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Fermented Fat and Oil: From Nutritional Function to Production and Regulatory Consideration

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Abstract

Background and Objective: Fermentation-derived fats and oils have emerged as sustainable alternatives to conventional animal and plant lipids. Oleaginous microorganisms, including yeasts, fungi, and algae, can accumulate triacylglycerols with structures similar to vegetable oils and animal fats. Advances in precision fermentation now enable tailoring of lipid profiles for nutritional and functional purposes. This review aims to examine recent progress in microbial fat production, highlight applications, and identify remaining barriers to mainstream adoption.

Method: This review synthesizes findings from recent peer-reviewed literature, focusing on strain engineering, bioprocess optimization, downstream lipid recovery, and post-fermentation modifications. Special emphasis is placed on technological innovations, regulatory considerations, and consumer perception to provide a holistic understanding of fermentation-derived fats.

Results and Conclusion: Fermentation-enabled fats demonstrate significant potential in applications such as cocoa butter equivalents, palm oil substitutes, and animal-fat analogs for plant-based meats and dairy products. These fats provide improved texture, oxidative stability, and nutritional benefits compared with traditional lipids, supported by advances in engineered yeasts, microbial oils with healthier fatty acid profiles, and pilot-scale demonstrations from industry. Nonetheless, challenges in cost reduction, scalability, regulatory approval, and consumer acceptance persist. Collectively, progress in metabolic engineering, process optimization, and post-fermentation strategies is paving the way for microbial fats to become viable, sustainable, and functional ingredients in mainstream food systems.

What is "already known":	• Precision-fermented microbial fats offer a sustainable alternative to conventional animal and plant lipids. • Engineered yeasts and microbes now enable tailored fatty acid profiles for nutritional and functional food applications.
What this article adds:	• Fermentation-derived oils show strong promise as cocoa butter equivalents, palm oil substitutes, and animal-fat analogs. • Microbial fats deliver improved texture, oxidative stability, and healthier lipid profiles compared to traditional oils. • Metabolic engineering and bioprocess optimization are driving pilot-scale industrial demonstrations forward. • Cost reduction, regulatory approval, and consumer acceptance remain key barriers to mainstream adoption.

1. Introduction

Industrial reliance on conventional fats, whether derived from livestock, oilseeds, or tropical plant-ations, poses mounting sustainability, ethical, and supply-chain challenges. Oleaginous micro-organisms (yeasts, fungi, algae, and bacteria) offer an alternative route, accumulating intracellular triacylglycerols as single-cell oils with compositions analogous to plant and animal lipids. Unlike crop-based oils, microbial fermentation decouples fat production from arable land, seasonal cycles, and climate variability [1], while precision fermentation enables on-demand tailoring of fatty acid profiles and triacylglycerol structures [2]. Beyond sustainability, fermentation-derived fats can be engineered for superior nutritional and functional performance. Specific strains synthesize long-chain omega-3 fatty acids (DHA/EPA) without relying on fish oil [3], while others produce cholesterol-free oils with reduced saturated fat. Functionally, engineered *Yarrowia lipolytica* and related hosts have generated cocoa butter equivalents and beef-tallow analogues with customized melting behavior, solid fat content, and crystallization properties suited for confectionery and plant-based meats [4]. However production costs exceed than vegetable oils, and indus-trial-scale fermentation at food-grade volumes is not yet economically trivial [5, 6]. Regulatory pathways for novel microbial ingredients remain fragmented across jurisdictions [2], and achieving full functional equiv-alence, particularly polymorphic stability and sensory fidelity, requires further refinement. Consumer accept-ance and supply chain integration add further complexity.

This review critically examines post-fermentation strategies that bridge microbial oil production to mainstream food applications. We survey downstream recovery methods (cell harvesting, disruption, extraction), fractionation approaches, and chemical enzymatic modifications that tailor physical properties without trans-fat formation [7]. We also explore blending and formulation strategies to enhance functionality. By delineating current progress and persistent gaps, from bioprocess economics to regulatory frame works, we aim to provide a timely roadmap for researchers and industry stakeholders working to integrate fermentation-derived fats into sustainable food systems.

2. Opportunity for Functional and Nutritious Fermented Fats

2.1. Tailored Lipid Profiles through Fermentation

Precision fermentation enables control over fatty acid chain length, saturation degree, and triacylglycerol (TAG) structure. While wild-type microbes naturally produce a limited range of long-chain fatty acids (primarily C16–C18), metabolic engineering broadens this spectrum through modifications of desaturases, elongases, and acyltransferases [8]. For instance, replacing native Δ^9-desaturase in *Yarrowia lipolytica* with a heterologous variant eliminated palmitoleic acid while boosting stearic and palmitic acids, shifting the TAG profile toward cocoa butter mimicry [4]. Beyond genetics, Cultivation parameters, such as carbon source, temperature, and oxygen availability, significantly influence microbial fatty acid profiles, with temperature acting as a major determinant of saturation and chain-length distribution [8, 9]. Controlling fatty acid profiles enables tuning of physical properties such as melting point and solid fat content, as higher saturated fatty acid proportions generally raise melting points, allowing microbial lipids to functionally resemble solid fats [10]. This strategy has produced cocoa butter equivalents (CBEs) and beef-tallow analogues with customized crystalization and melting behavior [4, 10]. For example, *Rhodosporidium toruloides* under electro fermentation increased saturated fat from ~37% to 50%, yielding a solid fat profile analogous to beef tallow [4, 10]. Nutritionally, fermented fats offer advantages over animal fats and tropical oils. They can be formulated with lower saturated fat and higher monounsaturated or omega-3 content. Yali Bio has developed a precision-fermented dairy fat alternative with an improved fatty acid profile compared to coconut oil, offering reduced saturated fat and increased monounsaturated fat content [3, 11]. Microbial oils are naturally cholesterol-free and can be produced without trans fats. Certain engineered yeasts and algae synthesize DHA/EPA, providing essential fatty acids without fish oil [3]. Startups are already commercializing fermented fats with improved health profiles, such as dairy-fat alternatives with around 50% less saturated fat than coconut oil [11, 12].

Table 1. Examples of companies using precision fermentation to produce tailored food-grade fats and oils (2020+).

Company	Oil/Fat Target	Main Food Application	Location	Reference
Yali Bio	Fermented dairy fat alternative (coconut oil replacer)	Non-dairy ice cream, plant-based dairy and meat products	USA (California)	[11]
Nourish Ingredients	Animal-fat analogs (e.g. Tastilux™ for meat, Creamilux™ for dairy)	Enhancing flavor/mouthfeel in plant-based meat and dairy alternatives	Australia	[13]
Melt&Marble	Beef tallow-like fat (precision-fermented)	Juicy, fat-rich component for plant-based meats	Sweden (Gothenburg)	[14]
C16 Biosciences	Palm oil substitute via microbial fermentation	Sustainable replacement for palm oil in food manufacturing (e.g. spreads, baked goods)	USA (New York)	[12]
NoPalm Ingredients	Yeast-derived tropical oil alternatives (tailor-made “palm” oils)	Drop-in replacer for palm and other tropical oils in foods (e.g. confectionery, bakery)	Netherlands	[12]

2.2. Key Food Applications and Functional Requirements

2.2.1. Chocolate & Confectionery

Cocoa butter (CB) alternatives must match its sharp melting profile (solid at 20–25°C, melting at 34–37°C), glossy finish, snap, and mouthfeel, properties governed by symmetric monounsaturated TAGs (POP, POS, SOS) [15]. Conventional CBEs from shea, sal, or palm fractions are limited in supply and often differ in sensory performance [16, 17].

