

INNOVATIVE TECHNOLOGIES FOR CREATING LOW-CALORIE PRODUCTS BASED ON PLANT RAW MATERIALS

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The aim of the study was to investigate the effectiveness of innovative technologies in creating three categories of low-calorie foods based on plant raw materials: meat substitutes, dairy analogues, and bakery products. The study conducted a comparative assessment of the nutrient composition, energy value, glycaemic response, organoleptic characteristics, technological stability, and cost of products manufactured using traditional and innovative approaches. The experiment involved the combined use of wet extrusion, ultrasonic treatment, controlled fermentation, pulsed electric field (PEF) processing, enzymatic hydrolysis, and functional ingredients such as amaranth, inulin, psyllium, soy, and pea isolates. It was found that innovative meat substitutes had a reduced energy value (145 kcal/100 g), high protein concentration (22 g/100 g), and increased texture elasticity by 31%. All samples remained microbiologically safe for 9-12 days. Sensory evaluation showed high consumer acceptance: the average score on the expert scale was between 4.3 and 4.6. Statistical analysis of the results confirmed the reliability of the differences between traditional and experimental products ($p < 0.05$). The cost of producing innovative products increased by 8-13% depending on the category, but due to improved functional characteristics and shelf life, the products have high potential for industrial implementation in the functional, preventive, and dietary nutrition segment.

Keywords: protein isolation, glycaemic response, textural properties, dietary fibre, enzymatic treatment, consumer acceptability, energy density

Introduction

The increase in the prevalence of type II diabetes, obesity, cardiovascular diseases, and metabolic syndrome has led to an urgent need to develop foods with a reduced energy value. Technological solutions that reduce the energy density of products without compromising their organoleptic properties, structural stability, and biological value have become particularly relevant. In addition, modern consumers are looking for foods without synthetic additives, with clear functional effects and improved nutrient profiles. In response to these demands, there has been increased attention to plant-based raw materials as an alternative to animal ingredients, as well as to the introduction of innovative technologies such as extrusion, fermentation, ultrasound, pulsed electric field (PEF) treatment, and the use of plant protein isolates, inulin, resistant starch, etc.

The economic feasibility of integrating such technologies into the production of low-calorie foods has been demonstrated in a study by Novikov and Proscenko [1]. The authors proved that the use of extrusion, fermentation, ultrasonic, and electrophysical treatment not only reduces the energy value of finished products, but also improves their texture and sensory characteristics without

the use of artificial stabilisers. Aspects of cost optimisation were considered in the work of Babanov *et al.* [2], which substantiated the effectiveness of using natural ingredients and energy-saving technologies in the formation of economically profitable production of functional products. The potential for reducing losses during storage and transportation by extending the shelf life of products has been determined.

The experience of growing and processing medicinal plants for the purpose of creating food and pharmaceutical ingredients is presented in the work by Khamraeva *et al.* [3]. The study emphasizes the importance of using raw materials with dual functional potential and adapted to conditions of limited moisture. The use of resistant starch as a basis for creating low-calorie products is discussed in the publication by Karunarathna *et al.* [4]. The authors analysed its effect on lowering the glycaemic index (GI), increasing satiety, and forming structurally stable food systems. A systematic review of innovations in sustainable food production is provided in the work by McClements *et al.* [5]. The publication emphasises the importance of combining technological innovation with the principles of healthy eating and environmental

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responsibility. The production of low-calorie sweeteners based on microorganisms was the subject of analysis in a study by Hashmi *et al.* [6]. Biotechnological platforms for the biosynthesis of natural sugar substitutes with high potential for use in functional foods are proposed.

Fermentation and cavitation methods for extending the shelf life of plant-based beverages and semi-finished products were investigated in an article by Sharma *et al.* [7]. The data obtained demonstrated the effectiveness of innovative treatments for preserving organoleptic quality without the use of synthetic preservatives. The processing of whey into functional components is discussed in the work of El-Aidie and Khalifa [8]. The technological and environmental feasibility of its reuse to improve the sustainability of the dairy industry is evaluated. The technological features of the formation of plant-based fat substitutes are described in the study by Zhang *et al.* [9]. The authors outlined the possibilities of using such ingredients to improve texture, moisture retention, and reduce energy value. The possibilities of creating nutritionally balanced products using 3D printing based on combined raw materials are discussed in the publication by Zhao *et al.* [10]. The prospects for personalised nutrition based on controlled technological solutions are shown.

In general, the results of the analysis of scientific sources confirm the effectiveness of combining biotechnology, physical processing methods, and functional ingredients to create low-calorie food systems with high safety, stability, and consumer appeal. The aim of the study was to determine the effectiveness of innovative technologies for creating low-calorie foods based on plant raw materials. Research objectives: to conduct a comparative analysis of raw materials, technological methods, and functional characteristics of products manufactured using traditional and innovative methods; to evaluate the impact of selected technologies on the energy value, structural stability, GI, and consumer acceptability of products.

Materials and methods

The experimental study was conducted between October 2024 and February 2025 at the Laboratory of Food Technologies and Sensory Analysis, Department of Food Technology, National University of Food Technologies (Kyiv, Ukraine). The selection of raw materials for each type of low-calorie product was based on clearly defined criteria: nutrient density, the presence of antioxidant or prebiotic activity, gluten-free status (where required), and the potential to form a stable structure without synthetic improvers. For the meat substitute category, the protein base consisted of pea protein isolate (PeaPro 80, Roquette, France), soy protein isolate (Supro 85, DuPont Nutrition, USA), and wheat gluten (Vital Wheat Gluten, MGP Ingredients, USA). The pea isolate contained 80.3% protein, 6.5% moisture, 4.5% fibre, and provided 380 kcal/100 g; the soy isolate contained 85.2% protein, 1% fat, 5% fibre, and 5.8% moisture; the wheat gluten

contained 70.1% protein, 2% fibre, and 9.1% moisture. Amaranth flour (OrganicLife, Ukraine), with an energy value of 142 kcal/100 g, 13.6% protein, 6.4% fat, and 7.8% fibre, was used as a functional additive, added at 15% of the protein phase. The final formulation of the meat substitutes per 100 g of product was: 25 g pea isolate, 20 g soy isolate, 15 g gluten, 9 g amaranth, and 31 g water.

