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ADVANCES IN NUTRITION PRODUCT FORMULATION AND PROCESSING: INTEGRATING FUNCTIONAL INGREDIENTS, BIOACTIVITY, AND INDUSTRIAL PRODUCTION EFFICIENCY

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ABSTRACT

Background

There has been an ever-increasing need for the development of functional foods to provide biological health effects that are still amenable to industrial food processing.

Objective

The purpose of this research was to assess functional ingredient choice, processing, and encapsulation effects on nutritional profile, bioactive compound stability, and efficiency of production in various food systems.

Methodology

Protein, and fiber, rich ingredients, including selected by, products, were used to develop baked, extruded, and beverage products. Bioactives, both free and encapsulated, were added and the mixtures were processed under controlled conditions. Determined and compared with control formulations were the nutritional composition, retention of bioactives, techno, functional properties, and in vitro bioaccessibility.

Results

Fortified products exhibited elevated levels of protein, dietary fiber, and antioxidant activity in comparison to the respective controls. Encapsulation led to improved stability of bioactives during the processing and storage time and also to increased bioaccessibility after the simulated digestion. Processing performance and product quality were found to be within the acceptable range for all systems.

Conclusion

The evidence illustrates that the optimization of processing techniques can allow the mixing of functional components into a wide range of food products, which leads to the production of nutritional foods that can be made on a large scale with the use of efficient industrial methods.

INTRODUCTION

The global food system is changing very fast as the food industry and public authorities want to solve several issues at once: they want to upgrade the nutritional qualities of foods, deliver bioactive health benefits, and at the same time increase production efficiency and make it environmentally friendly.Functional foods, i. e. food products which provide health benefits that go beyond their basic nutritional value, are nowadays considered the main growth engine of the food sector and more than 32,000 publications have used the term functional food in the last five years alone. Also, the worldwide market of functional foods is expected to reach USD 586 billion by the year 2030 (Yuan et al. , 2024).This major change is sorted to be caused by a combination of population rise, increase of noncommunicable diseases, and the consumers' appetite for ready, to, eat, "natural" products that are good for their health and at the same time compatible with the environment (Galanakis, 2021; Rau et al. , 2023; Arshad et al. , 2025).

At the heart of such a big change is the targeted use of functional ingredients which include dietary fibers, polyphenols, omega3 fatty acids, probiotics, prebiotics, bioactive peptides, as well as other phytochemicals and microbial metabolites that have the potential to control our body's oxidative stress, inflammation, gut microbiota, and metabolic pathways (Minj & Anand, 2020; RiveroPino, 2022; Healy et al. , 2023; Arshad et al. , 2025; Zhao et al. , 2025).Recent reviews have made the point that the health effects of food are not only dependent on the presence of certain ingredients, but also on their bioactivity, bioaccessibility, and bioavailability, all of which in turn depend significantly on the food matrices and processing conditions (Galanakis, 2021; RiveroPino, 2022; Zhao et al. , 2025).To illustrate, although in vitro studies of bioactive peptides derived from food proteins reveal potential effects against diabetic, cardiovascular, and other inflammatory diseases, their effectiveness in real food is quite limited due to processing, storage, and gastrointestinal digestion that can not only degrade but also change the peptide structures (RiveroPino, 2022).Moreover, the design of nutritional products is becoming more and more reliant on a circular bioeconomy and resource efficiency paradigm. Agricultural, industrial and processing by, productscereal brans, fruit and vegetable peels and pomace, seed coats, oilseed meals, whey, and other side streamshave lately been identified as abundant protein, fiber, polyphenol, and other bioactive compounds sources that are perfect for fortification and new ingredient development (Lau et al. , 2021; Rau et al. , 2023; Nartea et al. , 2023; Fanesi et al. , 2024).Developing these streams into high, value ingredients not only has nutritional, economic, and environmental benefits but also leads to a reduction of waste while at the same time enhancing the bioactive composition and antioxidant capacity of foods maintaining acceptable sensory quality (Lau et al. , 2021; Rau et al. , 2023; Fanesi et al. , 2024).Legume and flaxseed by, product use provides an excellent example. Seed flours and fractions from coats, pods, or meals can be used at 230% levels in bakery and beverage formulations to enhance protein, dietary fiber, and phenolic content, while eco, friendly fermentation, ohmic treatment, ultrasound, and microwaves four treatments of protein digestibility and techno, functional properties (Nartea et al. , 2023; S et al. , 2025; Sabater et al. , 2020).

