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FEATURES OF COMPOSITION DESIGN FOR GRAIN-BASED FUNCTIONAL FOOD PRODUCTS WITH PLANT-DERIVED INGREDIENTS

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Abstract. The rising prevalence of cardiovascular diseases, type 2 diabetes, certain types of cancer, and other conditions primarily caused by overweight and obesity has driven research into targeted health-oriented foods. This, in turn, has led to a significant increase in the production of functional food products. While the prebiotic effect is now a well-established scientific fact that has influenced dietary preferences, the need to improve the efficiency of production and the application of functional foods necessitates refining their formulation models and expanding the range of complementary ingredients. Synthesizing the research of numerous authors has allowed for the inclusion of extruded grains, honey and bee products, nuts, and hydrobionts as complementary ingredients. Furthermore, the efficacy of various food compositions is determined by their bifidogenic effect, which serves as a key factor in establishing the functionality of most targeted food products. The study determined that extruded corn, wheat, and barley grains exhibit the highest bifidogenic effect. It was also established that using corn as a base for extrudates in combination with plant ingredients such as pumpkin, parsley root, and carrot is highly effective, as these combinations promoted the maximum bifidogenic response. The highest counts of Bifidobacterium adolescentis cells were observed with the addition of the following extrudates: corn grain and pumpkin (7,7·107 CFU/g), corn grain and parsley root (5,4·107 CFU/g), barley grain and pumpkin (5,2·107 CFU/g), and corn grain and carrot (4,7·107 CFU/g). Given the industrial scale of pumpkin and carrot production, as well as the significant volume of by-products generated during their processing, it has been determined feasible to utilize them in the production of functional food products based on corn extrudates.

Keywords: functional food products, formulation model, complementary ingredients, corn grain, barley grain, wheat grain, pumpkin, carrot, celery root, parsley root, Jerusalem artichoke, bifidogenic effect.

Introduction. Formulation of the problem

While the health impact of both combined food products and their individual ingredients has been observed through practical experience since ancient times, recent scientific research has elucidated the mechanisms by which bioactive substances in specific food ingredients affect human health, primarily by modulating the microbiome, which in turn prevents a range of diseases [1]. Furthermore, while urban expansion and dominant industrial economic activities have improved many aspects of life quality and healthcare, they have simultaneously altered social interactions, leisure time, physical activity levels, and food accessibility; consequently, quality of life and longevity have become increasingly dependent on the safety, quality, and diversity of the diet [2]. In general, while modern populations enjoy increased leisure time and access to a broader range of food products, daily routines now demand less physical activity; however, these shifts have complicated the balance between energy intake and expenditure, as well as the consumption of essential nutrients and bioactive compounds. This imbalance has led to a global rise in the prevalence of overweight and obesity, significantly increasing the incidence of cardiovascular diseases, type 2 diabetes, certain types of cancer, and other conditions, which has prompted the search for targeted food products designed to improve human health [2]. Since the 1980s, food products that demonstrate effects on physiological functions and human health have been commonly referred to as functional, although their definition is often misinterpreted due to a lack of legal recognition in most countries [3]. However, Granato et al. (2017) recently defined functional foods as industrially processed or natural products that, when consumed regularly as part of a diverse diet at effective levels, exert potentially positive health effects that extend beyond basic nutrition [4]. In 2010, Roberfroid et al. established that the prebiotic effect is defined as the «selective stimulation of growth and/or activity of one or a limited number of microbial genera/species in the gut microbiota that confers health benefits to the host» [5].

Thus, the prebiotic effect is currently a well-established scientific fact confirming the functional nature of food products, which has led to a shift in dietary preferences and, in turn, significantly contributed to the intensive development of the global food market. According to research by Pakhucha E.V. and Sievidova I.O., global sales of functional food products exceeded $267 billion in 2020 (with the USA alone accounting for $47.9 billion), while sales of naturally healthy food reached $259 billion, and global sales of organic food and beverages surpassed $105 billion [6]. The global functional food market, valued at $280.7 billion in 2021, is projected to continue growing at a compound annual growth rate (CAGR) of 8.5%, reaching over $600 billion by 2030 [7].

