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Fermentation-derived Fats and Oils: from Engineering Strategies to Emerging Technology

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ABSTRACT

Developing novel fat and oil ingredients through fermentation is an emerging field with great potential to address sustainability, health, and functionality challenges in the food industry. This review highlights new strategies such as precision fermentation for specialty fats, waste-to-oil bioconversion, hybrid blends with plant-based fats, and scalable bioreactor designs. Despite promising applications in food sectors, there are still challenges like high production costs, and scalability barriers. Advances in feedstock diversification, co-product valorisation, and innovative fermentation systems are key to overcoming these hurdles. A few companies demonstrate progress, while economic and technological innovations are expected to enable mainstream adoption in the coming decade.

What is "already known":	• Oleaginous microorganisms can produce single-cell oils (SCOs), which accumulate lipids up to 70% of their dry biomass, making them attractive alternatives to traditional fat sources • SCO is desirable in terms of rapid production and resource efficiency.
What this article adds:	• Potential of fermentation-derived fats and oils as a novel solution to address sustainability, health, and functionality challenges within the food industry has been addressed • Despite the promising applications of microbial fats, the high production costs, scalability issues, and technological barriers • Downstream processing has remained significant hurdles to widespread commercialization. • Advances in metabolic engineering, strain optimization, and precision fermentation are key strategies to enhance productivity and economic feasibility • Importance of consumer perception, regulatory challenges, and transparent branding strategies to build trust in fermentation-derived fats, stressing the need for education on their sustainability and health benefits for market acceptance.

1. Introduction

The global demand for sustainable and renewable sources of fats and oils is rapidly increasing due to environmental concerns and the depletion of fossil fuel reserves [1, 2]. Traditionally, plant and animal sources have been the main providers of lipids for food, fuel, and industrial applications [3]. However, the scalability of conventional oil crops is limited due to their low lipid content (often below 5% of biomass) and competition with food production for other agricultural land [4, 5]. Additionally, extraction and conversion processes, including oil extraction and transesterification, can be technically complex, environmentally burdensome, and economically costly [6]. Oleaginous microorganisms are capable of producing single cell oils (SCOs) and have emerged as promising alternative lipid producers, offering advantages such as rapid growth rates, adaptability to diverse substrates including agro-industrial wastes and the ability to accumulate lipids up to 70% of their dry biomass under controlled cultivation conditions [7, 8]. These serve as valuable sources of polyunsaturated fatty acids (PUFAs) crucial for human health and nutrition [9, 10], and saturated fatty acids (SFAs) important for functionality in food applications. Furthermore, these possess fatty acid profiles similar to plant oils, making them suitable for various applications such as food additives [9, 11].

Despite these benefits, the high cost of fermentation and lipid extraction at industrial scale still limits commercial viability. Lipid recovery from oleaginous yeasts is often hampered by rigid cell walls, poor mass transfer, and inefficient solvent-based extraction methods, making downstream processing a cost-intensive bottleneck [12]. Recent advances in metabolic engineering and process optimization have focused on enhancing lipid yield and reducing production costs by improving strain performance and utilizing inexpensive substrates [1, 13]. Given the growing interest in using carbon or fat-rich food residues as fermentation substrates, a deeper understanding of microbial performance under such conditions is essential for advancing sustainable and stable bioprocesses [14].

This review explores current strategies and technological advancements in microbial lipid production, emphasizing fermentation-derived fats as sustainable alternatives in the food industry. Additionally, it examines commercial-scale production, addresses real-world challenges and existing barriers, and highlights companies worldwide that have successfully advanced in this field.

