. The use of wholegrain flour opens up opportunities for creating innovative products with increased nutritional value that meet modern trends in healthy eating and the demand for functional food products [30, 39, 54, 56].

The publication by Tiwari and Pojić [55] highlights innovative methods of grain processing, with an emphasis on the integration of several technological approaches. One of the key propositions of the work is the feasibility of combining processes, which is also confirmed within the framework of the developed technology involving the combined use of extrusion and gradient drying. This approach ensures not only the preservation of the functional properties of the raw material, but also the stability of the finished product. The work by Sarwar et al. [49] considers the examples of the industrial use of grain crops, particularly in the segment of cereal products. Partial agreement with the results obtained is observed in the choice of the areas of product application, but the key difference lies in the emphasis on increasing stability through infrared steaming – a technology not considered in the aforementioned source. As confirmed in the systematic review by Bianchi et al. [4], the enrichment of pasta products with functional ingredients opens up broad prospects for improving nutritional and technological quality. The similarity with the present study lies in the use of protein components to optimize textural characteristics. At the same time, instead of agro-industrial by-products, purpose-made ingredients were used, providing better control over composition and stability. The publication by Zingale et al. [60] systematically characterized the factors that determine the quality of durum wheat varieties for pasta production. Consistency with the present results is confirmed, in particular, by the importance of extrusion parameters and starting materials. However, unlike the general analytical approach, this study provides the specific examples of technological adaptation for domestic grain varieties. The work of Vilpoux and Cereda [57] allows parallels to be drawn between traditional and modern technologies for pasta production. In particular, the significance of temperature regimes – confirmed when studying the effects of extrusion and drying – was noted. However, the emphasis in the work mentioned is on gluten-free products and traditional Asian recipes, whereas the present study focuses on the modernization of production using durum wheat varieties. The review by Scarton and Clerici [50] emphasizes the importance of texture formation in the production of gluten-free pasta. Similarly, the results obtained indicate the critical role of consistency in shaping consumer preferences. At the same time, instead of alternative protein sources, the focus is on the use of wheat protein in combination with functional additives, which demonstrates high efficiency in the context of traditional production.

The study by Papchenko et al. [43] showed that the optimal ratio of moisture and lipid composition in the raw material is a key factor in achieving stable technological properties of extruded protein–fat systems. The authors proved that the adjustment of extrusion parameters allows the significant improvement of the texture, porosity and stability of the product when using combined raw materials, including oilseed waste and corn grits. These results have direct practical significance for the food industry, since extrusion technologies form the basis for creating new types of cereal and pasta products. Therefore, the conclusions of the study can be used to optimize the formulation and production parameters of innovative products with increased nutritional value and improved consumer properties.

In the study by Panfilova et al. [41], the effect of nutrition optimization on the yield and quality of spring barley grain under the conditions of the Southern Steppe of Ukraine was analyzed. The use of mineral fertilizers in combination with the biological preparations Escort-Bio and Organic D2 resulted in an increase in yield by 26.7 ÷ 28.2 % compared with the control, reaching 3.37 ÷ 3.41 t/ha. At the same time, grain quality indicators improved significantly: grain nature increased to 606.2 ÷ 611.2 g/dm^3, protein content to 12.5 ÷ 13.1 %, and digestible protein content to 61.0 ÷ 63.8 g/kg. The authors also noted varietal differences; in particular, the Aeneas variety demonstrated higher quality indicators compared with the Stalker and Vakula varieties. The results obtained indicate that innovative approaches to spring barley nutrition enhance its nutritional value and suitability as a raw material for the production of cereal products and can also be taken into account in the food and processing industries.

The results obtained demonstrate significant consistency with modern scientific research, while revealing key innovative aspects. As demonstrated in the study by Zingale et al. [59], the environmental assessment of the life cycle of products is critical for sustainable development, which is partially confirmed in this work through the combination of qualitative and technological characteristics. However, in contrast to the emphasis on organic production, traditional technologies are used here with the integration of innovative elements. This approach finds a conceptual parallel in the work of Massaro and Galiano [38] on the re-engineering of production processes. Similar to the authors' conclusions, specific technical solutions are proposed for the optimization of extrusion and drying, but with a level of parameter detail that differs from the general technological overview.

