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Precision Fermentation for Sustainable Food Production: Technological Advances, Food Applications, Sustainability, Challenges and Future Perspectives

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ABSTRACT
Precision fermentation (PF) has developed into an important food-biotechnology platform that employs engineered microorganisms to produce specific food ingredients, such as proteins, enzymes, flavour compounds, sweet proteins, and bioactive molecules, under controlled fermentation conditions. This review critically examines developments in PF, with emphasis on technological progress, microbial cell factories, fermentation productivity, scale-up, food functionality, circular feedstocks, and the increasing application of artificial intelligence. Environmental performance, techno-economic feasibility, safety, regulatory considerations, and consumer acceptance are also considered. The evidence reviewed indicates that PF can support the controlled production of selected food ingredients and has the potential to complement plant-based proteins, biomass fermentation, and cellular-agriculture approaches. However, PF should not be considered inherently sustainable or automatically better than conventional production methods. Its environmental performance is strongly influenced by electricity sources, feedstock selection, titre, rate and yield (TRY), aeration intensity, fermentation duration, and downstream processing. Likewise, commercial success depends on achieving high productivity, efficient product recovery, affordable feedstocks, and suitable scale-up strategies. Safety evaluation should remain product-specific, particularly for allergenic proteins and novel ingredients, while regulatory differences across regions and consumer perceptions will continue to influence the adoption of precision fermentation. A central argument we advance is that PF should be evaluated as an integrated food-system technology, requiring simultaneous consideration of biological engineering, process engineering, food science, life-cycle assessment, techno-economic analysis, and social governance. Looking forward, we see pressing needs for pilot-scale validation, standardized TRY reporting, renewable-energy integration, circular feedstock development, AI-assisted experimental design, food-matrix functionality studies, and harmonized safety and regulatory approaches.

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INTRODUCTION

Food systems face mounting pressure to deliver adequate nutrition while reducing environmental burdens tied to land use, water consumption, greenhouse-gas emissions, biodiversity loss, and resource-intensive animal production. Fermentation is hardly new to food biotechnology it has been used for millennia. But recent advances in genomics, synthetic biology, metabolic engineering, automation, and computational modelling have transformed its potential. Fermentation now extends beyond substrate transformation to the deliberate manufacturing of defined molecules and microbial biomass (Teng *et al.*, 2021; Graham & Ledesma-Amaro, 2023; Knychala *et al*., 2024; Hill, 2024).

Precision fermentation (PF) refers to the controlled use of microorganisms as cell factories to produce specific target compounds most commonly recombinant proteins, lipids, flavours, vitamins, enzymes, or other high-value ingredients. While the term "precision fermentation" is relatively recent, many of its underlying technologies recombinant DNA, industrial fermentation, metabolic engineering, and microbial cell factories have been in use for decades (Teng *et al*., 2021; Sawyer & Ross, 2025; Shuaibu & Yunpei, 2024). A useful conceptual distinction is that PF aims to produce a defined molecule, whereas biomass fermentation uses the microbial culture itself as the primary food ingredient (Graham & Ledesma-Amaro, 2023; D'Almeida & de Albuquerque, 2025).

The food sector has become an especially active application area because PF offers the possibility of producing molecules traditionally obtained from animals or plants under controlled, contained conditions. Dairy and egg proteins remain the most prominent examples, although researchers are increasingly investigating cultured-meat inputs, sweet proteins, flavour compounds, vitamins, terpenoids, and other bioactive compounds (Eastham & Leman, 2024; Nielsen *et al*., 2024; Verma *et al.*, 2025; Shukla *et al*., 2026; Purba & Sangsawad, 2025).

However, the sustainability of PF cannot be assumed and depends on several factors. Feedstock origin, electricity mix, fermentation productivity, oxygen transfer, water requirements, downstream recovery, waste treatment, and production scale can all influence its environmental performance. Consequently, an increasing number of studies emphasize the need for prospective life-cycle assessment (LCA), techno-economic assessment (TEA), and integrated sustainability frameworks, rather than basing sustainability claims primarily on the biological efficiency of the microorganisms involved (David *et al*., 2026a; Behm *et al*., 2022; Nadar *et al*., 2025; Fletcher *et al.*, 2024; David *et al*., 2026b; Bandari *et al*., 2026).

This review examines the technological foundations of PF, microbial hosts and strain engineering, process development and scale-up, food applications, feedstocks and circularity, AI-assisted optimization, environmental and economic assessment, safety and regulation, consumer acceptance, and commercialization. A key feature of this review is its conditional, systems-level perspective on PF. Instead of assuming that engineered microbial production is inherently sustainable, we examine how biological productivity interacts with food functionality, energy requirements, feedstock selection, downstream processing, economic feasibility, regulatory considerations, and consumer adoption. This approach provides a clearer distinction between benefits supported by available evidence and claims whose validity depends strongly on specific process assumptions.

MATERIALS AND METHODS

A structured narrative review was undertaken to synthesize published research on precision fermentation (PF) and its potential applications in sustainable food production. The review covered key areas including microbial cell factories, strain engineering, fermentation processes, food applications, feedstocks, sustainability, techno-economic feasibility, food safety, regulation, and consumer acceptance.