2. Material and Methods

Oleaginous microorganisms defined as those capable of accumulating over 20% of their dry cell weight as lipids represent a diverse group of microbes including certain species of algae, fungi, and bacteria [15, 16]. These organisms naturally synthesize and store triacylglycerols (TAGs) under nutrient-limited conditions, offering a biotechnological route to lipid production that is decoupled from traditional agriculture. Among these, oleaginous yeasts such as *Yarrowia lipolytica* and *Lipomyces starkeyi* stand out due to their faster growth rates, ease of genetic manipulation, and higher tolerance to industrial stresses, making them more suitable for large-scale bioprocessing compared to algae or filamentous fungi [5, 17-19]. Unlike conventional fat sources such as palm oil or animal fat, microbial lipid production does not require large land areas, freshwater resources, or deforestation-linked monoculture systems. As such, it offers a scalable and environmentally responsible alternative that supports global sustainability goals by mitigating land use change, reducing pressure on biodiversity, and eliminating the need for animal or plant inputs in the lipid supply chain [14]. These microbial lipids that also referred to as single cell oils (SCOs), are particularly attractive in the context of climate-smart agriculture and future food systems, where land-efficient, animal-free, and modular bio-manufacturing solutions are in high demand. Alongside opportunities some problems and bottle-necks related to single cell oil production are as follow;

2.1. Cost Competitiveness

Despite substantial technological progress, the production cost of fermentation-derived fats remains relatively high compared to conventional plant-based oils and continues to pose a significant barrier to large-scale commercialization [14, 20]. To overcome this economic barrier, recent research has focused on improving strain efficiency, utilizing low-cost or waste-derived feedstocks, and developing integrated biorefinery strategies that allow for co-product recovery, thereby enhancing overall process economics and sustainability. Expensive feedstocks like glucose or refined sugars, high aeration and energy demands and low volumetric productivity (often < 0.5 g/L/h for many oleaginous microbes) are key cost drivers of microbial oils. To solve the problem breakthrough needed include transitioning to cheap lignocellulosic sugars and leveraging biorefinery co-products [21, 22].

2.2. Functionality Limitation

Many microbial oils lack the physical or functional properties of traditional fats used in food applications. Firstly, while traditional fats like cocoa butter and palm oil exhibit well-characterized polymorphic crystallinity essential for applications in chocolate and bakery products [23], the analogous crystallization behavior of microbial oils remains unexplored and represents a challenge for mimicking such functional properties. Secondly, microbial oils could have an imbalanced ratio of saturated to unsaturated fatty acids. This results in either a lack of structuring effect for food application, or leaves residual un-melted solid fat at body temperature, imparting a waxy or greasy mouthfeel. Third, highly unsaturated microbial oils (e.g., DHA, EPA-rich oils from algae) are prone to oxidation, which leads to rapid rancidity unless stabilized with antioxidants like tocopherols or rosemary extract [24].

2.3. Technological and Technical Challenges

Despite advances in microbial lipid production, several technological bottlenecks persist. Downstream processing, particularly oil extraction and purification, remains energy-intensive, impacting overall sustainability and cost-efficiency [7, 25, 26]. Moreover, there is a limited availability of microbial strains capable of synthesizing saturated fats, which are essential for mimicking the functional properties of traditional fats like butter [7, 27]. On the technical side, the use of lipid-rich food waste as a substrate can introduce complications in anaerobic digestion systems. Specifically, the accumulation of long-chain fatty acids (LCFAs) has been shown to disrupt microbial metabolism and decrease system performance under certain conditions [28, 29].

2.4. Supply Chain & Scalability

A key question in scaling fermentation-derived fats is Who will build the industrial infrastructure? Establishing a production facility with a capacity of over 100,000 tons per year is capital-intensive and technically demanding. Strategic partnerships between large agrifood corporations (e.g., ADM, Corbion) and specialized biotechnology companies such as (Acies Bio), a European CDMO with nearly two decades of experience in precision fermentation-are expected to be central in addressing this challenge. Unlike early-stage startups, Acies Bio provides integrated R&D-to-manufacturing solutions and has already attracted investment from ADM Ventures, highlighting its strategic role in building scalable infrastructure. Such collaborations are essential to bridge the gap between laboratory innovation and industrial deployment [30]. Unlike soy or palm oil production, which benefits from decades of infrastructure, microbial oil production lacks in commercial-scale fermentation facilities, especially for lipids

2.5. Regulation, Labeling, and Consumer Perception

2.5.1. GRAS, Novel Food, EFSA, FDA

Many microbial fats are derived from non-traditional organisms or use genetic modifications, triggering regulatory oversight. For examples in the United States. products must attain GRAS status (Generally Recognized as Safe) from the FDA to demonstrate safety for use in foods before entering the market [31, 32]. In Europe, they may require Novel Food approval under EFSA guidelines. This process is lengthy (12–24 months) and costly, particularly for small startups [33]. Additional labeling concerns include whether microbial oils qualify as "plant-based," "natural," or "clean label", which impacts consumer perception.

