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# Precision fermentation for the next generation of food ingredients: Opportunities and challenges

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ABSTRACT

Precision fermentation is an advanced process of traditional fermentation wherein microorganisms, such as bacteria, fungi, or yeast, are genetically modified to yield a desired product. It is an advanced biotechnological method for producing specific food ingredients, such as casein and citric acid. The integrity of precision fermentation lies in cutting-edge techniques that enhance the efficiency of microorganisms by inserting desired genes and in producing high-value compounds with greater efficiency. All the cutting-edge techniques involved are synergistic in terms of integration, rapid prototyping, and predictive power. Automation and artificial intelligence (AI) enhance the synthetic biology prediction and metabolic engineering, enabling iterative strain improvement cycles. Strain selection and its optimization are a strong foundation for successful precision fermentation process. Automation allows testing of several strain modifications in a short duration of time. Metabolic engineering efforts guided by AI tools help in assessing the outcome of genetic changes on production. The reliance on precision fermentation for a scalable and sustainable alternative to conventional methods has become more evident. Precision fermentation is becoming a solution for the high demand for sustainable and scalable food production methods by improving the efficiency of resources, minimizing waste production, and reducing the adverse environmental impact. In this review on precision fermentation, we have thoroughly examined recent advancements in precision fermentation techniques and their potential applications in the food industry. Additionally, the review discusses how precision fermentation can create customized food ingredients. It also addresses recent increase in consumer demand for personalized nutrition, plant-based alternatives, and allergen-free products. This present article discusses the technological advancements and the broader societal implications of precision fermentation, providing insights into how this field is poised to transform the food industry. Finally, we conclude by discussing the challenges and opportunities that lie ahead in fully utilizing the potential of precision fermentation for the future of food ingredient production.

## 1. Introduction

Precision fermentation is an advanced biotechnological process in which genetically engineered microorganisms such as yeast, fungi, and bacteria are utilized to produce specific biomolecules such as enzymes, proteins, and fats (Boukid et al., 2023; Teng et al., 2021). In precision fermentation genetic engineering, synthetic biology, and different fermentation techniques are combined to enable precise microbial production of compounds (Mirsalami and Mirsalami, 2025). This process has been widely explored in the pharmaceutical, cosmetics, and food industry as an alternative means to produce molecules of animal or plant origin without the use of their natural sources (animals or plants) (Augustin et al., 2024; Knychala et al., 2024; Boukid et al., 2023).

In the process of precision fermentation, specific genes are inserted into a microorganism to produce large amounts of the desired protein or compound. After the fermentation process, the desired molecule is isolated and purified for use. This process is more sustainable and scalable than traditional extraction and production methods and often has a

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lower environmental footprint (Nielsen et al., 2024; Knychala et al., 2024; Gupta & Shukla, 2017).

Precision fermentation is transforming the food industry by enabling the production of high-quality, animal-free ingredients with remarkable efficiency and sustainability (Ajayeoba and Ijabadeniyi, 2025). It can produce proteins that mimic those found in animal products (such as casein in milk or albumin in eggs). For instance, companies have successfully produced milk proteins without using cows, creating animal-free cheese, yogurt, and ice cream that closely resemble traditional dairy products in taste and texture. It offers a scalable alternative with a much smaller environmental footprint, allowing raw materials to be made in fermentation tanks rather than on large tracts of land. This reduces deforestation, water use, and carbon emissions (Nielsen et al., 2024; Augustin et al., 2024; Zimberoff, 2021). Precision fermentation is carried out under highly controlled conditions, ensuring consistent quality and yield and reducing variability in taste, texture, and nutritional profile. This is especially important in large-scale food production where consistent product quality is essential for consumer confidence and regulatory standards (Yap et al., 2024; Terefe, 2022; Siddique et al., 2022). Reduced reliance on livestock production is another benefit of precision fermentation which has important implications for animal welfare. It also increases food safety by reducing the risk of zoo-noses and food-borne illnesses that can arise from intensive livestock production (Knychala et al., 2024). As technology advances, precision fermentation processes are becoming more cost-effective.

Once established, the fermentation process can be scaled up to produce large volumes of raw materials in a relatively short time, making it more economically viable than traditional methods in the long run as shown in Fig. 1 (Adebo et al., 2018; Gupta and Shukla, 2017). Also, it allows the production of uniquely custom-designed ingredients for specific functions in food products. For example, flavor compounds, enzymes, and nutrients can be precisely designed to meet the needs of food manufacturers, creating new possibilities for food product innovation (Yadav et al., 2024; Teng et al., 2021; Formenti et al., 2014). The steps involved in precise fermentation are mentioned in Fig. 1. The intent of this article is to provide a detailed overview of how precision fermentation is reshaping the production of food ingredients, to cater a road map for its broad adoption, impact on global food sustainability and innovation.

## 2. Overview of fermentation technologies

Fermentation is a biochemical process in which microorganisms, such as bacteria, yeast, or fungi, convert organic compounds (e.g., sugars) into other compounds, typically in the absence of oxygen. This process is essential for producing a wide range of products, including food, beverages, biofuels and pharmaceuticals (Chavan et al., 2022; Sadh et al., 2018).

Traditional Fermentation relies on natural or minimally modified microorganisms to carry out fermentation. This is a cost-effective and simple method which requires minimal processing (Ramírez Rojas et al., 2022; Sharma et al., 2020). On the other hand, precision fermentation utilize genetically engineered microorganisms (GEMs) to produce highly specific products. This process is scalable, imparts high specificity and purity of the target product along with controlled production (Bogueva & Danova, 2024; Chai et al., 2022).(Table 1).

