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DEVELOPMENT OF NEXT-GENERATION FUNCTIONAL FOOD PRODUCTS THROUGH THE INTEGRATION OF FOOD TECHNOLOGY AND PRECISION NUTRITION

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Abstract

The world today is facing a unique food system challenge when it comes to meeting the complex need within the system for chronic disease prevalence, population aging and food needs that vary from person to person. This paper is a critical review of next generation of functional food products developed by fusing advanced food technologies with precision nutrition approaches. We review the molecular basis of precision nutrition and individual variation in dietary responses, as well as technological advances that facilitate the development of functional foods, such as nanoencapsulation, texture engineering via CRISPR approaches and artificial intelligence (AI)-assisted formulation. We then discuss strategies for developing personalized functional foods as they relate to the microbiome and the challenges and future directions for the field. The review shows that although considerable advances have been achieved in the knowledge and understanding of the molecular mechanisms underlying individual responses to food components, there are significant gaps in translating this knowledge to marketable and clinically proven functional food products. Despite the potential of AI and machine learning methods to improve formulation development and dietary recommendation personalization, data heterogeneity, model

interpretability, and regulatory substantiation remain challenges. In general, we propose that next-generation functional foods should be developed in an integrated fashion that includes mechanistic understanding, advanced delivery technologies, optimization based on data, and rigorous clinical validation.

INTRODUCTION

The definition of functional foods (foods with a health function, in addition to their nutritional function) has changed a lot since its birth in the 1980s. It started with strategies for fortification and enrichment and has gradually shifted to more complex methods, taking into account the variability of nutritional needs and metabolic reactions among individuals (Tan *et al.*, 2026). This paradigm shift is known as "precision nutrition" and involves a fundamental change in the way nutrition and health are understood, from population-based recommendations to individualized nutrition plans designed to optimize the nutrition status of each person based on their genetic, metabolic and microbial makeup (Grootswagers and Grootswagers, 2025; Rodgers and Collins, 2024).

The need for precision nutrition has been emphasized due to the fact that nutrition interventions have very variable results on individuals. Different components of human diets and bioactive compounds can induce different responses in different individuals, which is determined by a range of factors including individual differences in single nucleotide polymorphisms (SNPs), gut microbiota composition, metabolic status and epigenetic changes (Wu *et al.*, 2025; Donovan *et al.*, 2025). The variation is of huge significance when it comes to developing functional foods, as there may be a suboptimal one size fits all approach to addressing complex, multifactorial chronic diseases, which comprise the majority of the disease burden in the world.

At the same time, food technology has experienced a great transformation, along with progress in nutrition science. Recent advances in the field of functional food development include innovations in nanoencapsulation, precision fermentation, genome editing, and additive manufacturing, which has greatly broadened the functional food development toolbox (Liberty *et al.*, 2026; Tan *et al.*, 2026). These technologies can provide unrivalled control over the physicochemical properties of food matrices, the stability and bioavailability of bioactive compounds and the sensory properties that influence consumer acceptance. Moreover, the application of artificial intelligence and machine learning in the food formulation and development process has provided new opportunities for food optimization, personalization, and predictive modeling (Jananibala and Adeyeye, 2026; Wu *et al.*, 2025).

The aim of this review is to bring together the existing knowledge regarding the development of next generation functional food products using a combination of food technology and precision nutrition. The molecular basis of precision nutrition, covering nutrigenomics, epigenetics, and interactions with the microbiome is discussed, as are some of the key technological innovations that enable the development of functional foods; AI-driven approaches to formulation, and personalization are explored; and the challenges of translation that must be overcome to realize the potential of these integrated approaches are considered.