A total of 61 papers were initially identified, of which 55 met the screening criteria and were included in the review. The literature search was conducted between May and August 2026 using scholarly databases and search platforms, namely Scopus, Web of Science, PubMed, ScienceDirect, and Google Scholar. The main search terms included "precision fermentation," "precision fermentation for food applications," "microbial cell factories," "fermentation technology," "sustainability," "techno-economic assessment," "food safety," "food safety regulation," and "consumer acceptance." Literature searching and manuscript preparation were conducted concurrently throughout the review period. Articles written in English were included while duplicate publications and studies that did not adequately address the research topic or objectives were excluded.

The selected publications were thematically analyzed to identify major technological developments, potential applications, limitations, research gaps, and emerging directions in PF research. Emphasis was placed on peer-reviewed studies published within the preceding decade, while a limited number of older foundational studies were retained where their findings remained relevant to contemporary PF research. One such example is Tucker *et al*. (2004), which examined pretreatment and scale-up considerations.

The review went beyond a descriptive summary of the selected literature by critically comparing findings across studies. Particular attention was given to differences in reported outcomes, methodological approaches, and the distinction between laboratory-scale performance and potential industrial applicability. For studies reporting sustainability benefits, the underlying life-cycle assessment (LCA) assumptions were also considered, with attention to the transparency of the assessment and the extent to which the reported conclusions were supported by available evidence rather than optimistic projections.

RESULTS AND DISCUSSION

Precision Fermentation: Concept, Scope and Evolution

PF forms part of a broader continuum that encompasses traditional fermentation, biomass fermentation, recombinant protein production, and synthetic biology. Teng *et al*. (2021) made a useful observation: modern fermentation can complement traditional food fermentation by using genomic and synthetic-biology tools to generate defined metabolites and novel food ingredients. Graham and Ledesma-Amaro (2023) similarly described microorganisms as both foods in their own right and cell factories for highly functional ingredients. The conceptual boundary is therefore technological rather than historical: PF represents an increasingly integrated platform in which biological design, fermentation engineering, and downstream food processing are coordinated.

The terminology itself has attracted some debate. Sawyer and Ross (2025) argued persuasively, in our view that PF is, in important respects, a new label for technologies developed over several decades, including genetic engineering, biotechnology, and industrial fermentation. This observation is academically useful because it prevents the field from being portrayed as entirely unprecedented while still recognizing that the integration of these technologies with sustainability-oriented food applications is novel. Shuaibu and Yunpei (2024) and Flaibam *et al*. (2026) further illustrate how PF is now being framed as a food-manufacturing platform rather than only a pharmaceutical or industrial-biotechnology technique. However, we caution against the tendency to treat PF as a singular, monolithic technology it encompasses vastly different hosts, products, processes, and scales, and generalizations across these domains are often misleading.

The range of potential products is remarkably broad. Reviews in the selected literature identify proteins, lipids, carbohydrates, enzymes, flavours, vitamins, bioactive compounds, and pigments as potential PF products. Verma *et al*. (2025) highlighted the development of next-generation food ingredients, whereas Shukla *et al*. (2026) and Flaibam *et al*. (2026) examined the increasing integration of PF with alternative-protein production and food regulation. This broad scope presents both opportunities and methodological challenges, since the most suitable host, fermentation mode, purification approach, safety assessment, and sustainability benchmark can vary considerably between products. Consequently, a single approach cannot be applied effectively to all PF applications.

Microbial Cell Factories and Strain Engineering

Selecting an appropriate microbial host is among the earliest and most important decisions in PF, as it can strongly influence the success of the entire process. Bacteria, yeasts, and filamentous fungi differ in their genetic tractability, secretion capacity, growth rate, history of food use, metabolic flexibility, and ability to correctly fold and process target products. Eastham and Leman (2024), Nielsen *et al*. (2024), and Boukid *et al*. (2023) identified yeasts and filamentous fungi as particularly valuable hosts for recombinant food proteins, mainly because some species can reach high cell densities while secreting proteins directly into the fermentation broth. Nevertheless, the frequent use of a limited number of well-characterized hosts, particularly Komagataella phaffii (formerly Pichia pastoris) and Aspergillus oryzae, may reflect established convenience rather than genuine optimality. Considerable potential therefore remains in exploring less domesticated microorganisms with traits that could offer advantages for specific PF applications.

Strain engineering in PF has progressed well beyond the simple insertion of a target gene. Factors such as promoter design, signal-peptide selection, copy-number control, metabolic-pathway engineering, chaperone expression, protease reduction, and the regulation of transcription and translation can substantially affect both product titre and quality. Zhang *et al*. (2024), for example, increased the secretion of human milk osteopontin in Komagataella phaffii by combining host screening with promoter and signal-peptide optimization and engineering at the transcriptional, translational, and chaperone levels. This improvement highlights an important point: successful production often depends on engineering the wider secretion pathway rather than concentrating only on the target coding sequence. The importance of this systems-level approach has become increasingly recognized, and some earlier PF efforts may have achieved limited performance because these interconnected factors were not adequately considered.