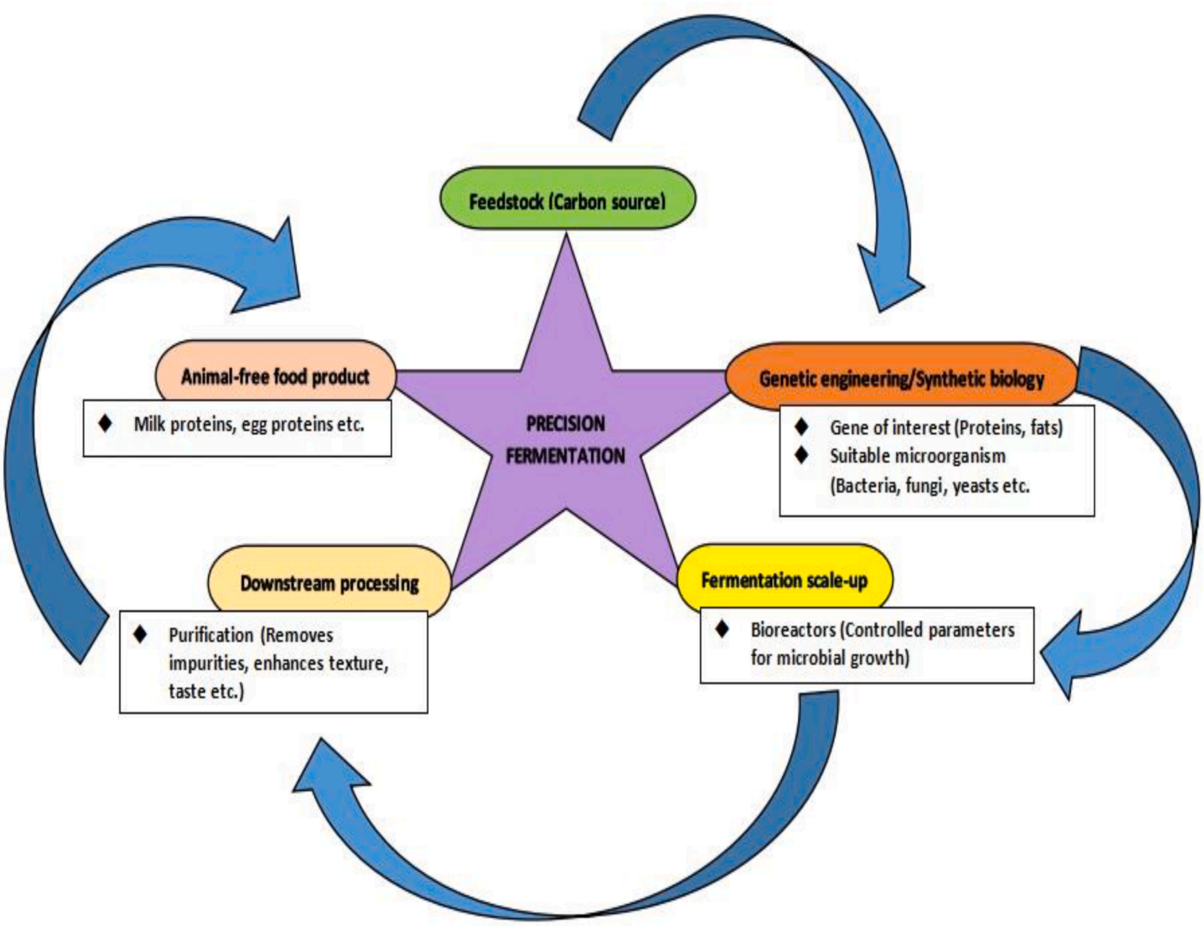


**Fig. 1.** Steps involved in precision fermentation.

**Table 1**
Traditional vs. precision fermentation.

| Aspect | Traditional Fermentation | Precision Fermentation |
|---|---|---|
| Microorganisms | Wild strains or natural isolates | Genetically modified organisms |
| Products | General compounds (e.g., ethanol, acids) | Specific molecules (e.g., proteins, enzymes) |
| Technology | Simple equipment, low-tech processes | Advanced bioreactors, molecular biology tools |
| Efficiency | Lower specificity, variable yields | High specificity, consistent yields |
| Cost | Lower initial cost, higher processing | Higher initial cost, lower processing costs |
| Applications | Food, beverages, basic biofuels | Pharma, alt-proteins, specialty chemicals |
| Regulations | Fewer regulatory challenges | Stricter regulation for GMOs |

### *2.1. Microbes in fermentation*

Microbial strains are the cornerstone of fermentation technologies, driving the production of diverse compounds - (that includes) food, fuels, pharmaceuticals, and industrial chemicals. Bacteria, yeasts, filamentous fungi, algae and cyanobacteria are the key microorganisms used in fermentation technologies (Table 2 & 3).

### *2.2. Strain selection and modification*

Strain selection and modification are foundational to the success of precision fermentation, as the choice of microbial host and it's engineering directly influence the efficiency, safety and scalability of target food ingredient production. Microorganisms are typically selected either for their native ability to produce the desired compound or for their amenability to genetic modification when used as heterologous hosts (Lubbers et al., 2025). Common framework organisms such as *Saccharomyces cerevisiae, Komagataella phaffii*, and *Bacillus subtilis* are favoured due to their well-characterized genomes, food-safe status and robust fermentation performance (Ledesma-Amaro and Bamezai, 2025).

Once a suitable host is identified, synthetic biology tools including CRISPR-based editing, modular pathway assembly and gene circuit design are used to insert and optimize biosynthetic pathways for the production of proteins, lipids, flavors or pigments (Peng and Wei, 2025). This process is increasingly guided by multi-omics data integration and computational modelling, enabling researchers to identify metabolic bottlenecks, predict strain performance and accelerate the design-build-test-learn cycle.

