EMERGING TECHNOLOGIES FOR FUNCTIONAL FOOD PRODUCTION: BIOACTIVE COMPOUND STABILITY, BIOAVAILABILITY, AND FUTURE PERSPECTIVES

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Abstract

Functional foods are a rapidly developing area of the modern food industry, providing bioactive components with potential physiological benefits beyond basic nutrition. This review analyzes modern technologies for functional food production and their effects on the stability, bioaccessibility, bioavailability, and quality of bioactive compounds. Literature from Scopus, Web of Science, PubMed, and ScienceDirect was reviewed using relevant keywords. The findings indicate that fermentation, microencapsulation, and nanoencapsulation can improve the stability and functionality of bioactive compounds, while non-thermal technologies such as high hydrostatic pressure, pulsed electric field, and ultrasound help preserve food quality. However, challenges remain regarding compound stability, bioavailability, sensory properties, safety, cost, and industrial scale-up. Future developments are expected to focus on advanced encapsulation, postbiotics, 3D food printing, and artificial-intelligence-assisted personalized nutrition.

Keywords: functional food, bioactive compounds, probiotics, prebiotics, postbiotics, fermentation, microencapsulation, nanoencapsulation, high hydrostatic pressure, pulsed electric field, bioavailability, 3D food printing.

1. INTRODUCTION

The increasing demand for healthy nutrition is strengthening the need in the food industry to develop products that are not only nutritionally valuable but may also support physiological functions of the human body. In this context, functional foods have become an important research area at the interface of food technology and nutritional science [1].

The concept of functional foods refers to food products that may provide specific physiological or metabolic benefits beyond their basic nutritional value. The functional properties of such products are associated with components such as probiotics, prebiotics, postbiotics, polyphenols, carotenoids, omega-3 fatty acids, dietary fibers, bioactive peptides, vitamins, and minerals [1,2].

However, incorporation of a bioactive component into a food product does not automatically ensure high functional efficacy. During processing, storage, and consumption, temperature, oxygen, light, pH, and interactions with the food matrix may alter the chemical and biological properties of bioactive components [1,3].

Stability and bioavailability are particularly important issues for polyphenols, carotenoids, and omega-3 fatty acids. In probiotic foods, a major technological challenge is maintaining sufficient microbial viability throughout production and storage [2,4].

Therefore, the main task of modern functional food technology is not limited to incorporating bioactive components into a product. It also involves ensuring their stability during processing and storage, controlling their release under gastrointestinal conditions, and facilitating their effective utilization by the human body.

In recent years, fermentation, microencapsulation, nanoencapsulation, high hydrostatic pressure (HPP), pulsed electric field (PEF), ultrasound, and 3D food printing have emerged as promising approaches for addressing these challenges [2,5–8].

The aim of this review was to analyze modern technologies used in the production of functional food products on the basis of scientific literature, identify their major advantages and limitations, and assess future development prospects.

2. MATERIALS AND METHODS

This study was conducted as a critical review of the scientific literature. The Scopus, Web of Science Core Collection, PubMed, and ScienceDirect databases were used for literature retrieval.

The primary search period covered 2015–2026. Selected earlier publications that provide fundamental theoretical foundations for the subject were also considered.

The selected literature was comparatively analyzed according to the type of functional component, processing technology, stability of bioactive compounds, bioaccessibility/bioavailability, product quality, and potential for industrial-scale application.

3. RESULTS AND DISCUSSION

3.1. Major bioactive components of functional foods

The literature analysis showed that functional food products contain components with diverse chemical and biological characteristics. Their technological properties and stability differ substantially Table 1.