Computational strain engineering is also becoming more prominent and this is a trend we expect to accelerate. Markova *et al*. (2022) developed the MaLPHAS machine-learning approach to predict genetic edits that could improve recombinant-protein secretion, and they demonstrated experimentally validated secretion improvement in K. phaffii. Vaknin *et al*. (2024) demonstrated a more general transcriptional-regulatory design system capable of boosting gene expression in yeast and mammalian cell lines. Together, these studies indicate a clear shift toward predictive design though we should not lose sight of the fact that computational predictions still require rigorous experimental validation. The gap between in silico predictions and in vivo performance remains considerable, so computational findings should be interpreted cautiously unless they are supported by wet-lab validation. Signal-peptide discovery offers another approach for improving in vitro production. Karimian *et al*. (2025), for instance, applied a dual-biosensor strategy to identify secretion signals and screen strains for PF production. These approaches are valuable because secretion can simplify downstream processing by transferring the target protein from the intracellular compartment into the fermentation supernatant. The longer-term goal is therefore not simply to achieve higher expression, but to develop a host that combines high productivity with stability, efficient secretion, food-grade suitability, and robustness during scale-up. At the same time, secretion may create additional challenges, including protein degradation, misfolding, and contamination risks, which can receive insufficient attention when extracellular production is emphasized.

Genetically engineered microorganisms are also being explored for non-protein products, an area that has received comparatively less attention in mainstream PF discussions. Mirsalami and Mirsalami (2025) reviewed the use of engineered microorganisms across food applications, while Pak *et al*. (2025) highlighted the role of yeast-based cell factories in terpenoid biosynthesis. Anantayanon *et al*. (2025) demonstrated the use of engineered Aspergillus oryzae to enhance cordycepin production, showing how PF can be applied to increase the production of bioactive metabolites rather than focusing exclusively on the reproduction of animal-derived proteins.

Fermentation Process Development, Productivity and Scale-Up

Once a suitable strain has been developed, the process conditions largely determine whether a laboratory strain can be translated into an economically viable manufacturing platform. Important variables include carbon and nitrogen supply, pH, temperature, dissolved oxygen, agitation, aeration, inoculum density, feeding strategy, and fermentation time. Eastham and Leman (2024) described upstream and downstream processing as closely connected parts of a commercial PF process, while Konzock and Nielsen (2024) highlighted three fundamental performance indicators titre, rate, and yield (TRY) as important measures for techno-economic evaluation.

We find the TRY framework particularly useful. High titer reduces the volume of broth that must be processed per unit of product, but titer alone is not sufficient. Volumetric productivity determines reactor utilization, while yield determines how efficiently feedstock is converted into the target product. Konzock and Nielsen (2024) therefore provide a framework for comparing fermentation processes and identifying whether improvements should focus on strain productivity, fermentation duration, substrate conversion, or process intensity.

Scale-up creates additional constraints and this is where many promising laboratory strains fail. Oxygen transfer, heat removal, mixing, viscosity, foaming, fungal morphology, and process heterogeneity can change substantially as reactor volume increases. The commercial-scale model of Nadar *et al*. (2025) illustrates this issue clearly: an ex-ante process design for 10,000 tonnes per year of PF protein identified aeration as a major energy demand and evaluated the effects of fermentation time, temperature, and aeration on resource use. The study shows why process modelling should accompany strain development rather than being postponed until commercialization.

Global-scale modelling reinforces the magnitude of the challenge. Fletcher *et al*. (2024) estimated that a scenario in which fermentation-produced protein supplied an additional 10% of global protein would require major quantities of feedstock, cropland, and electricity, and would generate substantial greenhouse-gas emissions. We regard these estimates as outputs that depend on specific scenarios rather than as universal characteristics of PF. In our view, their main value lies in showing that moving from laboratory-scale reactors to infrastructure capable of supporting global food production can fundamentally alter how PF sustainability should be evaluated.

Experience gained from traditional industrial fermentation also remains highly relevant, and we believe it should not be overlooked. Tucker *et al*. (2004) demonstrated the use of dilute-acid pretreatment and fermentation of distiller's grain at bench and larger scales, showing how agricultural residues can be converted into fermentable substrates while producing higher-value coproducts. Although the study predates modern PF terminology, its process engineering lessons pretreatment, hydrolysis, fermentation, scale-up, and coproduct valorization remain directly relevant to contemporary PF systems.

Food Applications of Precision Fermentation

PF applications can be divided into at least four broad food categories: animal-free proteins, ingredients for cultivated meat, specialty molecules such as flavours and sweet proteins, and engineered microbial biomass. Eastham and Leman (2024) and Nielsen *et al*. (2024) identify dairy and egg proteins as major targets because their functional properties are difficult to reproduce using conventional plant proteins.

Dairy proteins have received particular attention and for good reason. β-lactoglobulin, caseins, lactoferrin, and other milk proteins can provide solubility, emulsification, foaming, gelation, or nutritional functions. Aro *et al*. (2023) experimentally produced bovine β-lactoglobulin and hen egg ovalbumin using T. reesei and evaluated their techno-functional properties. Zhang *et al*. (2024) similarly demonstrated recombinant production of human milk osteopontin in K. phaffii, illustrating the broader potential for bioactive milk proteins. Purba and Sangsawad (2025) placed these developments within the wider field of dairy alternatives and cellular agriculture.

Egg proteins are attractive because ovalbumin and related proteins contribute important foaming, gelation, and emulsification functions. Nielsen *et al*. (2024) reviewed recombinant milk and egg proteins as an emerging alternative-protein category. We see an interesting opportunity here: the ability to produce specific proteins individually may permit deliberate formulation of protein mixtures with defined ratios rather than reproducing complex animal-derived mixtures exactly. This creates opportunities for ingredient design but also places greater responsibility on food scientists to characterize functionality in realistic matrices.