1. Molecular Foundations of Precision Nutrition

1.1. Nutrigenomics and Gene-Diet Interactions

At its core, precision nutrition relies on the understanding that dietary needs vary from person to person and can affect how the body responds to nutrition and its risk of disease due to individual genetic differences. The study of how nutrients interact with the genome, called 'nutrigenomics', has uncovered a host of gene-diet interactions that affect the impact of food components on health outcome (Phugat and Goel, 2025; Tan *et al.*, 2026). The interactions are mediated by several pathways such as nutritional components influencing the expression of genes and the impact of genetic polymorphisms on the bioavailability of nutrients, and the impact of the bioactive compounds on metabolic pathways that depend on the genetic background.

Single nucleotide polymorphisms (SNPs) in metabolic enzymes, nutrient transporters and signaling molecules can have significant effects on how different individuals respond to dietary interventions (Wu *et al.*, 2025). However, polymorphisms in certain genes, such as those that affect the regulation of body weight (FTO) and cardiovascular risk (MTHFR) have been shown to influence the effect of dietary fat and protein on body weight control and the requirement for folate, respectively. Identification of such gene-diet interactions gives a mechanism for the personalized dietary recommendations and functional foods that can be developed for specific genetic profiles (Mehta *et al.*, 2025).

But translating the results of nutrigenomics into actionable dietary advice is significant challenge. Individual gene-diet interactions are typically small in magnitude and multiple gene-diet interactions with environmental factors and lifestyle habits make it difficult to make actionable recommendations (Donovan *et al.*, 2025). Furthermore, there is limited evidence for nutrition supported by a nutrigenomic approach, with few large-scale RCTs providing evidence for the superiority of genotype-specific over traditional nutrition advice (Kassem *et al.*, 2025).

1.2. Epigenetic Mechanisms and Nutritional Programming

Epigenetic changes such as methylation of DNA, modifications of the histone proteins, and the contribution of non-coding RNA, are essential in the processes that determine the long-term impacts of nutrition on health outcomes (Tan *et al.*, 2026). These epigenetic marks are dynamic and respond to the nutritional status and potentially are able to alter the pattern of gene expression throughout the life span. Nutritional programming, the idea that early life nutrition affects epigenetic changes that affect metabolic health and disease risk in later life is particularly important (Phugat and Goel, 2025).

Mechanistic basis for nutritional programming is the impact of nutrients on the enzymes that put on and keep epigenetic marks. Folate, vitamin B12 and choline, as methyl donor nutrients, affect DNA methylation by regulating the supply of S-adenosylmethionine, which is the main methyl donor for DNA and histone methylation (Tan *et al.*, 2026). Likewise, polyphenols and other bioactive compounds have the potential to impact histone acetylation and deacetylation through their ability to modulate the activities of histone deacetylases and acetyltransferases. These epigenetic changes are a molecular mechanism by which diet could exert long-term impacts on health.

Epigenetics has the potential to have significant applications in functional food development. Epigenetic modifiers such as foods and bioactive agents may have therapeutic potential in the prevention and/or correction of epigenome changes associated with disease (Liberty *et al.*, 2026). Despite this, there are still lots of challenges to be addressed, such as finding valid epigenetic indicators of nutrition status and creating functional foods that will specifically impact particular epigenetic pathways (Mehta *et al.*, 2025).

1.3. Microbiome-Metabolite Interactions

The gut microbiome has become a significant player in the connection between gut health and nutrition, and is an important factor to consider when understanding the ability to modify nutritional outcomes (Ross *et al.*, 2024; Jananibala and Adeyeye, 2026). The gut microbiome consists of microorganisms that reside in the gut and play a crucial role in nutrient availability, host metabolic and immune pathway modulation, and bioactive metabolite production (Wang *et al.*, 2026; Tan *et al.*, 2026).

Gut microbiota serve as a major source of dietary metabolites that undergo a wide range of metabolic transformations and can affect host health (Liberty *et al.*, 2026). Butyrate, acetate and propionate are but a few examples of short-chain fatty acids (SCFAs) that are generated by the fermentation of dietary fibre by the gut microbiota and have been shown to exert important roles in host epithelia barrier function, immune regulation and metabolic homeostasis (Wang *et al.*, 2026; Koh *et al.*, 2016). The ability of digesting fibre to produce SCFAs varies significantly between people depending on the composition of gut microbes and diet (Slavin, 2013; Gibson *et al.*, 2017).