In addition to rational engineering, adaptive laboratory evolution and evolutionary engineering strategies are employed to enhance traits such as yield, tolerance to process stresses and product purity. However, engineered strains must not only be high-performing but also meet regulatory standards for safety, such as GRAS status in the U.S. or novel food approval in the EU, which can pose significant hurdles to commercialization (Powell et al., 2025).

Furthermore, strain development must consider downstream processing efficiency and cost-effectiveness at industrial scale, highlighting the importance of integrating biological, engineering and regulatory considerations from the earliest stages of development (Elazzazy et al.,

**Table 3**
Selection Criteria for Microbial Strains.

| **Parameters** | **Functions** |
|---|---|
| **Productivity** | **Ability to produce high yields of the target product** |
| **Substrate Range** | **Capability to use diverse feedstocks (e.g., lignocellulose, $CO_2$, methane)** |
| **Growth Characteristics** | **Fast growth rate, tolerance to industrial conditions** |
| **Genetic Engineering Potential** | **Ease of genetic manipulation and scalability** |
| **Regulatory Compliance** | **GRAS status or regulatory approval for use in food and pharmaceuticals** |

**Table 2**
Microbial strains used in fermentation technology.

| Microbes | Strains | Industrial applications | Advantages | References |
|---|---|---|---|---|
| **Bacteria** | *Lactobacillus* spp. | Lactic acid production for bioplastics (e.g., polylactic acid). | Acid tolerance, ability to ferment a wide range of sugars. | Ahmad et al. (2024) |
| | *Escherichia coli* | Production of insulin, enzymes, and other recombinant proteins. | Well-characterized genomes, fast growth rate, ease of genetic manipulation. | İncir & Kaplan (2024); Datta (2023) |
| | *Clostridium* spp. | Conversion of syngas to biofuels. | Higher availability of biomass, no competition with food and low feedstock cost. | Kim et al. (2016); Martin et al. (2016) |
| | *Corynebacterium glutamicum* | Production of amino acids (e.g., glutamate, lysine). | Robust and versatile metabolism. | Wendisch et al. (2016) |
| Yeasts | *Saccharomyces cerevisiae* | Production of bioethanol, recombinant proteins (e.g., vaccines), and alternative proteins (e.g., dairy proteins like casein). | GRAS (Generally Recognized as Safe) status, ease of cultivation, genetic engineering capabilities. | Nandy & Srivastava (2018) |
| | *Pichia pastoris* | Production of high-value enzymes and biopharmaceuticals. | High protein expression, post-translational modification capabilities. | Madhavan et al. (2021) |
| | *Yarrowia lipolytica* | Production of lipids, polyhydroxyalkanoates (PHAs), and specialty chemicals. | Lipid accumulation, ability to grow on unconventional substrates. | Miller & Alper (2019) |
| Filamentous Fungi | *Aspergillus* spp. | Production of citric acid, enzymes (e.g., cellulases, amylases), and pharmaceuticals. | High secretion capacity for enzymes and organic acids. | Gholami-Shabani et al. (2022) |
| | *Trichoderma reesei* | Enzymes for biomass degradation (e.g., cellulases, hemicellulases). | Well-suited for lignocellulosic biorefinery applications. | Keshavarz & Khalesi (2016) |
| | *Penicillium* spp. | Production of penicillin and other antibiotics. | Treatment of infections. | Lalchhandama(2021); Toghueo & Boyom (2020) |
| Algae and Cyanobacteria | *Spirulina* and *Chlorella vulgaris* | Food supplements, pigments (e.g., phycocyanin), and biofuels. | High protein content, photosynthetic efficiency. | Abreu et al. (2023); Andrade et al. (2018) |
| | *Synechocystis* spp. | Production of biofuels, hydrogen, and specialty chemicals. | Genetic tractability, ability to fix $CO_2$. | Montagud et al. (2015) |
| Other Emerging Strains | *Bacillus spp.* | Enzyme production (e.g., proteases, amylases) and probiotics. | Spore-forming, robust under industrial conditions. | Danilova & Sharipova (2020); Elshaghabee et al. (2017) |
| | *Methylococcus capsulatus* and *Clostridium autoethanogenum* | Conversion of methane or $CO_2$ to biofuels and chemicals. | Utilization of greenhouse gases as feedstock. | Akinsemolu & Onyeaka (2024); Heffernan et al. (2023); Ge et al. (2014) |

2025). Ultimately, successful strain engineering in precision fermentation combines molecular innovation with systems-level thinking to enable the sustainable production of next-generation food ingredients.

### 2.3. Advancements in fermentation techniques

Advances in fermentation techniques are revolutionizing bio-based manufacturing by enhancing productivity, sustainability, and scalability. Metabolic engineering and synthetic biology leverage CRISPR and artificial intelligence (AI) tools to optimize the production of biofuels, enzymes, and chemicals. Automation and digitalization, through IoT (full form), AI, and digital twins, optimize fermentation processes with real-time monitoring and predictive analytics (Ali et al., 2024; Patra et al., 2023), (Jiang et al., 2013). Solid-state fermentation (SSF) is effective for enzyme production and the utilization of agro-residues, while integration with lignocellulosic biorefineries enables the conversion of biomass into fuels and chemicals. Microbial consortia enable complex biotransformation for applications such as biogas production and pollutant degradation. Additionally, the consumption of agricultural residues, $CO_2$, and syngas supports the circular bioeconomy and reduces costs (Singh et al., 2022; Šelo et al., 2021). Nanotechnology further supports efficient fermentation through nanoparticles and sensors for better nutrient delivery, process monitoring, and enzyme stabilization (Vasantha et al., 2021).

