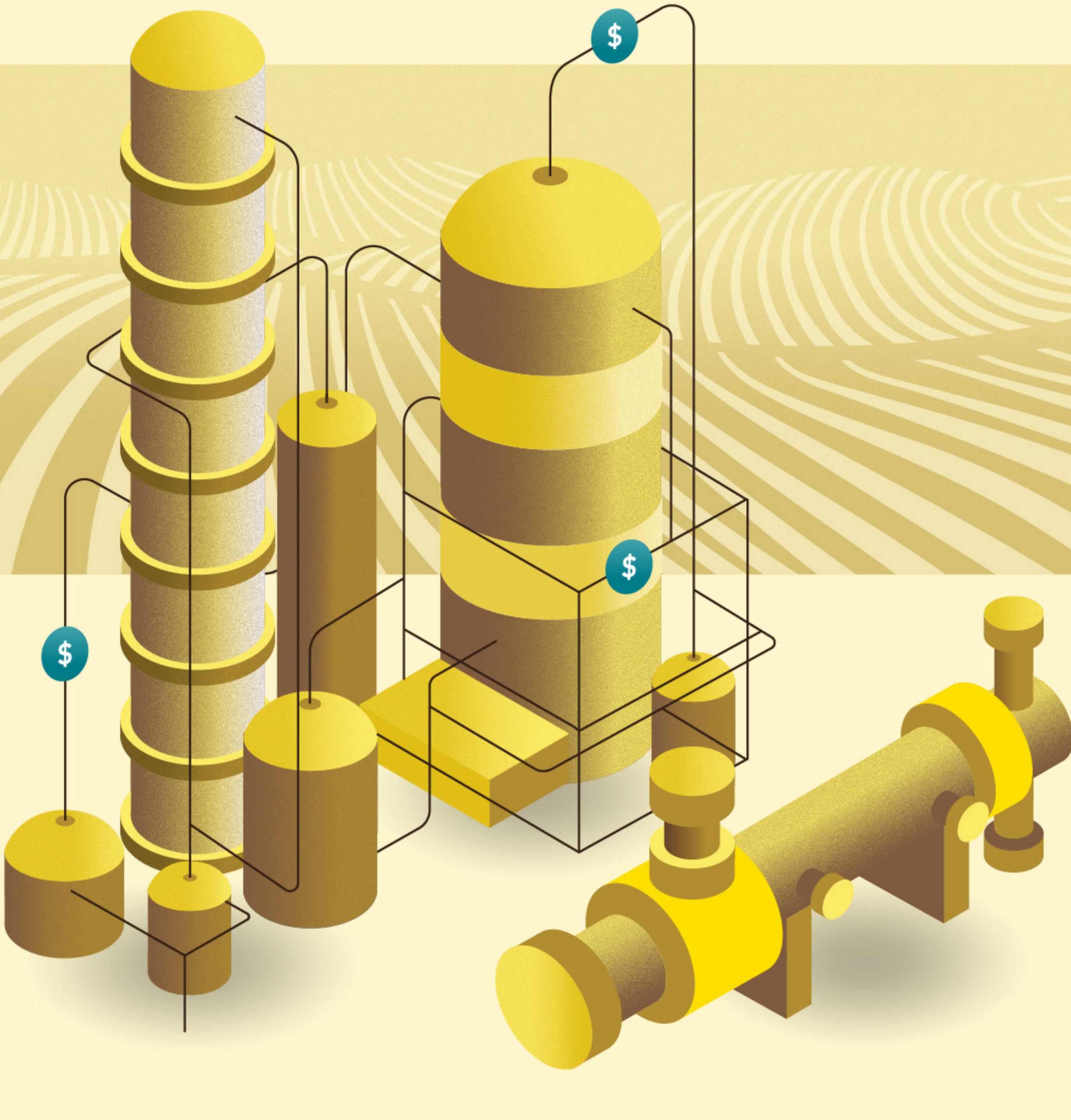
Driving down costs

Insights and recommendations from a meta-analysis of techno-economic models of fermentation-derived ingredients



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Executive summary

Fermentation-derived (FD) ingredients are gaining momentum in the alternative protein industry for their potential to match conventional ingredients in cost and taste. As interest grows among stakeholders working to feed the world in increasingly sustainable ways, companies, researchers, investors, and policymakers must understand the economic viability of FD products to drive large-scale investment and rapid technological development of the industry. This report provides the most comprehensive analysis to date of the cost competitiveness and cost drivers of FD ingredients based on a robust review of published techno-economic models (TEMs). By synthesizing existing knowledge, this report equips stakeholders to prioritize research and development needs, assess product targets, and invest in technological and process innovations that can improve the economic viability of FD ingredients—including achieving cost parity with conventional ingredients.

Scope

Techno-economic modeling is essential for evaluating the economic potential of new technologies and pinpointing innovations that enhance cost competitiveness. This analysis reviews published TEMs for three key classes of FD food products: biomass protein, precision fermentation-derived protein, and microbial lipids. The goal was to assess cost competitiveness and identify knowledge gaps and strategies for lowering production costs.

> *This report provides the most comprehensive analysis to date of the cost competitiveness and cost drivers of FD ingredients based on a robust review of published techno-economic models (TEMs).*

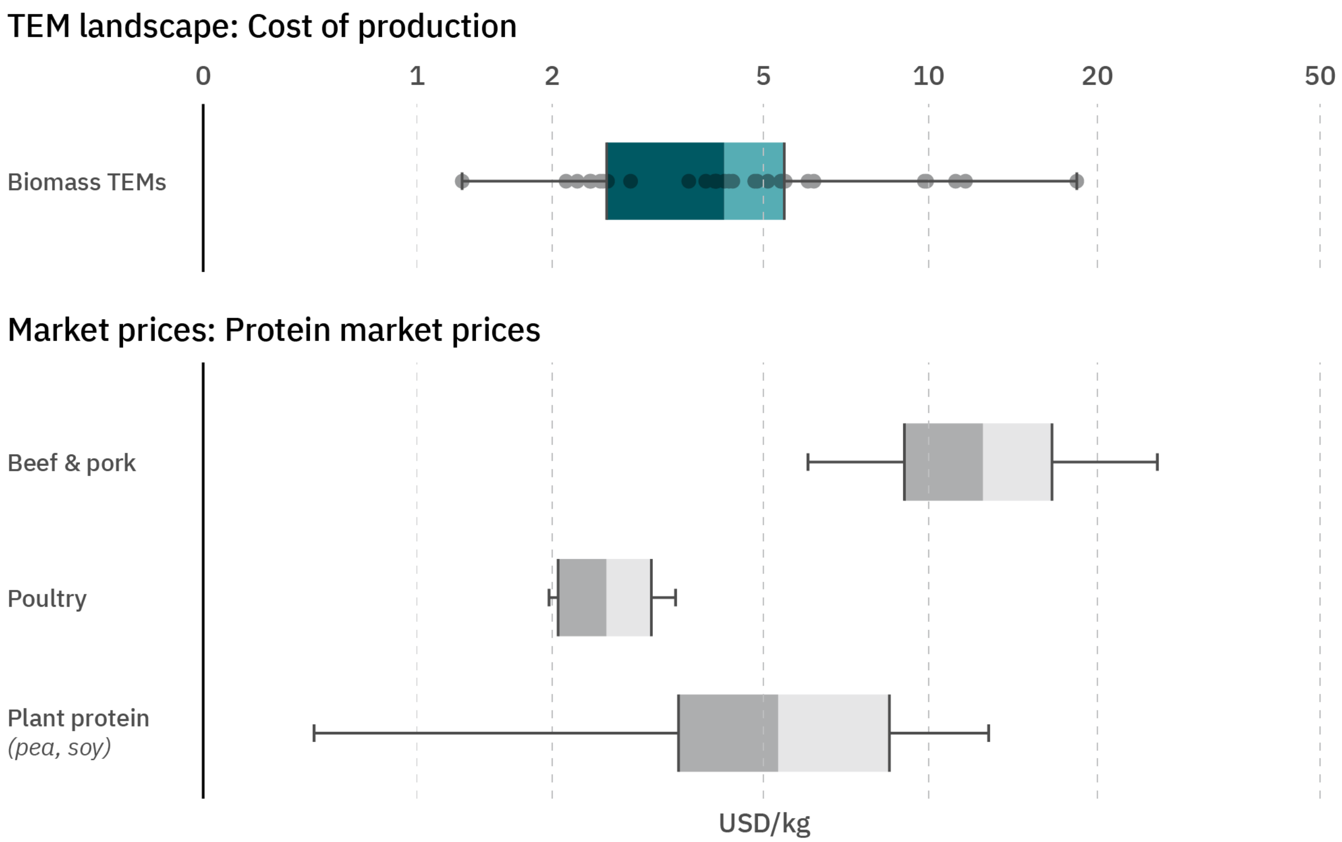

Figure 1. Biomass fermentation ingredient production cost (USD/kg); prices (in USD/kg) approach incumbent commodity ingredient market prices

Key insights

The following insights reflect the study's key findings on FD ingredient cost competitiveness, as well as the critical strategies and knowledge gaps that influence production costs.

1 Biomass proteins are closing the price gap with several incumbent proteins.

- Biomass cost of production (COP) from published TEMs converges around $4–$6 per kg (range $1.3–$18.1 per kg) across all biomass processes (Figure 1). A private case study, grounded in real-world process parameters, predicts a lower COP of $2.5/kg.
- Published and private TEMs suggest that cost parity with incumbent proteins, especially beef and pork, is within reach today. Poultry presents a tighter benchmark, requiring further cost reductions. Competing with commodity plant proteins is more challenging on a per-protein basis, as average biomass COP is at or above soy and pea prices.
- Biomass TEMs were the most prominent among published sources, with 25 models identified, offering broader coverage across fermentation approaches than TEMs for other product types. However, these models typically assume smaller production volumes and lower titers than commercial processes, resulting in higher estimated COP compared to private models.

2 **Limited precision fermentation (PF) TEMs obscure the understanding of progress toward price parity with commodity ingredients.**

- Published COPs were highly variable, ranging from <$20/kg to $14,000/kg, with a notable data gap in the $20–$200/kg range (Figure 2).
- The four published PF TEMs identified offer limited coverage of products and fermentation processes, as cost estimates and process metrics vary widely. Compared to industry benchmarks, these published TEMs underestimate production volume and titer.

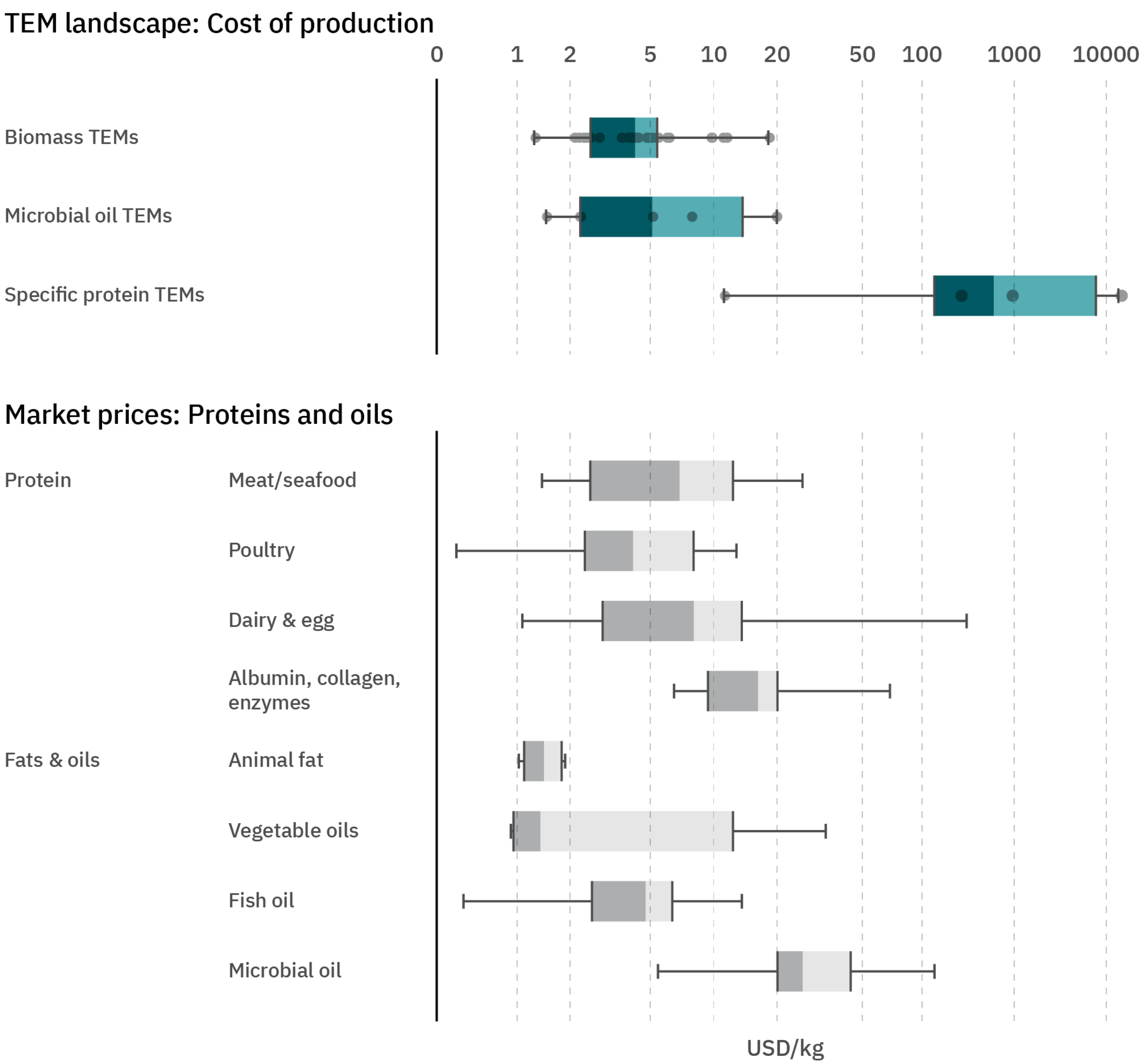

Figure 2. Biomass protein and microbial oil production costs highlight cost competitiveness with select incumbent ingredient market prices (USD)

3 **Microbial oils are competitive with some high-value incumbents, but cannot compete on price with commodity oils.**

- Microbial oil COP from seven published TEMs ranges from $1.5 to $19.6/kg, with omega-3 oils modeled at the upper end (Figure 2). These costs are far above commodity oil and fat prices. However, certain high-value oils, particularly omega-3-rich oils, are traded at prices that do support these COPs. This finding is reinforced by the successful commercialization of FD omega-3 products today.
- Feedstock cost reduction is needed for microbial oils to compete with commodities.
- The seven public TEMs identified for microbial oils do not reflect the diversity of strains and bioprocesses used in industry. Published TEMs evaluating sucrose or glucose feedstocks generally reflect commercial parameters for production volume and fermentation titer values. Published omega-3 oil TEMs are modeled below commercially relevant scales, indicating further cost reduction potential.

