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ADVANCED FOOD BIOTECHNOLOGY — A COMPREHENSIVE REVIEW (2025)

Original Research

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ABSTRACT

Background: Food biotechnology has evolved from traditional fermentation techniques to an advanced era driven by synthetic biology, precision fermentation, genome editing, and cultivated food systems. These innovations have opened opportunities to address global challenges in nutrition, sustainability, and food safety. The integration of omics, machine learning, and process intensification has further accelerated product development, while regulatory frameworks such as FDA GRAS notices and EFSA's QPS list continue to adapt to ensure consumer safety.

Objective: The purpose of this narrative review is to synthesize recent developments in advanced food biotechnology, highlighting enabling technologies, applications, and regulatory frameworks, while critically examining challenges and research gaps.

Main Discussion Points: Key enabling platforms include precision fermentation, CRISPR-based genome editing, and AI/ML-guided strain and process engineering. Applications span precision-fermented dairy proteins, single-cell proteins, cultivated meats, next-generation probiotics, postbiotics, phage-based biopreservation, and specialty metabolites. Analytics such as whole-genome sequencing and multi-omics approaches have become essential for quality assurance and outbreak surveillance. Safety and regulatory perspectives from the U.S., EU, and international jurisdictions reveal both progress and disparities, particularly in the treatment of novel proteins and gene-edited organisms. Challenges persist in scaling production, reducing costs, standardizing safety assessments, and achieving consumer acceptance.

Conclusion: Advanced food biotechnology represents a paradigm shift with significant potential to reshape nutrition and sustainability. While the evidence base is promising, long-term safety, scalability, and regulatory harmonization remain critical priorities. Addressing these gaps through multidisciplinary research and transparent policy development will be essential to translate innovation into mainstream clinical and dietary practice.

Keywords: Precision fermentation; synthetic biology; cultivated meat; probiotics; food enzymes; regulatory frameworks.

INTRODUCTION

Biotechnology has historically shaped food production, ranging from ancient practices such as lactic acid fermentation to modern enzyme-driven food processing. Over the past decade, the rapid emergence of affordable sequencing technologies, genome editing tools such as CRISPR, and high-throughput design–build–test–learn (DBTL) platforms has redefined how microorganisms and cells can be programmed as biofactories for food ingredients and even complete foods (1,2). These advances not only accelerate innovation but also expand the potential of biotechnology to address growing global challenges in food security, sustainability, and human health. At the same time, regulatory agencies and policymakers are adapting their frameworks to keep pace with these scientific breakthroughs (3,4). In the United States, the Food and Drug Administration (FDA) has introduced Generally Recognized as Safe (GRAS) notices for precision-fermented proteins, while in Europe, the European Food Safety Authority (EFSA) continues to refine its Qualified Presumption of Safety (QPS) framework to guide safe adoption of microbial and cellular technologies (1–5). These evolving policies highlight the recognition that food biotechnology is no longer a niche scientific endeavor but a mainstream driver of innovation in food systems. Despite these developments, questions remain regarding scalability, consumer acceptance, long-term safety, and harmonization of regulatory practices across regions (6-8). Digital and analytical tools are increasingly applied to characterize complex products, yet gaps persist in linking molecular data with nutritional, functional, and clinical outcomes. This underlines the need for a comprehensive synthesis of emerging platforms, product pipelines, and regulatory landscapes to inform stakeholders and guide future directions. The objective of this review is therefore to integrate current knowledge up to August 31, 2025, with a particular focus on enabling biotechnological platforms, major classes of food products, digital and analytical innovations, and the evolving safety and regulatory frameworks, while critically assessing research gaps that require attention for the responsible advancement of food biotechnology.

ENABLING PLATFORMS IN ADVANCED FOOD BIOTECHNOLOGY

Synthetic biology and precision fermentation

Synthetic biology has transformed the production of food ingredients by enabling microbes to act as precision factories. Precision fermentation leverages engineered microorganisms such as *Komagataella phaffii*, *Trichoderma reesei*, and *Saccharomyces cerevisiae* to generate dairy proteins, enzymes, and vitamins with improved purity and reduced environmental impact. Recent developments highlight successful commercialization of recombinant β-lactoglobulin, where precision-fermented whey proteins have gained FDA approval under “no questions” GRAS letters since 2020, with new approvals continuing in 2024–2025 (1,2). Reviews emphasize how promoter libraries, glycoengineering, and tolerance mechanisms are improving yields, though challenges in scale-up remain significant (3).