Precision fermentation offers a promising route. Engineered *R. toruloides* produced TAGs with 87–91% palmitic, stearic, and oleic acids, around 80% monounsaturated fat sn-2, and around 50% POP/POS/SOS content, approaching CB's profile. X-ray diffraction confirmed desirable β-polymorph crystallization, though the fat was slightly softer than CB [18]. Similarly, *Y. lipolytica* engineering has reduced polyunsaturates to better mimic CB [4].

However, full replication of CB's polymorphic stability and bloom resistance remains challenging. Fermented CBEs often form spherulitic crystals and may bloom faster than authentic CB [15, 18]. *Advanced metabolic engineering and fermentation optimization (including the use of CRISPR/Cas9, cocoa-specific acyltransferases (GPAT, LPAT, DGAT), and adaptive evolution) aim to improve symmetric TAG yields and crystalline behavior* [16, 19]. Integrated approaches from enzyme engineering to bioprocess optimization are paving the way toward functionally equivalent fermented CBEs [16].

2.2.2. Plant-Based Meat and Dairy Alternatives

Plant-based meats and dairy often lack the juiciness, mouthfeel, and flavor of animal products due to the limitations of plant-derived fats like coconut and palm oil, which impart off-flavors and lack adipose-like structure [13, 14].

Precision fermentation addresses these sensory gaps by producing fats with tailored fatty acid profiles that mimic animal fat, including branched-chain and polyunsaturated fatty acids that generate savory volatiles [20]. Startups like Melt&Marble and Nourish Ingredients are creating fats that replicate beef or pork aroma and flavor [14]. Fermentation also enables co-production of flavor compounds (diacetyl, acetoin, umami amino acids) through bacterial or fungal metabolism [13, 21].

To replicate the slow rendering and juiciness of animal adipose tissue, microbial fats are engineered with higher stearic and palmitic acid content to increase melting points[22, 23]. Structured approaches include oil-encapsulated yeast powders ("micro-adipocytes"), sunflower oleosomes for creamy mouthfeel, oleogels for marbling, and nano-encapsulated oils [23-26]. Hybrid systems combining fermented designer fats with structured plant oils offer cost-effective texture and flavor solutions [13].

Challenges remain: microbial fats lack the full complexity of animal adipose (phospholipids, cholesterol, blood-derived compounds), affecting sensory fidelity [13]. Oxidative stability requires antioxidant protection [23-27]. Regulatory hurdles include GRAS or Novel Food approvals, especially for

GMO-derived products [23], and complex labeling issues, terms like "butter" are legally restricted, requiring qualifiers like "fermentation-derived" [13, 28].

Despite these challenges, fermented fats offer a transformative opportunity to bring plant-based alternatives closer to the sensory richness of animal-derived foods [13].

2.2.3. Bakery & Spreads

Palm oil is widely used in baking fats and spreads for its neutral flavor and semi-solid consistency, but its cultivation drives deforestation and biodiversity loss [29]. Sustainable alternatives are urgently needed.

Oleaginous yeasts like *Rhodotorula glutinis* naturally produce oils with around 30–35% palmitic acid, closely matching palm oil's fatty acid profile [30]. Companies like Clean Food Group have developed yeast-derived "Clean Palm Oil" with comparable taste and baking performance [31]. Other startups are engineering yeasts to boost mid-chain fatty acids for bakery applications [12].

A key challenge is replicating palm oil's crystallization behavior. Palm oil and dairy fat form stable β′ crystals essential for smooth, spreadable textures. Fermentation-derived lipids may not crystallize in the same ideal polymorphic form, risking grainy or soft textures [32]. Solutions combine strain engineering (to adjust saturation and TAG species) with post-processing techniques—fractionation, full hydrogenation (trans-fat-free), and enzymatic interesterification, to achieve the desired solid fat content and β′ crystal structure [33]. These integrated approaches aim to deliver fermented fats that meet the functional requirements of spreads while maintaining sustainability [33].

2.2.4. Frying Oils and Shelf-Stable Foods

High-heat applications require fats that remain solid at room temperature and melt slowly during cooking to impart juiciness and mouthfeel, like beef tallow or chicken fat. Current plant-based formulations using coconut or palm oil often lack these properties [34, 35]. Precision fermentation enables "designer" fats with animal-like properties. Nourish Ingredients' Tastilux, rich in long-chain omega-6 phospholipids, provides meaty aroma and mouthfeel at <1% inclusion [36]. Melt&Marble has engineered yeast to produce a beef-tallow analog with high saturation and melting behavior matching real beef fat [29, 34]. These fats deliver both flavor and textural functionalities that vegetable oils lack [34, 36].

Cost and scalability remain major barriers. Fermentation-derived fats are currently several-fold more expensive than commodity oils, and production at hundreds of thousands of liters is not yet achieved [37]. Strategies to overcome this include: (i) hybrid approaches blending small amounts of high-impact fermented fats with cheap plant oils [36]; (ii) improving oxidative stability through metabolic engineering for high-oleic or saturated profiles [37]; (iii) using low-cost feedstocks like agricultural waste or gas fermentation; and (iv) streamlining downstream processing (e.g., whole biomass utilization) and co-product valorization . Continued R&D is expected to drive costs down over time [37].

2.3. Nutritional Advantages of Fermented Fats

Fermented fats can be engineered for superior nutritional profiles. By modifying pathways in *Y. lipolytica*, medium-chain and monounsaturated fatty acids can be produced instead of long-chain saturates, supporting better lipid metabolism and cardiovascular health [38].

Precision fermentation also enables the inclusion of omega-3 PUFAs (DHA/EPA) not found in most plant oils [35]. Yali Bio reported a fermented dairy fat with around 50% less saturated fat than coconut oil while maintaining a higher melting point (around 30°C vs 21°C), demonstrating the dual benefit of healthier composition without sacrificing functionality [37]. By fine-tuning chain length, unsaturation, and essential fatty acid content, precision fermentation can produce "designer" fats aligned with modern nutritional guidelines, replacing trans fats and high saturates with high-oleic, omega-3-rich oils. In the long term, these enhancements could make fermented fats not just functional replacements but nutritionally superior alternatives [37].

3. Strain Engineering: Customizing Lipid Profiles for Food Use

Metabolic engineering of oleaginous microorganisms has enabled the production of lipids with tailored fatty acid profiles and triacylglycerol structures. This section

reviews key strategies, including precursor supply enhancement, blocking competing pathways, engineering of key enzymes, and genome editing tools.

3.1. Key Microbial Hosts

Oleaginous yeasts such as *Rhodotorula toruloides* and *Yarrowia lipolytica* have been extensively engineered for lipid overproduction. In *R. toruloides*, overexpression of native acetyl-CoA carboxylase (ACCase) and diacylglycerol acyltransferase (DGAT) significantly increased lipid accumulation [39, 40]. *Y. lipolytica*, a GRAS organism, has been engineered for enhanced production of polyunsaturated fatty acids (PUFAs) Bacterial platforms such as *Rhodococcus opacus* offer complementary advantages, including rapid growth and tolerance to inhibitory compounds. This organism is a widely studied oleaginous yeast achieving high fat content (>20% of cell mass) stored as triacylglycerols (TAGs). Recent metabolic engineering strategies have focused on enhancing nutritional fatty acid content, especially polyunsaturated fatty acids (PUFAs), in *Y. lipolytica* [41-43].