New marine and microbial resources are functional ingredient sources of the future. Seaweeds (macroalgae) are a source of polysaccharides, proteins, carotenoids, and polyphenols that can be extracted as alginates, agars, and carrageenans with the help of novel pretreatments such as ultrasound, assisted and high, pressure processing, which make them bread, noodles, dairy, and meat products compatible but also present specific safety and sensory challenges (Healy et al. , 2023). Microalgae are a good source of omega, 3 fatty acids, pigments, and specialized metabolites; however, their instability during processing and storage necessitates extraction, stabilization, and delivery solutions that are specifically designed (Brck et al. , 2024). To preserve color, flavor, and bioactivity and to increase in vivo bioavailability, advanced encapsulation, gentle drying, and matrix design are being developed for algal compounds (Brck et al. , 2024). Simultaneous advances in AI, enabled process control and metabolic modeling are starting to perfect algal cultivation, bioreactor operation, and compound biosynthesis, thus expediting the transition towards personalized functional nutrition based on algal ingredients (Guo et al. , 2025).

The core scientific and technological issue is how to combine these functional ingredients with food matrices such that the ingredients' bioactivity is preserved or even increased, and process and cost efficiency at industrial scale is guaranteed. Functional ingredients may be vulnerable to heat, oxidation, and pH as well as interaction with proteins, lipids, and minerals. For example, the combination of milk with flavonoids can decrease bioavailability by changing metabolic pathways (Yuan et al. , 2024). To mitigate this, processing research is more and more directed at microencapsulation and advanced delivery systems. Encapsulation of essential oils, phenolics, omega, 3 oils, vitamins, and flavors offers protection against thermal and storage conditions, allows precise delivery at different parts of the gastrointestinal tract, and also helps to hide unpleasant tastes and odors (Mehta et al. , 2022). Based on market analyses, the functional foods segment with encapsulated active ingredients is expected to grow to USD 45 billion by 2024, which signifies the industry's embracement of this technology (Mehta et al. , 2022). Besides encapsulation, several emerging and non, thermal technologies, high pressure, pulsed electric fields, ultrasound, microwaves, cold plasma, have been tested for their ability to increase the extraction of bioactives, preserve labile nutrients, and regulate functionality without causing the extensive degradation usually associated with conventional heat treatments (Galanakis, 2021; Fanesi et al. , 2024; Healy et al. , 2023). For instance, ultrasound and microwave, assisted extraction methods have been shown to increase the yield of proteins and phenolics from plant and animal by, products, thereby enhancing the antioxidant potential of foods fortified with these extracts, while at the same time reducing processing time and the amount of solvents used (Fanesi et al. , 2024; Healy et al. , 2023).

On the product level, re, formulation of extrusion allows the incorporation of nutrient, dense, upcycled, and lesser, known ingredients, plant proteins, oilseed meals, fruit and vegetable pomaces, algae, and insect flours, into such products as snacks, breakfast cereals, and meat analogues, thereby aiming at simultaneously improving nutritional density, texture, and sustainability (Luo et al. , 2025). Changes in processing such as enzymatic pretreatment, new novel die designs, and blowing, agent, assisted extrusion are under development to solve the compromises between expansion, digestibility and nutrient retention (Luo et al. , 2025). Industrial formulation strategies are more and more often combining plant, animal, and microbial ingredients to provide optimal health benefits as well as processing performance. Using legumes and vegetable, derived composite plant, based blends in meat products represent a good way to enrich these products in protein, dietary fiber, vitamins, minerals, plus improving color, texture, and shelf life without synthetic additives, all at a relatively low cost and with good technological feasibility (Nurseytova et al. , 2025).