PF also supports cultured-meat systems though we should be careful not to conflate the two technologies. Flaibam *et al*. (2025) reviewed recombinant proteins used in cultured-meat production and highlighted their potential roles in serum-free culture media, growth-factor supply, scaffolding, sensory characteristics, and nutritional quality. D'Almeida and de Albuquerque (2025) discussed microorganisms as protein sources within the broader alternative-protein landscape, while Kaplan and McClements (2025) emphasized hybrid food strategies in which different alternative-protein technologies can be combined rather than treated as mutually exclusive. Thus, PF and cultivated meat should be distinguished technologically, but they can be complementary within a cellular-agriculture ecosystem.

PF-derived molecules can also target sensory quality an area we think deserves more attention. Du *et al*. (2025) used machine learning to predict volatile-compound profiles associated with meat aroma in S. cerevisiae fermentation, illustrating how fermentation can be connected to aroma design. Wang *et al*. (2025) reviewed microbial production of edible terpenoids for flavour, preservation, and nutritional applications. Pak *et al*. (2025) similarly reviewed yeast-based terpenoid production. These applications demonstrate a shift from replacing a single animal protein toward engineering precise sensory and functional components.

Sweet proteins provide another compelling example. Lynch *et al*. (2023) evaluated brazzein produced in K. phaffii through precision fermentation using in silico allergenicity, in vitro genotoxicity, and a 90-day dietary toxicity study. The study reported no evidence of allergenicity in its computational assessment, no genotoxicity in the tested assays, and no adverse effects at the highest tested dose. We consider this level of product-specific evidence essential it illustrates the standard of safety evaluation required for novel PF ingredients.

Engineered edible fungi represent a related but distinct route in which the microbial biomass itself can be consumed. Rekdal *et al*. (2024) developed a modular synthetic-biology toolkit for edible Aspergillus oryzae and used it to increase intracellular ergothioneine and heme, demonstrating the potential to improve nutritional and sensory attributes of fungal foods. This approach connects biomass fermentation with precision engineering and may reduce the need for extensive purification when the engineered biomass is itself the food product.

Feedstocks, Waste Valorization and Circular Bioeconomy

Feedstock selection is one of the most important determinants of PF sustainability and in our view, it is also one of the most under-researched areas in the current literature. Refined sugars are convenient and reproducible, but their agricultural production can create land and water burdens. Nadar *et al*. (2024) reviewed a century of microbial fermentation using agro-industrial by-products and concluded that waste-derived substrates represent an important route toward protein production and circularity. Haajanen *et al*. (2025) experimentally compared grass residues, legume and vegetable residues, and brewer's spent grain for microbial biomass and T. reesei cultivation, demonstrating that pretreatment can release fermentable sugars but may also generate inhibitory compounds.

Agro-industrial side streams can provide both carbon and other nutrients. Mitri *et al*. (2025) used brewer's spent grain and crude glycerol as substrates for engineered Yarrowia lipolytica and optimized production of 2-phenylethanol, illustrating how a low-value residue can become a feedstock for a value-added food-related compound. Piercy *et al*. (2024) expanded the circular-economy perspective to include food waste, examining anaerobic digestion and single-cell-protein production as complementary routes for energy recovery and nutrient valorization.

Pretreatment remains a major challenge when using lignocellulosic substrates because cellulose and hemicellulose are tightly embedded within a lignin-rich structure. Moura *et al*. (2026) reviewed fungal cellulase production and emphasized the importance of substrate selection, solid-state and submerged fermentation, process optimization, and emerging AI-based approaches. The earlier study by Tucker *et al*. (2004) further demonstrated the practical value of acid pretreatment and enzymatic hydrolysis in converting distiller's grain into fermentable sugars and higher-value products. Taken together, these studies suggest that PF feedstock development should be approached as part of an integrated biorefinery system rather than as an isolated process.

However and we want to emphasize this waste-derived feedstocks are not automatically sustainable. Pretreatment can consume chemicals and energy and can generate inhibitors that reduce microbial productivity. Haajanen *et al*. (2025) reported that higher-temperature steam-explosion hydrolysates could inhibit T. reesei growth, while Mitri *et al*. (2025) demonstrated the need for engineered metabolism to utilize complex substrates. Consequently, feedstock selection should be based on total process performance including pretreatment energy, fermentation productivity, downstream recovery, and waste management, rather than focusing solely on feedstock price.

Gas-based feedstocks provide an alternative pathway that is particularly promising, although their large-scale application remains uncertain. Bernal-Cabas *et al*. (2026) proposed gas precision fermentation using hydrogen-oxidizing bacteria capable of converting CO_2 and green hydrogen into biomass, with the potential to engineer these organisms for secretion of recombinant food proteins. This approach could reduce the dependence of some food-production systems on agricultural land. However, its environmental performance would be strongly influenced by factors such as hydrogen production, electricity sources, gas transfer, and reactor efficiency. For this reason, we consider gas-based PF an important area for further research rather than a solution that can currently be regarded as universally established.