Analysis of recent research and publications

A significant share of functional food products in global markets is represented by dry breakfast cereals, the global sales of which amounted to $96.1 billion in 2023, with expert projections suggesting an increase to $107.9 billion by 2030 [8]. These data indicate that while the global functional food market is expected to grow 2.14 times by 2030 compared to 2021, the global sales volume of dry breakfast cereals will increase by only 12% relative to 2023; this disparity highlights fundamental shifts in consumer preferences and underscores the necessity of refining the formulation models for functional food products.

In 2008, authors L.V. Kaprelyants and A.V. Iegorova proposed a model for formulating the composition of next-generation functional food products [9], based on compliance with sanitary-hygienic, microbiological, toxicological, and radiation safety standards, while the selection of complementary ingredients was relatively limited to cereals, vegetables, fruits, dairy products, and fats [9].

However, today not only have the approaches to formulating functional food products evolved, but the range of complementary components has also significantly expanded. These ingredients, for instance, enhance the prebiotic effect, thereby creating the prerequisites for further refining the formulation model for next-generation functional food products.

Indeed, functional foods are present across nearly all food categories, although they are unevenly distributed across market segments. Generally, these products command a higher price point and require compliance with specific legislative requirements during their production and sale [10]. Furthermore, the development of functional foods must account for consumer demands, as consumer perception has been identified as a key factor for the successful exploitation of market opportunities [10].

Recent studies have demonstrated the positive impact of thermal processing on enhancing the prebiotic properties of grain. Additionally, research into the prebiotic characteristics of honey, bee products, hydrobionts, and various nuts has expanded the range of complementary ingredients available for the production of functional foods [12, 16, 18, 19, 20, 27].

The production technology for dry cereal breakfast products is based on the extrusion processing of grains and/or grain mixtures [11], which enables the creation of grain products and grain-based derivatives with functional properties [12]. Consequently, grain extrudates have become widely used not only in the manufacturing of dry breakfast cereals but also across a broad range of functional food products [13, 14].

Studies by Coppola et al. (2025) have established that honey oligosaccharides possess potential prebiotic activity by selectively stimulating the growth of beneficial microorganisms such as Lactobacillus and Bifidobacterium [15]. Sanz et al. (2005) identified that the primary oligosaccharides in honey include disaccharides – such as turanose, nigerose, melibiose, sucrose, and isomaltose – as well as four trisaccharides: maltotriose, panose, melezitose, and raffinose [16]. Furthermore, honey contains antioxidant compounds like flavonoids, amino acids, phenolic acids, and glutathione, making it an attractive ingredient for functional food production [16]. However, their manufacturing process must account for the time-dependent instability and thermolability of certain phenolic compounds and glutathione.

While the use of nuts in human nutrition and food production has been known since ancient times, recent studies have confirmed their significant prebiotic effect. This evidence supports the inclusion of nuts as a complementary ingredient in the manufacture of functional food products [18].

Nuts are rich in bioactive substances, serving as one of the most abundant sources of polymerized polyphenols, which are primarily represented in nuts by ellagitannins and proanthocyanidins [20, 21].

After cereal grains, nuts are the products richest in dietary fiber [22]. Among them, almonds have the highest fiber content (12%), consisting primarily of insoluble fiber and a small amount of soluble fiber [22]. Dietary fibers, or plant cell walls, are mainly composed of non-starch polysaccharides – non-extractable material that is neither digested nor absorbed in the small intestine [23]. The non-bioavailable cell walls in nuts are represented by supramolecular structures such as cellulose, hemicellulose, pectic substances, and non-carbohydrate components [24]. These cell walls retain significant amounts of lipids and consist of proteins and polyphenols that remain in the large intestine after duodenal digestion, making them available for fermentation by the gut microbiota [19]. It is these specific properties that allow nuts to be included in the list of complementary ingredients for the production of functional food products.