Additionally, *Saccharomyces cerevisiae*, a well-established GRAS host, has been successfully employed not only for lipid production but also for biofortification with essential minerals such as iron and zinc [44]. Recent editorials have highlighted the broader potential of fermentation-derived fats and oils to address sustainability, health, and functionality challenges in the food industry [45].

3.2. Key Strategies in Strain Engineering

3.2.1. Enhancing Precursor Supply (Push Strategy)

Increasing the availability of acetyl-CoA and malonyl-CoA is the first step toward enhancing lipid production. Overexpression of **ACC1** (acetyl-CoA carboxylase) and **ACL1** (ATP-citrate lyase) in *R. toruloides* increased fatty alcohol titers by 1.8- and 3.7-fold, respectively [40, 43, 46]. This strategy has also been successfully applied in *Y. lipolytica* and other oleaginous hosts.

3.2.2. Blocking Competing Pathways (Block Strategy)

Disruption of genes involved in lipid degradation (β-oxidation) or alternative lipid storage redirects carbon flux toward target products. Deletion of **DGA1** and **LRO1** in *R. toruloides*, which encode DGAT and lecithin:diacylglycerol acyltransferase respectively, increased fatty alcohol production by 2.3- and 4.4-fold [44, 48]. While deletion of the peroxisomal biogenesis gene **PEX10** was unsuccessful in *R. toruloides* (suggesting essentiality) this approach has been effective in other hosts [46].

3.2.3. Engineering Key Enzymes

Desaturases and elongases determine the final fatty acid profile. Inducible overexpression of **Δ12-fatty acid desaturase** in *R. toruloides* enriched lipids in linoleic acid (C18:2) [43, 47]. The transfer of DGAT-related pathways from yeasts to microalgae (*Chlorella*) has also enabled customized lipid production in non-yeast hosts [46, 48, 49].

3.2.4. Genome Editing Tools

The **CRISPR/Cas9** system has revolutionized microbial strain engineering. In *R. toruloides*, CRISPR/Cas9, together with RNA interference (RNAi) and characterized promoters, enables targeted genome editing [40, 46, 47]. These tools are increasingly applied to oleaginous bacteria such as *Rhodococcus opacus*, opening new avenues for industrial lipid production [50, 51].

3.3. Combinatorial Engineering Outcomes

Combining push and block strategies has yielded synergistic effects in lipid overproduction. In *R. toruloides*, the **ΔLRO1** strain achieved a fatty alcohol titer of **3.7 g/L** with a yield of **0.024 g/g glucose** [41, 48, 52]. This represents one of the highest reported titers for fatty alcohol production in this organism, demonstrating the effectiveness of redirecting carbon flux from TAG synthesis toward fatty alcohol biosynthesis.

Table 2. Summary of Key Strain Engineering Approaches for Customizing Food-Grade Lipid Profiles

Organism	Engineering Strategy	Outcome / Note	Reference
R. toruloides (IFO0880)	Overexpression: ACC1, ACL1	↑ fatty alcohol synthesis (ACC1: 1.8×, ACL1: 3.7×)	[46]
	Knockouts: DGA1, LRO1	Redirected acyl-CoA; LRO1 Δ most effective (~4.4× increase)	[46]
	Combined ACC1 & DGA1 Δ	Increased titers from ~106 mg/L → ~206 mg/L	[46]
	Bioreactor LRO1 Δ	~3.7 g/L fatty alcohol, yield 0.024 g/g glucose	[47, 48]
Y. lipolytica	Δ12-Desaturase overexpression	Linoleic acid–rich lipids	[47]
	Metabolic engineering for nutritional FA	PUFA accumulation strategies reviewed	[41]
Chlorella (engineered)	Introduced DGAT, LPAAT, PAP, GPDH genes	Improved lipid assembly via heterologous expression	[48]
General Tools / Platform	CRISPR/Cas9 editing, promoter engineering	Enabled precision strain engineering in microbial-cell-factory chassis	[46]

Additionally, combining DGA1 deletion with ACC1 overexpression increased fatty alcohol titers from 106 to 206 mg/L [46], indicating that enhanced malonyl CoA supply synergizes with reduced acyl-CoA diversion into TAGs. Interestingly, ΔLRO1 mutants showed elevated DAG (diacylglycerol) and TAG levels despite improved fatty alcohol production, implying a more complex role for LRO1 in lipid metabolism beyond its known function as a lecithin:diacylglycerol acyltransferase [46, 52]. This observation suggests that LRO1 may participate in regulatory or substrate channeling interactions that affect acyl-CoA partitioning.

4. Regulatory Considerations for Food-Grade Fermented Oils

4.1. Global Regulatory Pathways

In the United States, food ingredients produced by fermentation are regulated under the GRAS (Generally Recognized as Safe) framework, a voluntary, company-driven process requiring expert scientific evidence demonstrating safety under intended use conditions. If a GRAS notice is filed, the FDA reviews the dossier and issues a "no questions" letter confirming that the ingredient is considered safe. By contrast, the European Union treats novel microbial-derived foods under the Novel Foods Regulation (EU 2015/2283). Any food not commonly consumed in the EU before May 1997—including microbial oils—requires premarket authorization. The applicant submits a safety dossier to the European Commission; the European Food Safety Authority (EFSA) conducts a full safety assessment, and the Commission decides on approval. This centralized approach contrasts with the U.S. self-affirmation system. Key differences include the mandatory pre-market review in the EU versus the voluntary self-affirmation in the U.S., and streamlined EU timelines, with approval processes shortened to approximately 18 months under the new regulation. Novel microbial oils such as DHA/EPA-rich algal oils have been evaluated through this EU process, whereas in the U.S. such oils have been commercialized via GRAS notices citing historical use in foods [53-56].

4.1.1. Toxicology and Safety Assessment

Regulatory review of fermented oils requires rigorous toxicology testing. Authorities typically require 90-day (subchronic) rodent feeding trials alongside a battery of in vitro genotoxicity assays. For example, a 90-day oral toxicity study in Wistar rats on a PUFA-rich oil included daily monitoring, hematological and biochemical profiling, and full histopathology—no adverse effects were observed, illustrating the type of subchronic study regulators expect [57-60].

Following these precedents, EFSA guidance recommends conducting 90-day rodent feeding studies (OECD TG 408) measuring body weight, clinical chemistry, hematology, histopathology, and calculating a No-Observed-Adverse-Effect-Level (NOAEL). Concurrently, in vitro genotoxicity assays—including the Ames test (OECD TG 471) and in vitro micronucleus test (OECD TG 487)—are performed to rule out mutagenic or chromosomal damage. If initial assays raise concerns, follow-up in vivo testing may be required. These guidelines mirror requirements for conventional food additives, with an emphasis on

validated study design and compliance with Good Laboratory Practice standards [61].