Table 1. Bioactive Components and Their Functional Properties

Bioactive component	Main sources	Functional significance	Main technological challenge	Potential solution
Probiotics	Dairy and fermented products	Support of gut microbiota	Sensitivity to heat and storage	Encapsulation
Prebiotics	Inulin, FOS, GOS	Substrate for beneficial microorganisms	Stability and formulation	Controlled processing
Postbiotics	Fermentation metabolites	Bioactive metabolites	Standardization	Controlled fermentation
Polyphenols	Fruits, vegetables, tea, cereals	Antioxidant and other biological activities	Low bioavailability	Nano/microencapsulation
Omega-3	Fish, microalgae, plant oils	Support of lipid metabolism	Oxidation	Emulsion/encapsulation
Dietary fibers	Cereals, legumes, fruits and vegetables	Gut function	Texture and sensory properties	Matrix optimization
Bioactive peptides	Milk, cereals, legumes	Various physiological functions	Processing sensitivity	Encapsulation
Carotenoids	Carrot, tomato, plants	Antioxidant activity	Light and oxidation	Encapsulation

Granato et al. [1] emphasized that development of functional food products requires evaluation not only of the biological efficacy of bioactive components but also of their

technological stability and safety. Probiotics, prebiotics, and postbiotics constitute important groups of functional food components. The efficacy of probiotics depends on their ability to reach consumers in sufficient viable numbers, whereas postbiotics provide an opportunity to use bioactive microbial metabolites without relying on live microorganisms [2,4].

3.2. Fermentation technology

Although fermentation has long been used in functional food production, modern biotechnological approaches are expanding its applications. During fermentation, microorganisms may produce organic acids, bioactive peptides, vitamins, and other metabolites [2]. Fermentation of cereals and legumes may reduce certain antinutritional factors and improve the utilization characteristics of proteins and phenolic compounds. In dairy products, fermentation forms the basis of many probiotic functional foods. However, fermentation outcomes strongly depend on the microbial strain, temperature, pH, substrate composition, and process duration. Therefore, standardization of fermentation under industrial conditions remains an important technological issue [2].

3.3. Microencapsulation

Microencapsulation is a widely used technology for protecting bioactive components from environmental influences. In this approach, a bioactive component is surrounded by a protective wall material, reducing degradation caused by oxidation, moisture, light, or temperature. Probiotics, omega-3 fatty acids, polyphenols, and vitamins can be protected using microencapsulation [5]. Major techniques include spray drying, freeze drying, extrusion, coacervation, and ionic gelation. Recent studies indicate that the value of encapsulation lies not only in protecting bioactive components but also in enabling their controlled release under gastrointestinal conditions [5,6].

3.4. Nanoencapsulation and bioavailability

Nanoencapsulation is a modern approach aimed at improving the dispersion, physical stability, and bioaccessibility of bioactive compounds. Polyphenols are a representative example. Although many of these compounds have considerable biological potential, their solubility in the food matrix, chemical stability, and behavior under gastrointestinal conditions may limit bioavailability. Consequently, modern delivery systems aim to optimize the sequence of food matrix, digestion, release of the bioactive compound, bioaccessibility, intestinal absorption, metabolism, and biological effect [6].

3.5. High hydrostatic pressure technology

High hydrostatic pressure (HPP) is a non-thermal technology that enables food processing under relatively low thermal load. HPP can improve microbiological safety while allowing some nutritional and sensory properties to be retained better than under conventional high-temperature processing [7]. A major limitation of HPP is the high initial cost of equipment and the need to optimize technological parameters for specific food matrices [7].

3.6. Pulsed electric field

Pulsed electric field (PEF) technology is based on applying short-duration electrical pulses to food products. It can induce electroporation of cell membranes, thereby improving mass transfer and release of certain bioactive compounds. PEF is considered promising for processing fruit and vegetable juices, extraction processes, and microbiological stabilization of selected food products [8]. Its effectiveness depends on electrical conductivity, moisture, microstructure, and applied electrical parameters.