4 **Improved feedstock costs, feedstock conversion, and capital efficiency emerge from published TEMs as key levers of cost reduction.**

- Public TEMs identify feedstocks and raw material costs, facility capital costs, and performance process metrics as leading COP drivers (Figure 3).

Key cost reduction opportunities:

- Reduce capital costs and improve capital efficiency of Gen 2 sugar and gas feedstock processes to enable optimized economies of scale.
- Improve gaseous Gen 2 feedstock processing efficiency to tap into low-cost feedstocks.
- Increase yield and titer, reduce batch time, and streamline product recovery.

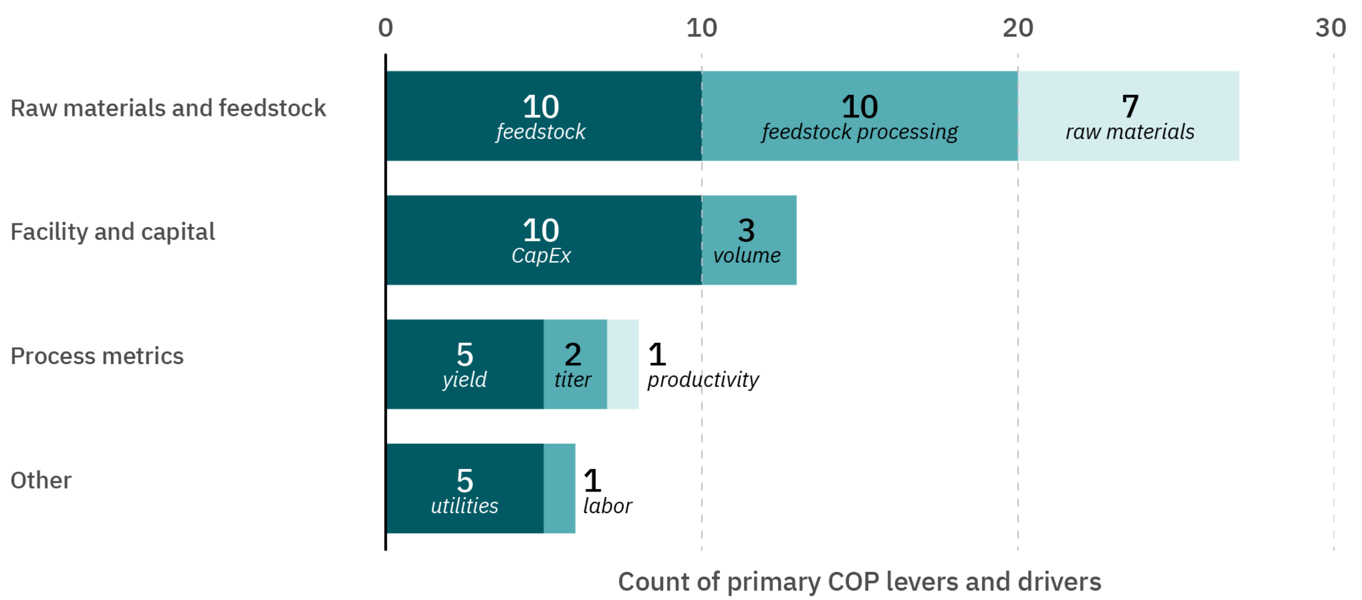

Figure 3. Cost of production driver overview in published TEMs by cost category

Key recommendations

Fermentation-derived food proteins and oils can lead to benefits such as more efficient use of raw materials and reduction in food waste, supply chain stability, new economic opportunities, and national security. These benefits derive primarily from the flexibility and efficiency of fermentation and its use of low-cost agricultural inputs, including sidestreams that may create additional income streams for farmers. The flexibility of fermentation processes and equipment also allows for the production of other goods, like fibers and materials, in fermentation facilities. Despite this promise, current feedstock and raw material costs, facility and capital costs, and unoptimized process metrics create unfavorable economics for FD food protein and oils. Producers, policymakers, and modeling practitioners can play a vital role in driving innovation and enabling cost-competitive, commercial-scale fermentation, as outlined below.

For fermentation ingredient producers

Fermentation-derived ingredient producers can drive the development and cost-competitive commercialization of fermentation through these three actions:

1. Focus commercialization efforts on biomass protein products with favorable COP, as revealed in this analysis.

The economics suggest opportunities to expand production, broaden ingredient applications, and improve cost efficiencies. Due to strong economic potential, producers can allocate resources to overcome remaining commercialization challenges with confidence.

2. Drive innovations that improve costs, including:

- Scale manufacturing through innovations that unlock economies of scale and improve capital expenditure (CapEx) and feedstock efficiency.
- Reduce capital costs and improve process efficiency via novel bioreactor design, and streamlined piping, filtration, and utility optimization.
- Optimize strain development and extraction processes to improve efficiency in utilizing Gen 2 feedstocks (such as agricultural sidestreams, forestry residues, or gases), enabling broader usage and higher feedstock conversion.
- Increase fermentation titer and productivity to reduce unit costs.
- Maximize downstream process recovery—an often underemphasized area in published studies with significant cost impact.

3. Share aggregated industrially relevant cost and process parameters with the research community to support translational research and improve stakeholder recognition of the sector's commercial viability.

Publishing aggregated and anonymized ranges for key performance indicators—such as yield, titer, downstream processing recovery, and vessel volumes—would enable more accurate modeling.

For policymakers

Governments and regulatory agencies can catalyze cost-competitive commercial-scale fermentation using three key policy levers:

1. Fund research and development, including:

- Open-access research into the development and optimization of food-safe high-performing microbial stains, feedstock processing, downstream processing recovery, and specialized equipment such as advanced bioreactors.
- Publicly accessible TEMs for fermentation-derived ingredients with high-volume opportunities like whey, casein, egg white proteins, and omega-3 oils.

2. Leverage incentives to support scale up and manufacturing, such as:

- Investments that support the creation of public-private fermentation hubs with shared pilot plants and scale-up facilities to reduce the CapEx burden on individual companies. These contract manufacturing and development organizations can enable efficient commercial scale up and support regional economies.
- Support for low-cost electricity in biomanufacturing, such as industrial rate incentives, on-site renewable energy programs, shared infrastructure investments, power purchase facilitation, and policies promoting energy efficiency and grid access.
- Grants, voucher programs, and tax incentives to support manufacturing planning activities and offset costs. Such programs may support engineering plans, site selection, techno-economic assessments, life cycle assessments, and equipment purchase and installation.
- Incorporation of foods with fermentation-derived protein and oil ingredients into public procurement, including for the military and humanitarian assistance food channels.
- Loan programs that offer lower interest rates to reduce the impact of CapEx on the cost of production.

3. Support the standardization of techno-economic data analysis, for example:

Best practices, data and parameter standardization, reporting metrics, and model assumptions of TEMs to enhance accuracy, comparability, and practical relevance.

For techno-economic modeling practitioners

Practitioners across sectors can enhance the impact of TEM for the industry by focusing on two priority activities:

1. Standardize best practices for FD biomanufacturing TEMs.

Best practices should establish input and output standards, flexible frameworks, and accurate modeling of upstream and downstream processing, while properly accounting for scaling effects and key bioprocessing parameters. Models should be published with detailed input and reporting parameters to enhance transparency. Just as ISO standards guide life cycle assessment and carbon accounting, a similar framework for TEMs would improve the quality and reliability of available models.

2. Publish TEMs across a wide range of fermentation-derived protein and oil pathways to benchmark current performance and highlight opportunities.

This analysis uncovered a lack of publicly available TEMs to evaluate many current commercial processes operating at full scale. These include precision FD beta-lactoglobulin, edible microbial oils, and a wide range of mycoproteins. Modelers must strike a balance between protecting proprietary data and maintaining competitive advantage, while still sharing process metrics that are useful and informative to the broader field. Developing approaches that enable meaningful benchmarking without disclosing sensitive details is critical to advancing collective understanding.

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Introduction

Fermentation-derived (FD) ingredients—from biomass products like mycoprotein to precision fermentation proteins and fats—have garnered much attention in the alternative protein industry for their potential to deliver on price and taste parity to conventional ingredients. Given the need to feed more people in far more sustainable and secure ways, interest in the economic viability of these food products is growing among companies, nongovernmental organizations, researchers, investors, and policymakers. A focus on key technical solutions will enable their future success.

Techno-economic assessment (TEA) is an important tool for evaluating economic feasibility by estimating production costs and identifying innovations that can improve cost competitiveness. However, the wide variety of FD ingredients—spanning diverse products, microbes, processes, feedstocks, and market areas—makes it difficult to compare models and prioritize R&D efforts. While this diversity underscores fermentation's potential, it also presents challenges for stakeholders seeking to identify the most impactful innovation opportunities and R&D priorities.

Open-access techno-economic models (TEMs) offer valuable insights into the scalability and viability of FD ingredients and help reveal technical gaps. However, most TEMs are proprietary.

As such, limited published data exists to inform the overall economics of FD products. While externally published resources such as primary literature, white papers, and web tools highlight key technical challenges, their information can be disparate, scattered, inconsistent, of poor quality, or lack key details.

A clearer definition of the current state of fermentation techno-economics in the public domain is needed to assess how far away (or close) the industry is to achieving cost parity with conventional proteins and other food ingredients, and where key data gaps exist.

To that end, this report presents a summary and meta-analysis of fermentation techno-economic models to identify cost drivers, assess cost competitiveness, and highlight technological gaps.

The findings aim to equip stakeholders with a clearer picture of current barriers and opportunities by informing efforts to prioritize research, address publication gaps, identify potential product targets, and guide investments in technology and process innovations essential to improving the economic viability of FD proteins, including achieving cost parity with conventional ingredients.

Glossary of terms, abbreviations, and acronyms

Term	Explanation
AP	Alternative protein (AP).
CapEx	Capital expenditures (CapEx); the cost associated with the construction or preparation of a facility, purchase and installation of equipment, and other costs such as engineering and design.
OpEx	Operational expenditures (OpEx); the variable and fixed costs associated with the production of an end product with a facility.
COP	Cost of production (COP) is the capital and operational costs to produce a fermentation product of interest.
COGS	Cost of goods sold (COGS) describes the costs to make and deliver a product. This usually includes COP plus additional costs for packaging/palleting and shipping, etc.
Price	Market price typically represents COGS plus margin.
	All are expressed as cost per unit of product produced ($USD per kg-product).
FEL	Front-end loading (FEL): The strategic planning of a project, typically divided into sequential, gated steps from conceptualization, planning, procurement, and construction, to project completion.
Fixed costs	Overhead costs such as labor, maintenance, insurance, property tax, and capital depreciation.
Variable costs	Costs of feedstocks, raw materials, chemicals, utilities, waste disposal, etc.
Gen 1	First generation feedstocks (Gen 1): Canonical feedstocks for microbial fermentation that include sugar and sugar derivatives, such as sucrose (sugarcane/sugarbeet), glucose (corn or wheat dextrose), and glycerol.
Gen 1 + upstream	Gen 1 + upstream processing: Models with Gen 1 feedstocks that include conversion of the raw material into the fermentable feedstock, such as on site conversion of starch to glucose.
Gen 2	Second-generation feedstocks (Gen 2) are carbon feedstocks that do not compete with food production. Examples include agricultural sidestreams, forestry residues, municipal/industrial wastes, and carbon gases.