Genome editing of food microbes and crops

Genome editing, particularly CRISPR/Cas systems, has become indispensable for tailoring production hosts and crops for food biotechnology. Applications range from streamlining microbial genomes for robust fermentation to stacking agronomic traits in crops serving as feedstocks. The regulatory environment, however, varies widely, with the U.S. adopting product-based approaches while the EU applies process-based restrictions (4). These differences pose challenges for harmonization and international trade. Nonetheless, genome editing continues to accelerate the development of resilient microbial strains capable of tolerating high-stress fermentation conditions.

Bioprocess intensification and downstream processing

Process intensification is central to reducing costs and enabling large-scale adoption. Continuous fermentation and high-cell-density fed-batch operations, coupled with in situ product removal, are increasingly employed to improve efficiency (5). Downstream processing has benefited from membrane filtration and advanced clarification techniques, ensuring consistent product quality. The integration of process analytical technologies (PAT) such as Raman spectroscopy allows real-time monitoring, minimizing variability and ensuring regulatory compliance. Despite these advances, scaling bioprocesses beyond pilot facilities continues to be a major barrier, particularly for cultivated foods.

AI/ML across the DBTL cycle

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Artificial intelligence (AI) and machine learning (ML) have rapidly integrated into the design–build–test–learn (DBTL) cycle of food biotechnology. Predictive algorithms now assist in protein design, metabolic flux balancing, and adaptive fermentation control. Recent studies show digital twins and model predictive control systems significantly reduce batch variability, improving both yield and cost-effectiveness (6). However, the reliance on large training datasets highlights the need for standardized data infrastructures, which remain underdeveloped in food biotechnology.

APPLICATIONS

Food enzymes

Food enzymes such as proteases, amylases, and lipases continue to underpin brewing, dairy, and baking industries. Microbial systems dominate production due to cost efficiency and regulatory familiarity. EFSA assessments under Regulation (EC) No 1332/2008 and U.S. GRAS approvals illustrate the strong global demand for safe enzyme use in food (2,7). Despite progress, some enzymes face allergenicity concerns, underlining the need for more comprehensive toxicological profiling.

ALTERNATIVE AND ENHANCED PROTEINS

Precision-fermented dairy proteins

Precision fermentation has enabled the large-scale production of dairy proteins such as β-lactoglobulin, now incorporated into beverages and dairy analogues. FDA approvals since 2020 demonstrate regulatory confidence in these products, while environmental life cycle assessments suggest reduced greenhouse gas footprints compared with conventional dairy (8). However, consumer perception and labeling remain contentious, particularly regarding transparency around “animal-free” claims.

Single-cell proteins (SCP) and mycoprotein

Single-cell proteins (SCP), derived from hydrogen-oxidizing bacteria or filamentous fungi, provide sustainable alternatives with low land and water footprints. Mycoprotein derived from *Fusarium* species has gained renewed attention due to positive environmental life-cycle analyses (9). Emerging studies indicate significant climate benefits when SCP production is powered by renewable energy, though questions remain about scalability and long-term nutritional equivalence.

Cultivated (cell-cultured) foods

The approval of cultivated chicken in the U.S. by FDA and USDA in 2022–2023 marked a regulatory milestone. While commercialization has begun in select markets, challenges in bioreactor scalability, serum-free media, and consumer adoption persist (4,10). Singapore and Israel remain pioneers in cultivated food approvals, emphasizing how regulatory agility can accelerate innovation.

Probiotics, next-generation probiotics, postbiotics

The definition of postbiotics was clarified in 2021 as “inanimate microorganisms or their components conferring health benefits,” aligning with ISAPP consensus (11). Traditional probiotics like *Lactobacillus* spp. remain under QPS lists, but next-generation candidates such as *Akkermansia muciniphila* are undergoing clinical evaluation. While promising, their regulatory pathways remain uncertain, especially given concerns around antimicrobial resistance.

Biopreservation and phage-based controls

Bacteriophages offer targeted antimicrobial interventions, particularly against *Listeria monocytogenes* and *Salmonella*. FDA GRAS letters in 2024 for Salmonella-targeted phages reflect growing regulatory acceptance (12). Despite their efficacy, concerns about phage resistance and integration into HACCP-based frameworks highlight areas requiring further research.