There is significant inter-individual variation of gut microbial composition and metabolic capacity with implications for precision nutrition. The functional food targeting the microbiome such as probiotics, prebiotics and synbiotics can have widely differing effects, depending on the base microbiotic profile of the consumer (Jananibala and Adeyeye, 2026; Hill *et al.*, 2014). This observation implies that microbiome personalized functional food could yield significant improvements in effectiveness, but there are many further hurdles in identifying microbiome phenotypes and forecasting outcomes to targeted intervention (Wang *et al.*, 2026).

Table 1: Key Molecular Mechanisms Underpinning Precision Nutrition

Mechanism	Description	Nutritional Relevance	Key References
Gene-Diet Interactions (SNPs)	Genetic variants influence nutrient metabolism and dietary responses	Personalized nutrient requirements; targeted functional foods	Wu *et al.*, 2025; Mehta *et al.*, 2025
Epigenetic Modifications	DNA methylation and histone acetylation modulated by diet	Long-term nutritional programming; disease prevention	Tan *et al.*, 2026; Phugat and Goel, 2025
Microbiome-Metabolite Axis	Gut microbes produce bioactive metabolites (e.g., SCFAs) from dietary substrates	Individualized probiotic/prebiotic responses	Wang *et al.*, 2026; Koh *et al.*, 2016
Nutrient Sensing Pathways	Dietary components activate metabolic signaling (e.g., mTOR, AMPK)	Metabolic health; aging interventions	Tan *et al.*, 2026; Ross *et al.*, 2024

2. Technological Innovations in Functional Food Development

2.1. Nanoencapsulation and Bioavailability Enhancement

The bioavailability of many bioactive compounds in functional food development such as polyphenols, carotenoids and lipophilic vitamins is one of the major hurdles (Subramani and Ganapathyswamy, 2022; Gopi and Balakrishnan, 2021). Most of these compounds have low water solubility, chemical instability and fast metabolism, which can restrict the attainment of biologically relevant concentrations within target tissues (Benech *et al.*, 2002). Nanotechnology-

based delivery systems have appeared to be a promising answer to these problems with the ability to protect, solubilize and target bioactive compounds (Frontiers in Nutrition, 2025; NIH, 2025). The first nanocarriers to be introduced to the food science arena were liposome-based. Such spherical vesicles made up of phospholipid bilayers have the ability to encapsulate hydrophilic as well as lipophilic compounds, thereby protecting sensitive compounds from degradation (Subramani and Ganapathyswamy, 2022). There were reports that the shelf-life of vitamin C or other labile nutrient is increased from days to months when encapsulated in liposomes (Gopi and Balakrishnan, 2021). In the same way, the efficiency of nisin in the control of foodborne pathogens in food matrices has been shown to be more stable and effective when encapsulated in liposomes (Benech *et al.*, 2002).

Solid lipid nanoparticles (SLNs) are a second generation of the encapsulation technology which has many advantages for use in functional food applications. These are lipid nanoparticles, which have lipids with room temperature solid state, thus offering a more rigid protective environment for the encapsulated nutrients (Yu *et al.*, 2020). The studies have shown that SLN encapsulation can enhance the stability and bioaccessibility of various bioactive compounds, such as curcumin, with reported encapsulation efficiencies of more than 87% and substantial improvement in the oral bioavailability (Frontiers in Nutrition, 2025). Further, SLNs can be used in functional food products because of the lipids used, which are generally recognized as safe (GRAS) (NIH, 2025). Encapsulation of several bioactive compounds in a single particle is an emerging area in the field of nanoencapsulation (NIH, 2025). These systems can provide simultaneous application of more than one active ingredient, which may provide synergistic effects and complementary stability. Another possibility is to control the ratio of active substances in co-delivery platforms, enabling personalization of nutrient content. But there are major hurdles in optimizing these complicated systems such as controlling the interactions between the various bioactive compounds, as well as the release kinetic (Frontiers in Nutrition, 2025; NIH, 2025).