## 3. Applications of precision fermentation in food ingredients

Precision fermentation enables sustainable, scalable, and precise production of compounds, often with improved purity and functionality (Augustin et al., 2024). Precision fermentation is transforming the food industry by enabling the creation of high-quality, sustainable, and functional ingredients tailored to consumer demands as shown in Table 4.

**Table 4**
Applications and Advantages of food ingredients produced via Precision fermentation.

| Food Ingredients | Applications | | Advantages |
|---|---|---|---|
| Proteins and Amino Acids | Alternative Proteins | Production of animal-free casein, whey, and egg proteins for dairy and egg substitutes. Example: Perfect Day's whey proteins for plant-based dairy. | Animal-free, allergen-free, and customizable properties. Consistent quality and scalability. |
| | Specialized Amino Acids | Production of essential amino acids like lysine, tryptophan, and methionine for food fortification and animal feed. | |
| | Collagen and Gelatin | Animal-free production of these proteins for use in confections, desserts, and functional foods. | |
| Enzymes and Biocatalysts | Food Processing | Lactase for lactose-free dairy products. Amylases and proteases for baking, brewing, and tenderizing. | Tailored enzyme properties (e.g., stability, specificity). Reduced chemical processing in food manufacturing. |
| | Flavor and Texture Enhancement | Lipases for cheese flavor development. Transglutaminase ("meat glue") for binding proteins in food. | |
| | Sugar Alternatives | Enzymes for converting starches into low-calorie sweeteners like allulose. | |
| Flavor Compounds | Vanillin | Microbial production of bio-based vanillin as a sustainable alternative to synthetic or natural extraction. | Enhanced sustainability and cost-effectiveness compared to traditional extraction. |
| | Fruit and Herb Flavors | Precision fermentation of compounds like limonene (citrus) or methyl anthranilate (grape flavor). | Customization of flavor profiles for niche markets. |
| | Umami Enhancers | Microbial production of glutamate or inosinate for savory foods. | |
| Nutraceuticals | Vitamins | Vitamin B12, D, and K2 production for food fortification and supplements. | High purity and bioavailability. Sustainable production without reliance on natural sources like fish or plants. |
| | Omega-3 Fatty Acids | Fermentation-derived EPA and DHA as sustainable alternatives to fish oil. | |
| | Antioxidants and Polyphenols | Production of resveratrol, astaxanthin, and other bioactive compounds. | |

## 4. Technological advances driving precision fermentation

Synthetic biology, metabolic engineering and AI tools have collectively positioned precision fermentation as a transformative solution for sustainable and scalable bio manufacturing (Patra et al., 2023; Lawson et al., 2021; Helmy et al., 2020). The primary technological advancements that enable this revolution are discussed below and summarized in Fig. 2.

### 4.1. Metabolic engineering

Metabolic engineering involves the process of redesigning microbial metabolic pathways to optimize the production of desired compounds. with the help of advanced molecular techniques such as CRISPR-Cas systems. These techniques induce precise genetic edits for target product optimization; pathway optimization, which enhances the yields and minimizes by-products; also, pathways from other organisms are introduced to produce non-native compounds (Ko et al., 2020; Kumar et al., 2016). Applications of metabolic engineering include genetically modified microbes to produce specific proteins, such as casein and collagen, and also, optimizing the production of secondary metabolites like vitamins and antioxidants. The benefits of metabolic engineering include enhanced yields, reduced waste, and the ability to produce novel or rare compounds. (Abavisani et al., 2024; Su et al., 2020; Mallikarjuna & Yellamma, 2019).

### 4.2. Synthetic biology approaches

Synthetic biology approaches involve designing and constructing novel biological devices, and systems, or re-designing existing systems, to create microorganisms tailored for specific tasks. Most important innovations in this field include gene circuits for custom regulatory networks that enable dynamic control of metabolic pathways and cell-free systems that use cell extracts to prototype and test pathways before complete microbial engineering., Further, Biofoundries for rapid strain construction and testing, and chassis organisms like *Saccharomyces cerevisiae, Escherichia coli* (Navale et al., 2021), and *Pichia pastoris* (Gao et al., 2021), optimized for fermentation are also key innovative

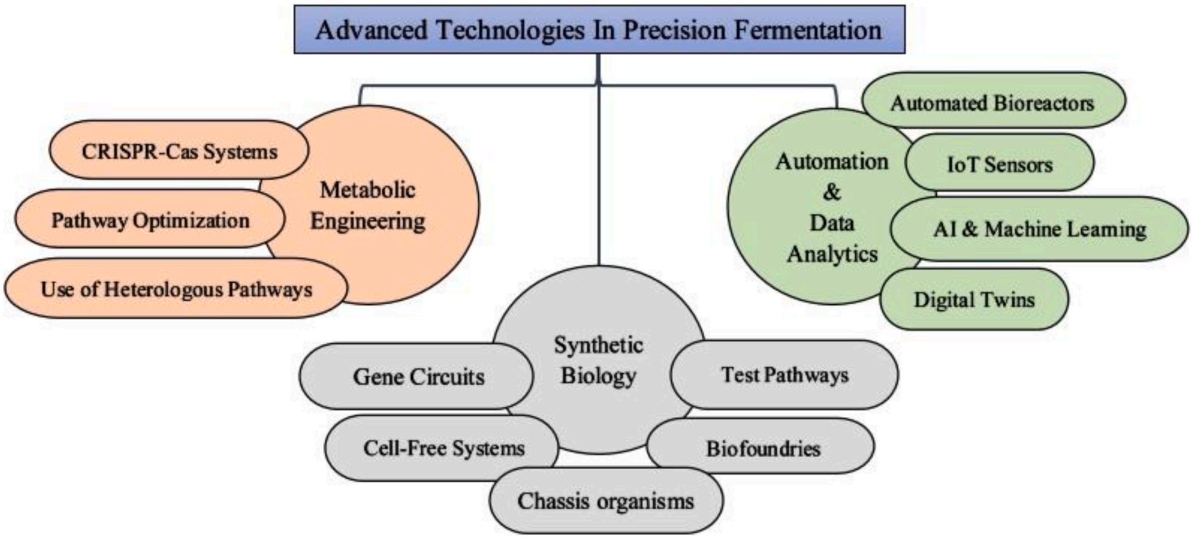


**Fig. 2.** Advances and innovations in precision fermentation.

areas of synthetic biology. Applications of synthetic biology include the syntheisis of new enzymes for food processing and the production of dairy and meat analogs, offering benefits like customization for specific applications and reduced time for strain development (Shi et al., 2022; Zhang and Nielsen, 2014).