2.5.2. Consumer perception: labeling challenges

While sustainability claims surrounding fermentation derived fats resonate with environmentally conscious consumers, skepticism persists among others. These facts are sometimes perceived as overly processed or unnatural, particularly when associated with technical terms like "precision fermentation" or "engineered microbes," which may evoke concern or mistrust in the absence of adequate public education. To address these perceptions, transparent and positive branding, using terms such as "climate-smart," "animal-free," or "fermented oils from yeast", can enhance consumer appeal. Clear storytelling that communicates the sustainability, safety, and health benefits of microbial fats will be essential to fostering consumer acceptance [34, 35].

2.5.3. Strategies for Consumer Trust and Branding

Consumer acceptance remains a critical challenge in the commercialization of fermentation-derived fats. While terms like plant-based are well-established in consumer markets, phrases such as fermented fat or microbial oil may trigger hesitation or confusion.

Early market research suggests that using the term "cultured oil" resonates more positively with consumers compared to "microbial oil", potentially due to its association with concepts like cultured meat or precision fermentation. Recent studies conducted by NoPalm Ingredients in Europe further highlight the importance of terminology, showing that labels referencing oil of yeast origin or yeast oil, are both well understood and associated with sustainability [36, 37]

3. Engineering Strategies for Enhanced Lipid Production

Recent advancements in microbial biotechnology and process engineering are reshaping how fats and oils can be produced through fermentation [38]. The following emerging strategies are key to improving the feasibility, functionality, and scalability of fermented lipid ingredients in food systems:

3.1. Strain Engineering and Synthetic Biology

CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) is a natural genetic system found in bacteria and archaea that helps protect them from viral infections and invading genetic elements. In genetic engineering scientists have adapted this natural system to create CRISPR-Cas9, a powerful tool for precise and efficient gene editing. CRISPR-Cas9 allows targeted cutting and modification of DNA in living organisms, revolutionizing fields like medicine, agriculture, and biotechnology. Using CRISPR/Cas systems, metabolic rewiring, and synthetic biology platforms to increase flux through lipid biosynthetic pathways in oleaginous microorganisms such as *Yarrowia lipolytica* [19, 20, 21, 39, 40], *Mortierella alpine* [40-42], and *Aurantiochytrium* sp. [43]. These modifications enable overexpression of key enzymes (e.g., ACC, DGAT, FAS), knockdown of competing pathways, and improved NADPH regeneration, ultimately boosting lipid yield and selectivity. Further investigations on novel genetic targets in oleaginous yeasts are warranted to overcome current limitations in microbial lipid production [44].

One of the most recently applicable oleaginous yeast capable of accumulating lipids up to 70% of its dry cell weight is *Lipomyces starkeyi*, making it a promising candidate for single-cell oil (SCO) production [45, 46]. This yeast can utilize various carbon sources, including industrial wastes and cellulosic hydrolysates, for lipid production [47]. Recent research has focused on enhancing lipid yield and productivity through strategies such as parameter optimization, two-stage systems, metabolic engineering, mutagenesis, and co-cultivation with algae [44]. Genetic engineering tools have been developed to improve lipid production efficiency, with increased acyl-CoA synthesis identified as crucial for enhancing productivity [45]. Despite its potential, genetic manipulation of *L. starkeyi* remains challenging, which hinders its widespread industrial adoption [47]. Ongoing research aims to overcome these limitations and further improve SCO production for applications in biodiesel and oleochemical industries [44, 46].