Term	Explanation
Production volume (MTa)	Total product output annually expressed as metric tonnes annually (MTa). Production volume is expressed in this report as product output, not fermentation volume.
Recovery rate (downstream yield)	The amount of product recovered after extraction and concentration, relative to the amount obtained from upstream cultivation. Expressed as percent yield (%), calculated as kg final product per kg initial product.
SSF	Solid-state fermentation (SSF): microbial growth and production where microbes grow on the surface of solid input nutrients in a chamber or vessel.
Submerged	Submerged fermentation: microbial growth and production within an enclosed vessel where inputs (nutrients, gases) and microbes are mixed in the liquid fraction.
TEA	Techno-economic analysis (TEA) seeks to evaluate the economic performance of a product, process, or service by assessing the cost contributions of the materials, infrastructure, and effort used to produce it.
TEM	Techno-economic model (TEM) is a single analysis of a specific set of input contributions used to create a particular end product, process, or service.
TPY	Titer, productivity, and yield (TPY).
Titer	Titer refers to the concentration of the expressed product in the fermentation system. In submerged fermentation, it is typically expressed as grams of product per liter of liquid culture (g/L). In solid-state fermentation (SSF), titer is expressed as grams of product per gram of solid substrate (g/g-substrate).
Productivity	Productivity measures how much product is made over time. In liquid fermentation, it is often expressed as grams of biomass or protein per liter per day. In solid-state fermentation, it is measured as grams of biomass per gram of substrate per day.
Yield (feedstock)	Yield measures how much product is produced per unit of feedstock added to the system, which is typically expressed in terms of grams per gram substrate (e.g., g-protein per g-glucose).
USP	Upstream processing (USP), the steps associated with microbial growth and production of an end product.
DSP	Downstream processing (DSP), the steps associated with end-product isolation and purification.

Analysis overview

Research approach

In this analysis, we reviewed the published TEM literature for FD food ingredients, primarily focused on biomass protein ingredients, precision FD single protein ingredients, and microbially derived lipids. Through this effort, we identified a set of TEMs specific to these ingredients, including secondary TEM ingredient models, and analyzed the cost of production (COP) ranges and process cost drivers, and compared modeled costs to incumbent product prices.

The report is organized into the following sections based on the four primary research questions described in Figure 4. An explanation of methodology for each step can be found in the Scope and methods overview section below (Figure 5) and Appendix 1.

Section 1
State of cost competitiveness

Landscape
TEM data and gaps

1. **What is the state of TEMs for fermentation-derived alt protein ingredients?**
   - Gather TEM in databases
   - Identify relevant literature
   - Filter models
   - Extract and normalize data

Report public domain TEM data, strengths, and gaps

Benchmark
TEM and market landscape

2. **How do public TEMs compare to private-sector benchmarks?**
   - Compare private vs public TEM benchmarks
3. **What are the current benchmark target ingredient prices?**
   - Landscape market data
   - Normalize price per ingredient and price per kg/protein

Understand placement of AP TEMs against commercial benchmarks

Section 2
Path to cost competitiveness

Analyze
TEM cost drivers

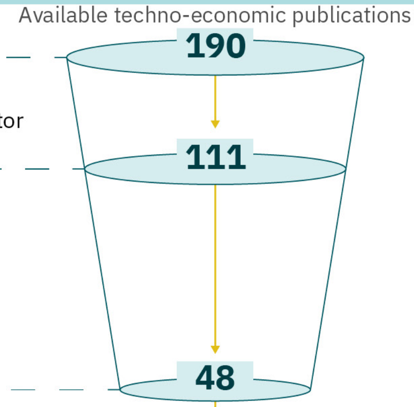
4. **Which parameters impact the COP for fermentation processes?**
   - Understand effects of CapEx and OpEx to COP
   - Evaluate TEM trends and cost drivers from public data
   - Explore cost driver sensitivity through private sector case-study

Highlight opportunities for cost reduction

Figure 4. Research approach overview

Scope and methods overview

Landscape



Literature search:
- Broad and narrow terms for techno-economics and microbial bioprocesses
- Published public literature and whitepaper databases available in the public sector

Scope check:
- Microbial fermentation processes to produced food ingredients
- Includes at least 1 fermentation process
- No pharmaceutical, biofuel targets, and phototrophic processes
- Models beyond pilot-scale production
- Published within last 15 years

Meets criteria:
- Details process design and system boundaries
- Identifies model assumptions for process and cost
- Details modeling process
- Reports key TEM outputs

Landscape and analysis

Ingredient TEM classification	Primary ingredient	Secondary ingredient	Total
Publications screened	-	-	**48**
Publications evaluated	25	8	**33**
Models evaluated	36	19	**55**

Primary ingredient:
Biomass, proteints, fats/oils

Secondary ingredient:
Amino acids, binder ingredient, sugar alcohol, sweeteners

TEM data capture

Techno-economic data extraction:
- CapEx and OpEx, and reported subcomponents
- Production scale volume (MTa)
- Microorganism (type, yield, titer, productivity)
- Process and model information (mode, DSP, etc.)
- Variable and fixed costs
- Product form, functional unit, concentration
- Cost of production (COP), minimum selling price (MSP)
- Reported COP drivers

Data calculation and normalization:
- Calculated COP comprised of materials, utilities, fixed costs, and depreciation
- Calculated CapEx and OpEx per year or per-kg product
- COP conversion to $/kg and $USD
- Inflation-adjusted to 2024

Benchmarking

Public vs private models:
- Evaluate Hawkwood private data vs public-sector
- Comment on variations in commercial assumptions and data gaps

Case-study: Biomass SCP
- Aggregate Hawkwood biomass data for yeast and microalgae
- Conduct sensitivity analysis on cost drivers in private model

Incumbent ingredient prices:
- Incumbent products comparable to AP ingredients
- Market price information from public databases
- Protein content data from ingredient databases
- Normalize price information to $/kg and $/kg-protein content
- Compare market cost to public/private TEM landscape

Figure 5. Scope and methods overview

Photo credit: Nature's Fynd

Section 1: State of cost competitiveness

A landscape of fermentation TEMs, commercial benchmarks, and ingredient market comparisons

Overview

This section summarizes the current landscape of fermentation TEMs available in the published literature. Key data points, including product type, feedstock type, production method, process parameters, and estimated annual production volume, are presented in summary figures. COP ranges are provided for biomass protein, precision FD protein, and microbial oils.

The section also compares published TEM data with industry-developed, private-sector models to evaluate how well published assessments reflect the current state of FD technology, with a focus on biomass and PF protein. Finally, modeled costs from both published and private sources are benchmarked against market prices for incumbent protein ingredients to assess progress toward price parity and identify remaining cost gaps.

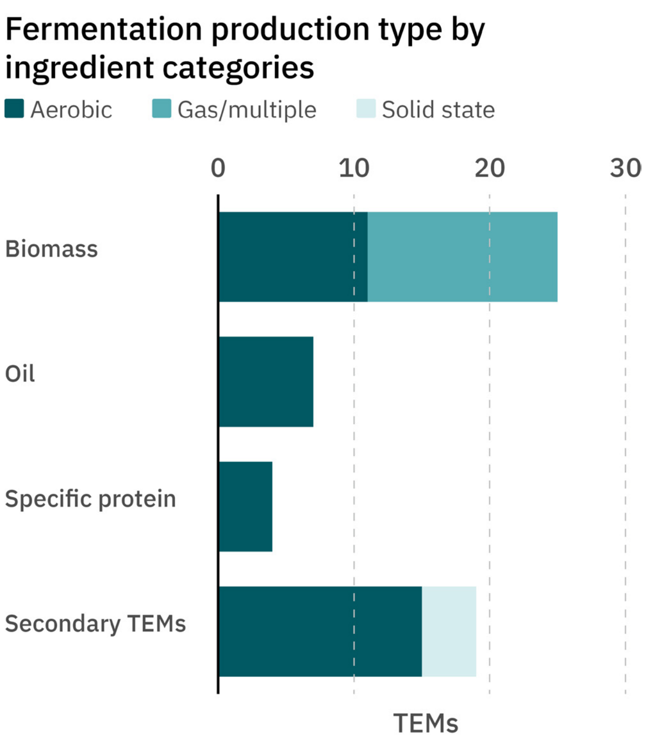
1.1 Landscape of fermentation TEMs in the published literature

To our knowledge, this analysis represents the first attempt to aggregate and normalize publicly available TEM data for meta-analysis and direct comparison across different ingredient types and production processes.

Of the 190 publications identified on biomanufacturing techno-economics, 48 (comprising 78 TEMs) were deemed in scope based on their scale and relevance to food applications (see Figure 5). Of these, 35 publications (55 TEMs) met quality criteria and focused on primary or secondary food-specific ingredients of interest.

The landscape shown in Figure 6 summarizes the TEM coverage and gaps based on ingredient target, fermentation type (aerobic, gas, or solid-state), and feedstock source (categorized as Gen 1 or Gen 2). Figure 6 provides a breakdown of the 55 TEMs by ingredient and fermentation type. Primary ingredients of interest, including biomass fermentation, precision fermentation "specific proteins," and microbial fats/oils, were addressed by 20 publications (36 TEMs).

Secondary ingredients, amino acids, binder ingredients, enzymes, sophorolipids, sugar alcohols, and sweeteners, were covered by 15 publications (19 TEMs) (Figure 6). Enzymes and sophorolipids are included in the landscape to help contextualize the performance and economic feasibility of PF proteins and microbial oils. Figure 6 also shows the breakdown of models by feedstock source type, demonstrating a lack of models focused on current Gen 1 sugar feedstocks. A high-level summary of coverage and data gaps is found in Figure 7.



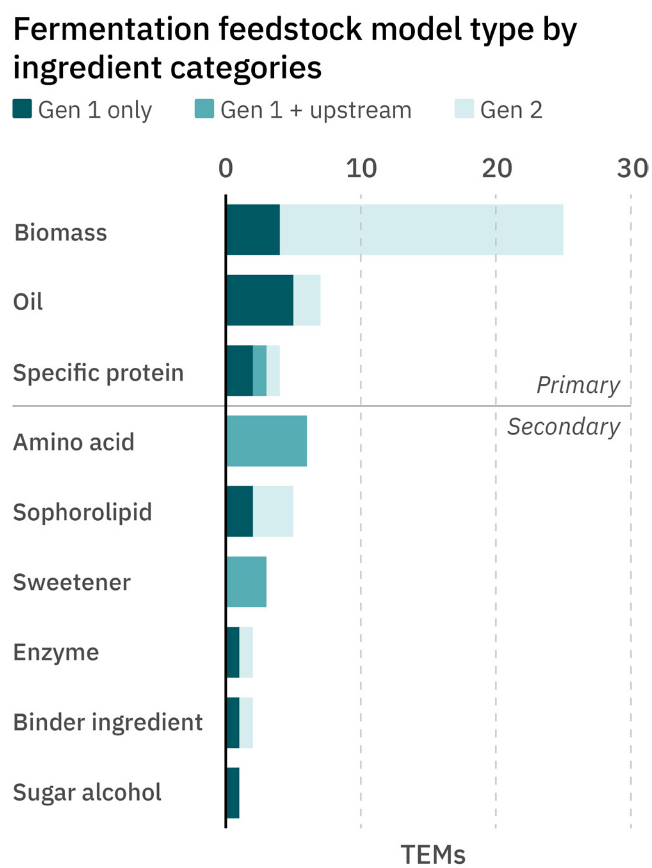


Figure 6. Overview of published, food relevant fermentation techno-economic models by (left) fermentation production type by ingredient categories and (right) fermentation feedstock model type by ingredient categories

High-level summary of fermentation TEM landscape

Biomass fermentation	Precision fermentation	Microbial oils
25 models (16 publications) – 11 aerobic – 14 gas	**6 models (6 publications)** – 4 specific protein – 2 enzyme	**12 models (8 publications)** – 7 oil – 5 sophorolipid
Good TEM coverage – Most robust TEM coverage of all FD ingredient approaches across 25 total models	**Poor TEM coverage** – Limited with only 4 specific protein models – Cost estimate and process metrics widely vary	**Moderate TEM coverage** – Gen1 feedstocks are well-represented by the microbial TEMs – The diversity of potential strains and bioporcesses are not well-represented
Data gaps – No SSF models – Limited models assessing Gen1 sugar feedstocks, yeast, and heterotrophic microalgae	**Data gaps** – Only 2 published and peer-reviewed PF protein models with disparate outcomes and model parameters	**Data gaps** – Limited omega-3 and omega-6 models despite commercial production

Figure 7. Summary of primary ingredient TEM landscape coverage and data gaps

1.2: Biomass fermentation: TEM landscape, commercial benchmarking, and market ingredient comparison

1.2.1 TEM landscape: published biomass fermentation TEMs offer broad coverage across various bioprocesses

Biomass fermentation, also known as single-cell protein (SCP), uses the high-protein content and fast growth of microorganisms to efficiently produce large quantities of protein. Microbial biomass can be the main ingredient of a food product or serve as one of several ingredients in a blend. A range of microorganisms have been commercialized and are being explored for their applications in biomass fermentation, from yeast and filamentous fungi to microalgae and gas-fermenting bacteria.

