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Review of Integrating Biotechnology and Functional Foods to Enhance Health and Sustainability

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Abstract

Technological advances in biotechnology are transforming food production and redefining the link between nutrition, health, and sustainability. From traditional fermentation to genome editing, these tools enable the creation of functional foods that enhance well-being and reduce environmental impact. Historically, low-energy fermentation methods improved the nutritional quality and preservation of foods while supporting gut and metabolic health. Today, emerging fields such as synthetic biology, precision fermentation, microbiome engineering, and artificial intelligence are accelerating innovation in personalised and nutritional approaches that complement conventional diets. These approaches can upcycle agricultural by-products, generate bioactive compounds, and mitigate chronic diseases through targeted microbial or molecular interventions. The purpose of this narrative review is to evaluate the role of biotechnology in developing functional foods that promote health and sustainability. Specifically, it examines how fermentation, biofortification, waste valorisation, and genome editing contribute to metabolic, immune, and cognitive health while supporting environmentally responsible food systems. By integrating traditional food wisdom with modern biosciences, this review highlights biotechnology's potential to bridge health promotion, sustainability, and innovation in the next generation of functional foods.

Keywords

Functional Foods, Biotechnology, Fermentation, Microbiome, Precision Nutrition, Sustainability

1. Introduction

Functional foods are foods or ingredients that go beyond basic nutrition. They also affect some physiological functions and help mitigate the risk of some chronic diseases. Due to the growing prevalence of non-communicable diseases, such as diabetes and obesity, interest in these foods has increased rapidly. The production of such foods is also challenged by global population growth, climate change, and the impending food supply crisis. Hence, there is a need for health-affirming and health-sustaining foods. Biotechnology could help address these challenges. It is the increasing manipulation of living organisms developed for specific purposes. These organisms may improve the nutrient value of crops, convert agricultural waste into value-added ingredients, or engineered microbes and enzymes may perform specific health-promoting functions. Although many of these techniques are not new, as they build on established practices such as fermentation, they are novel in that they provide tremendous precision at the molecular level.

Methodology

This review was developed through an extensive literature search focused on peer-reviewed articles published between 2015 and 2025. Databases searched included PubMed, Scopus and Web of Science. Keywords such as “functional foods,” “biotechnology,” “fermentation,” “microbiome,” and “precision nutrition” were combined with terms related to sustainability and chronic disease. Preference was given to papers published within the last five years to ensure currency of evidence. Classic reviews were included when they provided historical context. From the initial search results, titles and abstracts were screened for relevance. Full-text articles were assessed and grouped by thematic categories aligned with the structure of this article. Studies on culinary medicine and traditional Chinese dietary therapy were included to capture the intersection between food culture and modern science. Regulatory documents from the U.S. Food and Drug Administration (FDA) were examined to describe clinical and policy developments.

2. Lessons from Culinary Medicine & Fermented Foods

2.1. Culinary Medicine and Chinese Dietary Therapy

Culinary medicine (CM) blends nutrition science with practical cooking to help individuals choose foods that support their health. Unlike general dietetics or nutritional counselling, CM emphasises hands-on skills and patient-specific advice. A U.S. government article describes culinary medicine as an evidence-based field that utilises food to prevent and treat disease [1]. In programs for ethnically diverse patients with type 2 diabetes, CM interventions increase the consumption of healthy foods and provide a supportive community environment [2] [3]. CM also draws on cultural food traditions. Traditional Chinese medicine (TCM) incorporates medicinal foods and dietary regulation to maintain balance in the body. A recent review summarises clinical trials in which TCM dietary therapy may improve blood glucose, triglyceride levels, and body mass index in patients with impaired glucose tolerance or prediabetes [3]. The interventions used medicated diets tailored to the patient's constitution, demonstrating the potential of personalised nutrition within traditional frameworks.