### 4.3. Automation and data analytics

Automation and data analytics involve using robotics, machine learning, and data-driven tools to optimize fermentation processes (Yee et al., 2025). Key innovations in this field include automated bioreactors for high-throughput screening of microbial strains and fermentation condition optimization, IoT sensors for real-time monitoring of pH, temperature, oxygen, and product concentration to ensure precise process control. In addition, AI and machine learning are for predictive modeling in strain design, metabolic flux analysis, and process optimization, and digital twins, which create virtual models of fermentation systems to simulate and optimize process' s before scale-up (Pydipalli, 2024; Wainaina and Taherzadeh, 2023). The applications include optimizing industrial fermentation scale-up, accelerated development cycles, improved consistency, and cost-efficiency in production (Wankhede et al., 2024).

## 5. Sustainability and environmental impacts of precision fermentation

Precision fermentation is a transformative technology with profound sustainability advantages. Improving resource efficiency, significantly lowering carbon footprints and leveraging life cycle assessments to optimize environmental outcomes contributes to a more sustainable and environmentally friendly food and materials production system (fig 3) (Knychala et al., 2024).

### 5.1. Resource efficiency

Precision fermentation requires a smaller spatial footprint than traditional farming (Eastham and Leman, 2024; Singh et al., 2022). Also, fermentation processes use significantly less water than conventional agriculture, avoiding the water-intensive cultivation of crops or livestock feed. Feedstock versatility is achieved by utilizing renewable feedstocks like sugars from lignocellulosic biomass, food waste, or industrial by-products, with the potential to use $CO_2$ or methane as carbon sources through advanced microbial engineering. For example, producing animal-free dairy proteins, such as whey, through fermentation uses 60-90 % less land and water than conventional dairy farming (Augustin et al., 2024; Teng et al., 2021; Qureshi et al., 2019).

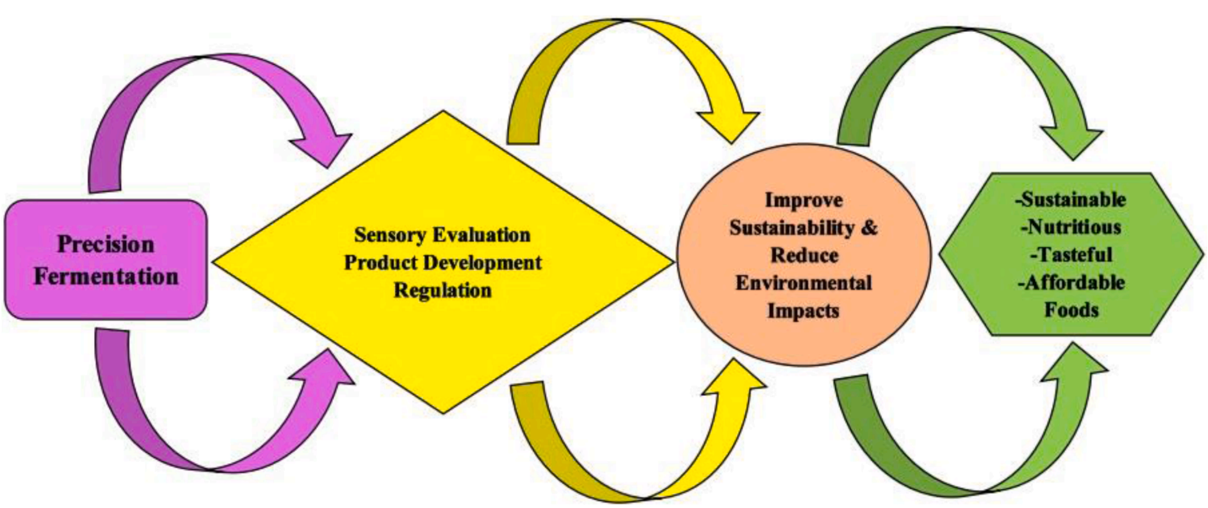


**Fig. 3.** Precision fermentation as sustainable and environment friendly approach.

### 5.2. Carbon footprint reduction

Precision fermentation lowers methane emissions and nitrous oxide emissions from synthetic fertilizers used in crop farming (Getahun and Yeman, 2025). Energy efficiency is achieved through advances in process optimization and the potential integration with renewable energy systems that minimizes carbon footprints. Moreover, fermentation processes support waste valorization by converting agricultural residues or industrial waste into valuable products, thus inhibiting waste-related emissions. Moreover, fermentation-based protein production has been shown to emit up to 90 % less greenhouse gases compared to traditional livestock farming (Caminiti et al., 2023; Humpenöder et al., 2022).

### 5.3. Life cycle assessments (LCAs)

In precision fermentation, LCAs (Life Cycle Assessments) provide a comprehensive impact analysis by assessing energy usage, water consumption, greenhouse gases emissions, and waste generation. Precisely, LCA evaluate the environmental impacts of a product from raw material extraction to disposal. LCAs also offer guidance for optimization by identifying "hotspots," such as energy use during downstream processing, that can be targeted for further improvements. For example, LCA studies of precision fermentation-derived proteins show significant environmental benefits, including reduced eutrophication and acidification potential (Rai et al., 2024; Vanapalli et al., 2023).