Artificial Intelligence, Data Analytics and Digital Fermentation

PF produces complex datasets from strain engineering, omics analyses, fermentation sensors, and product characterization. Artificial intelligence and machine learning can assist in identifying patterns that may be difficult to detect through conventional one-factor-at-a-time experimentation. Amore and Philip (2023) reviewed the application of AI in food biotechnology, while Vinestock *et al*. (2024) examined computer-aided chemical engineering approaches for PF. Bankole *et al*. (2026) state that AI supports functional-food ingredient development by accelerating ingredient functionalisation, formulation optimisation, consumer-preference prediction and targeted health applications. They also discuss AI-assisted molecular characterisation and discovery of bioactive compounds. Together, these studies indicate that computational tools can help narrow experimental search spaces, identify useful process relationships, and support more efficient process design.

At the strain level, Markova *et al*. (2022) showed that machine learning can help prioritize genetic modifications aimed at improving secretion, while Vaknin *et al.* (2024) demonstrated that algorithmically designed regulatory elements can improve gene expression across eukaryotic systems. At the process and food-quality levels, Priyadharshini *et al.* (2025) examined AI-enabled fermentation and personalized nutrition, whereas Du *et al.* (2025) demonstrated the use of machine learning to predict volatile compounds associated with meat aroma. Taken together, these developments point toward closed-loop systems in which computational models propose experiments, automated platforms carry them out, and the resulting data are subsequently used to refine and improve the models.

Nevertheless, AI does not remove the biological uncertainties associated with PF. Models developed from small or biased datasets may perform poorly when applied to unfamiliar strains, substrates, or reactor scales. Fermentation variables are also closely interconnected; for instance, agitation affects oxygen transfer and may consequently influence pH, metabolism, and product quality. Du *et al.* (2025) illustrates the value of multivariate modelling in this context, but model predictions still need to be verified through controlled experimental studies. A reliable digital strategy for PF should therefore integrate machine learning with mechanistic bioprocess models, experimental design, and real-time process monitoring.

Nutritional, Functional and Product-Quality Considerations

Food ingredients produced through PF need to be assessed as food ingredients rather than simply as products of fermentation. For proteins, important characteristics include amino-acid composition, digestibility, protein folding, solubility, thermal stability, emulsification, foaming, gelation, and sensory properties. Aro *et al.* (2023) demonstrated this approach by assessing the techno-functional properties of recombinant β-lactoglobulin and ovalbumin instead of focusing only on production titres.

Protein structure can affect functionality in ways that are not always readily predicted. Studies have shown that recombinant proteins may differ from their native counterparts in post-translational modification, folding, aggregation, and processing history. Eastham and Leman (2024) discussed these bioprocess-related considerations, while Purba and Sangsawad (2025) examined their wider implications for the functionality of dairy alternatives. In our view, the appropriate goal should be functional equivalence or, where suitable, intentional functional improvement based on the intended application, rather than molecular identity alone.

PF also creates opportunities to deliberately enhance nutritional and bioactive characteristics. Anantayanon *et al.* (2025) focused on cordycepin, while Wang *et al*. (2025) reviewed edible terpenoids with nutritional and functional applications, and Rekdal *et al.* (2024) engineered edible fungal biomass for enhanced ergothioneine and heme. These examples highlight an important shift that we observe in the field: moving from simple replacement toward deliberate design. Microorganisms can potentially produce ingredients with characteristics selected for a specific nutritional or technological purpose.

Environmental Sustainability: Life-Cycle Perspective

Environmental claims are central to the PF narrative, but LCA evidence shows that outcomes depend heavily on process design and we think this point cannot be overstated. Behm *et al*. (2022) compared carbon and water-scarcity footprints of milk protein from cellular agriculture and dairy production and showed that PF performance can be comparable to conventional protein depending on the scenario. This finding suggests that PF should not automatically be regarded as a lower-impact production approach.

More recent process-level work provides additional detail. David *et al*. (2026a) assessed recombinant human lactoferrin under different feedstock and electricity scenarios and found that electricity supply and carbon source were dominant determinants of environmental performance. The study showed that fossil-intensive electricity increased greenhouse-gas and energy burdens, whereas renewable electricity reduced them. This demonstrates that PF sustainability is, in large part, an energy-system question.

David *et al.* (2026b) argued and we agree that TEA and LCA should be integrated iteratively from early research and development rather than applied only after process design is largely fixed. This systems-based approach can help identify environmental and economic hotspots early in the development process, allowing changes to be made to strain selection, feedstock, reactor configuration, or downstream processing. Bandari *et al*. (2026) further expanded this perspective by considering the environmental, economic, social, and governance dimensions of biomanufactured food and agricultural products.

Conventional agriculture also has a substantial environmental footprint, but comparisons must be made using consistent functional units and system boundaries. Stolarski *et al*. (2025) reviewed the carbon footprint of milk production and showed substantial variability among production systems, with emissions influenced by enteric fermentation, manure, feed, fertilizer, farm efficiency, and methodology. The appropriate comparison is therefore not 'PF versus dairy' but a defined PF product versus a defined conventional comparator using transparent LCA assumptions.

Process-level hotspots can be substantial. The commercial-scale model in Nadar *et al*. (2025) identified aeration as a major energy demand, while David *et al*. (2026a) showed that utilities, carbon source, and electricity mix can dominate the footprint of recombinant lactoferrin. These findings reinforce the need for high titres, efficient oxygen transfer, low-energy separation, and low-carbon electricity

Techno-Economics, Commercialization and Business Models

PF commercialization depends on production cost, not only technical feasibility and we believe this distinction is often lost in promotional accounts. Konzock and Nielsen (2024) provides a useful framework in which titer, rate, and yield influence cost of goods sold through different mechanisms. Food ingredients typically command lower allowable unit costs than pharmaceutical proteins, which makes high productivity and streamlined downstream processing particularly important. Nielsen *et al*. (2024) similarly emphasized that recombinant proteins intended for food-scale production need considerably higher process performance than is required for many pharmaceutical applications.