In recent years, there has been a significant increase in research regarding bioactive substances in hydrobionts, particularly in marine algae. The primary seaweeds used for human consumption include: Nori or red algae (*Porphyra* spp.), Aonori (*Monostroma* spp. and *Enteromorpha* spp.), Kombu (*Laminaria japonica*), Wakame (*Undaria pinnatifida*), Hijiki (*Hizikia fusiforme*), Mozuku (*Cladosiphon okamuranus*), Sea grapes or Green caviar (*Caulerpa lentillifera*), Dulse (*Palmaria palmata*), Irish moss (*Chondrus crispus*), Winged kelp (*Alaria esculenta*), Ogo (*Gracilaria* spp.), and *Callophyllis variegata* [26]. These marine algae contain polysaccharides with a degree of polymerization (DP) ranging from 2 to 9, and occasionally from 8 to 20. These include galacto-oligosaccharides (GOS), agarose-derived oligosaccharides (AGAROS), xylo-oligosaccharides (XOS), neoagaro-oligosaccharides (NAOS), alginate-derived oligosaccharides (ALGOS), arabinoxylans, galactans, and glucans. As components of dietary fiber, they are not degraded by enzymes in the upper gastrointestinal tract and exhibit a prebiotic effect [27]. Such properties allow marine algae to be included in the list of complementary ingredients for the production of functional food products.

The effects of omega-3 fatty acids are widely recognized in the treatment and prevention of cardiovascular diseases, as well as in managing immunological, neurological, reproductive, and cardiovascular complications, and supporting general well-being [28]. Fish, particularly fatty marine fish, is a rich source of omega-3 fatty acids [29]. However, these fatty acids are unstable when exposed to oxygen, light, and heat. To ensure their protection, the addition of plant extracts containing phenolic compounds is recommended. This highlights the complementary nature of functional food ingredients such as omega-3 fatty acids and vegetables [29].

Thus, the model for formulating functional food products requires refinement, taking into account recent research findings, particularly those from the last decade. Furthermore, while extensive studies have recently been published regarding the prebiotic effects of extruded grains and the efficacy of various plant-based additives, there remains a lack of sufficient data on justifying the composition of such food products to achieve the maximum bifidogenic effect. This research gap necessitates a dedicated study.

Research materials and methods

The research materials for comparative analysis included data obtained by other authors, as well as samples of corn, wheat, hulled oats, barley, buckwheat, and millet grains. Additionally, plant ingredients such as pumpkin, carrot, Jerusalem artichoke, celery root, and parsley root were utilized. To determine the bifidogenic effect, classical research methods were employed, including the microbiological seeding of cultures from the genus *Bifidobacterium* (species *Bifidobacterium adolescentis, Bifidobacterium longum*, and *Bifidobacterium bifidum*) onto nutrient medium, microscopy, isolation, identification, and microbial counting.

Results of the research and their discussion

Since Istvan Siro et al. (2008) identified consumer requirements and their perception of new-generation food features as key factors for the successful exploitation of market opportunities [10], it is appropriate to base the functional food formulation model on a generalized matrix of such requirements, adapted to local markets.

Furthermore, a wide range of researchers has scientifically substantiated the feasibility of expanding the list of complementary ingredients for functional food production. Specifically, Remigio Yamid Pismag et al. (2024) [12], Kristina Ivanova et al. (2017) [13], Valentina Obradovic et al. (2014) [14], and others have justified the use of extruded grain, which possesses bifidogenic properties, as the primary component of breakfast cereals.

Studies by Coppola et al. (2025) [15], Sanz et al. (2005) [16], and Mustar (2022) [17] have identified a high level of prebiotic characteristics in honey. Furthermore, research conducted by Venketeshwer Rao et al. (2021) [18], Rosa (2017) [19], Abe et al. (2010) [20], Pérez-Jiménez et al. (2010) [21], Salas-Salvadó et al. (2006) [22], Phillips and Cui (2011) [23], Grassby (2014) [24], and others has substantiated the use of various types of nuts as functional food ingredients. Andrea Gomez-Zavaglia et al. (2019) [25], Holdt (2011) [26], De Jesus Raposo et al. (2016) [27], Wang et al. (2006) [28], and others demonstrated the feasibility of using marine algae as a functional food ingredient. Furthermore, Michalina Banaszak et al. (2024) [29], Matilde Rodrigues et al. (2024) [30], and other researchers have presented a novel perspective on the efficacy of omega-3 fatty acids in establishing a prebiotic effect in food products.