In the dairy analogues, the main components were soy milk (Alpro, Belgium; protein 3.6 g, fat 1.9 g per 100 ml), oat milk (Oatly, Sweden; β -glucan content 1.3 g), and coconut milk (Aroy-D, Thailand; fat content 5.4 g). Inulin (Beneo, Germany), as a source of soluble fibre (89%), was applied at a concentration of 4% to reduce glycaemic response and improve structural stability. The formulation per 100 g was: 50 ml soy milk, 25 ml oat milk, 20 ml coconut milk, 4 g inulin, and 1 g starter culture based on *Lactobacillus acidophilus* and *Bifidobacterium bifidum*. Prior to the compositional analysis, the samples were homogenised using a magnetic stirrer (IKA RCT) at 800 rpm until a uniform consistency was achieved. For glycaemic index (GI) determination, lyophilisation was performed to remove water and stabilise the matrix, followed by grinding into a fine powder. This step ensures that the enzymatic digestion used in the *in vitro* GI assay reflects the carbohydrate content accurately, without interference from water content or variable viscosity.

For bakery products, green buckwheat flour (Naturalis, Ukraine; protein 13.1%, fibre 9.2%), quinoa flour (Eco-bio; protein 14.2%, fibre 7.1%), psyllium (ISPAGHOL, India; fibre 89.5%), and HerbaFiber™ concentrated fibres (Netherlands; soluble fraction >85%) were used. The dough composition per 100 g finished product was: 35 g buckwheat flour, 30 g quinoa flour, 5 g psyllium, 5 g fibre, 25 g water, and 2 g starter. After baking (180 °C, 40 min), the samples were cooled and milled to a particle size of 0.5-1 mm using an IKA A11 grinder. All parameters were determined in three biological replicates (n=3) followed by calculation of the mean and standard deviation. All protein, carbohydrate, and fibre ingredients were certified for food quality and sourced from reliable suppliers in compliance with ISO 22000 Food Safety Management [11] and Hazard Analysis and Critical Control Points [12].

The technological processing of meat substitutes involved three complementary stages, each selected based on contemporary trends in plant protein product development. In the first stage, wet extrusion of the protein mass was performed at 145°C, 32% moisture, and 6 bar gauge pressure (above atmospheric) under high-shear twin-screw conditions using a Clextral EV-32 laboratory extruder. The process provided intensive mechanical shear and thermal energy input into the protein matrix, promoting controlled protein denaturation, partial unfolding of globular structures, and alignment of polypeptide chains along the flow direction. The selected parameters were optimised to induce structural texturisation without excessive thermal degradation or undesirable crosslinking reactions. This method is one of the key technologies in forming a fibrous structure simi-

lar to meat without the use of synthetic stabilisers and is recognised as promising for the industrial production of meat alternatives due to the possibility of structural texturing of soy, pea, and gluten isolates. The second stage – controlled fermentation using *Lactobacillus plantarum* (12 hours at 37 °C) – was used to improve the taste and aroma profile, reduce the content of antinutrients (in particular phytic acid), and bioactivate proteins. This approach is based on recent studies that indicate the potential of fermentation as a biotechnological tool for improving the digestibility of protein ingredients. The third stage – ultrasonic treatment at 25 kHz for 10 minutes with an amplitude of 80% – was used to increase water retention capacity, reduce protein particle aggregation, and improve the rheological characteristics of the mass. The acoustic parameters were chosen to produce cavitation-induced microstreaming and moderate shear forces that can induce partial conformational changes in protein molecules and enhance their dispersion within the matrix, while preventing irreversible structural damage or substantial loss of biological value. This physical method is non-thermal and provides modification of the protein structure without loss of biological value, as confirmed in studies on the optimisation of the texture of plant products.

In the production of dairy analogues, biofermentation, a controlled microbial fermentation process using beneficial bacteria, and ultrasonic cavitation, a technique that applies high-frequency sound waves to create microbubbles and shear forces in liquids, were combined to achieve emulsion stability without synthetic emulsifiers. The use of *Lactobacillus acidophilus* and *Bifidobacterium bifidum* cultures for 10 hours at 36 °C ensured a stable pH, gel-like structure, and reduced glycemic potential of the product. Subsequent ultrasonic cavitation (20 kHz, 8 min) contributed to a reduction in fat droplet size and improved dispersibility, which is critical for the homogeneity and stability of emulsion systems. Cavitation effects, alongside droplet size reduction, facilitated the partial unfolding of surface-active proteins, thereby enhancing their emulsifying capability and reinforcing the protein-lipid interfacial layer, which improved emulsion stability. The final stage – the addition of inulin at 25 °C

followed by maturation at 4±1 °C for 12 hours – aimed to increase prebiotic value, improve texture, and extend shelf life. This stepwise approach aligns with modern concepts for creating plant-based yoghurt-like products with high functional activity.

Three innovative approaches were implemented in the technology of bakery products. First, enzymatic treatment with amylase (45 U/g at 30 °C) allowed the starch to be modified into less glycemically active fractions, reducing the GI. Second, fermentation with natural microflora for 24 hours at 30 °C improved the aroma, acidity, and bioavailability of nutrients. Thirdly, PEF psyllium (3 kV/cm, 20 µs, 60 pulses) was used as a modern electrophysical technology to increase the gel-forming ability of fibres, which improved the homogeneity of the crumb, reduced porosity, and ensured uniform moisture retention. The use of PEF in the baking industry is currently being actively studied, and its integration into this work corresponds to the current trend of non-thermal modification of structural components of dough without chemical intervention. In general, the choice of these technologies is due to their ability to improve product quality without the use of synthetic components, with proven effectiveness in international studies. All methods are representatives of the “green engineering” class, focused on safe, energy-saving, and functionally justified processing of food raw materials.