## 6. Regulatory landscape and challenges in precision fermentation

Precision fermentation is advancing rapidly, but regulatory frameworks, public perception, and intellectual property issues influence its growth. Understanding and navigating these aspects are essential for industry players (Ronchetti et al., 2024; Hashimy and Benjamin, 2024).

### 6.1. Current regulations in different regions

Regulations governing food-related applications of biotechnology vary across the globe. In the United States, FDA (Food and Drug Administration) and USDA (The United States Department of Agriculture) regulate food products, requiring novel ingredients to receive a GRAS (Generally Recognized As Safe) designation, with mandatory labeling for products derived from genetically modified organisms (GMOs) if genetic engineering is involved (Hallagan et al., 2020; Grossman, 2019). In the European Union, the European Food Safety Authority (EFSA) emphasizes requiring an extensive pre-market approval process that ensures safety, traceability, and transparency, along with stricter labelling requirements for GMO-derived products, that impact consumer acceptance (Evans, 2019; Kleter et al., 2018). In Asia, regulations differ by country; In China it is overseen by the Ministry of Agriculture and Rural Affairs, focusing on biosafety and labeling (Babar and Xu, 2023); In India it is regulated by FSSAI, with ongoing updates to GMO-related guidelines (Ghosh, 2024); Global harmonization efforts are led by the Codex Alimentarius Commission, which sets international standards for safety, quality, and labeling to promote consistency across markets (Fortin, 2023). (Evans, 2019; Kleter et al., 2018). In Asia, regulations differ by country; In China it is overseen by the Ministry of Agriculture and Rural Affairs, focusing on biosafety and labeling (Babar and Xu, 2023); In India it is regulated by FSSAI, with ongoing updates to GMO-related guidelines (Ghosh, 2024); Global harmonization efforts are led by the Codex Alimentarius Commission, which sets international standards for safety, quality, and labeling to promote consistency across markets (Fortin, 2023).

### 6.2. Safety assessments and public perception

Safety assessments for precision fermentation include toxicology testing to ensure the absence of harmful by-products or allergens. Also, it involves protein characterization and functionality of fermentation-derived proteins to confirm the identity (Ong et al., 2024; Ronchetti et al., 2024). Further, it also evaluates the potential ecological impacts of engineered microbes, such as containment and biodegradability (Hollander, 2018).

However, challenges remain, particularly in ensuring the safety of non-traditional feedstocks or by-products, and addressing unintended metabolic effects resulting from genetic engineering. Public perception is influenced by consumer concerns, such as distrust of GMO-related products and a misunderstanding of precision fermentation as "unnatural" (Wunderlich and Gatto, 2015). To gain the public trust, transparent labeling, education campaigns highlighting safety and sustainability benefits, and third-party certifications (e.g., non-GMO certifications for non-modified end products) are essential (Nuryanti and Wesseler, 2019). A successful example of this approach is the growing acceptance of alternative proteins, like animal-free whey, driven by clear communication about their environmental benefits (Sexton et al., 2019).

### 6.3. Intellectual property (IP)

Patents are the laws used to protect innovations in genetically engineered strains, metabolic pathways, and downstream processes, but concerns arise over "patent thickets," where overlapping patents may stifle innovation (Van Overwalle, 2015; Carneiro et al., 2024). In addition to patents, many companies rely on trade secrets, such as proprietary microbial strains and fermentation protocol that carry the risk of misappropriation or reverse engineering by competitors (Iqbal et al., 2023). The conflict between proprietary systems and open-source approaches in synthetic biology is considerable, with collaboration frameworks like the BioBricks Foundation aims to promote shared innovation while respecting intellectual property (IP) rights (Grewal et al., 2017). A key challenge is to ensure balancing the protection of innovators' rights with ensuring accessibility for emerging markets, as well as preventing the monopolization of technology by large corporations, which could limit the participation of smaller players.

### 6.4. Challenges in the regulatory landscape

The lack of harmonization in regulations across different regions imposes barriers to international trade and scalability. in addition, time-intensive approval processes for safety and labeling can delay the market entry of new products. Rapid scientific advancements often outpace existing regulations, necessitating continuous updates to ensure compliance. Maintaining a balance between innovation and maintaining safety presents a delicate regulatory challenge, as ensuring the safety of new products without hindering progress remains a key concern (Lescrauwaet et al., 2022).

### 6.5. Key strategies to address challenges

Strategies to overcome challenges include early involvement with regulators, during initial phase of product development to streamline the approvals process (Marcellin et al., 2024). Public education plays a crucial role in increasing awareness about the benefits of precision fermentation and addressing misconceptions surrounding GMOs (Bogueva et al., 2024). Additionally, transparent IP policies that encourage fair licensing agreements can enhance innovation and shared frameworks for development. With the continuous growth of the precision fermentation process, regulatory systems must evolve to balance innovation, safety, and public trust (Augustin et al., 2024). Companies that address these challenges, with transparent practice policies and robust safety data, are likely to gain a better edge while fostering consumer acceptance.

## 7. Market trends and future perspectives in precision fermentation

Precision fermentation is rapidly emerging as a transformative industry, driven by technological advancements, sustainability imperatives, and shifting consumer preferences. The precision fermentation market is poised for substantial growth, driven by consumer demand for sustainable, ethical, and high-quality products (Marcellin et al., 2024; Augustin et al., 2024).

Continued innovation in strain engineering, feedstock utilization, and process optimization will further enhance its potential. Addressing regulatory and public perception challenges through transparent communication and education will be critical for scaling adoption and unlocking the full potential of this transformative technology.