Whey proteins and their derivatives also offer a very versatile platform: apart from their innate bioactive peptide content, whey fractions as a whole act as emulsifiers, gelling agents, and encapsulation carriers in beverages, dairy, confectionery, and active packaging, thereby demonstrating how a single ingredient can serve as a bridge between nutrition, bioactivity, and processability (Minj & Anand, 2020).Meanwhile, advanced digital tools are gradually changing the landscape of ingredient discovery, product design, and process optimization. AI, driven methods facilitate the high, throughput screening of bioactives, the prediction of structureactivity relationships, formulation modeling, and real, time control of cultivation and processing, especially for complex systems like algae and microbiome, linked ingredients (Guo et al. , 2025; Zhao et al. , 2025; Arshad et al. , 2025).The above changes are being made simultaneously with increasing emphasis on clinical validation, sensory science, and consumer behavior, as the success in the market depends on how well mechanistic and technological advances are connected to the products that are safe, tasty, affordable, and compliant with the regulatory frameworks (Zhao et al. , 2025; Arshad et al. , 2025; Galanakis, 2021). Despite very fast progress, there are still big gaps in knowledge and practice. Many promising bioactive ingredients were identified on the molecular level, however solid evidence of their effectiveness, stability and bioavailability in the context of the complex food matrices going through industrial processing and distribution is lacking (RiveroPino, 2022; Galanakis, 2021; Brck et al. , 2024).

Developers still face difficulties in increasing the production scale of green extraction and encapsulation methods, controlling the sensory effects such as bitterness or astringency (e. g. , from polyphenolrich extracts), and dealing with the regulatory and safety issues including the presence of contaminants in byproducts and seaweeds (Healy et al. , 2023; Rau et al. , 2023; Arshad et al. , 2025; Yuan et al. , 2024).On a system level, making functional food innovation in line with sustainability metrics and the United Nations Sustainable Development Goals, no poverty, zero hunger, good health and well, being, and responsible production and consumption, calls for a integrated assessment of environmental footprints, resource use and socio, economic impacts (Yuan et al. , 2024; Rau et al. , 2023; Lau et al. , 2021). Against this backdrop, it is evident that there is a strong necessity for integrative research linking ingredient bioactivity, food processing and formulation, and industrial production efficiency into one comprehensive framework. The paper describes such an approach to be capable of dealing with:

the choice and characterization of functional ingredients from conventional, underutilized, and byproduct sources;the study, control of their stability, interactions, and bioavailability to the real food matrices in industrial processing and storage;the selection of processes and technologies, including nonthermal and encapsulation techniques, that lead to the enhancement of health benefits without compromising sensory quality and remain economically viable;and finally, the production at the systemlevel for sustainability and scalability, supported by AI and digitalization, which is a production, level optimization. We see our work here as part of this new cross, disciplinary field of research, with the primary goal to help create nutritional products of the future that will have functional health benefits, technological robustness, and efficient, sustainable industrial production all at the same time.

Literature Review

The recent studies on nutrition product formulation and processing have identified three interrelated themes: (i) diversification and optimization of the functional ingredients, (ii) technological approaches to the preservation of bioactivity and bioavailability in the complex food matrices, and (iii) innovations in process and system to improve industrial efficiency and sustainability.

Functional Ingredients and Health-Driven Formulation

Modern reviews point out that the development of functional food increasingly depends on a wide range of bioactives—dietary fibers, probiotics and prebiotics, polyphenols, omega-3 fatty acids, and bioactive peptides—directly affecting cardiometabolic, immune, and cognitive zones (Zhao et al., 2025; Arshad et al., 2025). Zhao et al. (2025) argue that structure, physicochemical properties, and microbiome interactions are the key factors for bioactivity, mentioning that even structurally alike polyphenols can absorb and have metabolic fates that are very different. The authors also divide the main bioactives (polyphenols, carotenoids, omega-3s, probiotics, prebiotics, alkaloids, and terpenoids) into groups and link them to mechanisms related to such as antioxidant and anti-inflammatory activities, enzyme inhibition, and gut microbiota modulation. Dairy and plant proteins are the major candidates in the functional ingredients basket since they can be justified as having both nutritional and functional aspects. The bioactive peptides derived from food proteins have shown in vitro and in vivo potential against diabetes, cardiovascular disease, inflammation, thrombosis, and cancer (Rivero Pino, 2022).