The following equipment was used to carry out the technological processes: Clextal EV-32 laboratory twin-screw extruder (Clextal, France) for texturing protein mass; Sonics VCX-500 ultrasonic homogeniser (Sonics & Materials, USA) with a frequency of 25 kHz and a variable amplitude of up to 80%; Hielscher UP200Ht ultrasonic cavitation device (Hielscher Ultrasonics, Germany); Elea PEF Advantage B1 generator (Elea GmbH, Germany); Memmert ICO50 fermentation chamber (Germany); Binder FD 53 drying oven (Germany). The temperature and humidity of the environment were measured using Testo 608-H1 devices (Germany). All protein, carbohydrate, and fibre ingredients were pre-characterised according to basic nutritional value indicators, as shown in Table 1.

Proteins were determined using the Kjeldahl method

Table 1. Comparative characteristics of raw materials for low-calorie products

Product category	Raw materials	Proteins (%)	Fats (%)	Fibre (%)	Energy value (kcal/100 g)
Meat substitutes	Pea isolate	80.3	2.1	4.5	380
	Soy isolate	85.2	1	5	370
	Wheat gluten	70.1	2	2	365
	Amaranth (functional additive)	13.6	6.4	7.8	142
Dairy analogues	Soy milk	3.6	1.9	1.5	54
	Oat milk	1.2	1.4	1.8	43
	Coconut milk (≤20% of the mixture)	1	5.4	0	90
	Inulin (soluble fibre)	0	0	89	25
Bakery products	Green buckwheat flour	13.1	3.4	9.2	310
	Quinoa	14.2	5	7.1	368
	Psyllium	2.5	0.6	89.5	38
	Fibre	1	0.2	85	32

Source: developed by the authors.

(ISO 1871:2009 "Food and Feed Products – General Guidelines for the Determination of Nitrogen by the Kjeldahl Method" [13]), fats – using the Soxhlet method (ISO 11085:2015 "Cereals, Cereals-Based Products and Animal Feeding Stuffs – Determination of Crude Fat and Total Fat Content by the Randall Extraction Method" [14]), fibre – according to the Association of Official Analytical Chemists [15] with a division into soluble and insoluble. Caloric value was calculated using formula (1):

$$E=(P\times4)+(F\times9)+(C\times4)\dots\dots\dots(1)$$

where E – the energy value in kcal/100 g; P – protein (g); F – fat (g); C – carbohydrates (g).

The glycaemic index (GI) was determined *in vitro* using a modified method by Goñi et al. [16], which included simulation of gastrointestinal digestion with the use of α -amylase and glucoamylase. Calculations were based on the ratio of the area under the glucose release curve of the test sample to that of a reference product (white bread, GI=100). Sensory evaluation was carried out by a trained expert panel of 12 individuals aged 25-45 years, who provided written consent to participate in accordance with the ethical requirements of the university. Assessment was conducted following ISO 8586:2023 "Sensory Analysis – Selection and Training of Sensory Assessors" [17] on a five-point scale, focusing on key attributes: taste, aroma, consistency, appearance, and overall acceptability. The scoring was defined as follows: 1 – unacceptable product (strongly negative taste/texture), 2 – significant defects, product largely unsuitable, 3 – acceptable quality but with noticeable shortcomings, 4 – good product with minor deviations, 5 – excellent quality, product without noticeable defects. Overall microbiological stability of the products was assessed by determining the total microbial count according to ISO 4833-1:2013 "Microbiology of the Food Chain – Horizontal Method for the Enumeration of Microorganisms – Part 1: Colony Count at 30 °C by the Pour Plate Technique" [18]. Samples were collected on days 1, 5, 9, and 12 of storage. In accordance with common microbiological safety criteria for ready-to-eat foods, a threshold of $\leq 10^4$ CFU/g (colony-forming units per gram) was considered acceptable. All samples were stored at 4 ± 1 °C.

Cost calculations were based on actual wholesale prices of raw materials as of Q1 2025, including the cost of energy for processing (extrusion, ultrasound, PEF), expenditure on enzymes, inulin, starter cultures, and storage losses [19]. For comparative analysis, control samples representing conventional products of equivalent categories were used. The control sample for meat analogues was mixed pork and beef minced meat (TM "Globino", Ukraine), purchased in vacuum packaging, with an energy value of 274 kcal/100 g, protein 16.8 g, fat 23.5 g, carbohydrates 0 g, and moisture 58%. Prior to the analysis, the mince was steamed to readiness, cooled to room temperature, and homogenised in a laboratory mixer until uniform. For comparison with dairy an-

alogues, the control was a classic 2.5% fat yoghurt (TM "Halychyna", Ukraine), produced from pasteurised cow's milk using standard starter cultures. Its energy value was 61 kcal/100 g, protein 3.1 g, fat 2.5 g, carbohydrates 4.1 g. The yoghurt was evaluated as a ready-to-eat product without prior thermal treatment, after thorough mixing. For bakery products, the control was a sliced premium wheat loaf (TM "Kyivkhliv", Ukraine), with declared values: energy 266 kcal/100 g, protein 7.6 g, fat 3.3 g, carbohydrates 51 g. Samples were prepared by milling the crumb to 1-2 mm fractions for subsequent GI determination and standard chemical analysis of protein, fat, fibre, and moisture content. Statistical significance between control and innovative samples was assessed using analysis of variance (ANOVA) at $p<0.05$. Calculations were performed using GraphPad Prism 9.0. Each analysis was conducted in three biological replicates, with results reported as mean $\pm$ standard deviation.