Thus, the model for formulating the composition of functional food products [9] can be enhanced by incorporating new complementary ingredients – such as grain extrudates, honey and bee products, nuts, and hydrobionts (including marine algae and omega-3 fatty acids) – based on an analysis of consumer expectations (Fig. 1).

Given the extensive list of grains, vegetables, and other complementary ingredients, it is necessary to justify the selection of those that best promote a maximum prebiotic effect, possess sufficient production resources, and meet the technological requirements for functional food manufacturing.

Innovative technologies such as high hydrostatic pressure, ultrasound, microwave processing, spray drying, and extrusion are employed in the production of functional foods. These methods involve minimal processing times and low temperature regimes, which prevent the degradation of bioactive compounds, extend shelf life, and preserve nutritional value, sensory quality, and food safety [31]. Among these technologies, the most effective and accessible is the extrusion technology developed at the Odesa National University of Technology [32, 33]. This process involves the extrusion of prepared grain mixtures and plant components subjected to short-term (15–25 s) thermal treatment. However, the question of selecting the optimal types of grain and plant components remains to be addressed.

A comparative analysis of the prebiotic properties of grains and selected plant components was conducted by seeding and monitoring the growth of Bifidobacterium and Lactobacillus species, which are among the most prevalent and beneficial representatives of the human microbiome [34]. The study accounted for the dominance of the genus *Bifidobacterium* in healthy individuals, specifically the species *Bifidobacterium adolescentis*, *Bifidobacterium longum*, and *Bifidobacterium bifidum* [35]. Following the inoculation of these *Bifidobacteria* species onto a standard nutrient medium and media supplemented with various types of raw and extruded grains (Table 1), it was established that, in most cases, prior extrusion of the grain had a positive effect on enhancing bifidobacterial growth. Among all grain types, extruded corn and wheat grains most effectively promoted the growth of *Bifidobacteria*. Furthermore, the most significant results were observed for the growth of *Bifidobacterium adolescentis* and *Bifidobacterium longum*.

The results presented in Table 1 indicate that the addition of extruded grain to the nutrient medium promoted enhanced growth of *Bifidobacteria*. However, corn grain may be preferred as, unlike barley, it does not require prior dehulling, which typically leads to increased production costs. Furthermore, the extrusion of corn grain exhibited higher process productivity (25% higher compared to wheat and 47% higher compared to barley), as well as lower specific energy consumption (18% lower compared to wheat and 35% lower compared to barley).

In subsequent experiments, the control (1) and samples of corn, wheat, and barley grains supplemented with 15% ground carrot (2), pumpkin (3), celery root (4), Jerusalem artichoke (5), and parsley root (6) were used for the inoculation of B. adolescentis (Fig. 2).

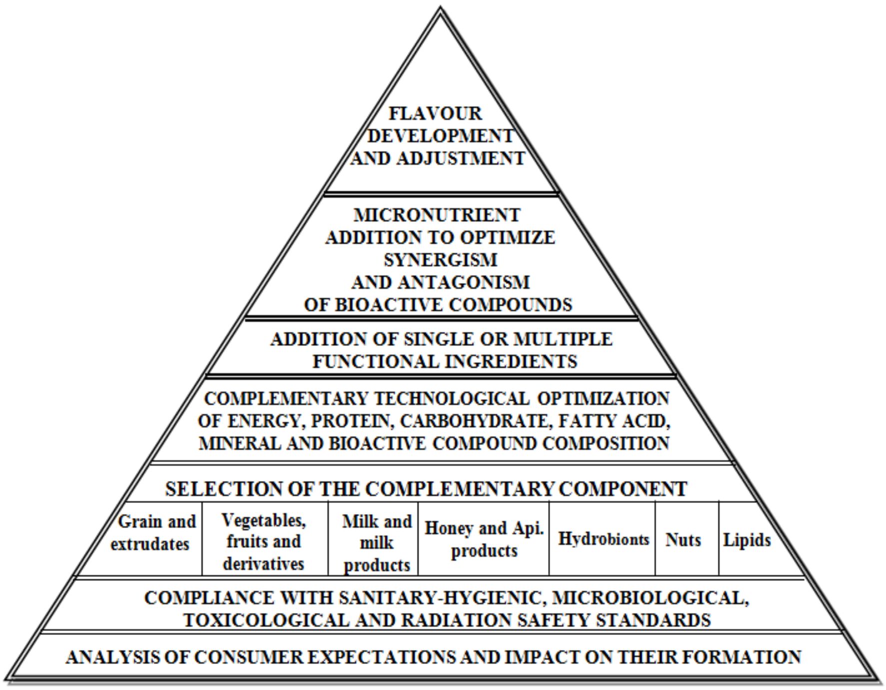

Fig. 1. Improved model for the formation of new generation functional food products