Flavor, color, and specialty metabolites

Precision fermentation has expanded the availability of specialty metabolites such as anthocyanins, vanillin, and vitamin B12. These processes reduce dependence on agricultural extraction, lowering environmental burdens. However, debates around consumer acceptance and natural labeling continue to shape their adoption.

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ANALYTICS AND DATA INFRASTRUCTURES

Whole-genome sequencing (WGS) and metagenomics in food safety

WGS has become integral to outbreak surveillance and food safety. The FDA's GenomeTrakr network now spans dozens of U.S. and international labs, enabling rapid tracebacks of foodborne outbreaks (13). Despite its successes, challenges remain in harmonizing international databases and ensuring equitable access to sequencing technologies in developing regions.

Multi-omics for fermentation and product quality

Omics tools—metagenomics, transcriptomics, metabolomics—enable the dissection of complex microbial communities, from cocoa fermentations to koji-based processes. These approaches improve starter design and valorize side streams, contributing to circular economy models (14). However, the translation of omics data into actionable product design remains an ongoing gap.

Process analytical technology (PAT)

PAT, integrating inline spectroscopy and dielectric sensors, is enhancing real-time bioprocess control. Adaptive algorithms ensure consistent quality, yet widespread implementation is hindered by the high costs of instrumentation and the need for skilled operators.

SAFETY AND REGULATORY FRAMEWORKS

U.S. (FDA/USDA)

GRAS and food additives

FDA's GRAS notifications remain central to the approval of enzymes and fermentation-derived proteins. Recombinant whey proteins, including β-lactoglobulin, continue to expand their applications across dairy analogues (1,2). While GRAS offers flexibility, reliance on self-determinations without public transparency remains a point of debate.

Cell-cultured foods

Regulatory oversight for cell-cultured foods in the U.S. involves FDA premarket consultations followed by USDA facility approvals and labeling. The dual-agency framework has enabled initial commercialization but remains resource-intensive for small startups (4).

European Union (EFSA)

QPS list

EFSA's Qualified Presumption of Safety (QPS) list is regularly updated and continues to provide a streamlined path for safe microbial applications (15). However, limitations arise for novel or less-characterized species, often delaying approvals.

Food enzymes & novel foods

Food enzymes are evaluated under Regulation (EC) No 1332/2008, while precision-fermented proteins require dossiers under the EU novel foods regulation. These rigorous evaluations ensure safety but slow innovation relative to other jurisdictions.

International perspectives

Singapore and Israel are leaders in precision fermentation and cellular agriculture approvals, reflecting agile regulatory ecosystems. Codex Alimentarius and OECD are driving harmonization efforts, though significant differences remain across regions.

Quantitative Snapshots (selected)

- FDA "no questions" letters for precision-fermented whey proteins: GRN 863 (Perfect Day, 2020) with multiple additional approvals through 2025 (1,2).
- GenomeTrakr expansion: >20 international labs, supporting hundreds of outbreak investigations annually (6).
- Phage GRAS outcomes: Listeria-specific phage P100 (GRN 198/218) and Salmonella-specific approvals in 2024 (8).

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- First cultivated chicken approvals: FDA consultation (2022) and USDA inspection grants (2023), marking initial commercialization (4).

CRITICAL ANALYSIS AND LIMITATIONS

Across the recent literature, several structural limitations constrain the strength of inference for advanced food biotechnology. Many investigations in precision fermentation and single-cell proteins rely on benchtop or pilot-scale studies with modest replicate numbers and short observation windows, limiting confidence in scalability, process stability, and batch-to-batch reproducibility (6–10). Clinical or quasi-clinical evidence for next-generation probiotics and postbiotics remains dominated by small, single-center trials with heterogeneous inclusion criteria and brief follow-up, which weakens conclusions about durable efficacy and safety in diverse populations (15,16). Early demonstrations of cultivated foods are largely pre-commercial case studies or engineering reports rather than randomized or controlled evaluations; nutritional equivalence, digestibility, and long-term tolerability therefore remain under characterized (17). Even for widely used food enzymes, much of the supporting evidence comprises in-house dossiers or functional assays without independent replication, making external validation difficult (2,5). Methodological bias is a recurring concern. Selection bias arises when fermentation performance or probiotic benefit is reported only for best-performing strains, media, or cohorts, while less favorable attempts remain unpublished (18,19). Performance bias is evident in open-label taste or sensory assessments of precision-fermented or cultivated proteins, where lack of blinding can inflate effect sizes (11–13). In safety dossiers underlying GRAS or novel food submissions, confounding can stem from incomplete exposure scenarios, limited allergenicity cross-reactivity testing, or reliance on read-across from related taxa rather than the production strain itself (20). For β-lactoglobulin and other recombinant dairy proteins, studies often focus on compositional equivalence and acute tolerance, leaving questions about cross-sensitization or cumulative exposure unanswered (11–13).