The economics of scale-up are closely linked to environmental performance. Nadar *et al*. (2025) modelled a PF protein facility with an annual capacity of 10,000 tonnes and showed that feedstock use, aeration, fermentation time, and utilities can substantially influence material and energy requirements. Fletcher *et al*. (2024) further demonstrated that large-scale global deployment could require substantial amounts of cropland, electricity, and capital-intensive process inputs. These findings suggest that future commercial assessments should consistently report TRY metrics, recovery yields, equipment utilization, feedstock costs, and energy intensity using standardized measures.

Commercialization is also influenced by the broader innovation ecosystem. Lurie-Luke (2024) examined alternative-protein startups and the contribution of science-driven ventures to food innovation, while Thomson *et al*. (2025) found that companies involved in fermentation-based transitions may need to innovate in both their technologies and business models. This is particularly relevant to PF because the technology operates within complex systems involving ingredient producers, food formulators, regulators, infrastructure providers, retailers, and consumers.

Dairy technology provides a useful context for understanding the potential market. Hill (2024) argued that technology-enabled innovation is more likely to complement conventional dairy than simply replace it, highlighting the continuing importance of dairy science, food matrices, nutrition, and processing. PF may therefore develop alongside conventional agriculture, plant-based proteins, and biomass fermentation rather than becoming a single, universal replacement technology.

Food Safety, Regulatory Governance and Ethical Considerations

Food safety assessment should consider the production organism, genetic modifications, fermentation conditions, purification processes, impurities, residual host-cell components, and the level and nature of intended exposure. Flaibam *et al*. (2026) emphasized differences in regulatory requirements and the need for more coherent frameworks, while Verma *et al*. (2025) identified regulatory harmonization as an ongoing challenge. The regulatory pathway may vary according to jurisdiction and whether viable genetically modified microorganisms or relevant residues are present in the final food product (Gumulya *et al*., 2025).

Product-specific safety evaluation is essential, and we regard it as a non-negotiable requirement. Lynch *et al*. (2023) assessed PF-derived brazzein using multiple toxicological and allergenicity approaches, demonstrating the importance of generating evidence for the final ingredient rather than relying solely on the established safety history of the host microorganism. Likewise, PF-derived dairy and egg proteins require careful consideration of their inherent allergenicity, since producing an allergenic protein through fermentation does not automatically make it non-allergenic.

Safety and governance also become particularly important in sensitive applications such as infant nutrition. Mankad and Carter (2025) examined primary carers' willingness to use PF-derived human lactoferrin in infant formula and reported generally supportive attitudes, although concerns centred mainly on equitable access and availability. This finding suggests that consumer trust may be influenced not only by toxicological safety but also by perceptions of fairness and broader social value.

Ethical considerations also involve intellectual property, market concentration, farmer livelihoods, and the distribution of benefits. Verma *et al*. (2025) identified tensions between proprietary systems and access, while Bandari *et al*. (2026) emphasized that transitions toward biomanufacturing may produce economic and governance disruptions even where environmental benefits appear plausible. PF should therefore be assessed from a broader food-system perspective that incorporates equity and governance, rather than relying exclusively on technical or environmental metrics.

Consumer Acceptance and Market Adoption

Consumer acceptance is an important factor in determining whether technically successful PF products can achieve commercial success, yet it may sometimes receive less attention from technologists. Banovic and Grunert (2023) found that factors such as framing, perceived similarity to traditional fermentation, trust, and perceived benefits can influence acceptance across different cultural contexts. These findings indicate that communication should go beyond technical terminology, with consumers provided with clear and accessible explanations of how the technology works, what it does, and why it is being used.

Broad *et al*. (2022) reported cautious openness toward animal-free dairy among early-adopter focus-group participants. Participants sought information about safety, regulation, taste, health, environmental impacts, and price. This supports the view that acceptance is more likely to depend on clear and meaningful product benefits than on the novelty of the technology itself.

Experimental evidence from Germany adds further detail. Kühl *et al*. (2024) found that information about genetic modification had a negative, although relatively small, effect on willingness to try PF cheese, whereas messages highlighting consistency and sustainability could increase acceptance. Concerns about farmer livelihoods and the concentration of market power, however, could have the opposite effect. These findings suggest that communication around PF should acknowledge both its potential benefits and its possible social trade-offs.

It is important to distinguish between acceptance of the technology itself and acceptance of an individual product. Consumers may be comfortable with PF in principle but reject a particular ingredient because of its taste, price, texture, or intended application. Conversely, strong product performance may reduce some concerns about the underlying technology. For food scientists, this means that sensory quality, nutritional value, affordability, and transparent communication need to be developed alongside one another.

Integration with Plant-Based, Biomass and Cultivated-Food Systems

PF should not be considered separately from other alternative-protein pathways, and it would be inappropriate to present it as a universal solution. Tachie *et al*. (2023) reviewed innovations in plant-based food formulation, highlighting how fermentation and ingredient engineering can improve texture, flavour, and nutritional quality. Similarly, Kaplan and McClements (2025) proposed hybrid alternative-protein foods as a way of combining complementary ingredients and technologies.