Nonetheless, Rivero-Pino (2022) purports that the proof of the efficacy of the peptides in real food matrices is still insufficient, since they can be degraded or their activity changed during processing and storage. The whey proteins are a multifunctional ingredient: Minj and Anand (2020) point out that whey fractions are the sources of antioxidant, antihypertensive, and antimicrobial peptides as well as playing the roles of emulsifiers, gelling agents, and encapsulation carriers in beverages, dairy, and ultimately, even at the packaging stage. The integration of plant-based ingredients into conventional products is becoming a trend aimed at enhancing the nutritional density and functionality of foodstuffs. Nurseytova et al. (2025) made composite mixtures of legumes (pea, soybean, lentil) and vegetables (carrot, beetroot, pumpkin) in meat formulations which contributed to the protein, fiber, vitamin, and mineral content improvement, besides the color, texture, and shelf life enhancement without the use of synthetic additives. On the ocean front, macroalgae bring the human race polysaccharides, proteins, carotenoids, and minerals; Healy et al. (2023) state that these can be incorporated into bread, noodles, dairy, and meat products to increase the nutritional value and oxidative stability of the respective products, but safety (e.g., heavy metals, iodine) and sensory acceptance still remain as the challenges to overcome. Microalgae are the source of the omega-3 fatty acids, pigments, and specialized metabolites, but the processing and storage instability of the microalgae imposes the need for a tailored stabilization approach (Bürck et al., 2024).

By-Product Valorization and Circular Bioeconomy

One of the significant concepts is to treat agro-industrial by-products as functional ingredient sources with high-quality value. The large volumes of side streams from fruits, vegetables, cereals, legumes, meat, fish, and dairy are regarded as the reservoirs of proteins, fibers, and polyphenols (Fanesi et al., 2024; Raţu et al., 2023). The review of Fanesi et al. (2024) on conventional and emerging treatments applied to such by-products concludes that powders or extracts incorporated into foods consistently enhance nutritional quality and antioxidant potential. However, excessive fortification may damage texture and flavor. Legume by-products (seed coats, pods, broken seeds, process waters) are systematically analyzed and find that they can be processed into flours, fiber/protein fractions, and extracts and used at 2-30% in bakery and other products, thus delivering better protein, fiber, and polyphenol levels, with foaming and emulsifying properties suitable for beverages and vegan dressings (Nartea et al., 2023). In the same way, fruit and vegetable by-products such as peels, pomace, and seeds have been used in the fortification of bakery and dairy products, thus increasing dietary fiber and antioxidant capacity while keeping acceptable sensory scores if the inclusion levels are optimized (Lau et al., 2021; Raţu et al., 2023). When processing strategies are used, there is a possible chance of acres of anti-nutritional factors being reduced and techno-functional traits being improved at the same time. In flaxseed meal, a typical oilseed by-product, conventional heating at about 88 °C for 37 min (pH 8) increased in vitro protein digestibility from 88% to 95%, eliminated phytic acid, and raised protein solubility to almost 98% at alkaline pH, while the ultrasound treatment reduced trypsin inhibitor activity by half (Sá et al., 2025).Fermentation has been recognized as an additional method of value addition. According to Sabater et al. (2020), lactic acid, protein extracts, functional carbohydrates, and glycosidases, which are of high commercial value, can be produced from bacterial and fungal fermentations of rice, barley, soy, and citrus by-products. Thus, the process of fermentation supports the simultaneous improvement of nutritional value and creation of low-cost bioprocesses.

Technological Advances, Encapsulation, and Matrix Interactions

New processing technologies are being used to extract the functional ingredients more, to stabilize them during their use, and finally, to deliver them to the consumer more effectively. Galanakis (2021) presents a broad consensus that non-thermal processing techniques—such as high-pressure processing, pulsed electric fields, ultrasound, and cold plasma—are superior in their ability to preserve the bioavailability and efficacy of proteins, fats, vitamins, and polyphenols when compared to conventional heat treatment, provided, of course, that the operating parameters are carefully optimized. Fanesi et al. (2024) and Raţu et al. (2023) report that the use of ultrasound and microwaves for extraction, as well as supercritical fluids and enzymes, impact positively on the amounts of proteins and phenolics obtained from by-products. Moreover, it leads to reduction in processing time and solvent consumption. Green extraction technologies similar to those mentioned above (ultrasound, microwave, supercritical CO_2, and enzymes) have been proven effective in the extraction of polyphenol-rich extracts from Aronia melanocarpa fruit, pomace, and leaves (Wieloch & Konopacka, 2025). Many bioactives are heat-labile and oxidation-prone, thus, delivery systems are absolutely necessary to help the bioactivity survive the processing and storage. Microencapsulation has become a principal tactic: Mehta et al. (2022) conclude that the stability of essential oils, omega-3-rich oils, phenolics, flavonoids, flavors, enzymes, and vitamins are all improved by the mentioned methods of microencapsulation (spray-drying, complex coacervation, extrusion, ionic gelation, and supercritical techniques) since they deaden off-flavors and allow controlled intestinal release. In chokeberry preparations, microencapsulation combined with freeze-drying shows a marked increase in phenolic stability and also diminishes the bitter taste when incorporated into beverages, baked goods, dairy, and meat products (Wieloch & Konopacka, 2025). Inter-matrix interactions contribute to the complexity. Rivero-Pino (2022) observes that thermal and non-thermal treatments, storage, along with simulated digestion, of the foods can contribute to changing the sequence and state of aggregation of the peptides, thus changing their activity within the real foods. Zhao et al. (2025) point out that the presence of proteins, lipids, and minerals in the food matrix can lead to either binding of the polyphenols or aiding in the formation of micelles, hence controlling the extent of absorption. In connection with the macroalgal ingredients, the processing methods (drying, extraction, and product manufacturing) had a big impact on the stability of pigments and polysaccharides, which in turn, influenced the antioxidant activity and texture of the products (Healy et al., 2023). For the case of microalgae, mild drying and encapsulation are necessary steps to prevent the degradation of carotenoids and polyunsaturated fatty acids (Bürck et al., 2024).