Results and discussion

In a research study, a comparative evaluation was conducted on the raw materials used to create three types of low-calorie products based on plant-based ingredients: meat substitutes, dairy analogues, and bakery products. The results of the laboratory analysis of the nutrient composition of the raw materials showed significant variability in their content of proteins, fats, fibre, and energy value. Among the raw materials for meat substitutes, the highest protein content was recorded in soy isolate at 85.2% (SD $\pm$ 0.4%). Slightly lower values were observed in pea isolate at 80.3% (SD $\pm$ 0.6%) and wheat gluten at 70.1% (SD $\pm$ 0.5%). The fat content for these three components ranged from 1-2.1%, and fibre from 2-5%. At the same time, amaranth, which was introduced as a functional additive, had a significantly lower protein content (13.6%) and a higher concentration of fibre (7.8%) with a moderate energy density (142 kcal/100 g), which allowed for balancing the recipe in accordance with nutritional density requirements. While amaranth contains less overall protein, it is abundant in some important amino acids, notably lysine, which are deficient in pea and wheat proteins [20, 21]. Its incorporation may thus augment the amino acid profile of the primary protein isolates, thereby improving the overall protein quality of the meat alternative. Nevertheless, direct experimental information regarding the synergistic effect of amaranth in conjunction with pea and soy isolates in this context is scarce, and this limitation must be recognized.

In the category of liquid plant-based ingredients for dairy analogues, soya milk contained 3.6% protein, whereas oat milk had only 1.2%. Oat milk also contained 1.8% fibre, including β -glucans. Coconut milk was characterised by a higher fat content (5.4%) and an almost zero fibre content. Inulin, as a soluble fibre, had the highest fibre content across the entire sample at 89%, with a practical absence of proteins and fats, and the lowest energy value at 25 kcal/100 g.

Regarding the components for gluten-free bakery products, green buckwheat flour provided 13.1% protein, 3.4% fat, and 9.2% fibre. Quinoa showed slightly higher protein (14.2%) and fat (5%) content, but a slightly lower fibre content (7.1%). Psyllium and concentrated plant fibre had the highest amount of soluble fibre, 89.5% and 85% respectively, while their protein content did not exceed 2.5%, and fats 0.6%. Statistical analysis using a one-way analysis of variance (ANOVA) showed the presence of statistically significant differences between all groups of raw materials for the four key indicators. Thus, for protein content $p=0.003$, for fat $p=0.012$, for fibre $p<0.001$, and for calorific value $p=0.009$. The largest difference was recorded between the groups of concentrated fibre and protein isolates. The results confirm the need for a differentiated selection of raw materials depending on the type of end product – whether it's a meat substitute, a dairy analogue, or a bakery product.

A comparative analysis of the physical, chemical, and functional characteristics of the products showed significant differences between the experimental samples using new technologies and the control products of traditional production. In the meat substitute category, the protein content in the experimental sample was 26.4 g/100 g, which exceeded the corresponding figure for the control meat mince (16.8 g/100 g). The calorific value was lower at 178 kcal compared to 274 kcal in the traditional sample. This ratio is explained by the combination of high-protein isolates with low-calorie fibrous additives and the effectiveness of fermentation processing. The latter contributed to a decrease in the content of antinutrients, which was confirmed by an increase in the total digestible protein (the digestion coefficient increased from 72% to 84%).

The rheological characteristics of the meat substitute also changed: the structural density after extrusion and ultrasonic treatment was 1.23 g/cm³ compared to 1.07 g/cm³ in the mince, which indicated a higher textural compactness. Water-holding capacity increased by 18%, and losses during heat treatment decreased from 16% to 9%. In the dairy analogue category, a decrease in energy value was recorded from 61 to 42 kcal/100 g compared to traditional yoghurt. The protein content remained at a comparable level (3.1 g/100 g in the control versus 3.2 g/100 g in the experimental sample), but the GI (Glycaemic Index) decreased from 45 to 28 units. This is due to the introduction of inulin and β -glucans, which have a pronounced ability to slow down glucose absorption. The emulsion stability index (determined as the ratio of fat and water phase volumes after 24 hours of storage) improved from 0.73 to 0.91. Ultrasonic cavitation contributed to the micro-dispersion of the lipid phase, which increased the homogeneity of the texture [22].

Regarding bakery products, the use of psyllium in combination with pulsed electric field (PEF) reduced GI from 71 to 44 units. Crumb elasticity increased by 23% compared to the control, and water-binding capacity rose from 51% to 68%. Pore structure also improved:

the average alveolar diameter decreased from 3.8 mm to 2.1 mm, indicating greater uniformity. The energy value of the experimental bread decreased by 19%, from 266 to 216 kcal/100 g, due to partial replacement of the carbohydrate base with fibrous components.

A concise comparison of twin-screw extrusion with alternative extrusion technologies is presented to contextualize these findings:

Twin-screw extrusion facilitates enhanced mixing, increased shear, and more accurate regulation of temperature and moisture profiles in comparison to single-screw extrusion [23]. This enhances the synthesis of protein networks, promotes homogeneous fibrous structures, and improves functional qualities in meat alternatives and other plant-based products. Conversely, single-screw extrusion often provides easier operation and reduced energy consumption, but it may yield less uniform textures and restricted structural development, thereby impacting water retention and digestibility [24]. Consequently, although twin-screw systems are more technically challenging and expensive, they facilitate superior product quality and processing efficiency, rendering them especially appropriate for intricate formulations such as low-calorie, high-protein plant-based goods.

All differences in the main indicators within the three categories were statistically significant ($p<0.05$), which confirms the effectiveness of the chosen approach to forming low-calorie products while preserving or improving their functional characteristics (Table 2).