3.7. Ultrasound technology

Ultrasound technology is based on cavitation and can be used to improve extraction of bioactive compounds, mass transfer, emulsification, and homogenization. Ultrasound-assisted extraction can increase recovery of phenolic compounds, flavonoids, and other bioactive substances from plant materials. However, excessive energy, unsuitable frequency, or

prolonged treatment may cause degradation of sensitive compounds. Therefore, optimization of processing parameters is essential.

3.8. Postbiotics

Postbiotics have emerged in recent years as a promising direction in functional foods. They comprise biologically active components produced by or derived from microorganisms. Their potential advantage is greater technological stability under certain processing conditions compared with live microorganisms. However, standardization, dose optimization, safety, and clinical efficacy in humans remain insufficiently resolved [9].

3.9. 3D food printing

3D food printing represents an emerging generation of functional food technology. It enables control over product composition, shape, texture, and the distribution of selected functional ingredients. The technology may facilitate personalized food formulations and precise incorporation of probiotics, vitamins, minerals, and other bioactive components [10,11]. Major limitations include production speed, equipment cost, food safety, and industrial scale-up.

3.10. Comparative characteristics of modern technologies

Modern technologies used in functional food production differ in their mechanisms of action, technological advantages, and limitations. Their effectiveness depends on the type of bioactive compound, food matrix, processing conditions, and desired functional properties of the final product. A comparative overview of the main technologies is presented in Table 2.

Table 2. Modern Technologies for Functional Food Production

Technology	Main function	Advantage	Main challenge	Prospect
Fermentation	Production of bioactive metabolites	Natural biotechnological process	Standardization	High
Microencapsulation	Protection	Improved stability	Additional processing step	Very high
Nanoencapsulation	Delivery/bioavailability	Potentially improved bioaccessibility	Safety	Very high
HPP	Preservation	Low thermal load	Equipment cost	High
PEF	Preservation/extraction	Rapid processing	Parameter optimization	High
Ultrasound	Extraction/emulsification	Improved mass transfer	Parameter dependence	High
Postbiotics	Functional ingredients	Stability	Clinical/regulatory issues	Very high
3D printing	Personalization	Individual formulation	Production speed	Very high

3.11. Integration of functional food technologies

The literature indicates that future functional food production systems may rely not on a single technology but on combinations of several technologies. For example, fermentation may be used to generate bioactive components, encapsulation to protect them, HPP or PEF to improve microbiological stability, and 3D printing to enable individualized formulation. Such integrated approaches may allow simultaneous control of technological stability, bioaccessibility, and adaptation to consumer needs.

The integration of emerging processing and delivery technologies provides new opportunities to improve the stability, bioaccessibility, and bioavailability of bioactive

compounds in functional foods. These approaches also contribute to the development of innovative, safe, sustainable, and personalized functional food products **Figure 1**.