2.2. CRISPR-Driven Texture Engineering

There is a paradigm shift in the process of developing functional foods using genome editing with CRISPR technology in food science (Liberty *et al.*, 2026). Instead of changing the texture of food during its post-harvest processing, CRISPR can change food texture at the biochemical level, altering the structure of starch, gluten and plant cell-wall components, to create the texture and nutritional properties.

The scope of potential applications of texture engineering with CRISPR is enormous and relevant. Altering amylose-amylopectin proportions in starch by gene editing can have a positive effect on glycemic responses and could be a form of molecular diabetes management to create functional foods for tackling the disease (Liberty *et al.*, 2026). Likewise, changes in the gluten epitope profile could be used to decrease the allergenicity without compromising baking properties for dough. The changes in firmness, water content, and degradation properties induced by genetic modification of cell-wall remodelling enzymes can afford novel opportunities for the development of food products for vulnerable consumers (Liberty *et al.*, 2026).

CRISPR-guided texture design may also have applications beyond clinical uses, including sustainability and performance nutrition. The ability to highly control the food texture at the molecular level may also help develop plant-based foods that better resemble the sensory characteristics of animal foods, which could assist with the transition to more sustainable food systems (Liberty *et al.*, 2026; Tan *et al.*, 2026). In addition, the combination of texture engineering using the CRISPR system and formulation optimization based on AI could expedite

the process of creating functional foods optimized for specific consumer groups or health benefits (Jananibala and Adeyeye, 2026).

2.3. Synthetic Biology and Precision Fermentation

The applications of synthetic biology are broadening the scope of food sources and are helping to create personalized food ingredients (Tan *et al.*, 2026). Fermentation processes can be used to produce specific bioactive compounds, such as vitamins, flavors and functional ingredients, using synthetic biology, by engineering microbial metabolic pathways. This method has several benefits over the traditional production methods such as less harmful impact on the environment, quality control and the ability to create compounds which are not easily found in nature.

Synthetic biology has a high potential for functional food applications because of the possibility to generate bioactive compounds known to benefit human health (Tan *et al.*, 2026). Specific polyphenols, carotenoids, or omega-3 fatty acid can be targeted in microbial production systems to be produced in high purity and yield. Moreover, with the progress of synthetic biology, biomolecules that could not be found in nature can be synthesized, which might be helpful to combine the efforts to invent novel functional molecules with optimized bioactivity (Tan *et al.*, 2026; Jananibala and Adeyeye, 2026).

The use of Generative AI is growing in the field of synthetic biology, such as de novo pathway design to produce a microbial consortium that can synthesize designer bioactives for therapeutic purposes (Wang *et al.*, 2026). The marriage of AI and synthetic biology is a promising strategy for functional food product development, allowing for the design and optimization of food production systems for specific bioactive compounds to be carried out in a rapid manner (Jananibala and Adeyeye, 2026).

Table 2: Advanced Technologies for Functional Food Development

Technology	Application	Key Advantages	Challenges	Key References
Nanoencapsulation (Liposomes, SLNs)	Protection and delivery of bioactives	Enhanced bioavailability; improved stability	Scale-up; cost; complex formulation	Subramani and Ganapathyswamy, 2022; Frontiers in Nutrition, 2025
CRISPR Texture Engineering	Molecular redesign of food structure	Precision modification; glycemic control; allergen reduction	Regulatory acceptance; public perception	Liberty *et al.*, 2026; Tan *et al.*, 2026
Synthetic Biology	Production of bioactives via fermentation	Sustainable; consistent quality; novel compounds	Metabolic engineering complexity; yield optimization	Tan *et al.*, 2026; Jananibala and Adeyeye, 2026
3D Food Printing	Customized fabrication of functional foods	Personalization; precise nutrient control	Printing resolution; ingredient compatibility	Wang *et al.*, 2026; Tan *et al.*, 2026

3. Artificial Intelligence and Data-Driven Formulation

3.1. AI in Formulation and Ingredient Optimization

Formulation methods such as empirical experimentation and response surface methodology are often used in traditional formulation methods but can be inefficient in the formulation of functional products in the multidimensional design space of functional product development (Jananibala and Adeyeye 2026). AI and machine learning can provide complementary strategies that can be used to speed up the process of hypothesis generation, find the best formulation, and forecast product performance.