The mechanisms proposed for TCM diet therapy include insulin-like bioactive compounds, high dietary fibre that slows glucose absorption, inhibition of adipocyte proliferation, and anti-inflammatory effects [4]. For example, recipes such as Jianpi Qushi replace certain staple foods with herb-enriched dishes and have shown superior improvements in fasting plasma glucose and two-hour postprandial glucose compared with routine health education [4]. These findings demonstrate the benefits of food in its own right. They also highlight the importance of local food knowledge and cultural context, which biotechnology can complement but should not supplant. Modern biotechnology can augment TCM dietary therapy by producing defined bioactive compounds found in medicinal foods. For example, precision fermentation can be used to synthesise key metabolites such as berberine-like alkaloids or ginsenoside analogues, enabling standardised functional ingredients that mirror therapeutic components of traditional herbs.

2.2. Fermented Foods: Ancient Biotechnology

Fermentation is one of humanity's oldest biotechnologies. Microorganisms metabolise sugars and other substrates to produce acids, alcohols and gases, thereby preserving food and altering its flavour and texture [5]. A 2022 review notes that fermented foods have been part of the human diet for nearly 10,000 years and contain bioactive peptides and metabolites that confer health benefits [6]. These foods include dairy products, sauerkraut, kimchi, sourdough breads and fermented beverages. The lactic acid fermentation process, employed with bacteria and yeasts, yields longer-lasting products, enhances digestibility, and generates valuable end products, including certain vitamins, short-chain fatty acids (SCFAs), and bioactive antioxidant peptides [5] [6].

There are also sustainable and environmental benefits associated with fermentation. The process requires minimal energy, can be carried out on-site, and eliminates the need for refrigerated storage in the short term. Thus, it lessens waste and fortifies the resilience of food systems. In addition to all of these, fermented products also modify gut microbiomes, since the live microorganisms contained in the food products can withstand the rigours of the digestive tract, and interact with gut communities, thus modulating immune and metabolic functions [5] [6]. The natural preservation of food and the therapeutic benefits of fermented products have increased interest in them.

2.3. Sustainability and Therapeutic Overlap

As with several other fields in the health and wellness sector, culinary medicine, diet therapy within traditional Chinese medicine, and the practice of incorporating fermented foods into one's diet are interconnected through the common theme of bioactive compounds. Numerous culinary medicine recipes incorporate fermented foods, for example, miso, yoghurt, and tempeh. In TCM, diet therapy also frequently incorporates fermented soy products, such as natto, which is a source of vitamin K and bioactive peptides of considerable health importance. These foods are also a source of prebiotics and probiotics, and consequently strengthen the gut system [5]. The preparation processes for these foods are relatively low-energy and utilise local ingredients, which also aligns with the principles of sustainability. Biotechnology, in terms of strain selection or engineering for higher targeted metabolite production, will only enhance several of these practices. Biotechnology will help to standardise production systems for defined health outcomes.

3. Modern Biotechnology Tools for Functional Foods

3.1. Microbiome-Targeted Therapies and Engineered Probiotics

The ability to modify the microbiome in the treatment of disorders is a novel application in the field of microbiome research [7]. The use of probiotics, prebiotics, and faecal microbiota transplantation (FMT) is one of the most common techniques. Targeting the microbiome through the use of probiotics, prebiotics, bacteriophages, and engineered bacteria has been reviewed. The review [7] mentions high cure rates for recurrent Clostridioides difficile infections (CDI) and a modest treatment success rate for inflammatory bowel disease. These treatments are designed to restore microbial diversity, modulate immune responses, increase levels of SCFAs, and enhance immune and anti-inflammatory SCFA production.

Synthetic probiotics modify bacterial functions in novel ways, using tools of synthetic biology. The creation of live biotherapeutic bacteria and biosensors that detect inflammatory molecules and control the release of therapeutic agents [8] takes biosensing to the next level. These control systems target the recognised limitations of some conventional probiotics, whose colonisation is often transient and whose actions may be non-specific depending on the strain [8]. Constructing a strain with a genetic circuit to release anti-inflammatory peptides or degrade toxic metabolites demonstrates the potential of modern biotechnology tools to augment the benefits of probiotics.