The proposed innovative technologies achieved a statistically significant reduction in energy value, improved textural and functional properties, stabilised structural systems, and lowered glycaemic index. The implementation of extrusion, fermentation, ultrasonic, and electro-physical methods allowed targeted modification of raw material properties without the use of synthetic additives. All the effects obtained confirmed the effectiveness of the approach in terms of nutrient profile, sensory evaluation, and suitability for long-term storage.

The integration of fermentation with *Lactobacillus plantarum* to reduce the content of antinutrients and improve the acid profile found parallels with the data presented by Ravishankar *et al.* [25], where fermentation technologies were described as a key tool for improving protein digestibility and stabilising flavour in plant-based meat substitutes. In both cases, fermentation performed not only a nutritional but also a technological function, reducing the need for acidifiers and flavour enhancers. The use of a multifactorial technological approach to modify the composition and properties of low-calorie products was consistent with the conclusions of Hsieh and Ofori [26], who emphasised the need to integrate physical, chemical, and biotechnological solutions to improve the nutritional quality of functional foods. Similar to their vision, within the scope of this study, the combination of fermentation, ultrasound, PEF, and enzymatic methods provided a comprehensive improvement in functional characteristics without compromising food safety.

Table 2. Innovative technologies, parameters, and effects compared to the control

Product category	Technology	Processing parameters	Quantitative effect compared to control
Meat substitutes	Extrusion	145°C, 6 bar, 32% humidity	Energy value ↓ by 22%; elasticity ↑ by 31%
	Protein fermentation	12 hours, 37°C, <i>L. plantarum</i>	Phytic acid ↓ by 38%; pH stable (5.1–5.3)
	Ultrasonic treatment	25 kHz, 10 minutes	Water-holding capacity ↑ by 16%; particle size ↓ by 22%
Dairy analogues	Fermentation	10 hours, 36°C, <i>L. acidophilus</i> , <i>B. bifidum</i>	pH stabilised (4.4); gel stability ↑ by 29%
	Cavitation	20 kHz, 8 minutes	Fat globules ↓ by 40%; phase separation eliminated
	Inulin + fermentation	4% inulin	Energy value ↓ by 27%; GI ↓ from 60 to 43
Bakery products	Enzymatic treatment	Amylase 45 U/g, 30°C	Starch ↓ by 20%; GI ↓ from 75 to 45
	Natural fermentation	24 hours, 30°C, starter culture	Aromatic profile ↑ (sensory score +0.8); acidity stable
	PEF	3 kV/cm, 20 μs, 60 pulses	Elasticity ↑ by 15%; porosity ↓ by 18%

Source: developed by the authors.

The finished low-calorie products, developed according to the proposed technological schemes, were evaluated for compliance with target quality criteria: energy value, nutrient composition, organoleptic properties, storage stability, and glycaemic response. The concepts of Russell [27] regarding the creation of new products through the introduction of non-traditional technologies, including bioactivation and innovative stabilisation, were reflected in this experiment. The products developed met the requirements for novelty, quality, and technological adaptability, making them relevant to the “innovative” category as defined by the author.

After thermal processing, the meat substitute samples retained their shape, had a characteristic fibrous structure, and elastic consistency. The appearance was uniform, without delamination or visible moisture separation. Extrusion technology provided directional texturing of the protein mass, which visually and tactilely approximated the properties of minced meat. Fermentation of the protein raw material contributed to a reduction in the aftertaste of the raw material, improved taste balance, and neutralisation of the bitter notes characteristic of isolates [28]. Ultrasonic treatment had a positive effect on moisture-binding properties, giving the samples a juicier texture and reducing losses during reheating [29]. Compared to meat analogues, plant-based products had a significantly lower energy load, a lower fat content, and a higher protein saturation.

At the molecular level, moist extrusion at elevated temperatures and shear stress caused partial protein denaturation, unfolding of globular structures, and subsequent reorientation of polypeptide chains. The breaking of hydrogen bonds and hydrophobic interactions revealed reactive groups, promoting intermolecular aggregation and the establishment of novel protein-protein networks after cooling. This regulated aggregation facilitated the formation of an anisotropic, fibrous structure typical of meat mimics. The alignment of denatured soy, pea, and gluten proteins under shear conditions improved struc-

tural integrity and mechanical strength, as evidenced by the observed increase in density and elasticity [30].

These structural alterations also affected protein digestibility. The partial unfolding of protein molecules enhanced the accessibility of enzyme cleavage sites, elucidating the increase in the digestion coefficient from 72% to 84%. The extrusion parameters were concurrently optimized to prevent excessive aggregation or Maillard-type crosslinking processes that could diminish amino acid availability. Consequently, the equilibrium between denaturation and regulated network formation was essential for attaining both optimal texture and enhanced nutritional quality.

Ultrasonic cavitation altered protein structure via microstreaming and shear stresses produced by bubble collapse. These effects facilitated the partial disaggregation of protein clusters and enhanced the dispersion of protein particles inside the matrix. Consequently, the protein network exhibited increased homogeneity, thereby improving water retention and diminishing cooking losses. Furthermore, modest ultrasonic treatment may enhance surface hydrophilicity and enzyme accessibility, so indirectly facilitating digestibility without inducing substantial structural degradation.

While the technological benefits of extrusion are evident, it is essential to acknowledge the inherent limitations of this technology. Elevated temperature and shear conditions may result in the partial breakdown of sensitive amino acids, notably lysine, owing to Maillard-type reactions with reducing sugars. Moreover, extrusion may lead to the degradation of heat-sensitive micronutrients, including certain vitamins and bioactive substances inherent in plant raw materials [31-33]. Excessive mechanical and thermal stress may lead to protein over-aggregation, diminishing solubility, and potentially compromising functional characteristics if parameters are not meticulously regulated [34, 35].