It is important to note that currently, AI has been found to be useful in multiple stages of functional food development such as pairing of ingredients, viability forecasting, sensory modelling and prediction of functional properties (Jananibala and Adeyeye, 2026; Wu *et al.*, 2025). For instance, machine learning systems can be utilized to explore huge databases of the properties of ingredients and outcomes of the formulations to search for promising combinations of ingredients and processing conditions. Likewise, forecasting tools can aid in predicting the viability of probiotic strains as a function of formulation and storage conditions, bypassing the need for a large number of experiments.

But there are some challenges that need to be tackled to realize the potential of using AI in the formulation of functional foods. Currently, most existing solutions are computational or at pilot scale, with few examples of integrating personalization through the microbiome and/or clinical endpoints (Jananibala and Adeyeye, 2026). Additionally, there is also a considerable heterogeneity in training data and the black-box nature of many AI models makes it difficult to support regulation and mechanistic understanding. Therefore, AI should not be used as a replacement for mechanistic studies or human trials, but rather as a supplement to making decisions (Jananibala and Adeyeye, 2026; Wu *et al.*, 2025).

3.2. Personalized Nutrition Recommendation Systems

Among its various applications, AI's potential in creating personalized nutrition recommendation systems for functional food development is one of the most exciting (Wang *et al.*, 2026; Tan *et al.*, 2026). AI platforms can leverage the microbiome, dietary preferences and practices, genetic information, and digital health records to develop personalized dietary plans and functional foods that cater to each person's metabolic requirements.

These systems have a variety of data sources and growing. CGMs offer continuous glucose monitoring, which allows for the detection of glycemic responses to food occurring in real-time, and can be used to identify individual glycemic response patterns (Kassem *et al.*, 2025). Metagenomic sequencing gives detailed information on the microbial composition and metabolic potential in the gut. Wearable biosensors can track physical activity, sleep patterns, and other lifestyle indicators affecting nutritional needs, which can be beneficial (Phugat and Goel, 2025). Combining these various data streams is very challenging yet open up tremendous possibilities for personalization.

The technology of 3D food printing is still in its infancy, but it has the potential to be an AI-driven technology that can put personalized nutrition recommendations into practice (Wang *et al.*, 2026). The potential for 3D printing to take molecular information and convert it into the creation of functional foods with tailored nutrient and bioactive content has the potential to make molecular information actionable in the field of nutrition. Precision functional food interventions for specific life stages, disease conditions or aging related needs in real time may significantly enhance precision and effectiveness of functional food interventions (Wang *et al.*, 2026; Tan *et al.*, 2026).

Challenges in Data Integration and Model Interpretability

Although there is great potential for functional food development by using AI, there are several significant challenges that need to be solved. One of the key challenges is the issue of data heterogeneity, where multi-source and multi-modal data are frequently in incompatible formats and standards (Donovan *et al.*, 2025; Wu *et al.*, 2025). This diversity makes it difficult to build up and test strong predictive models, and makes it difficult to compare and easily combine results from studies.

Another great challenge is the interpretability of these AI models. While many associations between food and health have been discovered, the molecular mechanisms for these associations are poorly understood (Wu *et al.*, 2025; Tan *et al.*, 2026). The current AI models lack mechanism insight, which makes it difficult to predict their performance and limits its reliability, and hinders the regulatory approval of AI created products. Thus, creating interpretable AI tools, by integrating expert knowledge into feature selection, model building, and causal interpretation, is an important priority in the field (Wu *et al.*, 2025).