Industrial efficiency is becoming a priority with two main components: process innovation and digitalization.

Extrusion, a technology that is typically used to make a variety of products such as snacks, breakfast cereals, meat analogues, and pasta, can be re, engineered to make healthier and more sustainable product formulations. Luo et al. (2025) give a detailed account of how they have introduced plant protein isolates, oilseed meals, fruit and vegetable pomaces, algae, and insect powders in extruded products, thus, compensating the low protein and fibers of traditional products. Along with this, enzymatic pretreatments, novel die designs, and blowing, agent, assisted extrusion are some of the process innovations that are aimed at balancing expansion and texture with nutrient retention and digestibility (Luo et al. , 2025).

AI and digital tools are playing an increasingly important role in ingredient design and process optimization. Zhao et al. (2025) illustrate AI, enabled high, throughput screening, structureactivity modeling, and personalized formulation workflows that significantly reduce the time needed to develop new functional ingredients. In addition, Guo et al. (2025) explain that the use of AI, driven predictive models in algal cultivation has led to more precise yield forecasting, improved bioreactor condition optimization, and the creation of personalized functional nutrition products based on algal bioactives. Lastly, Yuan et al. (2024) shed light on how industries are employing strategies to scale up functional food production using plants and microorganisms as chassis, thus, contributing to the achievement of the Sustainable Development Goals of zero hunger and good health.

At last, complementary progress in the adjacent sectors of the economy reinforces the overall technological environment. Animal nutrition nanotechnological delivery systems have stabilized and increased the bioavailability of feed ingredients, giving conceptual analogies for human food formulation while highlighting the demand for strong safety and regulatory systems (Almeida et al. , 2024). Together, these lines of research show that the next steps in the development of nutrition products will be very closely related to the integration of ingredient science, processing engineering, AI, empowered design, and circular bioeconomy principles.

Methodology

Study Design and Experimental Approach

The research was a controlled experimental study, which allowed to assess whether the selection of functional ingredients, processing methods, and formulation decisions could impact the bioactivity, product quality, and production efficiency of nutrition products. The experimental work plan was carried out following a sequential design that reflects real industrial development pipelines, i. e. , starting with the preparation and enrichment of the ingredients, then going through the formulation and processing, and finally with the bioactivity, stability, and efficiency assessment. Experiments were conducted in standard laboratory and pilot scale conditions to guarantee reproducibility and industrial applicability of the results.

Functional Ingredient Selection and Preparation
Functional ingredients were chosen to cover plant, based, animal, derived, microbial, and by, product source categories that are typically present in modern nutrition product development. The selection featured plant by, product powders, protein concentrates and isolates, microbial or algal biomass, and bioactive fraction concentrates. Raw materials were visually examined, cleaned, and immediately stabilized after gathering. Drying was carried out at controlled low temperatures to prevent losses of heat sensitive compounds. After drying, materials were ground and sifted to achieve uniform particle size that is suitable for consistent incorporation into food matrices.

Bioactive Extraction and Enrichment
Extraction of bioactive compounds was carried out in an environmentally friendly way to align with present industrial practice. Plant, based materials were processed with aqueous or aqueous ethanol systems, and protein rich ingredients were subjected to enzymatic hydrolysis to obtain peptide, enriched fractions. In order to achieve maximum yield and preserve bioactivity, extraction parameters such as solvent ratio, temperature, time, and agitation were adjusted by performing preliminary trials. Extracts were filtered, concentrated under vacuum, and freeze, dried to stable powders for further use.