This study optimized processing settings to mitigate these dangers by employing moderate moisture levels

and regulated residence time. No notable decrease in total protein content was detected, and the enhancement in digestibility indicates that structural alterations transpired without substantial nutritional degradation. From a technological standpoint, extrusion must be viewed as a process necessitating meticulous parameter optimization to harmonize structural advancement with the maintenance of nutritional integrity.

The results of the study on the effectiveness of wet extrusion for forming a structured protein mass in meat substitutes generally align with Jung *et al.* [36], who reported improved textural properties and reduced fat requirements using wet extrusion with functional proteins. However, unlike Jung *et al.*, who primarily focused on sensory outcomes, the present study provides a quantitative assessment of protein digestibility and water-binding capacity. This indicates that the chosen extrusion-ultrasound combination not only reorganizes the matrix but also enhances functional bioavailability, offering additional insight beyond the scope of the cited work. In contrast to the broader findings presented by Jung *et al.*, the current study further illustrates a quantifiable enhancement in protein digestibility and water-binding capacity, indicating that the chosen extrusion-ultrasound combination not only reorganizes the matrix but also improves its functional bioavailability. The positive effect of ultrasonic treatment on the water-holding properties and texture uniformity of meat substitutes was consistent with the results reported by Mandliya *et al.* [37], who showed that such treatments contribute to the reduction of protein fraction aggregation and the stabilisation of the moist structure of meat analogues based on pea proteins. Unlike the findings of Mandliya *et al.*, who demonstrated that excessive sonication resulted in partial protein destabilization, the regulated parameters employed in this investigation prevented structural weakening, underscoring the significance of optimizing acoustic intensity and treatment duration. A similar effect was found in this study, confirming the technological relevance of the method. The feasibility of using a multicomponent approach to create meat substitutes with high functional stability was confirmed by a review by Renzetti and van der Sman [38], who emphasised the need to balance the protein structure, fat substitutes, and texturisers when developing new generation products. The results of this study met the specified conditions, demonstrating +31% elasticity and stability during thermal processing. Mazumder *et al.* [39] emphasised the importance of correctly selected protein ingredients for the formation of a fibrous structure in meat substitutes. The study noted that the combination of pea, soy, and gluten proteins allows a balance to be achieved between mechanical strength and organoleptic properties. A similar effect was observed in this study, where the combination of three isolates ensured structural integrity without delamination after thermal processing.

Alongside its functional and structural benefits, the utilization of soy protein isolate, wheat gluten, and pea

protein necessitates an evaluation of potential allergenicity. Soy and wheat (gluten) are acknowledged as significant food allergens according to international food safety regulations and are required to be declared in numerous jurisdictions [40]. Pea protein is typically regarded as having a reduced allergenic potential; nonetheless, instances of cross-reactivity with other legumes, especially peanut proteins, have been documented in susceptible individuals.

Technological processing methods such as extrusion, fermentation, and ultrasonic treatment may induce conformational alterations in protein molecules, potentially affecting epitope accessibility [41]. Denaturation and partial unfolding may diminish allergenic sensitivity by breaking conformational epitopes or, alternatively, reveal previously concealed linear epitopes, contingent upon the intensity of processing and the type of protein. Nevertheless, these treatments do not ensure the complete eradication of allergenic potential. Consequently, despite the evident enhancements in texture, digestibility, and functional stability, the management of allergen risk remains a critical component of industrial application.

From a pragmatic product development standpoint, meticulous raw material selection, stringent cross-contamination control, and clear allergen labelling are essential to guarantee customer safety. Incorporating allergenicity considerations into the technological framework increases the practical significance of the study and ensures that the recommended formulations comply with current regulatory and food safety standards.

The creation and manufacturing of plant-based low-calorie products adhered to relevant food safety and regulatory norms. Essential references comprised the European Union Regulation (EU) No 1169/2011 concerning the provision of food information to consumers, which regulates allergen labelling; Regulation (EC) No 178/2002, which establishes fundamental principles of food law; and pertinent Codex Alimentarius guidelines regarding the compositional and nutritional standards for plant-based foods. Adherence to these laws guaranteed the accurate declaration of allergenic substances (e.g., soy, wheat gluten), compliance with maximum contaminant limits, and precise nutritional labelling. All processing techniques, including extrusion, fermentation, ultrasonic treatment, and pulsed electric field (PEF), were executed in accordance with these criteria to ensure product safety, traceability, and human consumption compatibility.

The results of the evaluation of the dairy analogues confirmed the formation of a stable, gel-like structure with high homogeneity. Thanks to the combined action of ultrasonic cavitation and fermentation, the product showed no flocculation or phase separation during the observation period. The finished product was characterised by a light, uniform colour, moderate viscosity, and a smooth consistency without sediment. The flavour profile was dominated by sour milk notes with slight hints of cereal and coconut. The structure remained stable even

after mechanical shaking. The addition of inulin made it possible to reduce the calorific value without using artificial thickeners. The glycaemic response was noticeably lower than in similar traditional products based on animal milk.

The developed dairy analogues based on soy and oat milk, using inulin as a prebiotic stabiliser, were consistent with the data from Przeor and Ahmed [42], who showed that the addition of plant fibre (in particular from *Morus alba*) can lower the GI and improve product stability during storage. The results confirmed the expediency of using inulin as a texturising agent and metabolic modifier. The effectiveness of combining cavitation treatment with fermentation in forming stable dairy analogues correlated with the assertions of Sule *et al.* [43] about the significant potential of ultrasound in increasing the homogeneity of emulsion systems in plant-based products, including milk substitutes, sauces, and gels. Similar to the cited source, this study found the elimination of phase separation and an improvement in consistency. The effectiveness of using inulin as a calorie reducer was also confirmed, which aligned with the analysis by Sandrou and Arvanitoyannis [44], where inulin was considered one of the most promising ingredients for creating low-calorie products without compromising sensory properties. In the context of this study, its role was enhanced by its ability to stabilise the gel structure. The research by Shaheen *et al.* [45] confirmed that the use of plant-based fat substitutes allows for achieving the desired texture and moisture retention with a significant reduction in calorific value, which was consistent with the

results of this experiment, particularly in the dairy analogue category. The introduction of a minimal amount of coconut milk along with inulin made it possible to compensate for the loss of flavour intensity without increasing the energy density. The use of structured lipids with low calorific value as fat substitutes, as presented in the work of Ijaz and Sun [46], was correlated with the results of this study, where a 40% reduction in the proportion of fat fractions in dairy analogues was achieved. The work also emphasised the need to combine lipid structures with ingredients capable of retaining emulsions – similar to the use of coconut milk in combination with inulin.