The ethical issues are also very urgent. Lots of nuanced personal data, such as genetic, dietary, and microbiome profiles, are vital for AI-driven personalized nutrition, yet they pose significant privacy and data ownership concerns, as well as challenges with transparency of algorithms and informed consent (Wang *et al.*, 2026). In addition, if the training data is biased, for example, if minority groups are underrepresented, this can result in imbalanced outputs that diminish equity in AI-driven healthcare solutions. AI model training, using federated learning models where AI models are trained across multiple decentralized datasets with no direct data sharing, is under investigation as a mitigation strategy (Wang *et al.*, 2026).

Table 3: AI Applications in Functional Food Development

AI Application	Function	Data Inputs	Current Limitations	Key References
Formulation Optimization	Predict ingredient combinations and processing parameters	Ingredient properties; historical formulations	Limited clinical validation; pilot-scale only	Jananibala and Adeyeye, 2026; Wu *et al.*, 2025
Personalized Nutrition	Generate tailored dietary recommendations	Genetics; microbiome; lifestyle; CGM data	Data heterogeneity; privacy concerns	Wang *et al.*, 2026; Kassem *et al.*, 2025
Sensory Modeling	Predict consumer acceptance and sensory properties	Physicochemical data; consumer panels	Generalizability; cultural variability	Jananibala and Adeyeye, 2026; Wu *et al.*, 2025
Predictive Viability	Forecast probiotic stability and functionality	Strain characteristics; formulation parameters	Model opacity; mechanistic gaps	Wang *et al.*, 2026; Jananibala and Adeyeye, 2026

4. Microbiome-Targeted Functional Foods

4.1. Probiotics, Prebiotics, and Synbiotics

The modulation of the gut microbial ecosystem is a main component of the functional food development, and there are some well-established approaches, such as the use of probiotics, prebiotics, and synbiotics (Hill *et al.*, 2014; Gibson *et al.*, 2017). The mechanisms by which these interventions work is becoming better understood, ranging from the production of bioactive

metabolites, through modulation of immune response, to strengthening of epithelial barrier function (Wang *et al.*, 2026; Koh *et al.*, 2016).

Live microorganisms containing a beneficial effect when taken in sufficient quantity are known as probiotics, and have been widely investigated for their beneficial effects on the health of the gut and systemic physiology (Hill *et al.*, 2014; Sanders *et al.*, 2014). The representative probiotic strains such as Lactobacillus and Bifidobacterium species have several mechanisms of improving the structural integrity of the intestinal barrier: the production of antimicrobial substances, competition with pathogens for the adhesion sites of the intestinal barrier, and modulation of host immune responses (Hemarajata and Versalovic, 2013). Probiotics also produce other bioactive metabolites that back gut epithelial function, and the metabolic activities of these gut microbes also lead to the production of SCFA.

Prebiotics are select dietary fiber ingredients that promote the growth and metabolism of desirable microorganisms, such as fermentable fibers like inulin, fructo-oligosaccharides (FOS), and galacto-oligosaccharides (GOS), and resistant starch (Gibson *et al.*, 2017; Slavin, 2013). They can enhance microbial diversity, select out SCFA-producing bacteria and enhance mineral bioavailability. The prebiotics' impacts are also influenced by the initial gut microbiome composition, suggesting the need for personalized use of these agents (Wang *et al.*, 2026).

The postbiotics, which are preparations of inanimate microorganisms and/or their components, are a new class of microbiome-based interventions based upon their health promoting effects (Salminen *et al.*, 2021; Aguilar-Toala *et al.*, 2018). Postbiotics provide the benefits of microbial activity without the necessity of live microorganisms, such as by supplying stable microbial bioactives, including butyrate, peptidoglycans and bacteriocins. For immunocompromised persons or elderly people who are at risk of live probiotics (Zolkiewics *et al.*, 2020, Wegh *et al.*, 2019), the use of this approach could be beneficial.