3.2. Adaptive Laboratory Evolution

Recent studies have highlighted the power of adaptive laboratory evolution (ALE) in enhancing lipid productivity and stress tolerance in oleaginous microorganisms. For instance, Chen et al. demonstrated that prolonged cultivation of lipid-producing yeasts under nutrient-limited environments can significantly improve substrate assimilation efficiency and overall metabolic robustness. Similarly, Sha et al. (2023) applied ALE strategies under oxidative stress and high C/N conditions to obtain evolved *L. starkeyi* strains, which exhibited enhanced lipid accumulation and greater resistance to common fermentation inhibitors. In addition, Zhang et al. (2022) reported that ALE not only accelerated microbial adaptation to industrial conditions but also improved growth kinetics and lipid output in engineered yeast. Various strategies such as two-stage cultivation, mutagenesis, and metabolic engineering have been employed to enhance lipid productivity in *L. starkeyi* fermentation systems [44, 48, 49].

3.2.1. Random Mutagenesis and High-Throughput Screening

Random mutagenesis combined with high-throughput screening techniques has emerged as an effective strategy for enhancing lipid accumulation in oleaginous yeasts, enabling the rapid selection of superior strains with improved productivity and growth performance under industrial conditions [50-52]. Mutagenesis using UV irradiation, coupled with mutant screening via cerulenin selection, has proven to be an effective method for isolating *Lipomyces starkeyi* variants with enhanced lipid productivity. In one study, Tapia et al. (2012) identified mutant strain A1, which exhibited a 30.7 % increase in lipid productivity and 15.1 % higher biomass compared to the wild type, under xylose-based fermentation conditions [53]. Similarly, Park et al. (2021) employed EMS mutagenesis in combination with fluorescence-activated cell sorting (FACS) to enhance ω-hydroxy fatty acid production in *Yarrowia lipolytica*. The integration of mutagenesis with advanced screening platforms like FACS enabled the efficient identification of high-performing variants, showcasing the potential of this strategy for strain development in industrial lipid biosynthesis [52].

3.3. Co-cultivation and Microbial Consortia

Co-cultivation systems involving oleaginous yeasts and other microorganisms such as microalgae, bacteria, or filamentous fungi are emerging as a promising strategy to improve lipid yield and process efficiency. These mixed-culture approaches can leverage the complementary metabolic capabilities of different species to optimize substrate utilization, mitigate metabolic bottlenecks, and enhance lipid biosynthesis [44, 54, 55]. In addition, bacteria capable of degrading complex substrates (e.g., lignocellulosic biomass or food waste) can be co-cultured with lipid-producing yeasts like *Lipomyces starkeyi* to facilitate the release of fermentable sugars, increasing carbon availability and enhancing lipid accumulation [56]. Such synergistic interactions may also improve biomass productivity, maintain pH stability, and support the bioconversion of low-cost feedstocks under non-sterile or semi-controlled conditions. While co-cultivation systems offer several advantages, challenges such as interspecies competition, process control, and strain compatibility remain critical hurdles for industrial deployment. Advanced bioprocess engineering, microbial consortia design, and synthetic ecology tools are being explored to overcome limitations and unlock the full potential of co-culture fermentation in sustainable lipid production [44].

3.4. Precision Fermentation for Specialty Fats

Precision fermentation leverages genetically engineered microorganisms to produce specialty fats with tailored fatty acid profiles and functional properties. Companies like C16 Biosciences, with their Palmless™ technology, utilize fermentation to replicate tropical oil equivalents without relying on traditional sources, such as palm oil and cocoa butter, addressing both sustainability and ethical concerns [57]. Similarly, Nourish Ingredients produces flavorful fats through microbial fermentation, offering alternatives that closely mimic the sensory attributes of animal-derived fats for dairy alternative and meat alternative applications [58]. In the infant formula sector, startups such as Checkerspot have pioneered the production of microalgae-derived human milk fat analogues designed to more closely mimic the structure of breast milk [59]. Precision fermentation thus represents a transformative platform for creating high-value, customizable fats tailored to diverse food applications

4. Substrates and Feedstocks for Microbial Oils

4.1. Transition from Sugars to Waste-Based Feedstocks

The bioconversion of waste into microbial oils offers a sustainable and economic strategy for addressing both environmental concerns and resource scarcity. Some oleaginous microorganisms such as *Yarrowia lipolytica* [60-62] and *Rhodosporidium* Sp. [63, 64] are capable of converting diverse waste streams into single cell oils (SCOs), rich in triacylglycerols (TAGs). Oleaginous microbes can utilize carbon-rich substrates derived from wastewater, organic waste (industrial-organic-wastes-derived volatile fatty acids), agricultural residues, food waste [65-69]. Lignocellulosic hydrolysates from food/agro-waste, composed of glucose, xylose, and other sugars also serve as cost-effective substrates [19, 67].