This analysis uncovered 25 biomass fermentation TEMs (Figure 8; Appendix 2). These models cover submerged fermentation protein production via filamentous/mycelial fungi (5), yeast (4), microalgae (1), aerobic bacteria (1), multistage gas bacteria (2), and gas-fermenting bacteria (12). The feedstocks for fermentation in these models are similarly diverse and include gas carbon, cellulosic hydrolysates, acetate, and sugars. Despite the commercial production of biomass products via solid-state fermentation (SSF) tray systems, this landscaping exercise did not identify any SSF TEMs.

As an established commercial bioprocess, biomass fermentation would be expected to have extensive techno-economic coverage, including for scaled, commercial processes. However, of the 25 published biomass fermentation TEMs identified, only four modeled conventional Gen 1 systems, those using refined sugars as feedstock. Instead, most focus on hypothetical or early-stage systems, such as gas fermentation or cellulosic feedstocks, or on small-scale production.

While these forward-looking models are valuable for exploring the potential of emerging technologies, they do not reflect the current state of commercially deployed biomass fermentation processes.

Published biomass TEMs notably lack analysis of either fed-batch (current standard process) or continuous fermentation systems for aerobic yeast, microalgae, and bacterial SCP. Existing models for fungal mycoprotein and gas-fed bacterial systems typically assume continuous processes, which offer long-term productivity benefits but operate at lower biomass titers.

In contrast, published yeast models tend to focus on batch processes, which achieve higher titers in shorter timeframes. Fed-batch fermentation—a widely used method to improve titer, productivity, and yield—is largely missing from published models, potentially leading to underestimation of economic performance. Additionally, many published models do not report key process metrics such as titer and yield, making it hard to interpret and compare TEM results.

*Publication models yeast and fungal processes
NA = not available or not reported

Biomass TEM landscape
25 models (16 publications)

	Submerged: Aerobic				Submerged: Gas and multiple		Solid-state
# of TEMs (# publications)	11 (8)				14 (8)		0
Microorganisms # of TEMs (# publications)	Fungi 5 (3)	Yeast 4 (3)	Micro-algae 1	Bacteria 1	Bacteria Hydrogen oxidizing 12 (6)	Bacteria Methane oxidizing 2 (2)	
Feedstocks	Gen2=3 Gen1=2	Gen2=3 Gen1=1	Gen1	Gen1 +ups	Gen2: Syngas, CO_2 Syngas-acetate	Gen2: Methane	
Production mode	Continuous	Batch (3) Continuous (1)	Batch	Batch	Continuous (10) Two-stage (2)	Continuous	
Production volume *(MTa)*	3,400–40,000	58–10,000	285	914	1,015–218,400	820–108,000	**Data gap** No SSF biomass TEMs in the public domain
Total CapEx *($MM in 2024)*	$86–$892	$3.2–$95	$10.4	$3.7	$3.9; $181–$1,078	$3.6; $395	
Titer *(g/L)*	12.5–25	NA(3), 18.5	~11	NA	4.5–44	NA	
Yield	0.3–0.5	0.37–0.65	0.23	NA	0.19–0.45	0.19–0.80	
COP *($/kg)*	$3.9–$6.0	$5.0–$11.4	$18.1	$4.8	$2.4–$11.0	$1.3–$2.2	
Publication ID	#15, 49*, 85	#49, 178, 189	#125	#103	#93, 94, 96, 112, 190, 192	#64, 185	

Figure 8. Biomass TEM publication landscape for different fermentation types and microorganisms

1.2.2 TEM landscape: biomass cost of production

Published biomass fermentation models have an estimated COP range from $1.3 to $18.1 per kg-biomass, with a strong alignment around $4–$5 per kg-biomass (median $4.3/kg) across all bioprocesses (Figure 8; Appendix 1).

Fungal protein

Fungal protein was modelled in five TEMs (three publications) with comparable COP estimates, falling within the $4–$6 per kg-biomass range. The majority of the fungal protein models assessed production using lignocellulosic feedstocks (Gen2), which is not currently commercialized except in bioethanol production. All models assessed strains and model parameters similar to those found in mycoprotein biomass producer Quorn's process (Voutilainen et al. 2021; Risner et al. 2023; Upcraft et al. 2021).

Yeast biomass

Despite its status as a well-established commercial sector (e.g., yeast extract, baker's yeast), yeast biomass is represented by only four TEMs across three publications (Figure 8; Appendix 1). Reported COP estimates range from $5 to $11 per kg of biomass, with a median of $7.5/kg. The lowest COPs come from an industry white paper (Intelligen) modeling yeast extract and a comparative study of lignocellulosic feedstocks for yeast and fungal protein. The highest COP was associated with a Gen 2 feedstock valorization model using industrial waste (Gómez et al. 2022; Misailidis and Petrides 2020; Voutilainen et al. 2021).

Aerobic microalgae and bacteria

Only two publications focused on aerobic microalgae and bacterial SCP production, both reporting the lowest modeled production volumes (<1,000 MTa) and CapEx estimates (<$10 MM), likely due to the small production scale (Russo et al. 2022; Archacka et al. 2020). A single microalgal model focused on omega-3-rich biomass feed (Figure 8), had the highest estimated biomass cost ($18.1 per kg) (Russo et al. 2022). The low commercial production volumes and limited model coverage indicate a key gap for these processes.

Gas fermentation

Gas fermentation TEMs, including multistage processes, encompassed 14 models covering a range of production systems using autotrophic hydrogen-oxidizing bacteria and heterotrophic methane-consuming bacteria. Reflecting the early stage of the field and variability in process parameters, these models reported the widest COP range—from $1.3 to $11.0 per kg— with a median around $4.0/kg. CapEx estimates also spanned broad ranges—from $3 million to over $1 billion—driven by production scale (Figure 8). This included both undersized facilities (820-1015 MT/year) and hypothetical mega-scale facilities (>100,000 MTa), as well as volumes (15,000-45,000 MTa) consistent with today's commercial gas fermentation facilities (e.g., Calysta/Adisseo at 20,000 MTa) (Figure 8; Appendix 1). See section 2.3 for a comparison of CapEx and production volumes.

1.2.3 Commercial benchmarking: published biomass TEMs underestimate industry performance

Published TEMs provide insights into the state of fermentation ingredient production costs. However, a question remains: Do published biomass TEMs represent the current performance and expectations of the industry? Without access to private process and cost data across the industry, this is difficult to evaluate.

Nevertheless, when we attempted to evaluate the representativeness of published TEMs by comparing their process parameters and modeled COP to a subset of private TEMs developed by Hawkwood Biotech for commercial-scale aerobic yeast and microalgae SCP biomass production, a data gap was observed in the landscape (see the Case Study in section 2 for more information about these models).

Ranges for public and private aerobic fermentation biomass metrics are shown in Table 1 for fungi, yeast, and microalgae. Figure 9 presents COP ranges, production volume, CapEx, and performance metrics in more detail for both public and private aerobic fermentation data. Most published aerobic biomass fermentation models assess production volumes below commercial-scale, private models. Similarly, production costs are generally higher in the published TEMs than in the provided commercial benchmarks.

Table 1. Comparing aerobic biomass fermentation processes between public and private data

Source	Microbe Type (# TEMs)	Process Type	COP ($/kg)	Production Volume (MTa)	CapEx ($ MM)	Yield (g/g)	Titer (g/L)
Public	Fungi (5)	Continuous	$3.9 - $5.9	3,400 - 40,500	$86 - $892	0.3 - 0.5	12.5 - 25
	Yeast (1)	Continuous	$5.3	4,460	$95	0.37	18.5
	Yeast (3)	Batch	$5.0 - $11.4	60 - 10,000	$3.2 - $78	NA 0.5, 0.65	NA
	Microalgae (1)	Batch	$18.1	285	$10.4	0.28	11
	Bacteria (1)	Batch	$4.8	914	$3.7	NA	NA
Private	Yeast & Microalgal (3)	Fed-batch	$2.1 - $2.8	18,000 - 48,000	$139 - $324	0.45 - 0.50	100 - 150

NA = not available or not reported in the literature; Private model provided by Hawkwood Biotech – see Case Study for more details

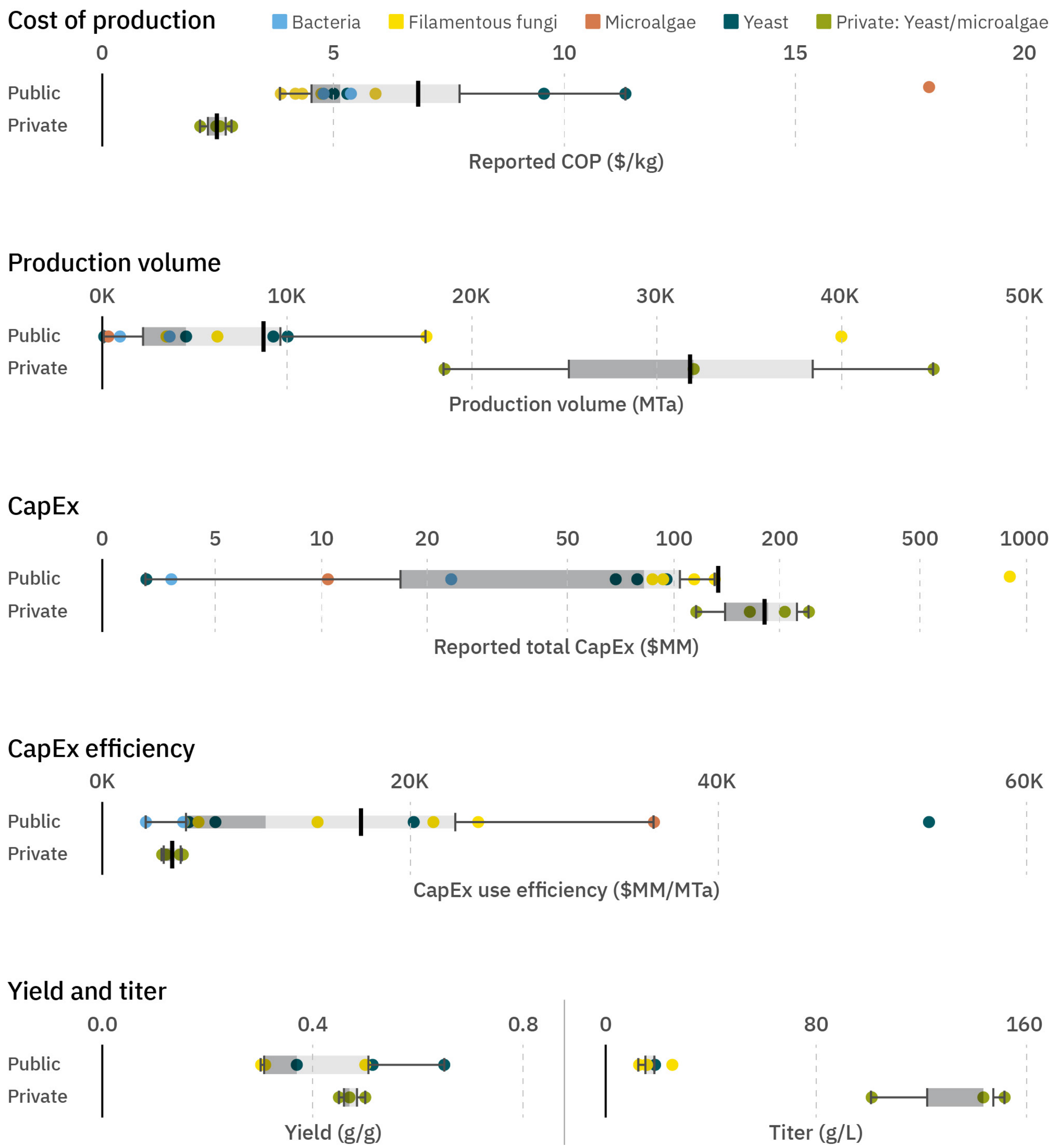


Figure 9. Aerobic fermentation for biomass protein data comparison: published vs. private

Production volume parameters were the most significant difference between public and private TEMs for aerobic SCP, likely driving a majority of cost differences

Published aerobic SCP TEMs report an average production volume of ~10,000 MTa with a COP of $7.0/kg, compared to 32,000 MTa and $2.5/kg in the private case study SCP model (Table 1; Figure 9). Not surprisingly, due to lower average production volumes, published TEMs modeled lower CapEx costs, but the private models have improved CapEx efficiency (lower CapEx to production volume ratio) (Figure 9). Feedstock yields for public and private models align within expected biological limitations for biomass production. However, titers diverge drastically due to organism and process differences (batch vs. continuous), and published sources often lack yeast titer data.

These variations may contribute to reported COP differences, suggesting that published TEMs often underestimate current industry process efficiency (e.g., titer), production volume, and overall COP. Cost drivers are further explored in section 2.

1.2.4 Biomass ingredient cost competitiveness

The following section benchmarks the published biomass modeled COP against incumbent protein ingredient market prices. As food ingredients (not an end product), biomass proteins compete with unstructured soy and pea protein ingredients (commonly used in plant-based meat) and, to a lesser extent, whole meat and ground meat ingredients in food formulations. Incumbent protein prices from plant proteins (pea and soy) and animal meat (fish, beef, pork, chicken, turkey) were gathered from wholesale and retail price markets to assess where microbial biomass proteins stand on competitiveness with these conventional protein ingredients (Figure 10).