3.2. Postbiotics and Metabolite-Based Foods

Postbiotics, which are non-viable bacterial components and metabolites, are emerging as functional food ingredients. They include soluble factors, cell wall fragments, and secreted molecules that provide health effects without the risks linked to live microbes [9]. Postbiotics are naturally found in fermented foods such as yoghurt, sauerkraut, and kombucha [9]. Their stability allows use in foods that are unsuitable for live probiotics. Research has shown antibacterial, antiviral, and anti-diabetic effects from different postbiotic preparations [9]. From a commercial perspective, postbiotic ingredients offer a way to supply bioactive compounds on a large scale without the need for live fermentation at the point of consumption.

3.3. Precision Fermentation and Bioreactors

Precision fermentation utilises microorganisms in controlled bioreactors to produce specific compounds that are traditionally obtained from animals or plants. The Food and Agriculture Organization of the United Nations (FAO) report describes how bacteria, yeasts, fungi, and microalgae can be programmed to synthesise proteins, fats, vitamins, and pigments [10]. The process involves upstream fermentation, where microbes are cultured to produce the target molecule, and downstream processing to purify it. Precision fermentation can create alternatives to dairy proteins, eggs and fish oils with a smaller environmental footprint. It also allows the production of bioactive peptides and metabolites for functional foods. These products are free from allergens, pathogens or contaminants that may be present in animal-derived ingredients. The scalability of bioreactors enables consistent production and reduces reliance on agricultural land.

3.4. Genome Editing and Biofortification

Gene editing tools, such as CRISPR-Cas9, transcription activator-like effector nucleases (TALENs), and zinc-finger nucleases (ZFNs), enable targeted modifications to the genomes of plants and microorganisms. CRISPR systems are particularly efficient and cost-effective, with RNA guides directing Cas endonucleases to specific DNA sequences [11]. Base editing and prime editing further reduce off-target effects. In plants, genome editing has been used to knock out genes that limit the accumulation of micronutrients. For example, CRISPR-Cas9 targeting of the rice gene OsZIP9 decreased zinc flux, revealing its role as a transporter [11]. Editing of OsNramp5 reduced cadmium accumulation and improved iron transport [11]. By modifying regulatory elements of genes involved in iron and zinc homeostasis, researchers can increase micronutrient content in crops [11].

Microbial fermentation also serves as a biofortification strategy. Fermentation can synthesise vitamins and increase mineral bioavailability in plant-based foods. Studies demonstrate that certain bacteria and yeasts raise levels of vitamin B_2, B_6 and B_{12} during fermentation [12]. For instance, fermentation of brewers' spent grain with *Propionibacterium freudenreichii* enriched the material with vitamin B_{12}, yielding 21 micrograms per 100 g after optimisation [12]. Co-fermentation of soymilk with riboflavin-producing *Lactiplantibacillus plantarum* and Lactobacillus acidophilus tripled riboflavin levels and improved sensory qualities [12]. Fermentation of orange juice with *Lactiplantibacillus plantarum* increased vitamin C content by about 19 per cent compared with unfermented juice [12]. These examples demonstrate that biotechnology can enhance the nutrient profile of foods without necessitating the genetic modification of crops. The wide array of biotechnology tools, their functional ingredients, health targets, and regulatory status are summarised in **Table 1**. The prefix "non" is not a word; it should be joined to the word it modifies, usually without a hyphen.

Table 1. Biotechnology modalities, target ingredients, health outcomes and regulatory maturity.

Modality/ Tool	Platform/ Strain or Crop	Target ingredient/ biomolecule	Primary health target	Example product/ claim	Maturity/ regulatory snapshot
Precision fermentation	Microalgae/yeast cell factories	EPA/DHA	Cardiometabolic & cognitive support	Microbial omega-3 oils	Commercialising; "novel food/ingredient"
Engineered probiotics	Synthetic circuits in probiotic chassis	Anti-inflammatory peptides	IBD, gut inflammation	Live biotherapeutic concept foods	Preclinical/early clinical trials
Postbiotics	Fermented foods (e.g., yoghurt, sauerkraut)	SCFAs, cell wall fragments	Immune and metabolic modulation	Stabilised powders	Food ingredient; stable in processing
Genome editing/biofort.	Edited rice (e.g., OsZIP9, OsNramp5)	↑Fe/↑Zn, ↓Cd	Micronutrient adequacy	Biofortified staples	R&D/field; jurisdiction-specific approval
Microbiome therapeutics	Rebyota®, Vowst®	Diverse microbes/ spores	Prevent recurrent CDI	FDA-approved therapies	Drug/biologic classification