### 7.1. Growth of the precision fermentation market

Globally precision fermentation market is expected to experience significant growth, reaching multi-billion-dollar valuations by the late 2020s, driven by sectors such as alternative proteins, enzymes, flavor compounds, and nutraceuticals (Kekich et al., 2009; Augustin et al., 2024). Key factors fueling this growth include the demand for environmentally sustainable food systems, technological advancements reducing production costs, and increasing regulatory approval of fermentation-derived ingredients (Augustin et al., 2024; Eastham et al., 2024).

Majority of the market companies range from established biotech companies like Ginkgo Bioworks and Perfect Day to startups focusing on niche applications such as alternative seafood proteins and sustainable fats (Goodman, 2023; Wilkinson, 2024). Additionally, venture capital investments are rising, with large food companies showing interest in diversifying into sustainable products, further driving the industry's expansion.

### 7.2. Consumer trends and acceptance

The growing popularity of alternative proteins is attributed to the rise in preference for flexitarian, vegetarian, and vegan diets. In addition, Wellness oriented consumers are seeking items that mimic the taste, texture, and functionality of traditional animal-based foods (Broad et al., 2022). They also prefer clean-label products with fewer allergens and personalized nutritional profiles. Moreover, ethical and environmental concerns are influencing consumer choices, with many emphasizing in reducing environmental footprints and transparent sourcing. Therefore, nutraceuticals like vitamins and omega-3s produced via precision fermentation are becoming popular (Panse et al., 2019; Bhat et al., 2024). However, challenges also remain, such as addressing skepticism about the safety profile, genuineness of fermented ingredients and overcoming pricing issues, as some products still carry premium prices that limit mainstream access.

### 7.3. Future innovations and research directions

Future innovations in fermentation will focus on enhanced strain engineering, including the development of next-generation microbial strains with improved productivity, stability, and robustness, supported by AI and machine learning for optimized genetic modifications as shown in Fig 4 (Yadav et al., 2024). Transformation to non-food biomass feedstocks will promote sustainability and lower costs. Innovations in bioreactor design and fermentation process will induce scalability and energy efficiency, via integrating renewable energy sources to minimize carbon footprints.

Future innovations in fermentation will focus on enhanced strain engineering, including the development of next-generation microbial strains with improved productivity, stability, and robustness, supported by AI and machine learning for optimized genetic modifications as shown in Fig 4 (Boodhoo et al., 2022). The diversification of products will extend beyond food and beverages to include bioplastics, bio-based textiles, and novel flavor compounds for food applications. Additionally, multifunctional microorganisms capable of producing complex compounds in a single fermentation process will be developed, alongside circular economy models that valorize industrial by-products and waste streams as inputs for fermentation.

### 7.4. Opportunities and challenges

The opportunities in the industry lies in customization of ingredients with specific functional or nutritional properties to meet diverse consumer needs. Additionally, possibility of global expansion presents a significant opportunity in emerging markets with growing demand for sustainable food solutions (Augustin et al., 2024). Collaborations of research institutions and biotech, food companies offer the potential to accelerate innovation and drive the development of new, more efficient products.

The challenges faced in the industry include achieving cost competitiveness, as attaining parity with traditional production methods remains a priority (Hilgendorf et al., 2024). The Complexity in the regulatory procedures poses a significant obstacle, as varying requirements across regions potentially lowering the pace of market entry. Another significant challenge is to address misconceptions of consumer

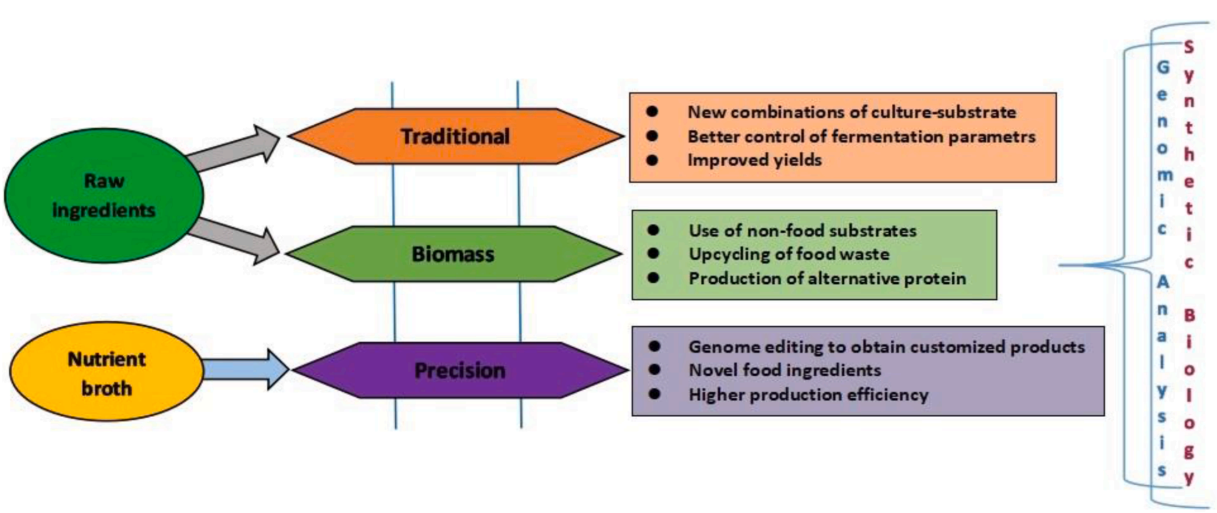


**Fig. 4.** Fermentation processes involving Genomic Analysis and Synthetic Biology.

awareness and foster trust in fermentation-derived products to ensure wider acceptance and understanding.