4.1.2. History of Safe Use

Producers can bolster safety by documenting prior use of related organisms or oils. For example, DHA- and EPA-rich oils from marine microalgae (e.g., *Schizochytrium* spp., *Crypthecodinium* spp.) have been used in infant formula and supplements for decades. Oils from the fungus *Mortierella alpine* (rich in arachidonic acid) have also been approved as infant formula ingredients. Where the production organism itself has QPS/GRAS status (e.g., *Saccharomyces cerevisiae*, *Yarrowia lipolytica*), that history of safe use can streamline safety justification. EFSA has issued positive safety opinions on *Y. lipolytica* biomass and *S. cerevisiae*-derived ingredients based on their familiar taxonomy and lack of toxigenicity. In some cases, regulators apply a "component-based" logic: since microbial oils consist of the same fatty acids (e.g., EPA, DHA, palmitic, oleic acid) found in plant oils or fish oil, their toxicological profiles are expected to be equivalent. This approach is reflected in the EU Novel Foods list and in FDA GRAS notices that compare novel oils to established dietary fats [53, 56].

4.1.3. Strain Selection and Engineering

Suitable host organisms are chosen based on safety and industrial performance. Common GRAS/QPS hosts include *S. cerevisiae*, *Komagataella* (formerly *Pichia pastoris*), *Y. lipolytica*, and microalgae (e.g., *Schizochytrium*, *Nannochloropsis*). These species are non-txic and have histories of food processing (e.g., yeast in bread and alcohol, algae in supplements). *Y. lipolytica* has been recommended for EFSA QPS status for production purposes, reflecting its nonpathogenic nature and absence of known allergens. By contrast, Gram-negative bacteria (e.g., *Escherichia coli*) require special consideration because of lipopolysaccharide (endotoxin) content. For food use, such strains are often engineered to eliminate endotoxin. A notable example is the "ClearColi™" *E. coli* strain, which carries targeted knockouts in lipid A biosynthesis to produce biologically inert LPS. In all cases, the production strain is fully characterized (often via whole-genome sequencing) and tested to ensure absence of toxins, virulent factors, or allergens. The choice of a recognized safe chassis reduces regulatory risk, and modern metabolic engineering (including endotoxin minimization) is increasingly compatible with regulatory standards [53, 62].

4.1.4. Process Transparency

Regulatory dossiers must demonstrate that non-lipid residues (microbial DNA, proteins, cells) are reduced to trace levels and analytically verified. EFSA guidance specifies PCR-based testing for residual production-strain DNA with a limit of detection of ≤10 ng DNA per gram or milliliter of product, alongside batch-wise documentation of downstream steps (clarification, filtration, centrifugation, adsorption) and method LoD/LoQ reporting. For protein residues, validated extraction and ELISA workflows support specifications targeting ≤1 ppm residual protein in highly refined oils, as demonstrated in evaluations of refined allergen-source oils. WHO/FAO and EFSA reviews conclude that neutralised, bleached, and deodorised (RBD) soybean oils contain very low residual protein after refining [63-66].

For allergen screening, EFSA applies a weight-of-evidence approach to potential allergenicity of novel foods. Core elements include in silico sequence comparisons of any residual proteins against curated allergen databases, in vitro digestibility (e.g., pepsin resistance) to gauge stability, and IgE-binding or sera testing when indicated; positive or equivocal results trigger targeted follow-up. EFSA's updated Novel Foods guidance reinforces the need to align analytical sensitivity, provide multi-batch compositional data, and tailor allergenicity data requirements to the protein content category of the novel food (e.g., "no protein" vs. "unknown" allergenic potential). In the U.S., highly refined oils from major allergen sources are exempt from FALCPA allergen labeling if protein is demonstrably absent; if any protein remains, labeling applies. EFSA's historical opinions on refined soybean oil reached similar conclusions (severe reactions are unlikely under conditions of production and use when protein is minimized) again underscoring purification plus sensitive analytical verification as the basis for safety and labeling decisions [16, 63, 67-70].

4.2. Recent Successful Commercial Cases

Over the last decade, several biotech companies have introduced precision fermentation-derived fats to the market, with a growing number of commercial

applications in the food industry. These innovations aim to replicate the functional and sensory properties of animal fats using engineered microorganisms, typically yeast or fungi, and represent a leap forward in sustainable fat production. For instance, Yali Bio, a California-based startup, developed structured fats through yeast fermentation that functionally mimic dairy fat but offer reduced saturated fatty acid content. The company's products are designed to replace coconut oil in dairy-free ice cream and plant-based butter, offering improved nutritional profiles and thermal behavior. Similarly, Melt&Marble, a European biotech company, has engineered *Saccharomyces cerevisiae* to produce animal-like fats, specifically mimicking the structure and melting point of beef tallow. Their microbial fermentation process allows for the development of tailored lipid profiles, contributing to enhanced mouthfeel and flavor in plant-based meat analogues. Nourish Ingredients, another notable player, focuses on producing trace amounts of lipids with highly specific organoleptic profiles. Their product, Tastilux™, is a fermentation-derived phospholipid complex that provides meaty aroma and flavor without the need for actual animal fat. These commercial successes highlight the scalability and sensory potential of fermented fats, signaling a paradigm shift in food design and sustainability. The technology has transitioned from lab-scale novelty to industrial application, facilitated by strain engineering, synthetic biology, and improved bioreactor designs [71-73].

4.3. Labeling, Allergenicity, and Consumer Perception

4.3.1. Labeling Challenges and Disputes

Across jurisdictions, naming for non-animal fats made via fermentation is constrained by existing food identity and dairy terminology rules, which were largely written for conventional products. In the EU, protected dairy terms (e.g., "milk," "butter") remain restricted to animal-derived products under Regulation (EU) No 1308/2013 and the CJEU's interpretation, which has shaped how dairy-like alternatives may be described. Fermentation-derived fats intended for first-time use in the EU fall under the Novel Foods framework (Regulation (EU) 2015/2283), triggering pre-market authorization and compositional and labeling scrutiny. In the U.S., standards of identity still anchor terms like "milk," "cheese," and "butter," but regulatory discussion increasingly centers on whether a bio-identical molecule can be labeled by its common or usual name when made via precision fermentation. A broader policy scan indicates that Asia-Pacific regulators are actively mapping new food sources and production systems, with China and regional authorities situating precision-fermented foods within novel-ingredient regimes while signaling the need for clear consumer information frameworks that can accommodate technology-enabled fats. Collectively, the recent legal and policy literature concludes that, for fats made by microbial fermentation, accurate category naming paired with truthful qualifiers (e.g., "fermentation-derived oil/fat," "non-animal dairy fat") aligns best with both compliance and consumer clarity, whereas leveraging reserved dairy terms without clear context risks enforcement actions, particularly in the EU [54, 74-79].

4.3.2. Allergenicity Considerations

From an immunological standpoint, major food allergens are proteins; purified fats and oils pose allergen risk primarily through residual proteins carried over from source materials or processing streams. Peer-reviewed evaluations and agency-peer-reviewed opinions consistently indicate that highly refined oils contain negligible (often sub-ppm) residual proteins and therefore have very low likelihood of provoking reactions in sensitized individuals. Refined soybean or peanut oils contain orders-of-magnitude less protein than crude counterparts, and clinical and analytical studies underpin their low allergenicity when fully refined; these principles are used to justify exemption of highly refined oils from allergen labeling in several jurisdictions when protein is demonstrably removed. Recent technical reviews and guidance emphasize rigorous methods to verify protein absence or near-absence (e.g., sensitive immunochemical or LC-MS assays), alongside bioinformatic and digestibility approaches if any novel proteins could remain. Where precision fermentation deliberately produces dairy-identical proteins that could co-occur with lipids (e.g., formulations combining fats with β-lactoglobulin), allergen labeling follows the protein identity rather than the production method; allergen

declarations must reflect the presence of milk proteins even if produced without cows [67, 70, 80-82].