4.2. Circular Economy and Biorefinery Models

Co-product valorization represents a biorefinery approach that maximizes the use of microbial cells by transforming residual biomass into high-value applications. Many microbial fat production systems generate high-protein biomass as a by-product. Rather than treating it as waste, companies are exploring its use as animal feed, pet food, or functional protein ingredients, thereby improving the overall economic viability of the process [26]. To improve economic viability, many microbial lipid production platforms are exploring co-product valorization, extracting value from residual biomass rather than discarding it. One promising route involves recovering microbial protein from lipid-extracted cells. After lipid harvesting (via solvent or mechanical disruption), the remaining biomass is rich in proteins and can be processed into high-value food or feed ingredients. Lipid-producing strains like *Yarrowia lipolytica* or *Mortierella alpina* can be engineered or selected for dual-purpose use, such as lipid extraction followed by protein recovery [70]. This biorefinery approach, using the full potential of the microbial cell, significantly offsets production costs, improves resource efficiency, and aligns with circular economy goals.

4.3. Gas-Based Fermentation System

Recent studies demonstrate that carbon capture can be coupled with microbial oil production by using autotrophic or mixotrophic oleaginous strains to fix CO_2 from industrial emissions. These approaches not only mitigate carbon emissions but also produce high-value lipids suitable for biodiesel and specialty fats. However, optimizing lipid production, strain selection, and scaling up these processes remain key hurdles [71]. Emerging companies such as Kiverdi and Colipi serve as leading examples of innovative waste-to-oil bioconversion technologies that contribute to the advancement of circular economy models. Kiverdi uses gas fermentation to efficiently convert these waste gases into valuable lipids and a variety of other biomaterials, including proteins and specialty chemicals. [72]. Similarly, Colipi employs a patented gas fermentation technology which designed bioreactors containing specific bacteria that transform CO_2 from sources like bioethanol, biogas, cement and steel plants, into oils, proteins, and other valuable biomaterials [73].

In addition to environmental benefits, these systems offer economic potential by leveraging waste materials that would otherwise require disposal. Optimization of bioreactor conditions, gas solubility, and metabolic pathways continues to improve the yields and scalability of waste-derived oils.

4.4. Integrating renewable energy into lipid biosynthesis

Improving the energy efficiency of microbial lipid production is essential for environmental and economic sustainability. One emerging strategy is electro-fermentation, where electrodes supply reducing equivalents (e.g., NADH, H_2) or modulate redox potential to guide microbial metabolism toward desired products such as lipids. This approach can be coupled with renewable electricity, allowing for partial decoupling from organic substrates and reduced carbon footprints. A prominent example is Solar Foods, which utilizes electricity from solar panels to drive electro-bioreactors that feed hydrogen and CO_2 to autotrophic microbes for producing fat-like substances. This not only reduces dependency on agricultural feedstocks but also enables closed-loop, low-emission lipid synthesis [74-76]. Such systems are still in early commercialization stages, but techno-economic models suggest that when powered by surplus renewable energy, they can compete with conventional lipid fermentation processes in terms of energy input per kilogram of product.

5. Bioreactor Design and Scale-Up Approaches

Bioreactor design choices, including configuration type (closed vs. open) and operational parameters (aeration, agitation, modularity), significantly impact both the scalability and productivity of microbial oil fermentation. Scaling microbial oil production requires transitioning from conventional batch systems to more efficient fed-batch or continuous fermentation platforms. These advanced systems improve volumetric productivity and allow for better control over key process parameters, such as nutrient feed rates and oxygen transfer [77].

Such developments validate the industrial feasibility of gas-based bioprocesses and offer a model for carbon-neutral fat production. Maintaining scalability is supported by Process Analytical Technology (PAT), which includes real-time measurements of pH, dissolved oxygen (DO), biomass concentration, and redox potential to ensure consistent bioprocess control [78]. In terms of bioreactor configuration, airlift and bubble column reactors are particularly advantageous for oleaginous microorganisms, as they enhance gas, liquid mass transfer with minimal shear stress, a critical feature for shear-sensitive lipid-producing strains [16]. These reactor types also reduce energy input compared to stirred-tank reactors, which is important at industrial volumes.