Footnotes: EPA: Eicosapentaenoic acid; DHA: Docosahexaenoic acid; IBD: Inflammatory bowel disease; SCFAs: Short-chain fatty acids; OsZIP9, OsNramp5: rice transporter genes linked to Zn and Cd flux; Fe: iron; Zn: zinc; Cd: cadmium; R&D: research and development; CDI: Clostridioides difficile infection; FDA: U.S. Food and Drug Administration.

3.5. Bioreactors as Sustainable Alternatives to Animal-Sourced Nutrients

Omega-3 fatty acids, such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), are essential for human health and are traditionally obtained from fish oil. Overfishing and environmental contamination limit supply. A 2023 review notes that synthetic biology and engineered microbial cell factories can produce stable and affordable sources of EPA and DHA [13]. Microalgae and yeast strains have been engineered to synthesise long-chain polyunsaturated fatty acids. Production in bioreactors reduces demand on marine ecosystems and provides a sustainable ingredient for functional foods. Combined with fermentation technologies, these approaches demonstrate how biotechnology can provide nutrients while minimising ecological impact.

4. Biotechnology for Sustainability

4.1. Waste-to-Value Conversion

The food industry generates significant waste. Up to 60 percent of vegetable processing output comprises peels, stems and other by-products that are rich in bioactive compounds [14]. These materials often end up in landfills, resulting in both environmental and economic losses. Fermentation offers a sustainable approach for converting agro-industrial waste into valuable functional ingredients. A 2025 review reports that the fermentation of vegetable by-products improves digestibility, reduces anti-nutritional factors, and adds probiotic cultures [14]. For example, lactic acid fermentation of carrot pomace produces a fibre-rich ingredient with enhanced mineral bioavailability. Fermentation of soybean meal with Bacillus licheniformis reduces phytic acid and increases protein hydrolysis [12]. These processes transform waste into value-added products, contributing to a circular economy.

4.2. Biotechnological Biofortification

Biofortification aims to increase the density and bioavailability of micronutrients in foods. Beyond genome editing, microbial fermentation can biosynthesise vitamins and minerals in plant-based matrices. Fermentation of oat and rice beverages with specific lactic acid bacteria strains increases the riboflavin content and produces prebiotic dextrans [12]. Fermented orange juice shows elevated vitamin C and shikimic acid due to microbial biosynthesis [12]. Fermentation of seeds and beans with *Bacillus subtilis* var. natto enhances vitamin K_2 (menaquinone 7) levels, with sunflower seeds reaching over 1000 micrograms per 100 g [12]. Microbial processes can also convert precursors into more bioactive forms; for example, fermentation converts provitamin A carotenoids into retinol equivalents [12]. These examples demonstrate scalable routes to fortify plant foods without synthetic additives. Specific examples of nutrient enrichment mediated by fermentation are outlined in **Table 2**.

Table 2. Examples of fermentation processes enhancing micronutrient content.

Substrate/ food matrix	Microbe/strain & process	Nutrient/ metabolite	Baseline	Post-fermentation	% change	Sensory/ quality notes
Brewers' spent grain	*Propionibacterium freudenreichii* (optimised)	Vitamin B12	~0 µg/ 100 g	21 µg/100 g	—	Improved yield post-optim.
Soymilk	*L. plantarum* + *L. acidophilu*s (co-ferm.)	Riboflavin (B2)	1×	3×	+200%	Improved flavour profile
Orange juice	*L. plantarum*	Vitamin C	100% baseline	119%	+19%	Comparable taste
Sunflower seeds (natto)	*B. subtilis* var. natto	Vitamin K2 (MK-7)	Low	>1000 µg/100 g	—	—

Footnotes: µg: microgram; g: gram; L.: Lactobacillus/Lactiplantibacillus genus; co-ferm.: co-fermentation; B2: riboflavin; MK-7: menaquinone-7 (a form of vitamin K2).