4.3.3. Consumer Perception and Acceptance

Cross-country studies show consumers are cautiously optimistic toward precision-fermented foods, with acceptance enhanced by perceived environmental and animal-welfare benefits [83] and by clear, non-technical explanations of the process [84]. A 2023 systematic assessment specific to precision fermentation and a 2024 cross-cultural study on animal-free dairy both report that transparent, benefit-oriented framing improves willingness to try and purchase [83, 85]. In experimental and survey work, acceptance is sensitive to wording: simple descriptors (e.g., "animal-free dairy made by fermentation") outperform technical jargon, and providing concise safety and sustainability context increases stated willingness-to-pay [86]. Broader reviews of novel foods similarly find that trust in regulators, perceived naturalness, and expected sensory parity are key purchase determinants.

5. Economic and Scalability Barriers

Fermentation-derived fats and oils face significant economic and scale-up challenges that currently limit their competitiveness with conventional lipids. This section reviews the key cost factors, bottlenecks, and emerging strategies to overcome these barriers.

5.1. Summary of Cost Factors

Fermentative lipid production incurs costs from multiple sources, primarily feedstock, fermentation (upstream processing), and downstream lipid recovery. High substrate costs, energy-intensive operations, and complex purification steps collectively contribute to unit costs that remain substantially above those of commodity vegetable oils [87].

5.2. Fermentation Bottlenecks

Despite intensive R&D, producing fats via fermentation remains far more expensive than sourcing traditional fats. The industrial-scale production of an economically viable commodity oil substitute is still elusive due to high unit costs. Key technical bottlenecks include: (i) low yields and titers of oil from fermentation, (ii) scale-up difficulties that reduce efficiency at industrial volumes, and (iii) dependence on costly feedstock [87, 88].

5.2.1. Low Yields, Scale-Up Challenges, and Feedstock Constraints

Oleaginous microbes convert only a fraction of carbon substrate into stored lipids, with carbon-to-lipid yield typically plateauing around 20–25% (w/w) even under optimized conditions, well below the theoretical maximum (around 32%) due to carbon loss to CO_2 and biomass[87]. Even with a hypothetically "perfect" strain, the minimum lipid price would still be roughly 2–3 times higher than palm oil [87].

Table 3. Key cost contributors in fermentation-derived oil production and associated challenges.

Cost Factor	Impact on Cost (Contribution)	Notes/Challenges (Examples)	
Feedstock (carbon & nutrients)	Often 30–50% of total operating cost in bioprocesses. High sugar prices (e.g. ~$0.4/kg glucose) can drive lipid production costs above $5/kg, whereas cheap waste-derived sugars (~$0.1–0.2/kg) markedly lower costs.	Rely on sugar or starch inputs that compete with food. Low-cost substrates (e.g. lignocellulosic hydrolysates, molasses, industrial off-gas) are needed to reduce raw material expenses.	[87, 88]
Fermentation (bioreactors & energy)	Major cost center due to capital, utilities, and time. In one 10,000 t/year SCO process, fermentation operations (reactors, aeration, harvest, drying) accounted for ~87% of total costs. Aeration and agitation make electricity a significant cost driver (each $0.01/kWh adds ~$0.10 per kg product).	Requires large sterile bioreactors with intensive mixing and cooling. Contamination risk necessitates sterilization (increasing downtime and energy use). Improving bioreactor efficiency and using cheaper designs (e.g. airlift reactors) or non-sterile operation can mitigate these costs.	[87]
Downstream lipid recovery	Intracellular oil must be extracted from biomass, adding processing costs. Achieving >95% lipid recovery requires multi-step operations (cell separation, drying, disruption, solvent extraction) that are energy intensive. In some estimates, downstream contributed ~40–50% of total costs when less optimized.	Challenges include breaking robust cell walls and separating oil from water and cell debris. Techniques like *in situ* or wet extraction (avoiding complete drying) can save energy. Using the whole biomass directly (bypassing extraction) is also proposed to eliminate costly purification.	[87, 89, 90]

Lipid titers in lab-scale studies (20–80 g/L) fall short of the >100–150 g/L needed for economic viability at scale. Achieving high cell densities (e.g., 185 g/L dry cell mass with 60% lipid content) would greatly improve productivity but presents engineering challenges (oxygen transfer, viscosity, foaming) [87, 88]. Scale-up from laboratory to industrial fermenters introduces additional inefficiencies. Large-scale operations suffer from suboptimal mixing, oxygenation, heat removal, and pH/nutrient gradients. Maintaining sterility is costly, and non-sterile designs risk contamination. Even with sterile operation, scale-up often fails to reproduce lab yields, requiring extensive pilot runs and process optimization [87, 88]. The cost of fermentation inputs, especially carbon sources, remains a major barrier. Refined sugars (glucose, sucrose) contribute heavily to production costs, one techno-economic analysis estimated a microbial oil cost of around $5.5/kg using sugar at around $400/tonne. Heavy reliance on food-derived sugars raises sustainability concerns, motivating a shift to lower-cost, non-food feedstocks [87].

5.3. Paths to Cost Reduction

To address these economic barriers, researchers are pursuing strategies to lower unit costs through feedstock innovation, yield improvements, energy integration, and co-product valorization.

5.3.1. Cheaper Feedstocks: Lignocellulosic Biomass and C1 Gases

Lignocellulosic biomass (crop residues, wood waste) offers a low-cost alternative to refined sugars, with sugar prices in crude hydrolysates estimated at roughly $0.10–0.20/kg [87]. Oleaginous yeasts like *Lipomyces starkeyi* can utilize mixed sugars and tolerate inhibitors present in crude hydrolysates, achieving lipid contents comparable to those on pure glucose [91, 92]. However, challenges include pretreatment costs, enzyme hydrolysis, and slower yields on complex substrates [91]. Gas-based feedstocks (methane, CO_2) are even cheaper and do not compete with food supplies. Methanotrophic bacteria convert natural gas into biomass (e.g., Calysta's FeedKind® process), while CO_2/H_2 fermentation (e.g., Solar Foods) uses renewable electricity to produce microbial protein [92]. Integrating gas fermentation for lipid production requires new bioprocess development and specialized organisms, but offers the potential for dramatically reduced carbon costs [91, 92].

5.3.2. Improving Yields and Titers: High-Density Cultures and Cell-Free Systems

High-cell-density cultures (>150 g/L lipid titer) can triple oil output per bioreactor volume, proportionally reducing unit costs [87]. Fed-batch or continuous cultures with optimized nutrient feeds, oxygen delivery, and cell retention can achieve extraordinary densities, as demonstrated by a "best-case" design of 185 g/L dry cell mass with 60% lipid content [87]. Bioprocess innovations such as novel bioreactor configurations and improved control algorithms are key to achieving these densities [87, 93].