In this analysis, an FD ingredient is considered to potentially compete on cost if its COP is within a comparable range of an incumbent protein's market price. However, it is important to note that production cost is not market price. Additional costs like processing, packaging, and distribution can widen the gap between alternative and conventional proteins. Further, cost is just one criterion for value. Many fermentation ingredients may offer a value proposition, such as reduced environmental impacts, supply chain resilience, or better flavor, texture, and fiber content for plant-based meat.

This can make it difficult to compare their value-add against incumbent protein ingredients that lack these characteristics. As noted earlier, published TEMs may overestimate COP compared to private models, underrepresenting the cost competitiveness of biomass ingredients.

Cost vs. price
Comparing modeled production costs (COP) to market prices offers a benchmark for cost competitiveness. However, costs and market prices are not equivalent, nor do they encompass the full range of an ingredient's value propositions.

Cost of production (COP) includes the capital and operational costs to produce a product. Here, COP are estimates from TEMs.

Cost of goods sold (COGS) describes the costs to make and deliver a product. This usually includes COP plus additional costs of packaging/palleting and shipping, etc.

Market price typically represents COGS plus additional ingredient markup. Market price can also be influenced by supply, demand, and competition.

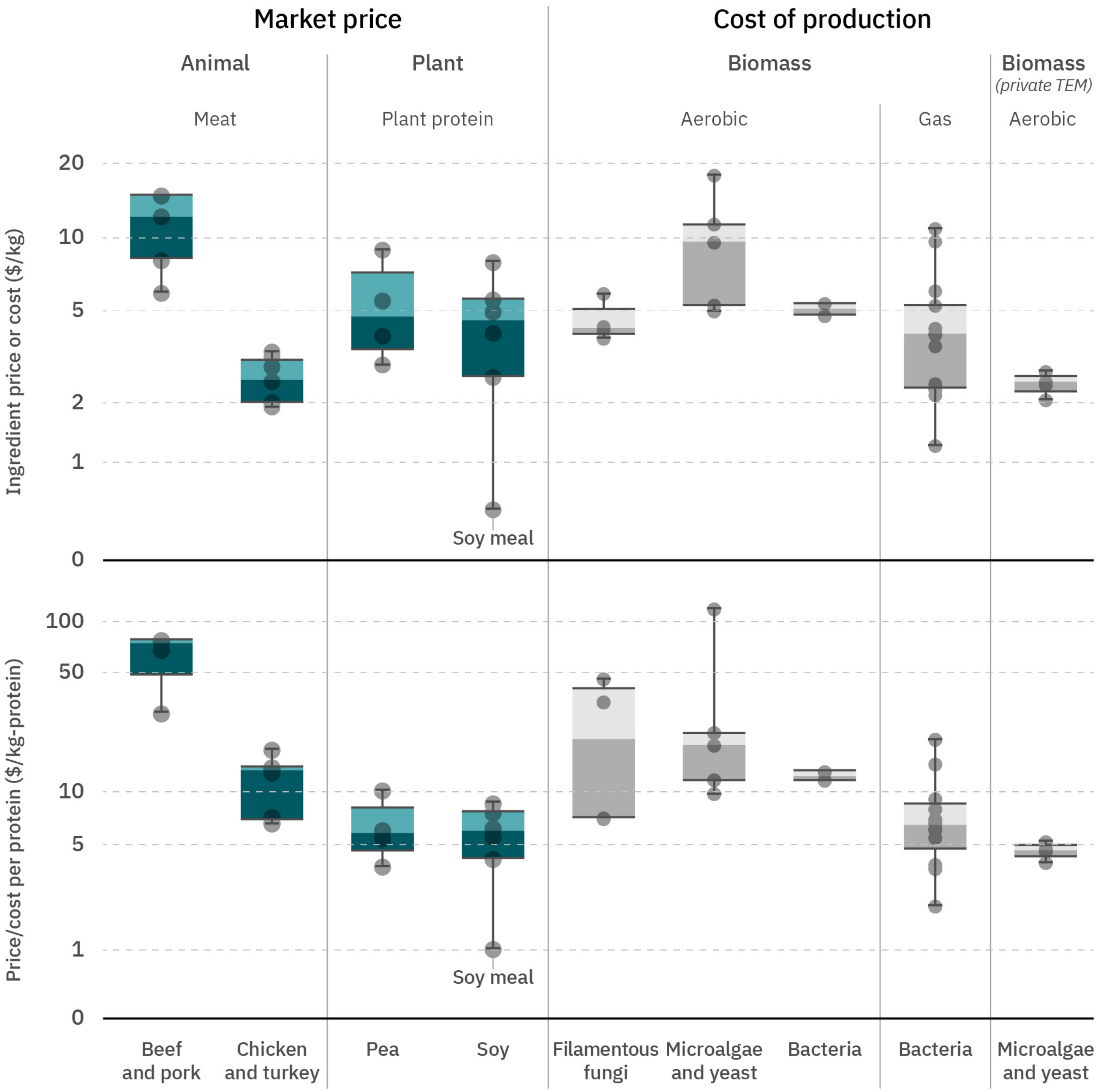


Figure 10. Comparison of market prices (left) of incumbent commodity ingredients versus cost estimates (right) for biomass fermentation ingredients. Top shows ingredient price or cost($/kg); Bottom shows protein normalized price or cost ($/kg-protein). Pea and soy prices include meal, concentrates, isolated, and textured soy protein. Beef and pork include whole, ground, and sliced products. Chicken and turkey include whole, ground, breast, and other cuts.

Cost vs. price comparison provides a benchmark of progress toward price parity. However, costs of production are not reflective of market prices.

Market price ranges are based on data from USDA ERS, USITC, and FRED. Trade data pricing should be interpreted with care, as it may not fully reflect market values due to product aggregation, limited specification detail, and atypical or negotiated transactions.

Biomass ingredients show potential for cost competitiveness with incumbent proteins

Several biomass ingredients show potential to compete on costs with the incumbent protein ingredients (Figure 10). The modeled COP in biomass published TEMs ranged from $1.3 to $18.1/kg and $2.1 to $120.7/ kg-protein (median $19.3/kg protein).

Market price ranges for soy protein concentrates/ isolates ranged in price from $3.0 to $9.0/kg and $3.8 to $10.6/kg-protein, while pea protein concentrate/isolate prices ranged from $2.7 to $8.0/kg ingredient and $3.8 to $10.6/kg-protein. Whereas ground and whole chicken/turkey and beef/pork ranged from $2.0 to $3.4/kg and $6.0-$15.0/kg, respectively (Figure 10). Overall, the COP for the biomass product category is within a comparable range of some incumbent protein market prices; however, a closer look is warranted across microorganisms and bioprocess categories.

Fungal mycoprotein costs: comparable with beef and pork; higher than poultry and plant proteins

COP estimates from fungal biomass TEMs were between $3.8–$6.0/kg-biomass and $7.0–$48.0/kg-protein. Mycoprotein has the potential to compete on a cost per kg-biomass with beef and pork whole and ground products ($2.0–$3.4/kg; Figure 10).

Some fungal biomass products, depending on the fungi, have a lower protein content, which reduces price competitiveness on a per protein basis. On a per protein basis, fungal biomass (median: $21.1/kg-protein) has a notable cost versus price gap, depending on the fungi, with plant protein concentrates ingredients (median: $6.0/kg-protein) and structured chicken/turkey (median $13.5/kg-protein) (Figure 10). However, mycoprotein is often touted for its texture and fiber content as a value-add, which may offer a taste-parity value proposition.

Gas-fermented bacterial SCP: Cost comparable to conventional protein ingredients

Bacterial SCP published TEMs demonstrate more competitive pricing against chicken and plant proteins on a per-kg protein basis compared to fungal mycoprotein (Figure 10). Published bacterial SCP models estimate median COP of $4.3/kg and $7.1/kg-protein. Several bacterial gas fermentation TEMs, modelled at very high production volumes, report COPs that are competitive with chicken and potentially with plant protein concentrate prices.

Private sector yeast and microalgal cost models improve on published models and demonstrate more attractive production costs against incumbent plant protein prices

Published yeast TEMs do not have competitive cost ranges (median of $7.5/kg; Figure 10). Notably, proprietary pricing data indicates that actual market sale prices for yeast biomass are lower than these modeled COPs, suggesting gaps between published TEM assumptions and real-world commercial conditions. For further comparison, a private-sector yeast SCP model, provided by Hawkwood Biotech, estimates a median cost of $2.5/kg and $4.2/kg-protein, which competitively positions these SCP ingredients with many conventional protein ingredients.

Overall, the higher protein content of yeast and many bacterial SCP ingredients enables them to compete on price with conventional protein sources. They also offer improved taste and functional properties, which may provide additional value. However, again, it is important to note that these figures reflect production costs, not market prices. Additional cost reductions, such as those discussed in section 2 of this report, will be needed to compete at market price points.

Biomass fermentation landscape summary

Biomass landscape

- TEM coverage: 25 models with 14 covering gas fermentation
- COP range: strong alignment in $4–$6 per kg biomass across all fermentation processes.
  - Fungal COP median of $4.3/kg-biomass
  - Yeast COP median of $7.5/kg-biomass
  - Gas fermentation COP median of $3.8/kg
- Progress on cost: Biomass TEM models are closing the gap toward cost parity with several incumbent proteins.
  - Fungal protein COP models demonstrate cost competitiveness with beef and pork protein, but have higher protein costs relative to chicken and plant proteins.
  - Private sector yeast and microalgal TEMs diverge from published models and demonstrate competitive production cost benchmarks.
  - Gas fermentation-derived bacteria SCP models demonstrate favorable costs compared to incumbent protein prices, including chicken and plant proteins.

Biomass: public vs private benchmarks reveal process parameter differences

- Published biomass protein models generally assess smaller production volumes than industry benchmarks. Academic parameters are often estimates or derivations of laboratory-scale data.
- Private industry data benefits from in-house development and scaling, leading to up-to-date modeling parameters. These parameters, as key performance indicators, are not usually made available to the public.
- Yeasts and microalgae are an integral ingredient in our food system, yet there is a gap between public and private data, demonstrating a need for greater information sharing.
- Data gap: Despite commercial entries, there are no TEMs to describe the state of SSF bioprocesses for cost reduction. This data gap is another example where a lack of benchmarked techno-economics for current processes interferes with an ecosystem-wide effort to understand COP for SSF approaches and improve upon it.

1.3 Precision fermentation: TEM landscape, commercial benchmarking, and market ingredient comparison

Precision fermentation (PF) harnesses micro-organisms to produce specific ingredients that can be used in various food products, such as egg and dairy proteins, as well as specific enzymes, flavors, colors, fats, and oils. This analysis assessed techno-economic publications of PF-derived proteins, including enzymes.

1.3.1 TEM Landscape: precision fermentation protein TEMs are limited in the published literature

In contrast to biomass fermentation, published PF TEMs are extremely limited, with only four models focused on food proteins (collagen peptide, thaumatin, lactoferrin, and an unspecified nutritional recombinant protein) (Figure 11).

The four PF TEM publications for food proteins:

- Analyze production from fungal hosts, including yeast (*Komagaetella phaffii*) and filamentous fungi (*Trichoderma reesei).*
- Estimate COP spanning four orders of magnitude, from less than $20/kg to $14,000/kg, with a notable data gap in the $20–$200/kg range.
- Model production volumes <2,500 MTa.
- Two are non-peer-reviewed industry white papers (Intelligen), which serve as educational TEM examples for modeling software.

The limited number of PF TEM publications offers a fragmented view of production cost estimates, despite strong commercialization interest in the private sector. The lowest reported COP, $11.2/kg for spray-dried protein (90% purity), comes from a peer-reviewed TEA of a recombinant food protein with the highest modeled titer and production volume among published sources (Voutilainen et al., 2021). In contrast, the highest COP estimate, approximately $15,000/kg, comes from a model of thaumatin sweet protein, which assumed very low titers and small-scale production (Figure 11). Industry white papers by Intelligen report COPs of $292/kg for lactoferrin and $1,043/kg for collagen peptide, both assuming a high-purity (~90%) dried protein product (Da Gama Ferreira et al. 2024a, 2024b)

Due to this scarcity, two additional TEMs on enzyme cocktail production were included, as their biomanufacturing processes closely parallel those used for PF-derived alternative proteins. Of the enzyme TEM publications in scope (n=2), a submerged fermentation cellulase model using filamentous fungi estimated production at $3.5 per kg-protein (de Lima et al. 2022), while a solid-state fermentation enzyme model estimated COP at $2.3 per kg enzyme broth (Sosa-Martinez et al. 2024). Neither enzyme model specified further downstream concentration or purification, as the fermentation broth is assumed to be the final product.

In PF for food proteins, the protein ingredient is concentrated by a series of downstream processing steps to achieve a higher concentration (60%–90%) and increased purity. Therefore, these enzyme production models do not reflect the costs associated with DSP of food ingredient proteins, and do not provide an accurate assessment of the complete cost of production per kg-protein (Figure 11). While cost comparators differ between enzymes and PF proteins for food, their production benchmarks and cost drivers are considered further below.