4.3. Food Safety and Standardisation

Fermentation and microbial engineering provide sustainability benefits, yet they also raise safety concerns. Donor-derived live biotherapeutic products (LBPs), such as Rebyota and Vowst, require strict screening to prevent the transmission of pathogens or allergens. Rebyota is made from screened human stool, processed into a 150-millilitre enema that contains a diverse mix of microbes, and administered as a single rectal dose [7] [15]. Vowst, approved in 2023, utilises ethanol-treated spore preparations administered orally following bowel washout [7] [15]. Manufacturing encompasses pathogen testing, cryopreservation, and controlled thawing to ensure product quality is maintained. Industrial-scale fermented foods must follow Hazard Analysis and Critical Control Point (HACCP) systems. Biotechnology can enhance safety by engineering strains that lack antibiotic resistance genes or virulence factors, and by utilising genomic sequencing to monitor microbial communities during production. Standards bodies, including EFSA and FSANZ, are building frameworks to assess both health claims and the safety of functional foods.

4.4. Environmental Footprint

Biotechnology can reduce the environmental footprint of food production. Precision fermentation requires less land and water than animal agriculture and produces lower greenhouse gas emissions. Bioreactors operate in controlled environments and can be powered by renewable energy. Using agricultural by-products as substrates further decreases waste and avoids competition with food crops. CRISPR-enabled biofortification may reduce the need for synthetic fertilisers and reduce soil depletion. Microbial production of omega-3 fatty acids reduces pressure on marine ecosystems [13]. Collectively, these technologies support climate-smart agriculture by enhancing resource efficiency and reducing greenhouse gas emissions.

5. Health Enhancement Pathways

Table 3 summarises selected microbiome and biotechnology-based products, their regulatory classifications, and implications for functional food positioning.

Table 3. Regulatory and clinical landscape of biotechnology-derived products.

Product/ ingredient	Classification (AU/EU/US)	Intended use/indication	Formulation & route	Core evidence	Quality/ safety controls	Notes for functional food positioning
Rebyota®	Biologic (drug)	Prevent recurrent CDI	150 mL rectal enema, single dose	FDA approval 2022	Donor screening, pathogen testing	Not a food; sets regulatory benchmark
Vowst®	Biologic (drug)	Prevent recurrent CDI	Oral spore capsules	RCT: recurrence ↓ 39.8→12.4%	GMP, ethanol treatment	Therapeutic; contrast for food claims
Postbiotic powder (generic)	Food/novel food ingredient	Immune/ metabolic support	Heat-killed fractions/ metabolites	Growing evidence	Identity/purity specs	Stable; label as postbiotic
Precision-fermented omega-3	Food/novel ingredient	Heart and brain health	Oil from yeast/microalgae	Reviews on sustainability	Residual solvent, allergen checks	Marine-free EPA/DHA alternative

Footnotes: AU: Australia; EU: European Union; US: United States; CDI: Clostridioides difficile infection; FDA: U.S. Food and Drug Administration; RCT: randomised controlled trial; GMP: good manufacturing practice; EPA: eicosapentaenoic acid; DHA: docosahexaenoic acid.

5.1. Metabolic Health: Diabetes, Obesity and Non-Alcoholic Fatty Liver Disease

Functional foods derived from fermentation and biotechnology can improve metabolic health. TCM dietary therapy has demonstrated improvements in fasting plasma glucose, two-hour postprandial glucose, and glycated haemoglobin in patients with impaired glucose tolerance or type 2 diabetes [4]. Mechanistic explanations include insulin-like compounds, high fibre content, and anti-inflammatory effects [4]. Fermented foods supply SCFAs such as acetate, propionate and butyrate that modulate energy metabolism and insulin sensitivity. Microbiome-targeted therapies aim to restore microbial balance and increase SCFA production. Probiotics engineered to secrete GLP-1 analogues or amylin mimetics could support glycaemic control. Faecal microbiota products, such as Rebyota and Vowst, are being explored for metabolic conditions beyond CDI. Engineered probiotics and postbiotic supplements may deliver specific metabolites, such as ursolic acid or conjugated linoleic acid, that influence lipid metabolism.