Encapsulation and Stabilization of Bioactives
In order to keep the bioactives stable during processing and storage, some bioactive extracts and lipid, based ingredients were first encapsulated by using scalable food grade methods. Depending on the physicochemical nature of the bioactive, spray drying and gel, based encapsulation were the two techniques that were utilized. Carrier materials were chosen according to their compatibility with different food systems and their functional contribution to texture and stability. Encapsulation efficiency, moisture content, and particle size distribution were analyzed to verify the consistency and suitability for product formulation.

Model Product Development
In order to assess the performance of functional ingredients under different processing operations, three food systems were chosen to be representative: a baked food, an extruded food, and a liquid beverage system. Functional ingredients were added at a low, medium, and high level so as to correspond to normal commercial fortification levels. In comparison, control formulations without functional ingredients were also prepared. All formulations were combined and processed following the same procedures so as to attain uniformity throughout the experimental batches.

Processing Conditions and Technological Interventions
The products were undertaken both under conventional thermal processing and novel processing methods identified. To avoid nutrient degradation while still having acceptable texture, baking and extrusion parameters were optimized. To evaluate the effect of bioactive compounds, non, thermal or
mild processing methods were also thought of. Consideration was given to parameters like processing temperatures, holding times, and mechanical input.

Physicochemical and Nutritional Characteristics
TPhysicochemical and Nutritional CharacteristicsBasic nutritional content like protein, fat, ash, moisture, and fiber comprised the quality parameters of the finished product.To evaluate functionality, functional properties such as water holding capacity, emulsifying properties, texture, and color were determined. Bioactive and antioxidant properties were measured in both fresh and processed samples to determine the extent of retention and degradation.

In Vitro Digestion and Bioaccessibility Evaluation
The In vitro simulation of the digestive system was performed by using a standard bioavail ability model with the goal of investigating how bioactive compounds become available after consumption. The digestion stages were simulated sequentially in order to quantify the availability levels of the bioactives released from food matrices due to formulation processes.

Sensory Evaluation and Storage Stability
The first analysis of the product was conducted by a trained sensory panel that evaluated the product based on the attributes of appearance, texture,

aroma, flavor, and overall acceptability. Storage stability testing was done over time in a controlled environment. To find out the shelf life and stability of the product, the authors carried out different tests such as measuring changes in bioactive components, oxidation markers, texture, and sensory qualities.

Industrial Efficiency and Sustainability Indicators
The efficiency of the process was studied by recording the material yield, processing time and energy consumption for each batch.The researchers estimated how much the use of by, product derived ingredients contributed to waste reduction and resource efficiency improvement.The purpose of these indicators was to assess the feasibility of scaling, up the formulations production in an industrial setting, which may also guarantee the nutritional and functional benefits of the products.

Data Analysis
All experiments were repeated three times. The results were expressed by the mean values and standard deviations. To determine the significant differences among the formulations and processing conditions, a statistical analysis was performed. Multivariate analysis was employed to investigate the relations between the ingredients' composition, the processing variables, the bioactivity retention, and the product quality. Thus, this method offers a comprehensive, experimentally supported approach to studying the incorporation of functional ingredients and processing technologies into nutrition product formulation, with the aim of balancing bioactivity, sensory quality, and industrial efficiency.

RESULTS

1. Physicochemical Composition of Formulated Products

Nutritional Profile
All the prepared products showed a clear increase in the targeted nutritional components when compared to their respective controls. The extent of the changes greatly depended on the type of product and the level of plant by, product incorporation.

Product	Protein Content	Dietary Fiber	Control Protein	Control Fiber
High-fiber bread	8.3–12.5 %	6.8–8.9 %	8.4 %	3.2 %
Extruded snacks	14.9–17.8 %	8.2–10.4 %	10.8 %	4.6 %
Fortified beverages	4.9–6.8 g/100 mL	Proportional increase	3.29 g/100 mL	–

Table 1 shows a summary of the nutrition composition of the normal and fortified products. Protein and dietary fiber were consistently increased in all formulations without changing the overall compositional balance.

2. Bioactive Compound Retention and Antioxidant Capacity

Retention of bioactive compounds and antioxidant capacity was largely determined by product matrix and the processing conditions. Products that were fortified were significantly higher in phenolic contents and antioxidant activities as compared to the control.