Cell-free bio-manufacturing offers a paradigm shift, channeling nearly all substrate to product without diversion to biomass. Early-stage examples include Arkeon Biotechnologies' cell-free gas fermentation platform, which produces amino acids from CO_2, H_2, and enzymes [94]. If applied to lipids, cell-free systems could enable highly efficient production of oils or fatty acids, overcoming inherent limitations of microbial metabolism [94].

5.3.3. Enhancing Energy Efficiency: Toward Electro-Fermentation

Large-scale fermentation is energy-intensive, so improving energy efficiency or sourcing cheaper energy is crucial. Co-locating fermentation with energy -generating processes (e.g., sugarcane biorefineries using bagasse for cogeneration) can provide "free" renewable electricity, reducing lipid selling price by $0.1–0.2/kg [87]. Electro-fermentation (EF) directly supplies reducing power to microbes via electrical current, altering redox balance and boosting lipid production. Arbter et al. [95] .demonstrated that cathodic EF enhanced lipid accumulation in *Rhodo-sporidium toruloides*, increasing saturated fat from 37% to ~50% and improving yield and productivity [95]. Renewable electricity could thus directly drive biochemical pathways, reducing the sugar needed for energy production [87, 95].

5.3.4. Co-Product Valorization

Valorizing co-products (especially defatted microbial biomass) can offset production costs. Spent yeast or fungal biomass is rich in protein (30–50% dry mass) and can be marketed as single-cell protein (SCP) for

animal feed or human food [87, 92]. Techno-economic analyses show that crediting the defatted biomass at $0.50/kg could reduce the required selling price of microbial oil to ~$1.3/kg, compared to >$4–5/kg without co-product value. In optimistic scenarios, co-product revenue can nearly cover production costs [87]. Other side streams (e.g., carotenoids, cell wall polysaccharides, extracellular metabolites) can also be valorized. The core concept is to shift from a single-product process to a bio-refinery, generating multiple outputs (lipid, protein, specialty chemicals) to maximize value from inputs [87, 92].

5.4. Scalability Considerations: From Pilot to Industrial Scale

Scaling fermentation-derived lipid production to industrial scales (kilotons per year) poses technical and economic challenges, particularly in downstream processing (DSP). Karamerou et al. found that downstream steps—fermentation, harvesting, and drying account for ~87% of total process cost in standard stirred-tank yeast oil processes. As production scales from ~8,000 to ~48,000 tonnes/year, lipid prices can fall from $1.81/kg to $1.20/kg, but only if downstream bottlenecks are controlled [87]. Biomass drying and cell disruption are major cost drivers. Wet lipid extraction, which omits drying, can reduce lipid prices significantly—from $1.81/kg to $1.55/kg (removing the dryer) or to $1.16/kg in a fully wet process [87]. Ghasemi Naghdi et al. reviewed wet algal biomass extraction methods, confirming that eliminating dehydration and homogenization lowers energy demand and cost, though performance varies by organism and solvent [89]. Integrated DSP approaches offer further promise. Masri et al. developed a fully integrated process using *Cutaneotrichosporon oleaginosus* with co-fermentation, in situ cell lysis, and no organic solvent, achieving 90% lipid recovery and an estimated cost of $1.60/kg lipid [90]. Castellini et al. showed that scaling a yeast-based biodiesel plant from 10,000 to 100,000 t biomass/year reduced costs from $12.8/kg to $3.63/kg, demonstrating economies of scale [96]. Feedstock dilution remains a challenge, as low sugar concentrations in lignocellulosic hydrolysates result in low lipid titers and dilute downstream loads, driving up DSP energy and capital requirements. Cell retention bioreactors (e.g., membrane bioreactors) or cell recycling can concentrate biomass and lipids, improving DSP efficiency [97]. Wastewater substrates offer cost advantages but introduce variability and solids content issues, necessitating robust separation technologies [98].

6. Processing Strategies to Enhance the Functionality of Fermented Fats

Fermentation-derived lipids often require post-processing to achieve the physical properties needed in foods. By applying conventional fat modification techniques to single-cell oils, producers can tailor melting profiles, solid fat content, and oxidative stability to mimic or improve upon traditional fats [7]. This section reviews key processing strategies – extraction, fractionation, hydrogenation, and interesterification – used to enhance the functionality of fermented fats.

6.1. Extraction of Lipids and Oil Body Systems

Oleaginous microbes accumulate intracellular lipid droplets that typically require cell disruption for efficient extraction. Mechanical or chemical lysis is essential to release the oil. Conventional solvent extraction (e.g. hexane or chloroform/methanol) recovers most lipids but poses environmental and safety concerns. To reduce solvent use, greener methods are being explored. Physical treatments such as pulsed electric fields or ultrasonication increase cell permeability and lipid yield without added chemicals [99]. Alternatively, aqueous extraction yields an oil-in-water emulsion analogous to seed oil bodies, wherein triacylglycerol droplets remain coated by phospholipids and oleosin proteins. By adding such emulsifiers to extracted microbial oil, researchers have created artificial oil bodies, stable emulsified fat droplets [100]. This integrated extraction-structuring approach retains native surfactants, aiding the incorporation of fermented fats into foods [7].

6.2. Fractionation for Tailored Melting Fractions

Fractionation is a thermomechanical process that separates fat into high-melting and low-melting portions by controlled crystallization. The oil is fully melted, then slowly cooled so that a fraction of the

triacylglycerols (rich in saturates) crystallizes as a solid "stearin," which is filtered out, leaving a liquid "olein". Dry fractionation (without solvents) is economical and avoids chemical modification. Fractionation has long been used industrially (e.g. splitting palm oil into stearin and olein) and can similarly be applied to single-cell oils [7]. Thus, fractionation offers a chemical-free way to adjust the melting behavior of fermented fats, although the solid fraction yield is limited by the fat's TAG composition.