Precision fermentation TEM landscape
6 models (4 publications, 2 white papers)

	Submerged: Specific protein				Submerged: Enzyme	SSF Enzyme
# of models	4				1	1
Host microbe (# of models)	Yeast (3)			Filamentous fungi (1)	Filamentous fungi	
	Komagataella phaffii (P. pastoris)			*Trichoderma reesei*	*Trichoderma reesei*	*Aspergillus sp.*
Product	Collagen peptide	Lactoferrin	Thaumatin	Generic protein	Cellulase	Cellulase, xylanase, pectinase
Feedstock	Gen1: glycerol		Gen1 + up: sugarcane	Gen2: wheat straw	Gen1: sugarcane	Gen2: food waste
Production mode	Fed batch		Batch	Fed batch	Fed batch	Batch
Production volume *(MTa)*	50	251	84	2,507	2,400	960
Total CapEx *($MM in 2024)*	$143	$123	$44	$165	NA	$4.7
Titer *(g/L)*	18	10	0.03	40	54	NA
Final protein *(%)*	High protein content ~90%				NA: listed at $/kg-protein	NA
COP *($/kg)*	$940	$260	$14,000	$11	$3.5	$2.3
Publication ID	#81 white paper	#177 white paper	#99	#49	#39	#100

Figure 11. Precision fermentation TEM publication landscape for different fermentation types and microorganisms

1.3.2 Commercial benchmarking: published PF protein TEM parameters fall short of commercial benchmarks

Precision fermentation models had limited coverage in the published literature, with high variation in process parameters and COP estimates. Further, the absence of PF TEMs estimating production costs in the \$20–\$200 per kg price range is notable, as many industry professionals tout this range as the current state of technology, given private sector commercial benchmarks. To explore commercial relevance, a comparison of PF model parameters in public and private TEMs is provided below.

Industry data provided by Hawkwood Biotech (Table 2) shows commercial protein production volumes and titers can be significantly higher than those presented in published PF protein TEMs. Published models estimate production volumes between 50 and 2,500 MTa, with three studies modeling <300 MTa, while private benchmarks range from 2,500 to over 25,000 MTa.

Similarly, public models report strain titers ranging from 0.03 to 54 g/L (average ~24 g/L), which is nearly half that observed in private models—an inconsistency that has been noted in other reports (Eastham and Leman 2024).

Additionally, while most public and private PF models assess batch and fed-batch processes, there is a lack of data on continuous production systems for PF proteins. Overall, published models not only remain limited in number but also fail to reflect current industry standards for production scale and upstream efficiency.

The state of PF progress toward price parity cannot be reliably assessed given so few publications, especially when models are not based on commercial assumptions or informed by private sector COP data. Future published TEMs must be informed by industry metrics to ensure they reflect commercially relevant production scales and process efficiencies.

Table 2. Comparing PF production volume and process metrics between public and private data

Area	Units	Public-sector data	Private-sector data
Production volume	MTa	50–2,500	2,500–25,000+
Titer	g/L	24 (average)	42 (average)
Yield on feedstock	g/g	0.01–0.20	0.03–0.17
Production mode	—	Fed-batch	Fed-batch

1.3.3 Precision fermentation ingredient market price landscape

The following section benchmarks public TEM cost data against market prices for incumbent protein ingredients to assess progress toward cost competitiveness and identify remaining gaps. PF proteins are being positioned to compete across a range of sectors—from commodity ingredients like casein, whey, and egg white proteins (e.g., ovalbumin), to higher-value products such as lactoferrin, serum albumins, and enzymes (Figure 12). To evaluate cost competitiveness, PF protein cost estimates are compared to wholesale market prices of conventional protein ingredients in Figure 12.

Market landscape of PF proteins: from high value, low volume to commodity ingredients

The market price for high-value ingredients like lactoferrin (whey-derived) ranged from $250 to $1,000/kg, while high-value albumins ranged from $40 to $70/kg in public trade databases (data not shown), making them attractive initial targets for precision fermentation companies. However, high-volume commodity food proteins such as collagen, dairy proteins (casein, whey), and egg proteins are more important for achieving broader market impact and displacing conventional animal-derived ingredients at scale.

High-volume commodity food proteins have lower market prices in comparison to the high-value ingredients (Figure 12). Food-grade hydrolyzed collagen and gelatin typically range from $6.5 to $9.3/kg at protein purities above 90%. Wholesale dairy proteins vary by type: casein ranges from $8.0 to $11.0/kg ($9.6–$12.2/kg-protein), while whey proteins span a broader range—from $1.2 to $17.7/kg ($6.7–$19.9/kg-protein). Higher-purity whey products, such as WPC80 and WPI, fall between $8.2 and $17.7/kg, or roughly $10.3–$19.9/kg-protein (Figure 12). Egg white protein prices range from approximately $1.6 to $14.0/kg, depending on purity, with protein-adjusted prices between $15.6 and $59.4/kg-protein (Figure 12). Given the ongoing supply chain disruptions from avian flu and the potential for improved functionality and cost-in-use, egg proteins represent a strong opportunity for precision fermentation innovation.

Limited precision fermentation TEMs makes it difficult to assess cost competitiveness with commodity protein ingredients

Published PF protein models generally show costs exceeding the $5–20/kg target for commodity proteins. Only one model estimates a competitive $11.2/kg for a recombinant nutritional protein. Other models show much higher costs, such as $15,000/kg for thaumatin due to low titers, and $292–$1,043/kg for lactoferrin and collagen peptide, reflecting high-purity applications. This data suggests that PF proteins currently struggle to compete with commodity protein prices, except potentially for high-value isolates like lactoferrin (>$200/kg, data not shown), and may demonstrate why several companies have targeted this higher value whey protein isolate.

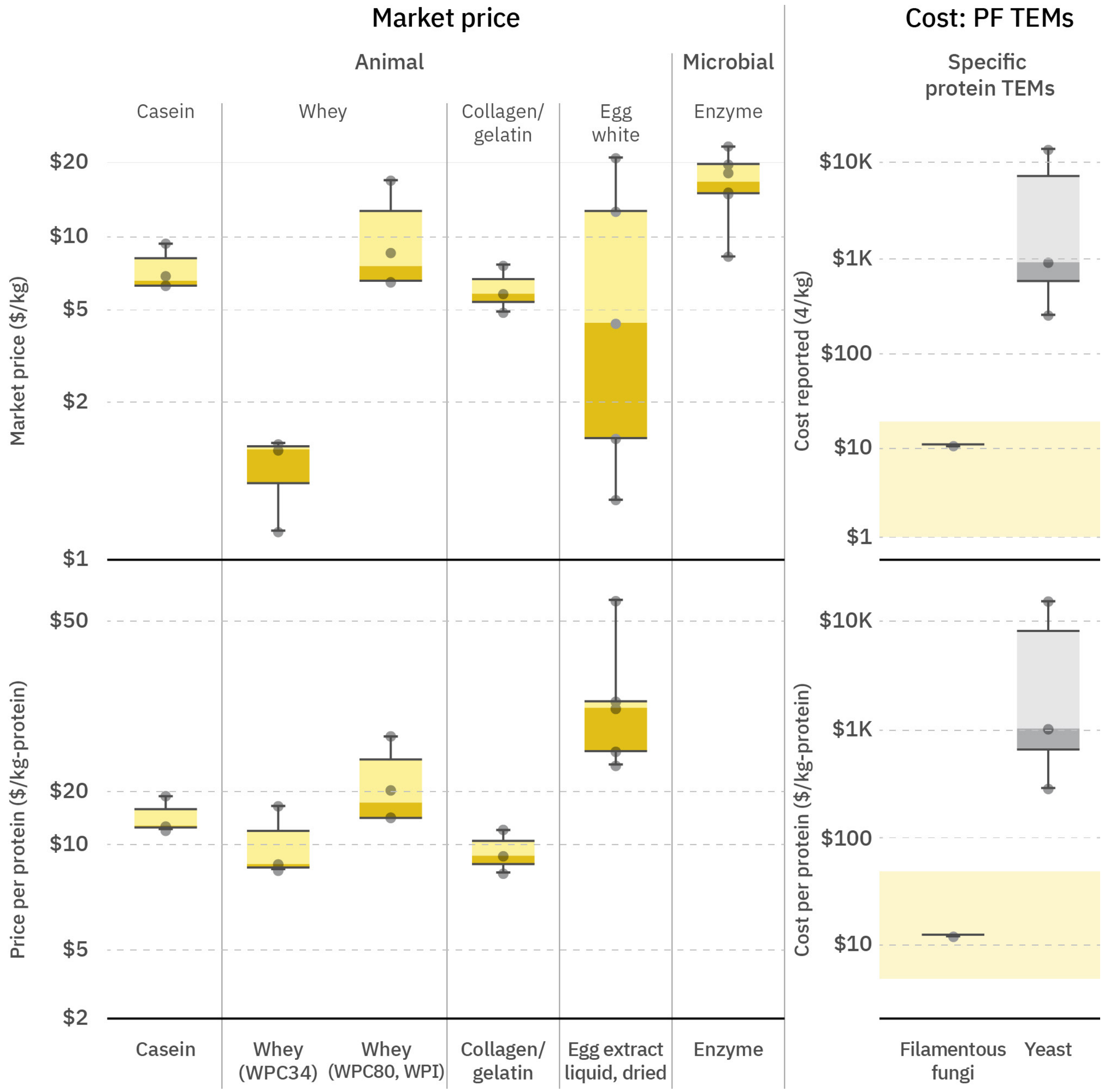


Figure 12. Comparison of market prices (left) for incumbent protein ingredients versus TEM COP estimates (right) for PF ingredients. Top shows price or cost per kg-ingredient, while bottom presents protein content normalized price and cost per kg-protein. Yellow reference box in PF cost = market price axis range. Microbial enzyme prices (trade import/export data) are shown to provide a reference point for a microbial protein product; however, protein-adjusted prices may be an order of magnitude higher due to the low protein content (1-5%) of enzyme solutions.

Cost vs. price comparison provides a benchmark of progress toward price parity. However, costs of production are not reflective of market prices.

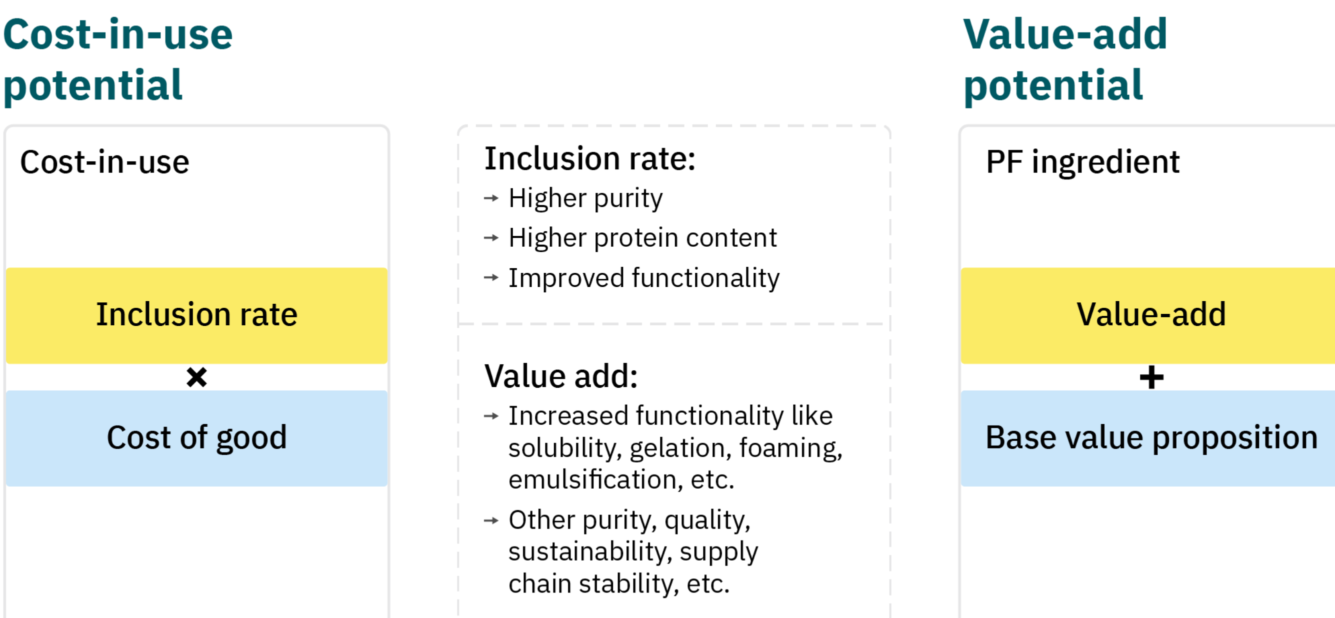
Market price ranges are based on data from ADPI, FRED, USDA ERS, and USITC. Trade data pricing should be interpreted with care, as it may not fully reflect market values due to product aggregation, limited specification detail, and atypical or negotiated transactions.

Precision proteins offer functionality that could enable cost-in-use competitiveness

To compete on price with commodity proteins, PF production costs likely need to push below these $5–$20 per kg commodity protein cost ranges and a normalized protein cost of $7–$15 per kg-protein. However, this direct comparison fails to consider cost-in-use, or the total cost contribution of the ingredient to the final product (Figure 13). Precision fermentation protein ingredients are used at various inclusion rates depending on the product. Some are formulated at low concentrations, like meat protein enhancers (<2%), sweet proteins (<0.1%), or bioactive nutrient proteins like lactoferrin (<1%), whereas eggs and dairy proteins are often formulated at higher concentrations (5%–35%).