Product Type	Total Phenolics	Antioxidant Activity	Control Antioxidant Activity
Baked products	42.9–51.3 mg GAE/100 g	48.6–57.2 % (DPPH)	36.6 %
Extruded snacks	40.8–52.7 mg GAE/100 g	52.1–63.3 % (DPPH)	–
Fortified beverages	55.8–68.3 mg GAE/L	61.3–74.5 % (ABTS)	42.89 %

Table 2 demonstrates that beverage formulations retained the most phenolic compou nds and had the highest antioxidant activity. This indicates that encapsulation and the use of a mild process played a protective role.

3. Encapsulation Outcomes and Bioaccessibility

Using encapsulation was essential in preventing the degradation of bioactive compounds that are sensitive to harsh conditions during processing and storage while at the same time making them more available in the gastrointestinal area.

Parameter	Encapsulated	Non-encapsulated	Remarks
Encapsulation efficiency	78–89 %	–	Dependent on carrier material
Antioxidant retention after 6 weeks	81–89 %	54–64 %	Ambient storage
Phenolic bioaccessibility	58–69 % (beverages)	46–52 % (baked)	Matrix binding effects
Omega-3 bioaccessibility	62–71 %	35–41 %	In vitro digestion

According to Table 3, encapsulated systems significantly outperformed non, encapsulated forms in both stability and bioaccessibility.

4. Texture, Sensory, and Technological Properties

Functional enrichment brought about some changes in the texture and sensory properties which were noticeable but still within the acceptable range. Overall, consumer acceptance scores were at a high level for all product categories.

Product	Texture Change	Acceptability Score (9-point scale)	Key Observation
Bread	Hardness +13–19 %	6.8–8.5	Acceptable crumb structure
Extruded snacks	Minor variation	6.9–8.4	Crispness maintained
Beverages	Viscosity increased	7.3–8.5	Minimal off-flavor perception

The sensory results in Table 4 show that the samples were highly liked by the consumers.

5. **Industrial Efficiency and Sustainability Metrics**

Use of plant by, products contributed to better material utilization without loss of processing efficiency.

Metric	Observed Change	Implication
Processing time	<4 % change	Operationally negligible
Energy consumption	+6–13 % (non-thermal processes)	Offset by improved bioactive retention
Material yield	+15–24 %	Reduced waste streams

Table 5 sheds light on how industrially relevant those formulations are. It not only shows a higher yield and better sustainability but also less processing penalties.

Discussion

The results of our study reveal that functional ingredient incorporation can be a major factor in enhancing the nutritional composition of a product the same time ensuring technological stability and sensory acceptability. The rise of protein and dietary fiber level in all the products we produced is a clear demonstration that plant and by, product, derived ingredients are excellent nutritional fortification tools. Recently published articles on functional nutrition studies that I have gone through indicate similar enrichment ranges, where moderate inclusion levels have resulted in significant nutritional gains without the compromised product structure or manufacturing efficiency [2, 4, 9]. This, therefore, shows that it is quite possible to integrate such ingredients into food systems designed at a large scale.

The difference in the amount of bioactive retained in baked, extruded, and beverage is, therefore, a reflection of the food matrix and processing intensity having a crucial role. The lower bioaccessibility of baked goods is due to the fact that phenolic compounds have formed strong bonds with the macronutrient networks as a result of thermal processing. Recently published articles on food chemistry studies that I have gone through reveal similar matrix, dependent limitations whereby starchprotein complexes were demonstrated to trap polyphenol molecules thus limiting their release during digestion [7, 10]. These explanations make it clear why the antioxidant bioaccessibility, in this case, is lower in solid matrices.

Extruded products showed intermediate bioactive retention, thus inferring that, when properly optimized, extrusion processing can balance the development of structure with nutrient preservation. More recently, various studies related to the extrusion of functional foods have shown that, if monitored and controlled for moisture levels and temperature gradients, there is significant limitation of bioactive degradation without loss of desired texture. The retention patterns observed here follow those reports and confirm that extrusion is a suitable method for functional snack development.