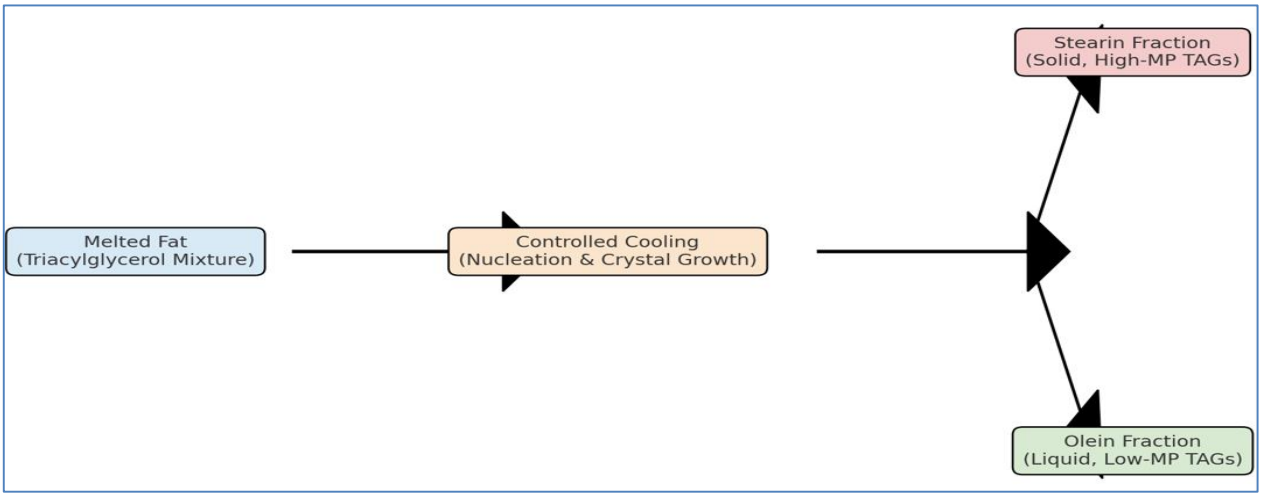

Figure 1. Dry fractionation process of fats

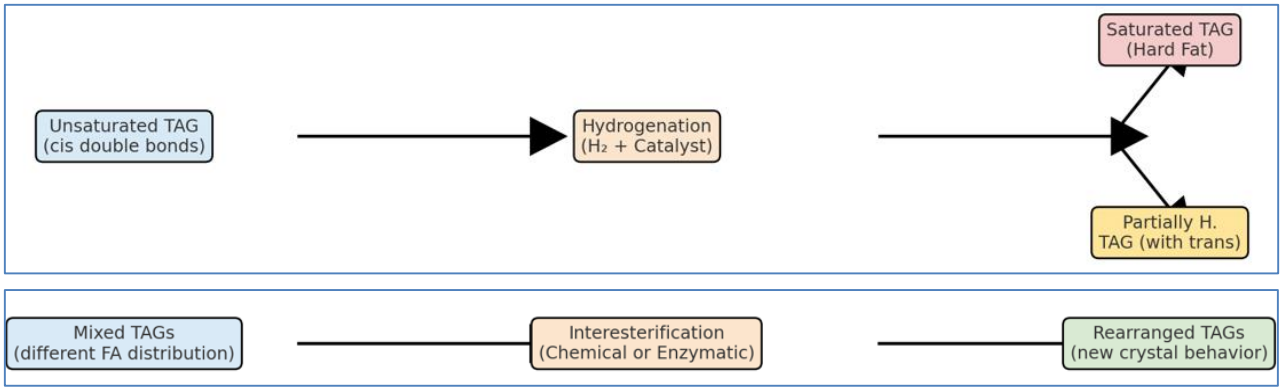

Figure 2. Hydrogenation vs. Interesterification effects on TAG structure

6.3. Hydrogenation to Increase Saturation and Stability

Hydrogenation is a chemical reaction that adds hydrogen to unsaturated fatty acids, converting double bonds to single bonds. This increases the saturation of the fat, raising its melting point and improving oxidative stability. Oils are hydrogenated by treating them with H_2 gas over a metal catalyst at elevated temperature [7]. Partial hydrogenation (stopping short of full saturation) produces semi-solid fats useful for margarine and shortening but also generates trans fatty acids as some cis double bonds isomerize to the trans form. Because dietary trans fats are harmful, regulations have virtually eliminated partially hydrogenated oils in food. Full hydrogenation (complete saturation) yields a trans-free product but produces a very hard fat. In practice, fully hydrogenated fats are often blended with liquid oils and then interesterified to attain a usable consistency. Today, interesterification and fractionation are generally favored over partial hydrogenation for structuring fats due to health concerns [7, 101].

6.4. Interesterification for TAG Redistribution

Interesterification rearranges fatty acids among triacylglycerol molecules without changing the overall fatty acid composition. By scrambling acyl groups between triglycerides, this process can alter a fat blend's melting and crystallization profile – for example, raising the melting point of a liquid oil or softening a fully saturated fat – while producing no

trans fats. Chemical interesterification typically uses an alkaline catalyst to randomly redistribute fatty acids [7]. Enzymatic interesterification employs lipases under milder conditions, allowing more controlled restructuring and preserving sensitive fatty acids. Interesterification is a key alternative to partial hydrogenation for creating structured fats with desired functionality. For example, interesterifying a blend of fully hydrogenated oil (hard fat) with liquid unsaturated oil can yield a fat that provides the creamy texture and melting profile of a conventional shortening, but with no trans fatty acids [33, 102].

7. Future Perspectives and Collaborative Pathways Forward

Advancing fermented fat processing will require concerted cross-sector collaboration that unites scientific innovation with industrial scale-up and supportive policy frameworks. Researchers, industry leaders, and policymakers each play vital roles: academia drives foundational R&D in microbial metabolism, companies provide engineering know-how and market pathways, and government bodies set regulatory and funding environments. A multi-stakeholder approach has been identified as essential for overcoming current barriers and accelerating precision fermentation solutions at scale. Building collaborative networks and governance structures among these sectors can ensure that breakthroughs in fermented fats translate from lab bench to commercial reality in a sustainable and equitable manner [103, 104].

One major frontier is the integration of artificial intelligence (AI) and machine learning (ML) to advance microbial strain engineering and bioprocess optimization. AI-driven tools can vastly improve the efficiency of designing high-yield lipid-producing microbes and refining fermentation parameters. For example, deep learning models can predict beneficial genetic edits in yeast or other oleaginous microorganisms to boost lipid accumulation, accelerating what was once an iterative trial-and-error process [105, 106]. On the process side, reinforcement learning algorithms and advanced sensors enable smart bioreactor control, dynamically adjusting factors like pH, temperature, and feed rates—to maintain optimal conditions and prevent failures [105, 106]. Early implementations in precision fermentation have shown dramatic gains, such as AI-guided strain modifications achieving up to 3-fold higher product yields and ML-based controls reducing bioreactor downtime by 60% [106]. Going forward, the convergence of biotechnology and data science is expected to continue revolutionizing fermented fat production. However, realizing this potential will hinge on collaborative data sharing and expertise exchange across disciplines; partnerships between computational scientists, metabolic engineers, and fermentation technologists will be key to deploying AI/ML innovations effectively in industrial lipid fermentation [103].

Another promising pathway is the development of hybrid fat systems that blend fermentation-derived lipids with plant-based or other structured fats to achieve superior functionality and cost-effectiveness. Precision fermentation enables the creation of "designer" fats with molecular profiles tailored to replicate those found in animal foods, offering a new toolkit to improve flavor and texture in plant-rich products. For instance, recent work has engineered oleaginous yeasts to produce a beef tallow analog – a solid fat with a high saturation profile that remains firm at room temperature and melts when heated, much like real beef fat. This fermented microbial fat closely mirrors the melting point and crystallization behavior of animal fat, thereby enhancing juiciness, mouthfeel, and slow flavor release in plant-based meat analogues. Such fermentation-derived fats can be used alone or in combination with conventional vegetable oils to create hybrid fat ingredients. By incorporating a small fraction of a highly flavorful or structuring microbial fat into a bulk plant oil, manufacturers can attain the sensory performance of animal fat while maintaining a cost-efficient base. This strategy leverages the strengths of each component: the authenticity and functionality of fermented fats (e.g. meat-like aroma compounds or high melting-point triglycerides) complement the volume and affordability of plant lipids. Going forward, continued innovation in hybrid formulations – and partnerships between fermentation startups and plant-based food producers – will broaden the application of fermented fats across alternative meat, dairy, and pastry