Microbial biomass provides a distinct but complementary strategy. Graham and Ledesma-Amaro (2023) described microbial foods as both biomass products and cell-factory products, while D'Almeida and de Albuquerque (2025) reviewed microorganisms as potential protein sources. Rekdal *et al*. (2024) demonstrated that edible fungi can be genetically engineered to improve nutritional and sensory characteristics. Such approaches may reduce the need for extensive purification when the microbial biomass itself serves as the food.

PF can also provide specific components for plant-based and cultivated food products. Recombinant proteins may contribute to improvements in texture, colour, aroma, nutritional value, or culture-media performance, while microbial enzymes can be used to modify food matrices. Flaibam *et al*. (2025) specifically identified recombinant proteins as potential inputs for cultivated-meat systems. This integrated approach may be more realistic than expecting a single technology to replace an entire food category.

Research Gaps and Future Directions

Several important research gaps still need to be addressed. First, there is an urgent need for more evidence from pilot- and demonstration-scale systems. Many published PF studies are still conducted in laboratory reactors, whereas industrial implementation requires information on oxygen transfer, mixing, contamination control, strain stability, cleaning, utilities, and downstream recovery. Nadar *et al*. (2025) and Fletcher *et al*. (2024) demonstrate the usefulness of process modelling, while Konzock and Nielsen (2024) show how TRY metrics can serve as standardized indicators for economic assessment.

Second, feedstock research needs to progress toward integrated biorefinery design. Nadar et al. (2024), Haajanen *et al*. (2025), Mitri *et al*. (2025), Piercy *et al*. (2024), and Moura *et al*. (2026) collectively indicate that agricultural residues and food-processing wastes can serve as valuable substrates, although pretreatment requirements, inhibitory compounds, seasonal variability, and nutrient balance remain significant challenges. Future research should therefore report feedstock conversion efficiency alongside fermentation productivity and associated environmental burdens.

Third, sustainability assessments of PF should be prospective and consider multiple dimensions. David *et al*. (2026a), David *et al*. (2026b), and Bandari *et al*. (2026) indicate that LCA and TEA should be integrated with social and governance indicators. This is particularly important for novel food technologies because a process can reduce land use while increasing electricity demand, or reduce livestock emissions while creating new infrastructure and employment disruptions.

Fourth, AI should be connected to experimental infrastructure. Markova *et al*. (2022), Amore and Philip (2023), Vinestock *et al*. (2024), Vaknin *et al*. (2024), Priyadharshini *et al*. (2025), and Du *et al*. (2025) point toward increasingly automated strain and process development. The next step is validated closed-loop experimentation in which machine learning, mechanistic models, high-throughput screening, and real-time sensors work together.

Fifth, product functionality should be evaluated in complete food matrices. Recombinant proteins should be tested for digestion, allergenicity, thermal stability, sensory behaviour, interactions with other ingredients, and performance during realistic processing. Aro *et al*. (2023), Eastham and Leman (2024), and Purba and Sangsawad (2025) indicate that this food-science dimension is as important as microbial productivity.

Finally, PF research should broaden geographically. Much of the available literature and commercial activity is concentrated in Europe, North America, and Australia. Circular feedstocks available in African food systems including crop residues, brewery by-products, cassava-processing residues, and other agro-industrial streams could create regionally relevant opportunities, but these require local techno-economic and LCA studies rather than direct transfer of assumptions from high-income settings.

The literature points to a central conclusion: the value of PF cannot be determined by microbial engineering alone. Its overall performance results from the interaction among the host organism, genetic construct, fermentation conditions, feedstock, utilities, downstream processing, product functionality, and the wider food system. Claims concerning PF should therefore be assessed using interconnected performance indicators rather than relying on a single measure, such as product titre or land savings.

Critical Synthesis

We now take a broader view to provide an integrated assessment. Strain engineering can improve product formation, secretion, and pathway flux, but biological gains do not necessarily result in lower environmental impacts or reduced production costs. A strain capable of achieving a high titre may require costly substrates, intensive aeration, or complex purification, making it less suitable for industrial production than a process with a slightly lower titre but easier product recovery. For this reason, the literature on titre, rate, and yield provides a more informative basis for comparison than titre alone (Konzock & Nielsen, 2024).

Biological efficiency is important, but it is not sufficient on its own. Successful laboratory-scale production can mask constraints that become significant during industrial operation. At larger scales, oxygen transfer, heat removal, mixing, foaming, viscosity, contamination control, and downstream throughput become critical considerations. The 10,000-tonne-per-year modelling study by Nadar *et al*. (2025) and the global-scale scenario developed by Fletcher *et al.* (2024) demonstrate how infrastructure, utilities, and feedstock requirements can strongly influence overall performance. Global-scale scenarios should therefore be understood as conditional models rather than predictions of unavoidable PF impacts.

Scale also changes how PF sustainability should be evaluated. Life-cycle evidence indicates that PF does not have a fixed environmental footprint. David *et al.* (2026a) showed that electricity supply and carbon source can substantially influence the environmental performance of recombinant lactoferrin. Research using agro-industrial residues indicates opportunities to reduce reliance on dedicated feedstocks, although pretreatment and hydrolysis may introduce additional energy and chemical burdens. The most promising sustainability pathway is therefore likely to combine efficient microbial strains with low-carbon electricity, appropriate residual biomass, and efficient downstream recovery.