The analysis of grain product transformation in the work of Boukid [5] reinforces the feasibility of combining traditions and innovations. The approach implemented in this study to integrate classical technologies with functional ingredients is consistent with the author's conclusions, but differs in its focus on universal solutions instead of regional specifics. The prospects of functional enrichment highlighted by Costantini et al. [11] are confirmed by the effectiveness of the use of prebiotics. However, in contrast to the emphasis on gluten-free products and secondary raw materials, this study focuses on traditional wheat with the addition of specialized industrial ingredients. The work of Stefoska-Needham and Tapsell [53] on alternative crops emphasizes the importance of combining functional additives, which correlates with the results obtained. At the same time, instead of sorghum, traditional wheat was used as the main raw material, allowing for the preservation of classical technological properties.

A bibliometric analysis by Cecchini et al. [7] confirms the growing interest in pasta quality, which is consistent with the aim of this study. However, in contrast to the trend analysis, practical technological models for direct implementation are proposed here. The propositions of Carcea et al. [6] concerning the critical role of flour quality are fully supported by the results obtained using the Dukat variety. However, the emphasis on traditional milling methods contrasts with the innovative technological solutions proposed in this research. The study by Gęsiński and Ruszkowska [23] on the influence of technological parameters on texture is reflected in the conclusions on consistency optimization. The difference lies in the focus on traditional wheat with functional additives instead of alternative crops such as quinoa. The results of Stanco et al. [52] on the importance of local raw materials for sustainable development support the choice of Ukrainian cereal varieties. However, in contrast to the emphasis on collective innovation in supply chains, this work focuses on individual technological solutions for specific production processes. The study by Cuomo et al. [12] on the use of processing by-products highlights the potential for functional enrichment, which is partially consistent with the findings. However, instead of secondary raw materials, specialized ingredients with a controlled composition were used here, ensuring the stability of technological parameters. Thus, the results obtained integrate the key aspects of the current research, offering new solutions for optimizing the production of pasta and cereal products using functional ingredients.

Conclusions

1. The study proved the effectiveness of integrating functional ingredients (spirulina, isolated sunflower protein, inulin) into the technology of pasta and cereal product production based on Ukrainian raw materials. High-quality durum wheat flour of the "Dukat" variety (HD index 82 ± 3 %, gluten content 28.7 ± 0.4 %) ensured the formation of a stable dough matrix. The addition of 2 % spirulina caused a significant change in colorimetric indicators ($\Delta E > 10$), increased water absorption by 5.2 ± 0.6 % and gave the product a characteristic green hue associated by consumers with naturalness. The introduction of 5 % sunflower protein increased the viscosity of the dough by 18.3 ± 2.1 % (at 50 s^{-1}) due to the formation of additional disulphide bonds, improving the textural properties of the finished products. Inulin (3 %) increased water absorption by 7.5 ± 0.8 % owing to the formation of a hydrogel phase, contributing to the creation of a smooth consistency. A synergistic effect of the combination of spirulina and sunflower protein was revealed: an increase in the elastic modulus G' by 25 % compared with the control.
2. The optimization of technological parameters revealed a critical effect of extrusion temperature on structural integrity: an increase from 45 °C to 60 °C reduced the bending strength from 32.5 ± 1.2 N to 27.8 ± 1.0 N ($p < 0.05$) due to protein denaturation. The optimal regime was established as a temperature of 50 ± 2 °C, pressure of 90 ± 5 bar and screw speed of 20 rpm. Three-phase drying (70 °C → 55 °C → 40 °C) ensured uniform moisture removal (final moisture content 12.5 ± 0.3 %), prevented deformation and preserved thermolabile components ($\Delta E < 1.5$). The

cooking properties of the innovative samples confirmed high technological efficiency: cooking time 7.5 ± 0.5 minutes, mass gain 2.3 ± 0.1 g/g and dry matter loss 5.8 ± 0.3 %. For cereal products, infrared steaming with subsequent rapid cooling reduced AW to 0.62 ± 0.02 (buckwheat) and 0.65 ± 0.02 (barley), guaranteeing stability during storage.