Isolated PF proteins, such as egg ovalbumin and sweet proteins, often contain a concentrated protein of interest rather than a mixture of various proteins. Higher protein concentration and purity, as well as improved functionality, can reduce the inclusion rate in the final product over conventional proteins. Thereby, reducing the total cost-in-use. While cost-in-use provides an opportunity for PF proteins, production costs still need to be driven down to competitive prices.

Cost-in-use, the ingredient cost in a product formulation. A combination of the ingredient cost and inclusion rate to determine how much the ingredient contributes to the total cost of a product.



*Inclusion rate: proportion of the cost of ingredient within the total cost or price of a product.

Figure 13. Description of cost-in-use

Precision fermentation protein landscape summary

TEM landscape:

- TEM coverage: Only 4 models (2 peer-reviewed, 2 white papers)
- COP range: <$20/kg to $14,000/kg, with a notable data gap in the $20–$200/kg range.
- Private sector benchmarks: Published PF TEMs largely underestimate the production volume needed to compete on price. Further, some published PF TEMs under-model titer.
- Data gap: Published PF TEMs primarily emphasize a narrow range of processes and organisms, potentially underestimating the full range of production efficiencies and potential for commercial viability. The sector would benefit from high-volume PF models exploring process improvement, such as high-titer advances, DSP recovery improvements, or continuous/semi-continuous production processes.

Progress on cost:

- Progress on cost: A single PF-protein TEM reporting $11.2/kg for a 90% protein powder suggests potential cost competitiveness with some commodity proteins. However, a lack of published TEM data and process benchmarks makes it difficult to accurately assess progress on price parity against commodity conventional ingredients.
- High-value target selection: For those building infrastructure and pipelines for PF proteins, high-value/low-inclusion rate proteins, like lactoferrin or sweet proteins, offer a chance to produce a high-value protein with lower demand, while gaining bioprocessing experience and scaling up production. Recent shifts in company target focus make sense from this perspective.
- Low-value target selection: Higher functionalities of PF-derived egg proteins could enable them to compete on a cost-in-use basis. Egg-white proteins have a higher commodity price and price per protein than dairy and collagen proteins, and further disruptions in egg-white protein supply chains could push this price further.

1.4 Microbial fats & oils: published TEMs and market ingredient landscape

Precision fermentation has the potential to produce fats and oils that offer improved flavor, functionality, and sustainability for alternative meats and dairy. These microbial lipids, typically derived from oleaginous fungi and microalgae, often referred to as single-cell oils, can serve as replacements for conventional fat sources such as commodity vegetable oils, omega-3 fish oils, and others.

1.4.1 TEMs landscape: published microbial oil TEMs are more aligned in cost than PF protein models, but are similarly limited in bioprocesses

While microbial oils received significant research attention for biodiesel applications, the landscape here focused on TEAs of microbial oils for food applications. This landscape identified only six TEA publications (seven TEMs) for food-grade microbial oil production models, six of which model generic "microbial oil" or "microbial palm oil" produced from yeast strains (Figure 14).Only a single microalgae TEM assessed microbial polyunsaturated fatty acid (PUFA) production despite current commercial microbial production of omega-3 and omega-6 PUFAs (See GFI's Omega-3 report).

Modeled COP ranged from \$1.5 to \$19.6 per kg-oil with a median of \$5.1 per kg-oil. The lowest cost estimate comes from a "best-case scenario" study that uses optimized parameters to calculate the theoretical minimum cost (\$1.5/kg oil) for producing microbial palm oil (Karamerou et al. 2021). In contrast, the highest estimate (\$19.6/kg) was derived from a sidestream valorization model with undersized capacity and lower production benchmarks (Gallego-García et al. 2022).

Finally, two papers modeled the median COP estimate at \$5.1 and \$7.8 per kg-oil when using higher production capacity and various carbon sources (Koutinas et al. 2014; Bonatsos et al. 2020). For more model information and comments, see Figure 14 and Appendix 1.

Five sophorolipid TEMs, reported across two publications, were identified. While sophorolipids have potential applications in food (Bueno-Mancebo et al. 2024), the models evaluated production for industrial use. Estimated costs ranged from \$3.4 to \$8.3 per kg: approximately \$3.4–\$4.0/kg via submerged fermentation (Ashby et al. 2013) and \$6.1–\$8.3/kg via solid-state fermentation—the only SSF oil model identified (Martínez et al. 2022). Despite similar COP ranges, the models showed wide variation in production volumes and capital costs (Figure 14), perhaps owing to the extremely high production titer of many sophorolipid-producing microbes. See section 2.3 for a comparison of process parameters.

The majority of microbial oil TEMs (n=5) utilize Gen 1 feedstocks, in line with current standard bioprocessing practices. Given the potential of microbial oils to enhance sustainability and functionality in food applications, there is a clear need for a broader library of TEMs covering a range of scaled production methods and feedstocks. The diversity of oleaginous yeasts and microalgae, each with distinct oil profiles, products, and process parameters, offers a significant opportunity for further modeling to benchmark production costs and identify key COP drivers.

Microbial fats and oils TEM landscape
12 models (8 publications)

	Submerged: Oils			Submerged: Sophorolipids	SSF Sophorolipids
# of TEMs (# publications)	7 (6)			2 (1)	3 (1)
Product	Omega-3 oil	Microbial oil		Sophorolipids	
Host microbe (# of models)	Microalga (1)	Yeast (6)		Yeast (2)	
Feedstock	Gen1: glucose	Gen1: glucose, sucrose	Gen2: food waste, molasses	Gen1: glucose	Gen2: processed oilseed
Production mode	Fed batch	Fed batch, other	Fed batch	Batch	Batch
Production volume *(MTa)*	3,100	8,053–48,315	1,153–16,720	90,700	384
Total CapEx *($MM in 2024)*	$101	$20–$100	$55–$124	$69	$9.2
Titer *(g/L)*	NA	72–112	16–62	100	NA
Yield *(g/g)*	0.125	0.23–0.25	0.12–0.17	0.48–0.60	0.52–0.66
COP *($/kg)*	$19.6	$1.5–$7.8	$2.3–$19.6	$3.5–$4.0	$6.1–$8.3
Publication ID	#67	#55, 165, 176, 153	#55, 184	#10	#12

Figure 14. Microbial oils TEM publication landscape for different fermentation types and microorganisms

1.4.2 Microbial oils ingredient market price landscape

Microbial fats and oils must compete with a range of incumbent product price markets from commodity vegetable oils to functional flavor fats and nutritional PUFAs. Thus, the landscape of microbial oil TEMs was compared to incumbent, conventional oil products, such as fish oils, animal fats, and vegetable oils. The market was also landscaped for microbial oils to assess current price points in the market.

Commodity vegetable oils and animal fats present a still-distant target for microbial oils

Based on current published TEM models, microbial oils are not cost competitive with commodity vegetable oils and animal fat, which realize market prices in the $1.1–$1.9 per kg-fat and $0.9–$1.4/kg oil range, respectively (Figure 15). In contrast, published models estimate that general microbial oil production costs range between $1.9 and $19.6 per kg. Few microbial oil TEMs indicate potential below $2 per kg-oil, with the lowest cost estimate of $1.5 coming from a hypothetical “best-case scenario” for producing microbial palm oil.

Scaling microbial oils to replace commodity vegetable oils and animal fats remains challenging. Reducing feedstock costs is the most significant lever for improving microbial oil economics, alongside increasing yields and recovery rates.

Higher-value, functional microbial fats represent a promising near-term application to enhance plant-based meat and other foods

While microbial oil COP is significantly higher than commodity oil prices, higher-value fats and oils represent more viable targets. In 2024, U.S. import prices for cocoa butter averaged $12.2/kg, and microbial oil imports (likely reflecting omega-3 and omega-6 rich oils) reached $29.9/kg. Combined with published TEMs, these figures highlight the economic potential of microbial oils to compete with premium incumbents, especially with global supply chain disruptions in functional fats like cocoa butter. Such microbial oils may be especially impactful in low-inclusion applications where sensory or nutritional performance is critical.

Omega-3 fatty acids represent a promising and active higher-value application for microbial oil production

Polyunsaturated fatty acids (PUFAs)—particularly omega-3s such as DHA and EPA—are essential nutrients with growing commercial demand across nutrition and food sectors, especially alternative seafood applications. PUFAs are widely used in infant formula, nutraceuticals, and functional foods, and are increasingly being produced through microbial fermentation.

Microbial omega-3s are becoming more cost-competitive due to rising global demand and constrained fish oil supply (GOED 2023). Fish oil prices vary widely, from $0.3 to $13.6 per kg, with high-quality options like cod liver and refined omega-3 fish oils ranging from $4.8 to $13.6 per kg wholesale (Figure 15), while consumer-packaged omega-3 oils are priced at premiums over $40/kg.

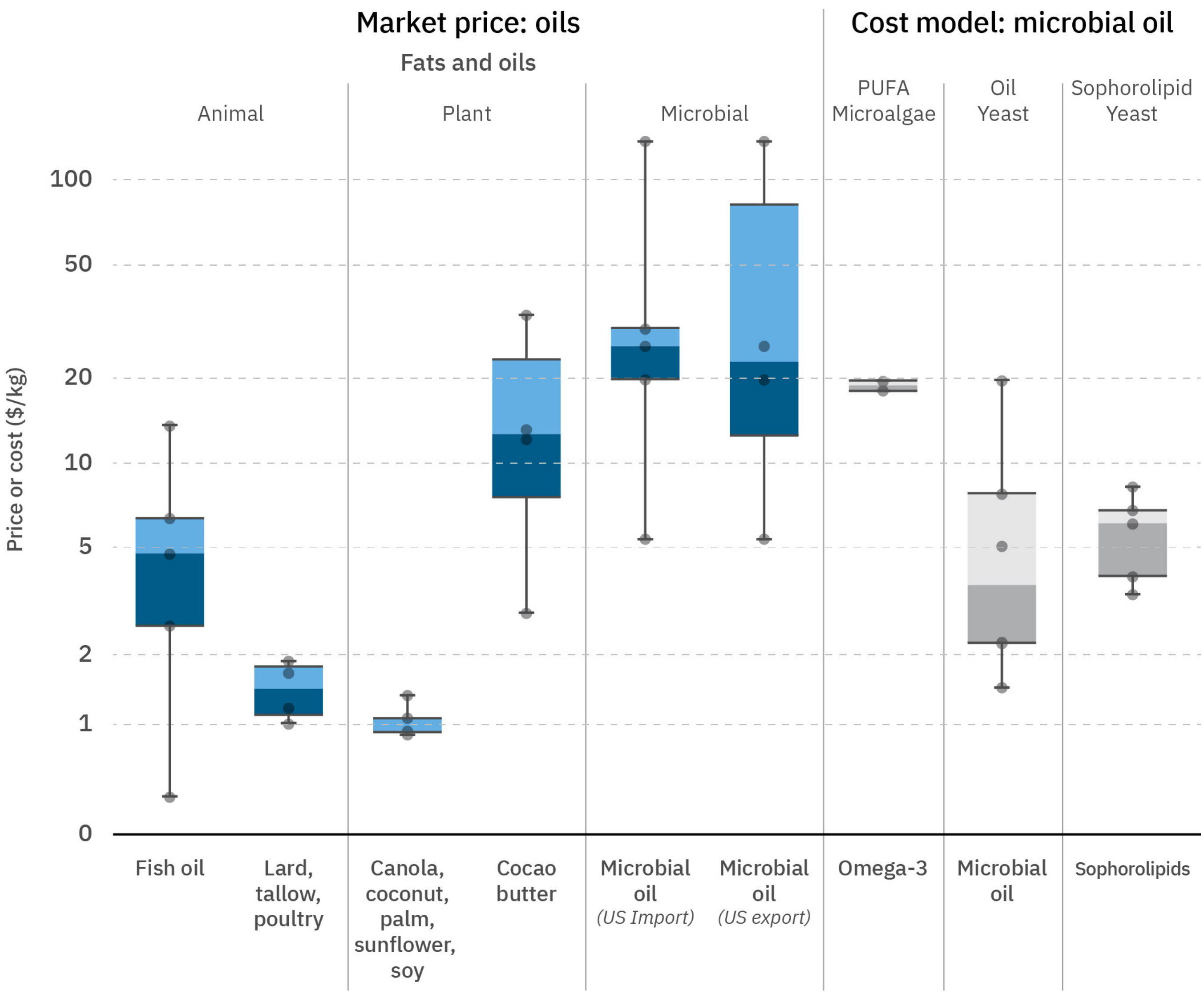


Figure 15. Comparison of market prices (left) for current animal, plant, and microbial oil products versus TEM COP estimates (right) for microbially produced oils. Trade price ranges are shown for both cocoa butter and microbial oils. For microbial oils prices, both U.S. import and export prices are included; export prices likely reflect high-value omega-3 oils produced in the U.S.

