



Precision Fermentation: A Sustainable Approach for the Production of Functional Ingredients

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Due to increase in population and changes in climate conditions, the world's food system is facing challenges, which highlights the need for efficient and sustainable production methods. Precision fermentation is one of the latest innovations that utilize microbes to produce valuable ingredients for food products. It utilizes metabolic engineering, bioreactor, and rDNA technology to produce specific proteins, lipids, enzymes, pigments, and vitamins. Precision-fermentation-derived foods are eco-friendly alternative foods to animal-derived foods. However, precision fermentation technology is not without obstacles in cost reduction, public acceptability, approval, and commercialization. In conclusion, precision fermentation technology is an innovative way to address concerns about food security, sustainability, and ingenuity in modern food production.

Key words: Metabolic engineering, Precision fermentation, Recombinant DNA technology, Sustainable food production

Introduction

The population is expected to increase to 9.7 billion by 2050 and the intensifying impacts of climate change are posing substantial pressure on the global food supply system. Addressing these issues requires increasing food production to satisfy the needs of a growing population while also reducing the environmental impact of current farming methods. Concurrently, in recent years, consumers' dietary choices have clearly shifted toward healthier options, and they have also become more conscious of the moral and animal welfare issues surrounding products derived from animals (Knychala et al., 2024). More ecologically friendly food production methods and food processing operations are required to support the growing population and create sustainable food systems to ensure food and nutrition security (Augustin et al., 2024).

Microbial fermentation has been widely used to produce various fermented foods. However, the inherent variability of traditional fermentation might raise safety issues because it may promote the growth of toxic chemicals and pathogenic microorganisms, which could deteriorate flavour and texture. Recent developments in synthetic biology and metabolic engineering have transformed microbial fermentation into precision fermentation (Hilgendorf et al., 2024). By using evolved or engineered microorganisms to manufacture food elements such proteins, lipids, flavours, colours, and vitamins in an environmentally friendly manner, precision fermentation offers a solution (Eastham & Leman, 2024). These proteins show potential as animal-free alternatives because they can mimic the taste and feel of products derived from animals more precisely than plant proteins (Keppler & Boom, 2025).

Precision fermentation process

The first step in the precision fermentation process is to carefully choose the desired ingredient (such as whey proteins, dairy protein casein, etc.) based on functional and

nutritional requirements. The DNA sequence encoding the target molecule is designed and inserted into the genome of microbe by recombinant DNA techniques. In industrial contexts, microorganisms that are categorised as generally recognised as safe (GRAS) are preferred.

The Engineered microbes are allowed to grow in controlled bioreactors during which the microorganism expresses the target compound during growth. To ensure purity, functionality, and safety, the target biomolecule undergoes downstream processing which involves cell separation particularly for intracellular product followed by protein extraction, purification, concentration and stabilization (Knychala et al., 2024).