## 8. Precision fermentation in industry

Precision fermentation has several successful applications in different industries (food, agriculture, pharmaceuticals and materials) (Augustin et al., 2024).

It has demonstrated its versatility and impact across industries from sustainable food ingredients to innovative materials. By addressing technical, regulatory, and consumer challenges, companies can leverage its potential for scalable, impactful, and profitable applications. Some notable case studies illustrating its industrial potential and the lessons learned from these implementations are given below.

### *8.1. Successful applications in industry*

#### *8.1.1. Animal-free dairy proteins*

Perfect Day is a company that specializes in producing whey and casein proteins through fermentation, offering an animal-free alternative for dairy products such as ice cream, milk, and cheese. Their key achievement involves engineering the *Trichoderma reesei* fungus to produce whey protein without the need for animals thus contributing to sustainability with reduced water usage and carbon emissions compared to traditional dairy farming (Day et al., 2022). The company has achieved notable market presence and consumer acceptance through strategic partnerships with established food brands. In addition, Perfect Day has demonstrated scalability, cementing its position as a leader in the alternative dairy space.

#### *8.1.2. Fermentation-derived enzymes*

Novozymes is a global company and their major innovations involve continuously improving microbial strains to optimize enzyme yields (Frost and Sullivan, 2011). Novozymes has dominated the global enzyme market by catering the requirement for sustainability, achieving high market acceptance due to the clear cost and environmental benefits of their products (Global Industrial Enzyme Market Report, 2013). A key insight is the importance of close collaboration with end-users and to develop tailored products that foster customer loyalty and satisfaction

#### *8.1.3. Sustainable omega-3 fatty acids*

Corbion is a key player in the production of EPA and DHA omega-3 fatty acids via fermentation of microalgae (Colonia et al., 2022). Among their key innovations include proprietary algae strains that are optimized for high lipid production. Further, the successful replacement of fish oil in aquaculture feeds, and reduce requirement of overfishing. Corbion has established itself as a leader in sustainable alternatives to marine-derived omega-3s. A key lesson learned is that addressing both ecological and economic challenges simultaneously enhances product adoption and market acceptance.

#### *8.1.4. Bio-based materials*

Bolt Threads company is a leading company relying on precision fermentation for the production of spider silk and mycelium-based leather alternatives (Qua et al., 2019). Their key innovative precision fermentation process involves to replicate spider silk proteins for textiles and developing sustainable alternatives to traditional leather using fungal mycelium. Major fashion/luxury brands are consumers company's products thus supporting sustainability. A key lesson learned is that targeting niche luxury markets with environmentally conscious consumers can lead to early success and strong brand positioning.

### *8.2. Challenges of implementation*

One of the major challenges faced during precision fermentation was attaining and optimizing strains for consistent yields during scale-up (Starz, 2024). Additionally, iterative prototyping and pilot-scale testing proved crucial for a smooth transition from the lab to industrial scale.

The long processes for approval for novel foods and ingredients emphasized the importance of early engagement with regulatory bodies to accelerate product approval and market entry. Also, consumers' apprehension about the safety of fermentation-derived products required transparent communication and an emphasis on environmental benefits to build trust and acceptance (Marcellin et al., 2024).

High cost compared with the traditional fermentation process was another obstacle; ensuring the superior quality, functionality, and sustainability of precision fermentation products proved crucial for differentiation (Augustin et al., 2024). Finally, establishing a market presence in a competitive landscape was facilitated by partnerships with established brands and industry players, which expanded reach and credibility.

## 9. Conclusion and future directions

Precision fermentation is rapidly growing area to transform food production, pharmaceuticals and materials. It offers resource efficiency by reducing the need for land, water, and energy, especially when compared to traditional agriculture and livestock farming. It significantly reduces methane gas emissions and relies on renewable fee stocks thus playing a pivotal role in carbon footprint reduction. LCAs indicate that fermentation-derived products, such as alternative proteins, have lower environmental impact than traditional animal-based products. While regulations for precision fermentation products are evolving, they vary across regions, with some markets (e.g., the European Union) having stricter requirements than others. Intellectual property rights (IPR) are key area for consideration. Patenting, collaborations and technology access are still debatable issues. Safety assessments are crucial for consumer confidence, and public perception remains a challenge especially regarding genetically modified organisms (GMOs) or genetically engineered microbes.

Advances in bioinformatics and AI will help optimize fermentation processes and design novel strains with complex biosynthetic pathways. Integration of renewable energy sources and fermentation systems will make the production process more environmental friendly and improve sustainability. Along with food and beverages, precision fermentation does positively impact pharmaceuticals, bio-based materials, and bioplastics sectors. International regulatory frameworks will be essential to facilitate global trade of precision fermentation-derived products. Collaboration between governments, scientists, and industry stakeholders is needed to ensure that regulations are balanced, clear and conducive to innovation.

Ongoing efforts to improve public perception through education and transparency will be critical. Environmental sustainability, several health benefits, and ethical production will resonate with increasingly conscientious consumers. Cost reduction strategies, including optimizing production processes and feedstocks, will help improve market access and foster greater adoption of precision fermentation products. The future of precision fermentation is promising, with recent advancements, it will positively reshape the industries by offering sustainable, efficient, and scalable solutions. Innovations, continuing research, effective regulation, and public engagement will grow the sector. Precision fermentation could be pivotal in achieving a more sustainable and resilient global economy as these advancements become more widespread.

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### Ethical statement

The authors declare that the current study does not require any ethical issues as no human or animal is involved.

### CRediT authorship contribution statement

**Kumkum Verma:** Writing – original draft. **Priti Duhan:** Writing – original draft. **Deeksha Pal:** Writing – review & editing. **Pooja Verma:** Formal analysis. **Poonam Bansal:** Writing – review & editing.

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