Publication bias likely shapes the apparent momentum of the field. Positive process intensification outcomes, high titers, or successful techno-economic assessments are more frequently reported than neutral or negative findings, especially when data originate from proprietary development programs (21). GRAS self-determinations that are not voluntarily filed to public inventories further exacerbate visibility bias, as null results or abandoned programs rarely reach the literature (12–15). Similarly, early cultivated-meat scale-up narratives typically highlight engineering breakthroughs, while cost overruns or unsuccessful reactor regimes are underreported, skewing perceptions of near-term feasibility (10–16). Outcome heterogeneity complicates cross-study comparisons. Process papers variously report productivity as titer, yield, space–time yield, or cost-of-goods, often with incompatible assumptions about depreciation, energy mixes, and labor (6–10). Life-cycle assessments differ in system boundaries, functional units, and co-product allocation, producing divergent climate or water footprints that are not easily reconciled (6–10). Probiotic and postbiotic studies span a wide range of strains, doses, and endpoints—from surrogate biomarkers to patient-reported outcomes—undermining meta-analytic synthesis (21,22). In phage-based biopreservation, efficacy is measured across disparate matrices, inocula, and hurdle combinations; without standardized challenge protocols, effect sizes are difficult to generalize (23). Even in WGS-enabled surveillance, laboratory methods, database curation, and case linkage criteria vary across jurisdictions, which affects comparability of traceback performance (16,17).

Generalizability remains limited by both biology and context. Strain-specific optimizations—for promoters, secretion signals, or stress-tolerance alleles—do not necessarily transfer across hosts, products, or scales, constraining external validity (17–19). Findings from well-resourced, continuous-monitoring facilities may not extrapolate to small or resource-limited plants lacking advanced PAT and soft-sensor infrastructure (Process Analytical Technology) (19,20). Nutritional and safety data generated in healthy adult volunteers rarely extend to children, older adults, or individuals with allergies or metabolic conditions, where risk–benefit profiles could differ (21). For cultivated foods, regulatory authorizations in a few countries do not imply acceptability or supply-chain readiness elsewhere, given varying energy grids, media inputs, and labeling norms (22–24). WGS surveillance networks like GenomeTrakr show strong performance in high-income settings, but coverage gaps in low- and middle-income regions introduce ascertainment bias into global outbreak analytics (25,26). Confounding technical and data-governance issues also limit cumulative learning. AI/ML models that optimize the DBTL cycle are frequently trained on small, proprietary datasets with inconsistent metadata; risks of data leakage, overfitting, and poor transfer performance are seldom probed in out-of-distribution tests (17–19). Downstream processing studies may attribute cost reductions to single innovations without adequately controlling for concurrent changes in media, feed strategies, or oxygen transfer, blurring causal inference (6–10). In phage applications, resistance evolution and microbiome-level impacts are not

systematically monitored beyond short time frames, leaving ecological trade-offs unresolved (12–15). Finally, incremental updates to EFSA's QPS list and divergent gene-editing rules across jurisdictions complicate comparative safety assessments, because similar organisms are evaluated under different evidence thresholds and qualification notes (18–20). Taken together, the evidence base is dynamic but uneven. Strengthening it will require larger, multicenter studies with prespecified endpoints; standardized reporting for process metrics, LCA assumptions, and clinical outcomes; transparent data deposition for strains and omics; and prospective assessments of long-term safety, allergenicity, and nutritional equivalence in underrepresented populations. Without these steps, policy and investment decisions risk over- or under-estimating both the benefits and the trade-offs of deploying advanced food biotechnology at scale (3–5).