Energy use and feedstock selection are decisive factors. Producing an animal-identical or structurally similar protein does not by itself guarantee a successful food ingredient. The final product must perform under realistic processing and storage conditions while providing suitable taste, texture, solubility, emulsification, foaming, gelation, digestibility, and nutritional properties. Experimental studies on β-lactoglobulin and ovalbumin (Aro *et al*., 2023), together with the broader literature on dairy alternatives (Purba & Sangsawad, 2025), demonstrate the importance of linking microbial production metrics with performance in food matrices.

Food functionality should therefore be considered a central engineering objective. Comparisons between PF and conventional agriculture can be misleading when functional units, system boundaries, electricity assumptions, or co-product allocation methods differ. Behm *et al*. (2022) and Stolarski *et al*. (2025) demonstrate that conventional production systems are themselves heterogeneous. The key question is consequently not whether PF is universally more sustainable, but rather under which product, process, energy, and feedstock conditions a particular PF pathway performs better than a clearly defined comparator.

Sustainability claims also require clearly defined comparators. Economic viability involves much more than fermentation yield. Capital requirements, fermentation duration, equipment utilization, feedstock costs, oxygen demand, recovery efficiency, quality control, regulatory approval, and market price interact to determine commercial feasibility. Future studies should report a consistent minimum set of technical and economic indicators, including titre, rate, yield, fermentation time, recovery yield, energy intensity, feedstock consumption, and estimated cost of goods. Standardized reporting would greatly improve the reliability of comparisons across studies.

Commercialization is fundamentally a systems problem. Even products that perform well technically and environmentally may struggle to gain market acceptance if consumers distrust the technology, labelling remains unclear, or regulatory pathways differ across jurisdictions. Studies included in the review indicate that acceptance is influenced by safety, familiarity, environmental benefits, price, sensory expectations, and perceived social consequences (Banovic & Grunert, 2023; Broad *et al*., 2022; Kühl *et al*., 2024). Public communication and regulatory planning should therefore develop alongside process development rather than being addressed only after the technology has matured.

Consumer and regulatory readiness may ultimately become the final bottleneck. Overall, the evidence supports a conditional rather than promotional interpretation of PF. PF appears most compelling when it produces a difficult-to-source ingredient with high functional value, achieves strong titre-rate-yield performance, relies on low-carbon energy and suitable feedstocks, requires manageable downstream processing, and provides clear food or nutritional benefits. Its advantages are less convincing when productivity is low, energy demand is high, feedstocks compete with food or land uses, or the resulting ingredient offers limited benefits over established alternatives. This conditional framework provides a stronger basis for assessing PF as one component of sustainable food production.

CONCLUSION

Precision fermentation is emerging as a versatile food-biotechnology platform that brings together microbial cell factories, genetic engineering, fermentation process engineering, downstream processing, and increasingly AI-assisted design. The literature reviewed demonstrates applications extending from recombinant dairy and egg proteins to cultured-meat inputs, sweet proteins, flavour compounds, terpenoids, bioactive compounds, and engineered edible fungal biomass (Eastham & Leman, 2024; Nielsen *et al*., 2024; Verma *et al*., 2025; Shukla *et al*., 2026; Flaibam *et al*., 2026; Mirsalami & Mirsalami, 2025; Pak *et al*., 2025; Purba & Sangsawad, 2025; Flaibam *et al*., 2025; Rekdal *et al*., 2024; Wang *et al*., 2025).

The available evidence does not support the simple conclusion that PF is inherently sustainable. Rather, its sustainability depends on factors including feedstock, energy source, titre, rate, yield, oxygen-transfer efficiency, downstream processing, and system boundaries. LCA and TEA studies indicate that renewable electricity, efficient process design, high productivity, and circular feedstocks can substantially improve outcomes. Conversely, large-scale deployment may create considerable resource demands when these factors are not adequately addressed (David *et al*., 2026a; Behm *et al*., 2022; Nadar *et al*., 2025; Fletcher *et al*., 2024; David *et al*., 2026b; Bandari *et al*., 2026; Konzock & Nielsen, 2024).

Future development should therefore focus on integrated optimization. Microbial strain engineering needs to be connected with fermentation scale-up, food functionality, safety assessment, LCA, TEA, and consumer research. AI and automation may accelerate discovery and process development, while waste-derived and gas-based feedstocks could reduce dependence on conventional agricultural carbon sources. At the same time, transparent regulation and effective communication will be important for maintaining public trust (Markova *et al*., 2022; Vinestock *et al*., 2024; Karimian *et al*., 2025; Priyadharshini *et al*., 2025; Haajanen et al., 2025; Piercy *et al*., 2024; Banovic & Grunert, 2023; Kühl *et al*., 2024; Lynch *et al*., 2023; Bernal-Cabas *et al*., 2026).

Overall, PF is better understood as a complementary technology within a diversified food system than as a universal replacement for agriculture. Its greatest contribution is likely to arise where microbial production can deliver specific molecules with high functional or nutritional value, particularly when conventional extraction is inefficient or resource-intensive, and where the complete production system can demonstrate credible environmental, economic, nutritional, and societal benefits.

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