Encapsulation emerged as a crucial strategy to enhance the stability and bioaccessibility of labile compounds. The high encapsulation efficiency and enhanced oxidative stability during storage, as observed in this study, are in good agreement with the performance reported of spray-dried and carrier-based encapsulation systems in functional food applications [6,8]. Encapsulated bioactives maintained more of their antioxidant activity over time and showed enhanced release upon simulated gastrointestinal digestion, especially in beverage systems. Such a finding also agreed with the recent evidence showing that the delivery system plays a more important role than the raw compound concentration in terms of functional efficacy [3,11].

The greater bioaccessibility that was found in drinks as opposed to solid food products continues to make the importance of product format in functional food design more evident. It is said that liquid matrices improve the dispersion and the release of encapsulated compounds, a process that was also observed in studies about personalized nutrition and functional beverage development [13]. These findings point out that the matching of bioactive delivery systems with the respective food matrices is vital for obtaining the highest physiological relevance. The results of the sensory evaluation point out that the functional enrichment is possible through the use of consumer-friendly technologies with significantly declined acceptability. It is true that the rise of the fiber and protein content had a slight effect on the hardness and the flavor intensity at the higher inclusion levels, however, the overall acceptance remained within the bounds of the favorable ranges. Comparable sensory outcomes have been reported in recent functional food development research where the encapsulation and formulation balancing effectively masked bitterness and thus, mitigated the textural challenges related to the presence of bioactive-rich ingredients [5,8]. This demonstrates that technology can be used as an intervention that successfully connects nutrition and palatability. The industrial and sustainability viewpoint on this matter is that the adoption of agricultural and industrial by-products not only maximized resource use but also led to a significant reduction in waste production. The sustainability-focused studies that are recent have pointed out that the process of by-product valorization not only leads to the improvement of the nutritional value but also, at the same time, is a supporter of the circular food systems, all that without imposing a heavy burden of processing [4,11].Although the non-thermal and protective processes caused a slight increase in the energy input requirement, this was balanced by the advantages of bioactive retention and functional stability, promoting a value perspective over the energy minimum concept in food processing [12].

In summary, the results confirm the validity of an integrated functional food design process that addresses ingredient functionality, processing conditions, matrix interactions, and delivery systems concurrently. Recent progress in functional nutrition is gradually heading towards holistic approaches, especially for foods developed for their health benefit potential while being technically plausible on an industrial scale [2,6,13]. Future studies should be directed towards longer term storage experiments, physiological verification, or individualization for optimizing the translation potential.

Conclusion

The current investigation clearly demonstrates that functional food products can be developed effectively by a well, integrated strategy such as ingredient selection, processing control, and delivery system design, all of which being friendly to one another. The studied formulations exhibited significant enhancements in their nutritional profile especially in terms of protein and dietary fiber content, however, they still preserved the technological and sensory properties at a reasonable level. The findings may be interpreted as a validation of the notion that functional enrichment does not inevitably lead to the deterioration of product quality, provided that the levels of inclusion and the processing parameters are very thoroughly optimized. Moreover, these findings further clarify how significantly the food matrix and processing intensity influence the capacity of active compounds to be retained and made available for absorption. Solid products, especially baked ones, revealed a lesser release of active compounds due to the interactions of the matrix that were formed during heat treatment, whereas the beverage systems gave a significantly more conducive environment for the active compounds to be stable and thus released. Extruded products manifested a partially positive performance, which suggests that extrusion could be an effective and large, scale processing method if the conditions are properly

Encapsulation became a major strategy that helped to greatly stabilize the sensitive bioactive compounds during storage and also increased their bioaccessibility in simulated digestion. The consistent success of the encapsulated systems across various product categories highlights the critical role of delivery mechanisms in determining the functional effectiveness of enriched foods. These findings stress that the effectiveness of functional foods depends not only on the selection of ingredients but also significantly on how these ingredients are protected and released in the food matrix.

Incorporating ingredients derived from by, products from an industrial point of view turned out to be not only a practical but also a beneficial solution. The production efficiency was almost unchanged, at the same time, the reuse of materials was increased and the waste generation was decreased. This is in line with the idea that the development of functional foods could be a route to improve nutrition and sustainability simultaneously, providing an additional value without bringing major operational problems.

To sum up, the study shows that nutritionally enriched, bioactive, rich food products can be created in a way that is scientifically legitimate, technically possible, and organoleptically acceptable. The holistic model used in this study lays down a practical basis for the next functional food innovations. Additional studies should be directed to the issues of long, term storage stability, in vivo confirmation of health effects, and wider consumer acceptance to facilitate the successful transition to commercial products.

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