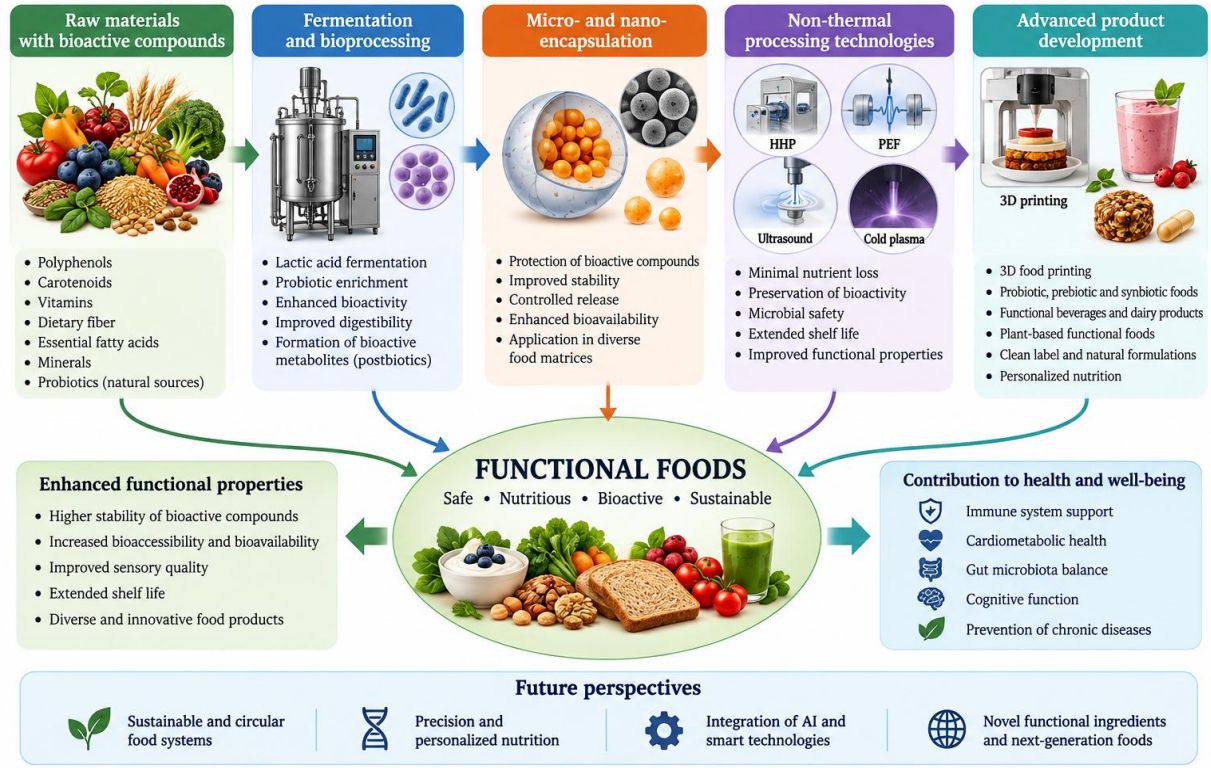

Figure 1. Integration of emerging technologies in functional food production and their potential benefits for health and well-being.

The integrated application of fermentation, encapsulation, non-thermal processing, and advanced product development technologies can improve the functional properties and technological stability of bioactive compounds. As illustrated in Figure 1, these approaches provide a technological basis for developing next-generation functional foods.

4. MAJOR CHALLENGES AND FUTURE PERSPECTIVES

Despite advances in functional food technologies, bioavailability, technological stability, sensory properties, safety, industrial scale-up, and regulatory requirements remain major challenges. A high concentration of a bioactive component in a food product does not necessarily mean that it will be highly bioavailable in the human body. Therefore, future studies should evaluate the stability → bioaccessibility → bioavailability → biological efficacy sequence in an integrated manner [1,6].

In addition, incorporation of bioactive components may alter the taste, aroma, color, or texture of foods. Consequently, consumer acceptance should be considered alongside technological and biological efficacy. New delivery systems, nanoencapsulation approaches, and postbiotic products require additional evidence regarding safety and clinical effectiveness [1,9].

Future development of 3D food printing, artificial intelligence, machine learning, and personalized nutrition technologies may expand opportunities to tailor functional foods to individual nutritional needs [10,11].

5. CONCLUSION

Functional food production is an important scientific and technological direction of the modern food industry, and its development is moving from simple fortification toward integrated technological systems based on controlled delivery of bioactive components.

Fermentation is important for generating bioactive metabolites and increasing the functional value of raw materials, while microencapsulation and nanoencapsulation are valuable for protecting sensitive components and improving their bioaccessibility. Non-thermal technologies such as HPP, PEF, and ultrasound expand opportunities to control food safety and quality while reducing thermal load.

Future development is expected to increasingly involve integrated approaches combining fermentation, encapsulation, non-thermal processing, and personalized formulation. In particular, postbiotics, advanced delivery systems, 3D food printing, and artificial-intelligence-assisted formulation are promising directions for developing the next generation of functional foods.

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