5.2. Immune Modulation and Gut Barrier Function

Fermented foods and probiotics strengthen gut barrier integrity and modulate immune responses. The beneficial microbes in fermented foods interact with pattern recognition receptors on intestinal epithelial cells, promoting the production of anti-inflammatory cytokines and enhancing secretory immunoglobulin A. Engineered probiotics can be designed to sense inflammation and secrete anti-inflammatory compounds [8]. Bacteriophage therapy, a component of microbiome-targeted approaches, can selectively eliminate pathogens and reduce dysbiosis. Postbiotics, which contain cell wall fragments or microbial metabolites, also exert immunomodulatory effects [9]. These interventions could complement treatment for immune-mediated conditions such as inflammatory bowel disease and allergies.

5.3. Gut-Brain Axis and Mental Health

The gut-brain axis links gastrointestinal function with mood and cognition [5]. Fermented foods produce neurotransmitter precursors and neuromodulatory metabolites, such as gamma-aminobutyric acid, serotonin, and tryptophan derivatives. Consumption of fermented dairy and vegetables has been associated with lower levels of anxiety and depressive symptoms [5]. Microbiome-targeted therapies may influence brain function via vagal signalling and immune modulation [5]. Engineered probiotics that synthesise neuroactive compounds or degrade toxins are under investigation. Combining fermented food traditions with synthetic biology could lead to foods that support mental well-being. The integration of AI-guided microbiome profiling with CM may identify dietary patterns that enhance mood and cognitive performance.

5.4. Personalised Nutrition

Artificial intelligence is increasingly used to tailor diets based on individual data.

A systematic review of AI-generated dietary recommendations notes that these systems map interactions among biomarkers, gut microbiome profiles, and dietary components to produce personalised plans [16]. Preliminary studies report improved glycaemic control and symptom relief in conditions such as irritable bowel syndrome and prediabetes. Wearable sensors and continuous glucose monitors provide real-time data that enable the rapid adjustment of dietary advice [16]. However, ethical and practical challenges remain, including data privacy, algorithm transparency, and user adherence [16]. AI could integrate TCM constitutional typing [17] with microbiome profiling to personalise functional foods. For example, individuals with a phlegm-damp constitution might benefit from fermented, fibre-rich foods and specific probiotics, whereas those with yin deficiency might benefit from cooling ingredients and anti-inflammatory compounds. Recent conceptual frameworks have proposed combining AI-driven pattern recognition with traditional constitutional diagnostics to generate hybrid models for personalised nutrition [17].

5.5. Public Perception and Consumer Acceptance

Despite strong scientific progress, public perception of biotechnologies such as genome editing, precision fermentation and engineered microbes remains mixed. Surveys in Australia, Europe and the United States indicate higher acceptance when products provide clear health or sustainability benefits, but hesitancy persists around concepts perceived as artificial or genetically modified. Transparent communication, culturally appropriate framing, and clear labelling are therefore essential for consumer trust and market adoption. Acceptance will depend not only on scientific merit but also on perceived naturalness, safety and ethical considerations.

6. Clinical and Regulatory Outlook

Regulatory agencies are beginning to approve microbiome-based therapeutics. In November 2022, the FDA approved Rebyota, the first live biotherapeutic product for preventing recurrence of CDI. It consists of screened donor stool processed into a 150-millilitre enema containing a diverse mix of microbes and is administered as a single rectal dose [15]. In April 2023, the FDA approved Vowst, the first orally administered FMT product made of ethanol-treated spores, to prevent recurrent CDI [18]. In a placebo-controlled trial, Vowst reduced recurrence from 39.8 percent to 12.4 per cent [19]. These approvals set precedents for other microbiome therapies and underscore the importance of rigorous donor screening and manufacturing controls. European and Australian regulatory bodies are also developing frameworks for functional foods and microbiome-based therapeutics.