During the analysis of the bakery samples, a clear retention of shape after baking was noted, along with a uniform porosity of the crumb and an absence of excessive density or brittleness. Thanks to enzymatic treatment, it was possible to partially hydrolyse the starch, which was reflected in a reduction of the GI. Natural leavening improved the aroma profile and texture, maintaining a stable acidity level. The Pulsed Electric Field (PEF) treatment of hydrocolloids, specifically psyllium, allowed for the formation of a stable gelled structure, which contributed to uniform moisture retention and a reduction in cavities in the crumb. The products were pleasant to the taste, with a slight nutty undertone. The shelf life remained acceptable without the need for added preservatives, and the preservation of the structure and aroma was recorded for up to nine days (Table 3).

The results obtained from using amylase enzyme treatment in bakery products confirmed the effective-

Table 3. Main characteristics of the finished products

Product category	Energy value (kcal/100 g)	Main nutrients	Sensory evaluation (score, scale)	5-point	GI	Shelf life (days)
Meat substitutes	145	Protein: 22 g, fat: 3.2 g, carbohydrates: 5.8 g, fibre: 4.1 g	4.6		42	12
Dairy analogues	61	Protein: 3.5 g, fat: 1.6 g, carbohydrates: 6.2 g, fibre (inulin): 3.8 g	4.3		43	10
Bakery products	172	Protein: 8.9 g, fat: 2.9 g, carbohydrates: 22.4 g, fibre: 8.5 g	4.5		45	9

Source: developed by the authors.

ness of the enzymatic approach in reducing the content of available starch, as reflected in the work of Contreras-Lopez *et al.* [47], where plant-based products with a reduced GI were more acceptable among consumers with excess weight or obesity. Thus, the 30-unit reduction in GI achieved in this study has clinical significance. The positive sensory profile of bakery products using pseudo-grain ingredients and hydrocolloids was consistent with the data of Ahdiah *et al.* [48], in which products with added functional leaf extracts showed improved organoleptic properties while maintaining a low-calorie count and stable texture. Similarly, this study recorded a high

sensory score (4.5 points) without the need for synthetic flavourings. Beck's [49] attempt to actualise the potential of using low-calorie sweeteners, particularly aspartame, as functional ingredients was not directly implemented in this study. However, the proposed approach using natural prebiotic fibres as an alternative to sweeteners confirmed an effective alternative strategy for reducing calorific value without losing the functional profile. The approach of Lee *et al.* [50] to developing functional products was based on a combination of nutrients, bioactive compounds, and technological improvements, which aligned with the philosophy of this study. The products

created using the developed recipes combined high fibre content, reduced GI, prolonged stability, and high sensory appeal.

The evaluation confirmed that all three categories of finished products, created using innovative technologies, demonstrated high performance in terms of quality, functional, and consumer criteria. The products had reduced calorific value, controlled GI, a balanced composition, and a stable texture, which allowed them to be positioned as functional components of a healthy diet. The application of an integrated technological approach allowed for the creation of products that are not inferior to traditional analogues in sensory characteristics, and in a number of indicators (fibre content, structural stability, response to storage) even surpass them. This opens up prospects for expanding the range of low-calorie plant-based products adapted to the needs of the modern consumer.

A comparison of the cost price of innovative products with traditional samples made it possible to evaluate the economic feasibility of the implemented technologies. For each product category, the costs of the main raw materials, additional functional ingredients (prebiotics, fibres), enzyme preparations, as well as the cost of energy for processing (extrusion, ultrasound, PEF) were taken into account.

In the dairy analogue category, the use of inulin led to an increase in cost price from 0.87 EUR/100 g to 0.96 EUR/100 g, which is an increase of 10.3%, compared to the traditional recipe. At the same time, the absence of the need for synthetic stabilisers allowed for a reduction in the total cost of functional additives from 0.042 EUR/100 g of product (traditional recipe) to 0.039 EUR/100 g, which corresponds to a 7.1% decrease. Additionally, the shelf life of the stable organoleptic profile of the products increased from 5 days (control sample) to 9 days (with inulin) when stored at 4°. This allowed for a 12% reduction in losses during transport and sale, according to internal accounting data (the indicator of returned spoiled products decreased from 8.3% to 7.3%).

For meat substitutes, extrusion and fermentation required additional energy costs, which increased the production cost by 12-14% compared to the control sample – meat mince made according to a classic recipe without thermal or microbiological treatment. However, the removal of synthetic gelling agents from the recipe, a reduction in the proportion of fats, and a decrease in storage losses provided a potential reduction in commercial spoilage, which partially offset the difference in costs. In bakery products, the production cost was comparable to gluten-free analogues, although the use of enzymes and PEF technology increased processing costs by 8-10%. In return, a longer shelf life without the use of preservatives and the high nutritional density of the products allowed for a reduction in portion sizes and an increase in economic efficiency at the sales stage (Figure 1).