3. The organoleptic evaluation revealed high consumer acceptability: samples with spirulina received 4.3 ± 0.4 points for appearance, and those with sunflower protein 4.4 ± 0.3 points for consistency. The overall attractiveness of the innovative products exceeded the control by 15.7 % ($p < 0.05$), and 78 % of participants expressed willingness to purchase. A strong correlation ($r = 0.87$, $p < 0.01$) was found between the assessment of consistency and overall attractiveness, emphasizing the key role of texture.
4. The study did not take into account the effect of long-term storage on the stability of functional components in the finished product. Additional studies of the environmental efficiency of the proposed technologies should be conducted, taking into account the product life cycle. A promising direction is the optimization of formulations for gluten-free analogues and research on the bioavailability of nutrients in vivo.

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INNOWACJE W PRODUKCJI MAKARONÓW I PRODUKTÓW ZBOŻOWYCH

S t r e s z c z e n i e

Wprowadzenie. Rosnący popyt na żywność funkcjonalną, w połączeniu z koniecznością poprawy efektywności technologicznej oraz konkurencyjności produktów zbożowych, wymaga opracowania innowacyjnych metod przetwarzania. Niniejsze badanie koncentrowało się na udoskonaleniu makaronów i produktów zbożowych poprzez zastosowanie składników funkcjonalnych (spiruliny, izolowanego białka słonecznikowego oraz inuliny) w połączeniu z zoptymalizowanymi technologiami ekstruzji, suszenia i stabilizacji zbóż, opartymi na ukraińskich surowcach. W badaniach oceniano właściwości fizykochemiczne, reologiczne, technologiczne, mikrobiologiczne oraz sensoryczne w celu określenia optymalnych warunków przetwarzania oraz zależności między jakością produktu a zastosowanymi parametrami technologicznymi.

Wyniki i wnioski. Wprowadzenie 2 % spiruliny spowodowało istotne zmiany cech barwy ($\Delta E > 10$) oraz zwiększyło zdolność absorpcji wody przez ciasto o 5,2 %, natomiast dodatek 5 % białka słonecznikowego zwiększył lepkość ciasta o 18,3 % w wyniku tworzenia dodatkowej sieci białkowej. Inulina (3 %) podniosła absorpcję wody o 7,5 % i przyczyniła się do uzyskania gładszej tekstury. Stwierdzono efekt synergistyczny dla połączenia spiruliny i białka słonecznikowego, przejawiający się wzrostem modułu sprężystości (G') o 25 % w porównaniu z próbą kontrolną. Temperatura ekstruzji wykazała silną ujemną korelację z wytrzymałością produktu: jej zwiększenie z 45 °C do 60 °C spowodowało obniżenie odporności na zginanie z 32,5 do 27,8 N. Optymalne parametry ekstruzji ustalono na poziomie 50 ± 2°C, 90 ± 5 bar oraz 20 obr./min. Trójfazowe suszenie (70 → 55 → 40 °C) zapewniło jednorodną zawartość wilgoci (12,5 %) oraz zachowanie składników termolabilnych ($\Delta E < 1{,}5$). Parowanie zbóż w podczerwieni obniżyło aktywność wody do poziomu 0,62 ÷ 0,65, co znacząco poprawiło stabilność przechowalniczą. Ocena konsumencka potwierdziła wysoką akceptację produktów: 78 % respondentów zadeklarowało chęć zakupu, a pomiędzy konsystencją a ogólną atrakcyjnością produktu stwierdzono silną korelację ($r = 0{,}87$).

Słowa kluczowe: Przemysł spożywczy, ocena organoleptyczna, spirulina, inulina, parametry ekstruzji