Engineered probiotics and postbiotic ingredients remain in experimental stages. Regulatory questions include how to classify these products—as drugs, supplements or foods—and what safety testing is required. Randomised controlled trials with omics-based endpoints are needed to establish efficacy and long-term safety.

Standardisation of microbial strains and fermentation conditions will be critical for reproducibility. Policymakers must also address equitable access, reimbursement and labelling. As more AI-guided nutrition platforms emerge, regulators will need to consider data privacy and algorithmic fairness.

7. Clinical and Regulatory Outlook

The convergence of ancient food wisdom and modern biotechnology offers exciting opportunities. Fermentation, once a household practice, now benefits from genomic tools that optimise microbial consortia for nutrient production, flavour and safety. Precision fermentation can generate animal-free proteins and fats. Genome editing enables crops to store key micronutrients. Artificial intelligence can combine microbiome profiles, metabolic markers, and traditional diagnostic approaches to design personalised diets.

Policy and market growth will play a central role. Governments should fund research on sustainable fermentation, promote the use of agricultural by-products as substrates, and set clear regulatory pathways for functional foods and microbiome therapies. Partnerships between researchers, industry, and local communities can help adapt new technologies into culturally appropriate foods. Sustainable functional foods can support healthier diets, cut environmental impact, and preserve culinary traditions. Biotechnology functions as a bridge linking food production, sustainability, and health.

8. Conclusion

The intersection of traditional knowledge and modern science is evident in the functional foods made possible by biotechnology. Advanced techniques, such as precision fermentation, synthetic biology, and biofortification, enable the production of foods that are not only nutrient-dense but also promote metabolic, immune, and cognitive health, as well as overall wellness. Upcycling and additional efficient production methods are ways to reduce waste and mitigate the environmental impact of food production. Engineered probiotics and postbiotics can offer specific benefits that bypass the need for live microbial colonisation. Defined expectations among regulators, industry partners, researchers and consumers, combined with unimpeded dialogue across scientific, policy and community sectors, will support responsible innovation. Ensuring equitable distribution of biotechnological advances, particularly access to functional foods and sustainable nutrition solutions, will be essential to translating progress into tangible public health benefits. The incorporation of microbiome science into food formulation could lead to hyper-personalised dietary regimens. Sustained cooperation among researchers, industry and policymakers will be crucial for biotechnological progress to benefit human health and protect the environment.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] La Puma, J. (2016) What Is Culinary Medicine and What Does It Do? *Population Health Management*, **19**, 1-3. https://doi.org/10.1089/pop.2015.0003

[2] Lim, E.C.N., Yu, X.F. and Lim, C.E.D. (2025) Beyond Pharmaceuticals: Integrating Chinese Culinary Medicine with Modern Nutritional Science for Holistic Diabetes Management. *Journal of Traditional Chinese Medical Sciences*. https://doi.org/10.1016/j.jtcms.2025.08.003

[3] Macias-Navarro, L., McWhorter, J.W., Guevara, D.C., Bentley, S.S., Sharma, S.V., Torres, J.H., *et al.* (2024) A Virtual Culinary Medicine Intervention for Ethnically Diverse Individuals with Type 2 Diabetes: Development of the Nourishing the Community through Culinary Medicine. *Frontiers in Nutrition*, **11**, Article 1383621. https://doi.org/10.3389/fnut.2024.1383621

[4] Liu, J., Yao, C., Wang, Y., Zhao, J. and Luo, H. (2023) Non-Drug Interventions of Traditional Chinese Medicine in Preventing Type 2 Diabetes: A Review. *Chinese Medicine*, **18**, Article No. 18. https://doi.org/10.1186/s13020-023-00854-1

[5] Lim, E.C.N., Yu, W.T.S. and Lim, C.E.D. (2025) Integrative Gut Health: How Fermented Foods Bridge Ancient Eastern Wisdom and Modern Microbiome Science. *Journal of Traditional Chinese Medical Sciences*, **12**, 499-508. https://doi.org/10.1016/j.jtcms.2025.07.002