4.2. Aging, Microbiome Dysbiosis, and Nutritional Interventions

There are significant alterations in gut microbiota in aging, which include a reduction in the abundance of beneficial commensals genera and an enrichment of the opportunistic proinflammatory taxa (Wang *et al.*, 2026; Ross *et al.*, 2024). These changes, along with loss of microbial diversity, are thought to be markers of gut dysbiosis in the elderly and are among the factors associated with chronic low-grade inflammation (often referred to as “inflammaging”) (Ross *et al.*, 2024).

There are many factors that determine the changes to the microbiome that are associated with ageing, such as gastrointestinal physiology, diet, medication use and immune senescence (Wang *et al.*, 2026). All these changes in intestinal motility, decreased production of gastric acid and impaired mucosal immune responses, contribute to modifying intestinal microbial flora. Dietary alteration during ageing, e.g., decreasing the fibre content, can also contribute to the imbalance of the microbiota (Wang *et al.*, 2026).

Generally, nutritional interventions targeting the microbiome are promising avenues for reducing dysbiosis in old age and for achieving healthy ageing (Wang *et al.*, 2026; Jananibala and Adeyeye, 2026). Probiotics, prebiotics and postbiotics are able to reestablish microbial homeostasis, enhance intestinal barrier integrity, alleviate inflammation and control metabolic homeostasis in older people (Wang *et al.*, 2026). However, the effectiveness of these interventions will vary from person to person, and microbiome variation among populations (due to ethnicity, geography, diet etc.) often means that results are sensitive to population (Wang *et al.*, 2026).

4.3. Tribiotic Strategies and AI-Enabled Personalization

Tribiotic strategies (combining probiotics, prebiotics and postbiotics in synergistic formulation) is an emerging approach to the modulation of the microbiome (Wang *et al.*, 2026). A combination of complementary mechanisms of action might lead to a more powerful and consistent effect with tribiotic formulations than with individual therapies. The optimization of these highly complex formulations is, however, fraught with challenges, such as balancing multiple components for stability, viability and interactions.

The use of AI in creating personalized tribiotic strategies (Wang *et al.*, 2026) is becoming more common. AI platforms can use microbiome data, dietary habits, and health indicators to develop personalized formulations that cater to each person's metabolic requirements and tastes.AI can use microbiome data, dietary preferences, and health metrics to design personalized formulations according to individual metabolic needs and tastes. Sentiment analysis, using NLP techniques, is being used to capture consumer feedback to inform the product optimization process (Wang *et al.*, 2026; Jananibala and Adeyeye, 2026). But the potential of these approaches must be overcome with issues of data standardization, model interpretability, and regulatory governance (Wang *et al.*, 2026).

Table 4: Microbiome-Targeted Strategies for Functional Foods

Strategy	Definition	Mechanism	Target Populations	Key References
Probiotics	Live beneficial microorganisms	Enhance barrier function; produce antimicrobials; modulate immunity	General population; immunocompromised (caution)	Hill *et al.*, 2014; Sanders *et al.*, 2014
Prebiotics	Fermentable fibers stimulating beneficial bacteria	Promote SCFA production; increase microbial diversity	Elderly; those with low fiber intake	Gibson *et al.*, 2017; Slavin, 2013
Synbiotics	Probiotic + prebiotic combinations	Complementary effects; enhanced colonization	All populations; specific for intestinal health	Wang *et al.*, 2026; Ross *et al.*, 2024
Postbiotics	Inanimate microbial components/bioactives	Provide stable metabolites without live organisms	Immunocompromised; elderly; critically ill	Salminen *et al.*, 2021; Wegh *et al.*, 2019
Tribiotics	Probiotic + prebiotic + postbiotic	Synergistic triple-action modulation	Aging populations; severe dysbiosis	Wang *et al.*, 2026; Jananibala and Adeyeye, 2026

5. Translational Challenges and Future Directions

5.1. Evidence Gaps and Clinical Validation

One of the main hurdles in the translation of precision nutrition strategies to the area of functional food is the evidence supporting the effectiveness of personalized nutrition interventions over traditional dietary guidelines (Wu *et al.*, 2025; Donovan *et al.*, 2025). There are many reports linking individual characteristics to dietary response, but these are frequently

based on small short-term studies that may not be able to be extrapolated to larger populations or clinically relevant results.