Different bioreactor configurations influence both the scalability and productivity of microbial oil fermentation. In several experiments, heterotrophic bioreactors maintained cell densities of about 12.8–15.5 g/L across scales ranging from 5 L to 11,000 L, while reviews of open and closed systems indicate that reactors operating at intermediate volumes (approximately 100–1,000 L) achieve biomass productivities up to 12 g/L/d and lipid levels reaching 49% [79, 80].

Closed designs with improved light exposure and mixing—exemplified by flat-panel, X-Shape, and serial configurations, yield 20% or more increases in biomass and fatty acid content compared to single large open systems [81]. Design-specific parameters—such as aeration rate (1.5–2 vvm), agitation speed (~600 rpm), and modular bioreactor configurations—have been shown to significantly influence cell density and lipid accumulation in *Aurantiochytrium limacinum* cultures [82]. Bioreactor design including configuration and operational parameters like aeration and agitation plays a pivotal role in balancing scalability and lipid productivity during microbial oil fermentation [83]. Additionally, modern scale up strategies increasingly leverage computational approaches, including CFD simulations integrated with data driven or mechanistic modeling, to optimize hydrodynamics, oxygen transfer, and heat removal in high cell density fermentations [77, 84, 85].

6. Emerging Alternatives to Fermentation

6.1. Enzymatic Lipid Synthesis (Cell-Free Systems)

Enzymatic lipid synthesis represents a promising cell-free approach to fat production, where isolated enzymes catalyze the biosynthesis of fatty acids and triglycerides directly from basic feedstocks. Unlike traditional microbial fermentation, these systems use no living cells. Enzymes such as acetyl-CoA carboxylase (ACC) and fatty acid synthases (FAS) are immobilized or suspended in solution to convert carbon sources (e.g., sugars, CO_2) into lipids [86]. One of advantages of enzymatic lipid production against microbial is that it generates no biomass waste, whereas fermentation produces large amounts of microbial biomass, which accounts for up to 30% of downstream processing costs.

Enzymatic lipid synthesis offers a cell-free alternative to microbial fermentation, enabling rapid, waste-free, and high-purity fat production through isolated enzyme catalysis, and although still at an early stage, several academic groups and emerging startups are actively advancing this approach toward future commercialization.

no company has yet commercialized large-scale lipid or fat production via cell-free enzymatic systems; this approach remains largely at the academic research stage, though platform companies like EnginZyme and Enzymit could potentially expand into this space in the future.

6.2. Roadblocks and technical challenges

One of the main challenges in enzymatic lipid synthesis is the high cost of industrial enzymes. Lipases currently cost around $1,000/kg, which must be reduced to below $100/kg to become competitive with microbial and plant-based fat production [87]. Additionally, the process relies heavily on NADPH, an expensive and unstable cofactor essential for fatty acid biosynthesis. Recent efforts to overcome this limitation include light-driven NADPH regeneration using TiO_2 or ZnO nanoparticles [88, 89], as well as the development of synthetic NADPH analogs at TU Berlin that mimic natural nicotinamide cofactors.

6.3. Outlook and future directions

If enzyme costs and cofactor regeneration barriers are addressed, enzymatic lipid synthesis could become cheaper than fermentation by 2030. Moreover, researchers are exploring hybrid systems, where microbes are used to express enzymes that are then extracted for use in cell-free lipid synthesis. Companies like Novozymes are testing this for palm oil alternatives. This develops industrial enzymes for modifying fats and oils (e.g., structured lipids or palm oil alternatives) [90]. In parallel, 3D-printed enzymatically structured fats are emerging, particularly for use in cultured meat to mimic marbling and texture an area pursued by companies like Stakeholder Foods [91].