[6] Leeuwendaal, N.K., Stanton, C., O'Toole, P.W. and Beresford, T.P. (2022) Fermented Foods, Health and the Gut Microbiome. *Nutrients*, **14**, Article 1527. https://doi.org/10.3390/nu14071527

[7] Lim, E.C.N. and Lim, C.E.D. (2025) Microbiome-targeted Therapies in Gastrointestinal Diseases: Clinical Evidence and Emerging Innovations. *Acta Microbiologica Hellenica*, **70**, Article 36. https://doi.org/10.3390/amh70030036

[8] Barra, M., Danino, T. and Garrido, D. (2020) Engineered Probiotics for Detection and Treatment of Inflammatory Intestinal Diseases. *Frontiers in Bioengineering and Biotechnology*, **8**, Article 265. https://doi.org/10.3389/fbioe.2020.00265

[9] Gurunathan, S., Thangaraj, P. and Kim, J. (2023) Postbiotics: Functional Food Materials and Therapeutic Agents for Cancer, Diabetes, and Inflammatory Diseases. *Foods*, **13**, Article 89. https://doi.org/10.3390/foods13010089

[10] Food and Agriculture Organization of the United Nations (2025) Can Precision Fermentation Offer a Safe and Sustainable Future for Food Production? https://www.fao.org/food-safety/news/news-details/en/c/1735814

[11] Banerjee, S., Roy, P., Nandi, S. and Roy, S. (2023) Advanced Biotechnological Strategies Towards the Development of Crops with Enhanced Micronutrient Content. *Plant Growth Regulation*, **100**, 355-371. https://doi.org/10.1007/s10725-023-00968-4

[12] Dhiman, S., Kaur, S., Thakur, B., Singh, P. and Tripathi, M. (2025) Nutritional Enhancement of Plant-Based Fermented Foods: Microbial Innovations for a Sustainable Future. *Fermentation*, **11**, Article 346. https://doi.org/10.3390/fermentation11060346

[13] Qin, J., Kurt, E., LBassi, T., Sa, L. and Xie, D. (2023) Biotechnological Production of *ω*-3 Fatty Acids: Current Status and Future Perspectives. *Frontiers in Microbiology*, **14**, Article 1280296. https://doi.org/10.3389/fmicb.2023.1280296

[14] Marcelli, A., Osimani, A. and Aquilanti, L. (2025) Vegetable By-Products from Industrial Processing: From Waste to Functional Ingredient through Fermentation. *Foods*, **14**, Article 2704. https://doi.org/10.3390/foods14152704

[15] Monday, L., Tillotson, G. and Chopra, T. (2024) Microbiota-Based Live Biotherapeutic Products for Clostridioides Difficile Infection—The Devil Is in the Details. *Infec-*

tion and Drug Resistance, **17**, 623-639. https://doi.org/10.2147/idr.s419243

[16] Wang, X., Sun, Z., Xue, H. and An, R. (2025) Artificial Intelligence Applications to Personalized Dietary Recommendations: A Systematic Review. *Healthcare*, **13**, Article 1417. https://doi.org/10.3390/healthcare13121417

[17] Lim, E.C.N., Cheng, N.C.L. and Lim, C.E.D. (2025) The Art of Medical Synthesis: Where Chinese Medical Wisdom Intersects with Artificial Intelligence. *Journal of Traditional Chinese Medical Sciences*. https://doi.org/10.1016/j.jtcms.2025.08.001

[18] U.S. Food & Drug Administration (2023) FDA Approves First Orally Administered Fecal Microbiota Product for the Prevention of Recurrence of Clostridioides Difficile Infection. https://www.fda.gov/news-events/press-announcements/fda-approves-first-orally-administered-fecal-microbiota-product-prevention-recurrence-clostridioides

[19] Seres Therapeutics (2023) VOWST Prescribing Information. Seres Therapeutics. https://www.vowst.com/prescribing-information