products, helping these foods more closely approximate their animal-based counterparts in taste and texture [21]. In tandem with technological advances, scaling up fermented fat production will necessitate shared manufacturing infrastructure and policy support. Establishing pilot plants, fermentation facilities, and processing hubs that can be accessed by multiple companies or research teams is an efficient model to accelerate innovation. Large-scale fermentation equipment and downstream processing units are capital-intensive, and very few startups can afford end-to-end facilities on their own. Shared infrastructure – whether through industry consortia, public–private partnerships, or biotechnology incubators – allows emerging ventures to validate processes at scale without prohibitive upfront investment. For example, regional "fermentation hubs" and bio-manufacturing accelerators are being proposed in several countries to provide fermenter capacity from the lab bench up to demonstration scale [107]. These hubs foster a collaborative environment where companies, universities, and government-funded institutes can co-develop processes and openly exchange know-how, speeding up learning curves. In addition, strong policy engagement is needed to facilitate growth of the fermented ingredients sector. Governments can play a role by funding critical infrastructure, updating regulatory frameworks to keep pace with novel foods, and creating incentive programs for sustainable food tech. Streamlining regulatory approval pathways for fermentation-derived fats (ensuring safety while avoiding undue delays) will be particularly important to enable market entry [14]. Overall, investment in shared resources and pro-innovation policy can help bridge the gap between laboratory successes and full-scale production, ensuring that fermented fat innovations are scalable and economically viable for broad adoption [14, 107]. Table 4 show a list of key post-fermentation fat processing methods and their effects on fat functionality. Also in Table 5 innovation pathways in fermented fats are listed and collaborative strategies for advancement are mentioned.

Table 4. Key post-fermentation fat processing methods and their effects on fat functionality.

Process	Mechanism/Description	Effects on Fat Properties	Key Considerations	Reference
Extraction	Disrupt biomass and extract lipids via solvent or aqueous methods. Aqueous methods can yield an emulsified “oil body” cream with native emulsifiers.	Recovers either crude neutral oil or oil-in-water emulsion, depending on method. Aqueous extraction retains natural emulsifiers, whereas solvent extraction provides higher purity.	Cell disruption is often the limiting step. Organic solvents pose safety and environmental issues; emerging non-solvent techniques (e.g. PEF, ultrasound) improve sustainability.	[99, 100]
Fractionation	Controlled cooling of a melted fat to crystallize high-melting TAGs, then separating solid (stearin) from liquid (olein).	Concentrates saturated, high-melting TAGs in the stearin fraction, while the olein is enriched unsaturated and remains liquid. No change in fatty acid structures.	Simple, chemical-free process (no trans-fat creation). Yield of solid fraction is limited by TAG composition. Used to obtain harder fat without hydrogenation.	[7, 33]
Hydrogenation	Addition of H_2 to double bonds (typically with Ni catalyst at high temperature) to saturate unsaturated fatty acids. Can be partial or full.	Increases saturation of fatty acids, raising melting point and solid fat content. Partial hydrogenation generates some trans fats.	Partially hydrogenated fats have good functionality but contain harmful trans FAs. Full hydrogenation gives a trans-free but very hard fat requires interesterification or blending. Due to trans-fat bans, partial hydrogenation is now avoided in foods.	[101, 102]
Interesterification	Exchange of fatty acids between triglycerides (using base catalyst or lipase) to rearrange TAG structures. Fatty acid types remain unchanged.	Produces a restructured fat with modified melting and crystallization behavior (e.g. can solidify an oil or soften a hard fat). No trans fats are formed, and original unsaturated fatty acids are retained.	Requires post-reaction refining to remove catalysts or enzymes. Enzymatic interesterification is more specific and gentler but more expensive. Widely adopted as an alternative to hydrogenation in margarines.	[7, 87, 102]

Table 5. Key innovation pathways in fermented fats and collaborative strategies for advancement.

Future Pathway	Opportunities (Next-Gen Innovations)	Collaborative Strategies (Academia–Industry–Policy)	Reference
AI & ML in Strain Engineering and Fermentation	*AI-optimized microbes* with higher lipid yields; *Smart fermentation* with real-time control to prevent failures.	Joint R&D between data scientists and fermentation experts; cross-sector data sharing to train models; regulatory guidance on AI in bioprocessing to ensure safety.	[103, 106]
Hybrid Fat Formulations (Mcrobial + Plant)	*Designer microbial fats* mimic animal fat's flavor and melting properties (e.g. yeast-derived beef fat analog); blending with plant oils achieves authentic taste/texture with lower cost.	Partnerships between fermentation startups and food manufacturers to co-develop hybrid products; sensory research with consumer insights; supportive labeling policies for blended novel ingredients.	[21]
Shared Infrastructure & Hubs	Dedicated fermentation facilities, pilot plants, and processing lines accelerate scale-up; lowers cost per company; fosters knowledge exchange.	Consortia and public–private partnerships to fund and operate shared facilities; government investment in fermentation hubs; standardized protocols from academia for scaling and safety to be adopted industry-wide.	[107]

Finally, by aligning these technological innovations with robust collaboration, the fermented fats sector can achieve wider impact across food, nutrition, and sustainability domains. Convergent efforts – integrating cutting-edge bioscience with pragmatic industry expertise and enabling policy – are expected to drive down costs and improve the performance of fermented fats, thereby making them accessible ingredients for mainstream use. As production volumes increase and processes become more efficient, precision-fermented lipids could be incorporated into a diverse range of products, from plant-based meats and dairy alternatives to functional oils and nutraceuticals. In the long run, continued innovation coupled with stakeholder coordination will help normalize microbial fats in the food system, allowing these sustainable ingredients to contribute significantly to healthier diets and a lower environmental footprint. With academia, industry, and government moving forward together, fermented fat technologies have the potential to revolutionize food systems and enable more resilient, eco-friendly nutrition pathways in the years ahead [14].

8. Conclusion

Fermentation-derived fats and oils are emerging as versatile, sustainable alternatives to conventional animal and plant lipids. By leveraging oleaginous microorganisms and precision fermentation, it is now possible to tailor fatty acid profiles and triacylglycerol structures that mimic or surpass traditional fats in both functionality and nutrition. These innovations present opportunities to reduce reliance on environmentally burdensome tropical oils, lower greenhouse gas emissions, and create fats with improved health attributes such as reduced saturated content or added omega-3 fatty acids. Furthermore, successful case studies in confectionery, plant-based meats, dairy alternatives, and bakery applications illustrate that fermentation can deliver fats with authentic melting behavior, texture, and sensory qualities. Together,

these advances establish microbial oils as an important frontier for sustainable food design and innovation. Nevertheless, critical hurdles remain before fermentation-derived fats achieve mainstream adoption. High production costs, scalability constraints, regulatory approval processes, and consumer acceptance continue to challenge their commercialization. Overcoming these obstacles will require integrated strategies spanning strain engineering, feedstock innovation, bioprocess optimization, downstream recovery, and transparent regulatory and consumer communication. Looking ahead, bridging these scientific, economic, and policy gaps will be essential to fully unlock the potential of fermentation-derived lipids as sustainable, healthful, and functional ingredients. With continued cross-disciplinary collaboration between researchers, industry, and regulators, fermented fats and oils can play a transformative role in building resilient food systems for the future.

9. Declarations

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9.2. Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

9.3. Author contribution

Negin Ahmadi: Conceptualization, Writing – Original Draft, Visualization, Project administration. **Amirhossein Golzan:** Writing – Review & Editing, Investigation, Formal analysis, Validation. **Zahra Montazer:** Conceptualization, Supervision, Writing – Review & Editing, Methodology, Resources.

9.4. Using Artificial Intelligent chatbots

AI chatbots used for graphic abstract and Protein data bank were used in this research.

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