6.4. Techno-Economic Comparison: Fermented vs. Enzymatic Fats in Chocolate

Fermentation-derived fats and enzymatically synthesized lipids are emerging as sustainable alternatives to palm-derived cocoa butter equivalents, particularly in premium chocolate formulations. However, their techno-economic profiles diverge significantly. By 2030, fermentation-derived cocoa butter analogs are projected to cost approximately \$8–10/kg, largely due to high production costs, complex downstream processing, and moderate conversion yields (e.g., ~150 g/L lipid titer with ~50% yield) [92]. Palm oil from fresh fruit bunches remains the industry benchmark with a production cost of around \$1.2–1.5/kg, but its environmental costs, particularly in the form of deforestation, methane emissions, and biodiversity loss, are increasingly factored into regulatory and market decisions [93]. Thus, fermentation-derived fats are expected to remain premium ingredients by 2030, with a cost around 7 times higher than palm oil, while enzymatic lipids could reach cost parity with palm oil by 2035, assuming sufficient scale-up and resolution of key bottlenecks [94].

7. Emerging Technological and future direction

Recent advances in metagenomic analyses have significantly enhanced our understanding of lipid metabolism and degradation pathways within complex microbial communities. These tools enable researchers to decode functional genes associated with lipid synthesis, degradation, and transport, offering new opportunities to engineer robust and efficient fermentation systems [29]. By mapping these pathways, scientists can tailor microbial consortia and adjust bioprocess parameters to improve both lipid yield and process stability, particularly under industrial-scale conditions. Looking ahead, several key technological directions are shaping the future of sustainable lipid production, such as cheaper and non-competitive feedstocks and AI-driven strain engineering.

A strategic shift is underway from sugar-based carbon sources to methane, carbon dioxide, and agro-industrial waste, which are more abundant, low-cost, and do not compete with food resources. These substrates also align with circular bioeconomy principles and carbon neutrality goals [25]. Artificial intelligence and machine learning models are increasingly applied to accelerate strain optimization. These tools allow for high-throughput screening, predictive metabolic modeling, and adaptive evolution strategies that shorten development cycles and maximize lipid productivity [95, 96].

Companies like Zero Acre Farms, Clean Food Group, and Libre Foods are actively pursuing these innovations, integrating them into their biomanufacturing pipelines to overcome cost, scale, and regulatory hurdles. By aligning biotechnology with systems biology and digital tools, the field is moving closer to commercially viable, environmentally friendly lipid alternatives.

8. Conclusion

As the demand for sustainable, deforestation-free fats intensifies, precision lipid production via microbial fermentation and enzymatic synthesis, stands at the frontier of food biotechnology. While fermentation-based fats are well-positioned to serve premium segments in the short term, enzymatic and hybrid systems may unlock commodity-scale applications in the next decade. Yet, technological uncertainties, infrastructure investment risks, and regulatory ambiguity remain critical hurdles. A successful transition will require a synchronized effort across innovation, policy, and consumer engagement. Food brands, investors, and policymakers must adopt agile, evidence-based strategies, balancing near-term viability with long-term scalability. With the right mix of incentives, public trust-building, and scientific breakthroughs, next-generation fats can redefine the global lipid supply chain in both environmental and economic terms. Despite rapid advances in lipid biotechnology, several open questions continue to shape investor confidence, brand strategy, and public policy. Although enzymatic processes bypass genetically modified organisms in their final products, consumer perception may still conflate "lab-grown" or "synthetic" with unnaturalness. Studies show that food technology acceptance is less influenced by technical accuracy and more by emotional and ethical perceptions. Also, the capital intensity of fermentation is nontrivial. For example, it has been predicted that $200–400 million is needed to build facilities capable of producing ~10,000 tons of microbial fat annuall.

9. Declarations

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9.2. Authors' Contributions

ZM & RM: Methodology, Visualization, Writing – original draft. Conceptualization, Resources, Methodology, Supervision, Writing – review & editing, Project administration, Funding acquisition. YS: Supervision, review & editing.

9.3. Declaration of Interest

The authors of this article declared no conflict of interest.

9.4. Ethical Considerations

All ethical principles were adhered in conducting and writing this article.

9.5. Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

9.6. Funding

This research was carried out independently with personal funding and without the financial support of any governmental or private institution or organization.

9.7. Using Artificial Intelligent chatbots

AI chatbot has been used in this study just for sorting of concepts and providing table of content.

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