IMPLICATIONS AND FUTURE DIRECTIONS

The findings of recent advances in food biotechnology carry important implications for both clinical practice and public health. Precision-fermented proteins, single-cell proteins, and cultivated foods have the potential to provide safer, allergen-controlled, and more sustainable sources of nutrition for patients with dietary restrictions or metabolic conditions. For example, recombinant β-lactoglobulin and caseins can be engineered to minimize allergenic epitopes, offering alternatives for populations sensitive to conventional dairy proteins (13). Similarly, postbiotics and next-generation probiotics hold therapeutic promise in modulating gut health and systemic immunity, although their translation into clinical recommendations will require standardized dosing, strain specificity, and long-term safety evaluations (11,12). In practice, clinicians may soon be required to integrate these novel food-derived interventions into nutritional counseling, allergy management, and preventive care. At the policy level, biotechnology-driven foods demand updated frameworks that balance innovation with consumer protection. Regulatory agencies such as the FDA and EFSA have established mechanisms such as GRAS notifications and the Qualified Presumption of Safety list, but these are strained by the rapid pace of emerging applications (12,13). Policymakers must anticipate not only compositional safety but also broader implications, including environmental sustainability and labeling transparency. Harmonization of international standards remains critical, as divergent regulatory treatment of genome-edited crops or cultivated meat complicates global trade and erodes consumer trust (14–16). Evidence-based guidelines will be required to help healthcare providers, dietitians, and regulatory bodies make informed decisions about the integration of precision-fermented proteins, alternative enzymes, and novel probiotics into both medical nutrition therapy and broader dietary recommendations.

Despite promising progress, unanswered questions remain substantial. Long-term clinical outcomes of consuming recombinant proteins or cultivated foods have not yet been comprehensively studied, particularly in vulnerable groups such as children, older adults, and patients with chronic disease. Environmental life-cycle assessments, while positive in many cases, show inconsistencies in boundaries, co-product allocation, and assumptions about renewable energy inputs, leaving uncertainty about their true climate benefits (17,18). For probiotics and postbiotics, variability in strain choice, clinical endpoints, and trial methodologies continues to obstruct consensus on efficacy (19,20). Additionally, resistance evolution in bacteriophage-based biopreservation and the ecological effects of sustained phage use in the food chain remain poorly understood (21). Future research must therefore adopt more rigorous methodological designs. Large, multicenter randomized controlled trials with extended follow-up are essential to establish the nutritional, metabolic, and immunological impacts of these emerging foods. Harmonized protocols for assessing allergenicity, digestibility, and microbiome interactions should be prioritized, along with systematic monitoring of long-term outcomes (22). In industrial biotechnology, techno-economic analyses should incorporate sensitivity testing for diverse energy mixes and regional infrastructure to improve generalizability (23). For cultivated foods, comparative nutritional studies with conventional products, coupled with consumer perception research, will be critical to determine adoption pathways. Meanwhile, phage-based biopreservation strategies require longitudinal monitoring of resistance development and ecological safety under real-world food chain conditions (24). Strengthening open-access data infrastructures for omics, fermentation performance, and regulatory submissions will also be crucial to accelerate cumulative progress (25,26). By integrating clinical evidence with robust regulatory science and transparent communication, food biotechnology can transition from experimental innovation to mainstream dietary and therapeutic practice. Addressing the outlined gaps through carefully designed, multidisciplinary research will ensure that these technologies deliver on their promise of safer, more sustainable, and health-promoting food systems.

CONCLUSION

This review highlights how advances in synthetic biology, precision fermentation, genome editing, bioprocess intensification, and AI-driven optimization are reshaping the landscape of food biotechnology, enabling the development of alternative proteins, cultivated

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foods, novel probiotics, and phage-based preservation strategies with promising clinical, nutritional, and environmental benefits. The evidence to date is encouraging but remains uneven, as most studies are constrained by small sample sizes, short follow-up durations, and methodological heterogeneity, limiting the strength of conclusions regarding long-term safety, efficacy, and scalability. Clinicians should remain attentive to the emerging role of precision-fermented proteins and next-generation probiotics in nutritional care, while researchers are urged to pursue large, multicenter, and standardized trials to strengthen the clinical and regulatory evidence base. Policymakers must also harmonize safety frameworks to ensure global consistency and consumer confidence. Ultimately, bridging existing gaps with rigorous, transparent, and multidisciplinary research will be essential to realize the full potential of biotechnology in delivering safe, sustainable, and health-promoting food systems for the future.

AUTHOR CONTRIBUTION

Author	Contribution
Muhammad Usama Aslam*	Substantial Contribution to study design, analysis, acquisition of Data Manuscript Writing Has given Final Approval of the version to be published
Esha Aslam	Substantial Contribution to study design, acquisition and interpretation of Data Critical Review and Manuscript Writing Has given Final Approval of the version to be published
Muhammad Shahbaz*	Substantial Contribution to acquisition and interpretation of Data Has given Final Approval of the version to be published

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