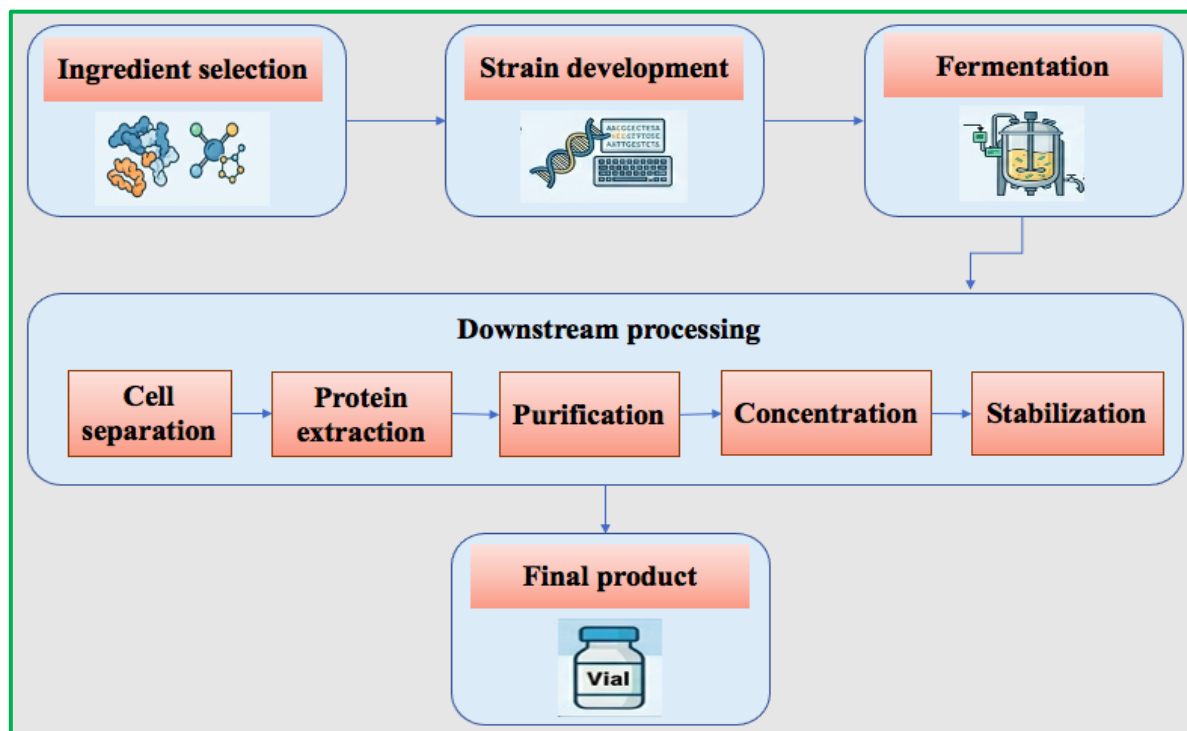


Fig: Precision Fermentation Process

Application of precision Fermentation-Derived ingredients

Since meat, eggs, and milk provide larger amounts of accessible proteins with necessary amino acids than the majority of plant-derived proteins, their production and consumption have increased due to the rapid population growth during the past few decades. By carefully controlling the fermentation conditions to produce identical or nearly identical versions of animal-derived proteins, precision fermentation offers a sustainable and ethical alternative to traditional food production (TCU et al., 2025).

Novel foods

Animal-free proteins

- Casein and whey proteins are produced to make milk, cheese, and yoghurt that are chemically equivalent to their conventional counterparts.
- Plant-based baked products and other items are enhanced by the addition of ovalbumin and other egg white proteins.
- Microbial muscle proteins, collagen proteins, and other speciality proteins are produced that function as emulsifiers or binders in a variety of food applications.

Other ingredients

- **Heme:** This protein, which comes from animal muscle, is created to give plant-based meats a "meaty" taste.
- **Vitamins:** The sustainable and regulated production of vitamins A, C, D, E, and B is achieved through precision fermentation.

- **Enzymes:** Crucial to food processing, enzymes such as rennet, which is used to make cheese, are now frequently made by precise fermentation in place of those derived from animals.
- **Sustainable oils and fats:** Precision fermentation is being used to produce palm oil substitutes that are more reliable and sustainable than conventional sourcing (Adeyeye et al., 2026)

Applications of precision fermentation in seafood sector

Precision fermentation is becoming a cutting-edge strategy in the seafood industry by facilitating the sustainable manufacture of components produced from fish. This technology can imitate the structural characteristics of fish and other marine creatures by synthesising muscle proteins like actin and myosin. This will improve the quality of seafood analogues. Recombinant systems can also be used to generate marine collagen and gelatin, ensuring constant quality and removing the unpredictability associated with fish by-products. By replacing fishmeal and fish oil in feed with proteins and lipids obtained from fermentation, the method also promotes sustainable aquaculture. In general, precision fermentation lessens the strain on marine ecosystems while enhancing food safety, traceability, and product consistency.

Challenges

The last three years have seen a growth in market investment, and the number of precision fermentation firms has expanded. Although it has potential for revolutionizing various fields, it also faces a number of challenges.

- The scale-up procedure is one of the biggest obstacles to precision fermentation. Although manufacturing at the laboratory scale demonstrates viability, moving to commercial operations is still challenging. Innovative engineering solutions and fermentation process optimisation are necessary to achieve cost-effective mass production without sacrificing quality.
- Existing regulatory structures are not adequately addressing the swift progress within the field of precision fermentation. The establishment of comprehensive standards is essential to ensure product safety, efficacy, and transparent labelling practices.
- Addressing ethical considerations, particularly concerning genetically modified organisms (GMOs), requires careful consideration and the implementation of updated regulations (Eastham & Leman, 2024).

Conclusion

Precision fermentation provides a scientifically regulated method for the development of high value food products. It enables the target synthesis of proteins, lipids, micronutrients and pigments by integrating recombinant DNA technology, bioprocess optimization, and metabolic engineering. In contrast to traditional methods, it mitigates contamination risks and diminishes variability, thereby enhancing product consistency and quality control. However, despite its significant potential, several obstacles remain. Economic feasibility necessitates considerable capital outlay for large-scale production, sophisticated fermentation infrastructure, and refined downstream processing techniques. Furthermore, regulatory frameworks must be adapted to accommodate safety evaluations, public apprehensions, and transparent labelling.

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