Table 1. The influence of grain type on the growth of *Bifidobacteria* (·10^7 CFU/g)

Grain type	*B. adolescentis*		*B. longum*		*B. bifidum*	
	raw	extruded	raw	extruded	raw	extruded
Control	2,1		1,8		2,3	
Oats*	2,5	2,7	2,9	2,8	2,2	2,4
Corn	4,5	4,85	4,7	5,3	4,4	5,0
Barley*	3,3	3,5	3,3	3,6	3,0	3,4
Wheat	2,2	2,35	2,15	2,30	1,8	2,0
Buckwheat*	1,8	1,9	1,9	2,0	1,75	1,8
Millet*	0,55	0,65	0,6	0,75	0,7	0,9

*hulled grain

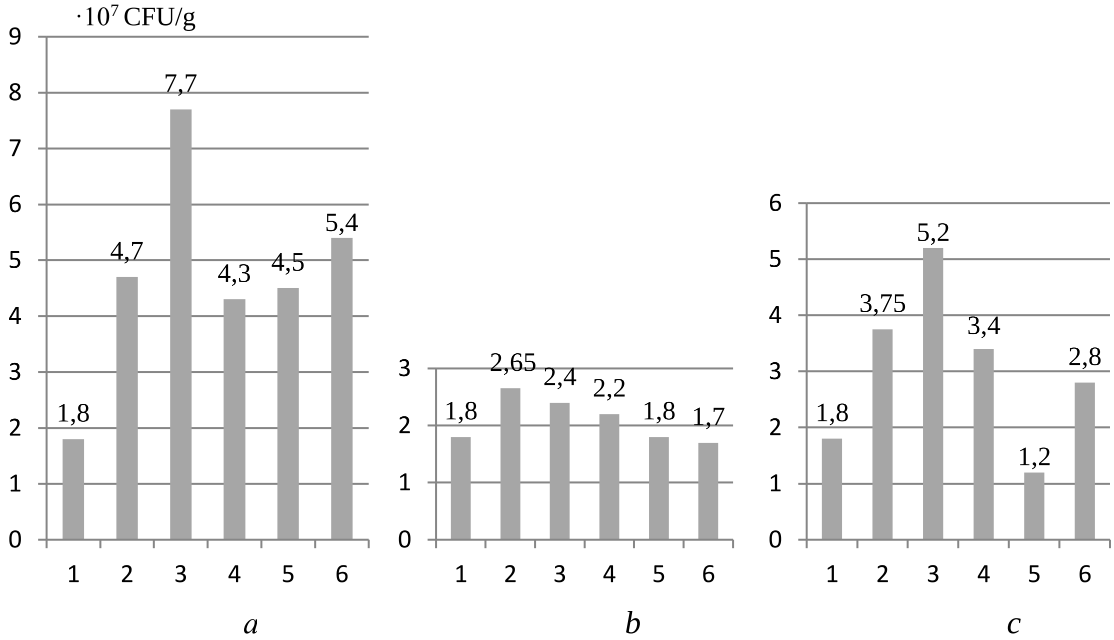

Fig. 2. Effect of various plant ingredients on the growth of *B. adolescentis* on extrudates

Based on corn (a), wheat (b), and barley (c): 1 – control, 2 – carrot, 3 – pumpkin, 4 – celery root, 5 – Jerusalem artichoke, 6 – parsley root.