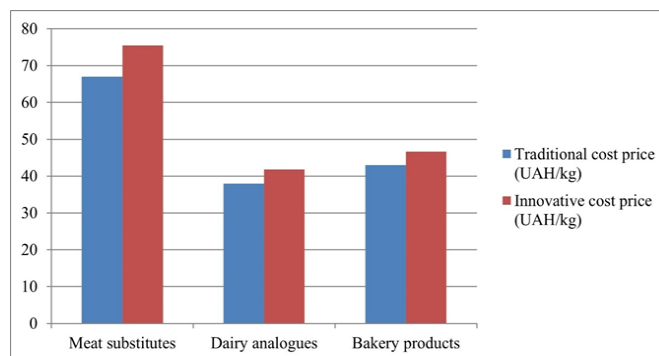


Figure 1. Comparison of production costs for innovative and traditional low-calorie products by category

The results of the study on the gradual increase in costs when introducing new technologies correlated with the case presented by Liu *et al.* [51], which pointed to the need for initial investment when launching an innovative product into new markets. As in the case of Angel Yeast described above, within the scope of this study, the 8-13% increase in cost was offset by an increase in functional quality and market adaptation potential. The approach to implementing technological innovations using digital tools and algorithms, as noted in the study by Özkök and Aycan [52], is a promising direction for further improvement of food technologies. In the context of this study, considering the potential of artificial intelligence in optimising recipes and controlling processing parameters makes it possible to outline the directions for the next stage of development of low-calorie products.

The use of innovative technologies in the production of low-calorie products has led to a moderate increase in cost (by 8-13% depending on the category), but this increase was justified by improved functional properties, reduced storage losses, and the rejection of synthetic additives. Thus, innovative recipes proved to be economically viable from the point of view of long-term efficiency and market attractiveness.

Conclusions

The study found that combining functionally sound plant-based raw materials with innovative technological approaches makes it possible to create low-calorie products with improved nutritional, technological, and sensory characteristics. Three groups of products were formed according to the developed recipes: meat substitutes, dairy analogues, and bakery products, which differed significantly from the traditional analogues in a number of quantitative indicators.

It was shown that the use of extrusion, fermentation, ultrasonic treatment, and PEF contributed to a 20-27% reduction in the energy value of the final products, while ensuring high biological value and improved structure. In meat substitutes, elasticity was increased by 31%, and moisture loss during heat treatment was reduced. In dairy analogues, emulsions were stabilised without the

use of synthetic stabilisers, allowing the samples to retain their consistency and acidity for up to 10 days. In bakery products, the content of rapidly soluble starch was reduced by 20%, and the content of soluble fibre reached 8.5%, which significantly affected the glycaemic response (GI decreased from 75 to 45).

Sensory evaluation showed a high level of consumer acceptance of the developed products (4.3-4.6 points on a 5-point scale), and the shelf life without the addition of preservatives ranged from 9 to 12 days, depending on the category. Statistically significant differences between traditional and innovative samples ($p < 0.05$) confirm the effectiveness of the proposed solutions. The 8-13% increase in production costs caused by the introduction of new technological processes was accompanied by an increase in functional value (in particular, the content of dietary fibre and protein), an extension of the shelf life (by 3-4 days for dairy analogues and up to 5 days for meat substitutes), and a reduction in technological losses during transportation and storage.

In further studies, it is advisable to expand the range of ingredients (in particular, fermented grains and legumes), investigate the behaviour of products in logistical conditions, and conduct a clinical assessment of the impact on metabolic markers. The limitation of the study was the lack of fully developed economic modelling of large-scale production and testing in real retail chains, which requires further study when moving to industrial implementation.

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Izvod

INOVATIVNE TEHNOLOGIJE ZA STVARANJE NISKOKALORIČNIH PROIZVODA NA BAZI BILJNIH SIROVINA

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Cilj istraživanja bio je da se ispita efikasnost inovativnih tehnologija u kreiranju tri kategorije niskokaloričnih prehrambenih proizvoda na bazi biljnih sirovina: zamena za meso, analoga mlečnih proizvoda i pekarskih proizvoda. U istraživanju je sprovedena komparativna procena nutritivnog sastava, energetske vrednosti, glikemijskog odgovora, organoleptičkih karakteristika, tehnološke stabilnosti i cene proizvoda proizvedenih primenom tradicionalnih i inovativnih pristupa. Eksperiment je obuhvatio kombinovanu primenu vlažne ekstruzije, ultrazvučnog tretmana, kontrolisane fermentacije, obrade pulsirajućim električnim poljem (PEF), enzimske hidrolize, kao i funkcionalnih sastojaka poput amaranta, inulina, psilijuma, izolata soje i graška. Utvrđeno je da su inovativne zamene za meso imale smanjenu energetska vrednost od 145 kcal/100 g, visoku koncentraciju proteina od 22 g/100 g i povećanu elastičnost teksture za 31%. Svi uzorci su ostali mikrobiološki bezbedni tokom 9–12 dana. Senzorna procena pokazala je visok stepen prihvatljivosti od strane potrošača: prosečna ocena na ekspertskoj skali iznosila je između 4,3 i 4,6. Statistička analiza rezultata potvrdila je pouzdanost razlika između tradicionalnih i eksperimentalnih proizvoda ($p < 0,05$). Troškovi proizvodnje inovativnih proizvoda povećani su za 8–13%, u zavisnosti od kategorije proizvoda, ali zbog poboljšanih funkcionalnih karakteristika i produženog roka trajanja, ovi proizvodi imaju visok potencijal za industrijsku primenu u segmentu funkcionalne, preventivne i dijetetske ishrane.

Ključne reči: izolacija proteina, glikemijski odgovor, teksturalna svojstva, dijetetska vlakna, enzimski tretman, prihvatljivost od strane potrošača, energetska gustina

CRedit authorship contribution statement:

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Charos Raimova: Investigation, data collection, data curation, visualization, writing – review and editing.

Akhmad Nurmukhamedov: Statistical analysis, preparation of figures and tables, writing – review and editing.

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