There is a need for large-scale long-term randomized controlled trials to assess the impact and efficacy of precision nutrition strategies compared to traditional nutrition approaches (Wu *et al.*, 2025; Donovan *et al.*, 2025). To determine the value of personalized interventions, clinically meaningful endpoints such as disease incidence, disease progression, metabolic improvement, or risk reduction in high-risk populations are of crucial importance. Future studies should actively seek to develop validation methods appropriate for individual interventions, including repeated crossover interventions within participants to establish the effectiveness of specific dietary interventions (Wu *et al.*, 2025).

5.2. Regulatory Frameworks and Commercialization

While the food regulatory framework is still evolving and uncertain in the context of precision nutrition interventions, it is split between different provisions (Wang *et al.*, 2026; Wu *et al.*, 2025). However, the position of AI-based products, customized formulations and personalized health claims is sometimes ambiguous, making the commercialization of precision nutrition solutions difficult. Creating regulatory frameworks that are adaptive, cross-sector, and inclusive of experts from the fields of food science, nutrition, medicine, and AI is crucial for fostering innovation while maintaining consumer safety (Wang *et al.*, 2026).

There are a number of regulatory issues that are especially urgent. For functional foods, the substantiation of health claims needs to be based on strong evidence from human studies, which are often difficult to design and interpret due to the individual variability of responses. AI-generated health claims and the dynamic formulations that can change based on individual or time use, pose new regulatory challenges (Wang *et al.*, 2026). The privacy and consent issues surrounding this use of personal data in the creation of food products for their functional benefits are important and should be managed through suitable governance frameworks (Wu *et al.*, 2025; Donovan *et al.*, 2025).

5.3. Accessibility and Implementation

To ensure precision nutrition and next-generation functional foods can be disseminated on a scale, accessibility and implementation challenges must be addressed (Wu *et al.*, 2025). Existing precision nutrition interventions are mostly expensive tests and analyses, which are not accessible to more impoverished populations. Cost-effective technical solutions are needed to increase access, such as low-cost delivery mechanisms and simplified testing procedures.

Enabling precision nutrition interventions (PNI) requires user-friendly models (Wu *et al.*, 2025; Donovan *et al.*, 2025). Science communication and public education will play a crucial role in raising awareness and acceptance of personalized approaches. Public-private partnerships and the need to reach populations that have been left out of the equation will be essential to resolve the digital divide and make sure that AI-driven nutrition technologies are accessible and equitable to everyone. (Wang *et al.*, 2026)

6. Conclusion

Food technology and precision nutrition represent an opportunity to revolutionize the development of functional food products, from a one-size-fits-all concept to a focus on interventions based on the genetic, metabolic and microbial profile of each individual. Research into understanding molecular variability in food responsiveness, novel delivery systems to protect

and target bioactive compounds and the application of AI for formulation and personalization advancements is considerable.

But significant hurdles still need to be overcome before the advances can be translated to commercially viable, clinically proven products. Current limited evidence base for precision nutrition approaches, along with regulatory uncertainty on personalized interventions and accessibility and equity concerns all must be addressed. Precision functional food strategies, which can be achieved by bridging the gap between computational modeling and microbiome science and nutritional evidence, will require mechanistic validation and human trials as complementary studies to computational approaches (Jananibala and Adeyeye, 2026).

We see the future of functional foods as being tailored to the biological differences between people, so that more effective and efficient strategies can be implemented for health promotion and disease prevention. To realize this vision, investment in research, development of appropriate regulatory frameworks and attention to the practical challenges of implementing and accessibility (Wu *et al.*, 2025) are needed. The fascinating combination of food technology and precision nutrition is already a paradigm shift in nutrition science and promises to change the relationship between nutrition and health on an individual and population level.

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