As shown in the results presented in Fig. 2, the highest counts of *B. adolescentis* cells were observed with the addition of the following extrudates: corn grain and pumpkin (7.7·10^7 CFU/g), corn grain and parsley root (5.4·10^7 CFU/g), barley grain and pumpkin (5.2·10^7 CFU/g), and corn grain and carrot (4.7·10^7 CFU/g). Thus, for further theoretical and experimental justification of the composition of grain-based functional food products, corn grain, pumpkin, parsley root, and carrot can be recommended. However, given the limited scale of industrial production for parsley root, pumpkin and carrot remain the most commercially attractive options. Global pumpkin production in 2023 reached 27.832 million tons [36]. China ranks first in pumpkin production with 16.14 million tons (58%), followed by India in second place with 5.57 million tons, and Ukraine in third with 1.11 million tons (4%). In 2020, global carrot production was approximately 45 million tons, with a forecast of annual growth [37]. China is also the leader in carrot production at 21.4 million tons, while Uzbekistan and the USA rank second and third with 2.77 million tons and 2.25 million tons, respectively [37]. Ukraine is among the top five producers, with a production volume of 0.87 million tons [37].

Conclusion

As a result of the conducted research, the model for formulating functional food products has been enhanced. This model accounts for consumer requirements as a key factor for the successful utilization of market opportunities, while also incorporating current trends in expanding the range of complementary plant-based ingredients and hydrobionts.

Comparative experiments established that corn grain is the most suitable substrate for the production of extruded functional foods. Among the plant components, extrudates of corn grain combined with pumpkin, carrot, and parsley root exhibited the most pronounced bifidogenic effect. Given that varietal differences in the chemical composition and bioactive compound content of pumpkin and carrot are substantial, further experimental studies to determine their specific bifidogenic potential are of significant interest.

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ОСОБЛИВОСТІ РОЗРОБКИ СКЛАДУ ДЛЯ ФУНКЦІОНАЛЬНИХ ХАРЧОВИХ ПРОДУКТІВ НА ОСНОВІ ЗЕРНА З ІНГРЕДІЄНТАМИ РОСЛИННОГО

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Анотація Зростання частоти прояву серцево-судинних захворювань, діабету 2-го типу, деяких видів онкологічних та інших захворювань, основною причиною яких є надмірна вага та ожиріння, сприяє розвитку досліджень з пошуку харчових продуктів цілеспрямованого впливу на стан здоров'я людей, що призвело до значного зростання обсягів виробництва функціональних харчових продуктів. Пребіотичний ефект зараз є добре встановленим науковим фактом, який призвів до зміни харчових уподобань, але необхідність підвищення ефективності виробництва і використання функціональних харчових продуктів призвела до необхідності удосконалення моделі їх формування та розширення складу компліментарних інгредієнтів. Узагальнення результатів досліджень багатьох авторів дозволило внести до числа компліментарних інгредієнтів екструдоване зерно, мед і продукти бджільництва, горіхи і гідробіонти, а ефективність застосування харчових продуктів різного складу визначати за проявленням біфідогенного ефекту, як основного чинника формування функціональності більшості харчових продуктів цілеспрямованої дії. В ході досліджень було визначено, що найвищим біфідогенним ефектом володіє екструдоване зерно кукурудзи, пшениці і ячменю. Також встановлена доцільність використання кукурудзи в якості основи екструдатів у поєднанні з такими рослинними інгредієнтами, як гарбуз, корінь петрушки і морква, що сприяло проявленню максимального біфідогенного ефекту. Найбільша кількість клітин Bifidobacterium adolescentis виросла при додаванні екструдатів: зерна кукурудзи і гарбуза (7,7·107 КУО/г), зерна кукурудзи і кореня петрушки (5,4·107 КУО/г), зерна ячменю і гарбуза (5,2·107 КУО/г), а також зерна кукурудзи і моркви (4,7·107 КУО/г). Враховуючи індустріальні масштаби виробництва гарбуза і моркви, а також значну кількість побічних продуктів при їх переробці визначено доцільність використання їх для виробництва функціональних харчових продуктів на основі кукурудзяних екструдатів.

Ключові слова: функціональні харчові продукти, модель формування, компліментарні інгредієнти, зерно кукурудзи, зерно ячменю, зерно пшениці, гарбуз, морква корінь селери, корінь петрушки, топінамбур, біфідогенний ефект.