Cost vs. price comparison provides a benchmark of progress toward price parity. However, costs of production are not reflective of market prices, which can be higher or lower due to factors such as market volatility, supply contracts, tariffs, and other pricing dynamics across trade and nontrade markets.

Market price ranges are based on data from FRED, USDA AMS, USDA ERS, and USITC. Trade data pricing should be interpreted with care, as it may not fully reflect market values due to product aggregation, limited specification detail, and atypical or negotiated transactions.

In comparison, U.S. export data for commercial microbial oils—likely representing high-volume microalgal omega-3 production—showed a weighted average price of $19.9 per kg in 2024. Microbial oil U.S. import data places prices even higher, averaging ~$30 per kg, likely reflecting PUFA-rich oils used in specialized applications (Figure 15).

These price points suggest that microbial PUFA oils can command a premium over commodity fish oils, making them attractive targets for fermentation. Published TEMs estimate microbial omega-3 costs of production at $18–$20 per kg (Figure 15), though these models are based on subcommercial production scales. With scaling, these costs are expected to decline. Phototrophic microalgae, not included in this analysis due to differing infrastructure and processing needs, have reported COP estimates ranging from $12 to $100 per kg (Wan Razali and Pandhal 2023; Chauton et al. 2015; Schade and Meier 2021).

While full cost parity with fish-derived omega-3s remains a challenge, microbial PUFA oils offer potential advantages in purity, consistency, and supply reliability. As global demand for omega-3s continues to rise, microbial production is well-positioned to play a growing role in high-value nutritional and functional applications.

See GFI's report on omega-3 ingredients for alternative meat and seafood

GFI surveyed companies and researchers working on alternative meat and seafood to learn more about omega-3 ingredient needs. Our results suggest that alternative proteins could represent a lucrative opportunity for algae, precision fermentation, and plant molecular farming companies producing long-chain omega-3s such as EPA and DHA. Learn more here.

Microbial oils landscape summary

TEM landscape

- TEM coverage: 7 models assessing omega-3 oil (1) and microbial oils (6)
- COP range: \$19.5/kg omega-3 and \$1.5–\$19.6/kg microbial oil
- Private sector benchmarks: Published oil TEMs have better alignment with commercial process parameters, especially Gen 1 feedstock models with higher production volume and titer assumptions. Oil TEMs also report yield and titer more consistently.
- Data gap: Published oil TEMs primarily emphasize a narrow range of processes and organisms, potentially underestimating the full range of production efficiencies and potential for commercial viability. The sector can benefit from evaluating TEMs of other oil profiles, microorganisms, and production methods, including continuous fermentation and in situ product recovery processes.

Progress on cost

- Commodity oils: Based on current published TEM models, commodity oils and fats will be difficult to compete with on price unless significant technical advances are accomplished, most notably reducing feedstock costs, followed by improving productivity and product recovery.
- High-value oils: Fish oil price increases have made microbial omega-3 production more cost-competitive, reflective of increasing trade volumes of microbial oils. Published omega-3 oil TEMs reflect ~\$20/kg COP, but only evaluate subcommercial scale production volumes, suggesting that industrial processes could achieve far lower COP.
- Target selection: Companies have set their sights beyond commodity oils to target low-inclusion, high-sensory-impact microbial fats that can improve plant-based meat formulations or offer potential health benefits. This strategy aims for a higher-value market entry point.

Photo credit: phM2019/Shutterstock

Section 2: Path to cost competitiveness: evaluation of COP factors via the TEM landscape and a case study

Overview

In this section, we define the primary components of COP and their relationships to total cost. We first identify COP drivers across the entire FD-ingredient landscape (Scope/Overview) and then examine commonalities and differences based on fermentation process types, feedstocks, and production volumes. Next, we compare performance metrics from published TEMs, focusing on the nuances of yield, titer, and productivity.

To highlight how different COP elements can influence costs, we analyzed a private-sector biomass model for SCP production and conducted a sensitivity analysis to evaluate the influence of key cost factors.

2.1 Components of cost of production

Cost of production refers to the total cost required to produce a unit of product, typically expressed as $/kg. It consists of both fixed and variable OpEx costs associated with raw materials, processing, facility operations, and labor (Figure 16).

CapEx is incorporated into fixed operating costs as depreciation and is spread over the annual production volume (Figure 16).

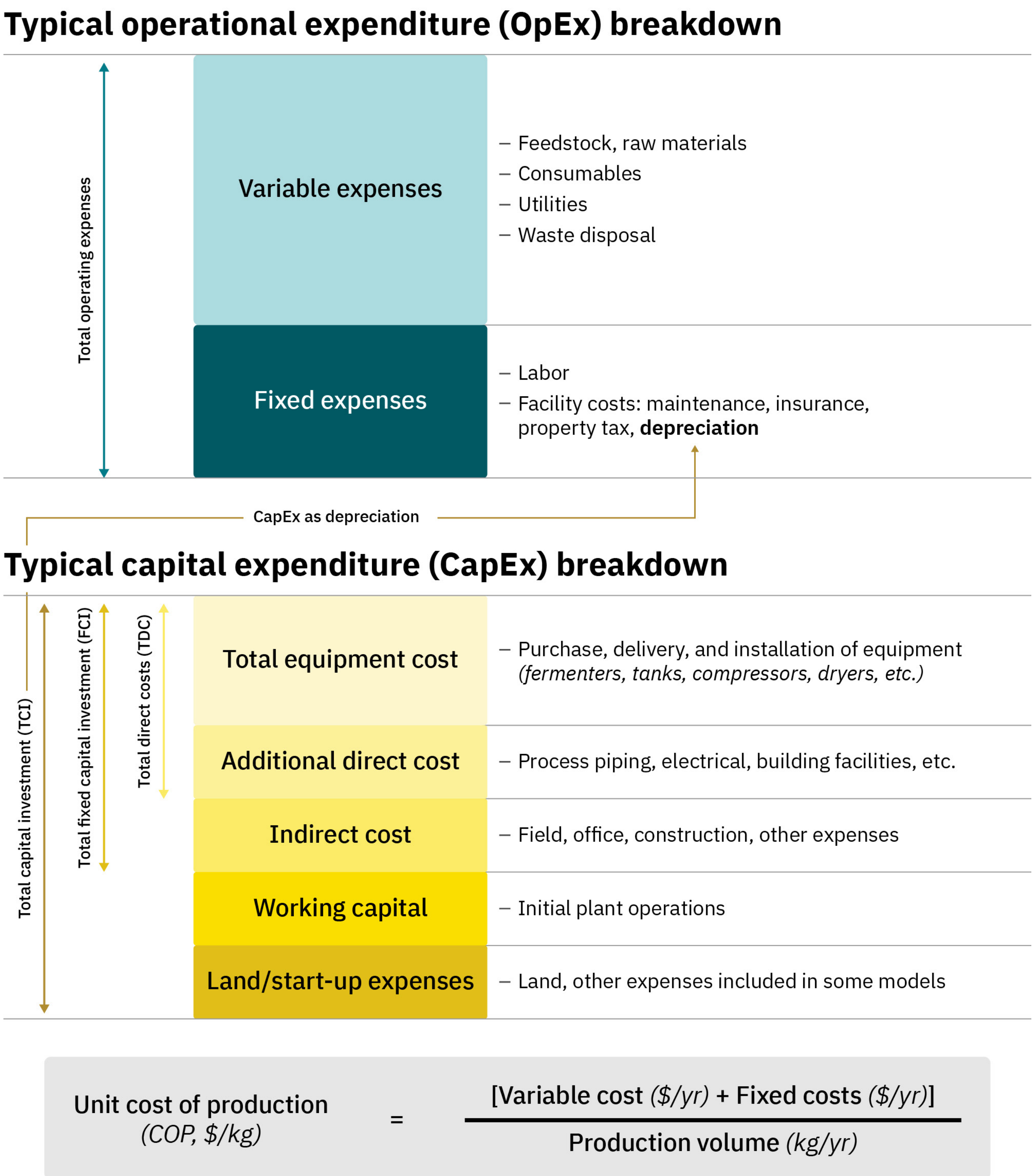


Figure 16. Components of COP based on OpEx and CapEx fixed and variable costs

2.1.1 Influencing COP: cost drivers and cost levers

COP can be influenced by changing the primary cost drivers or invoiceable expenses (e.g., raw materials, utilities, labor, depreciation) that make up fixed or variable OpEx. Cost levers, on the other hand, provide mechanisms to influence these drivers, often affecting multiple cost categories simultaneously (Figure 17). Cost levers include bioproduction efficiency, process rates, and overall output volume. Many cost levers can be optimized through R&D advancements, process improvements, and strategic plant engineering.

Additionally, financial levers, such as depreciation schedules and interest rates, impact CapEx cost drivers and fixed costs, altering long-term financial planning and investment decisions. Cost drivers are also influenced by external market factors, including feedstock and raw material prices, equipment costs, utilities, and construction materials (e.g., concrete, wiring, piping). The following sections explore cost drivers across the published TEM landscape and the cost levers that the industry can influence to reduce overall COP and increase the competitiveness of FD products and ingredients.

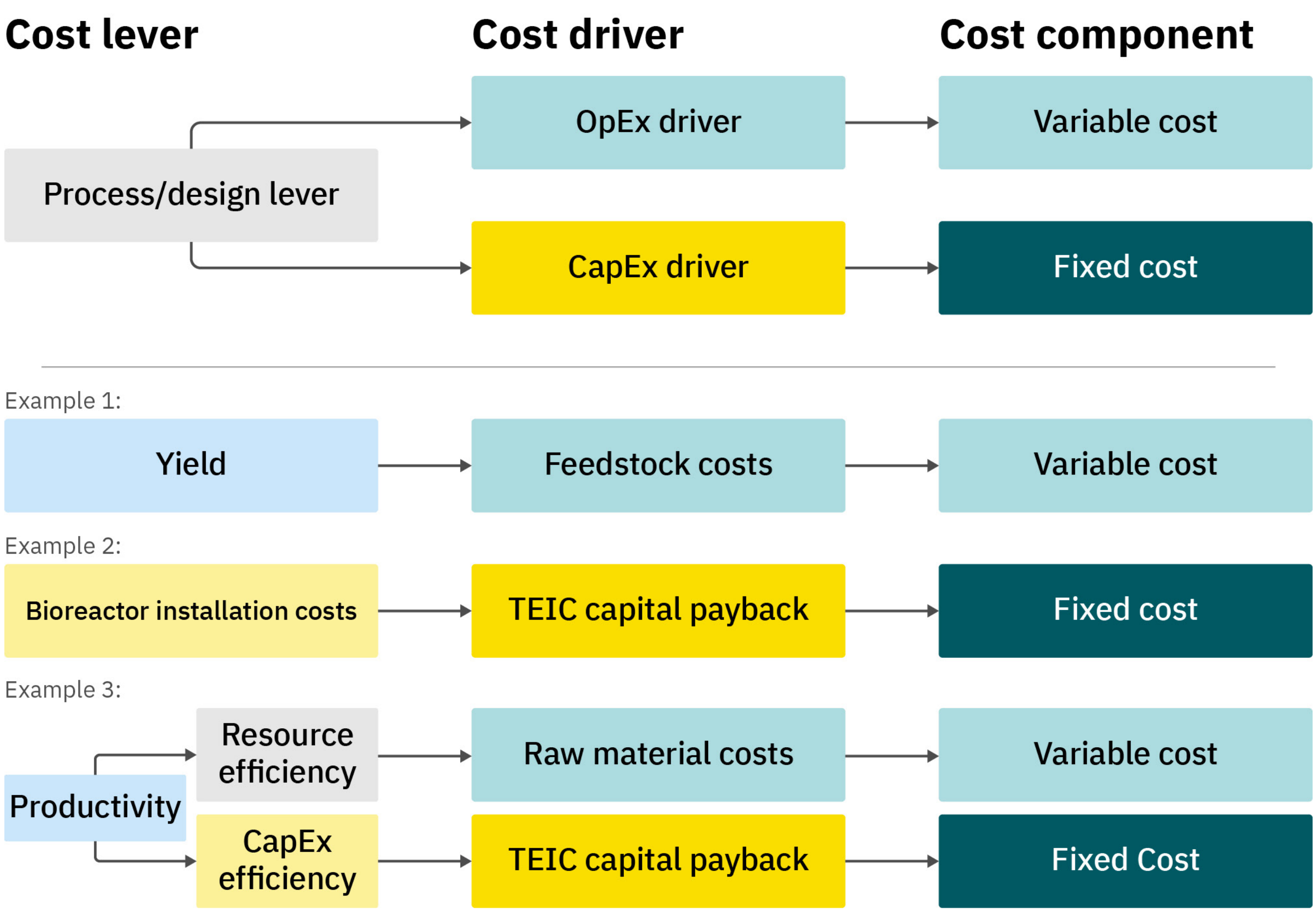


Figure 17. Process flow of factors that influence cost

2.2 A survey of published model COP drivers and levers

2.2.1 Identifying leading trends

Within an individual model, a COP driver analysis identifies the most significant areas for cost reduction. When examined across models, a COP driver analysis provides insight into broader industry challenges and opportunities, highlighting trends that shape the economic feasibility of fermentation-based production.

Leading contributors to COP were extracted from 54 of the 55 published TEMs (from 32 unique publications) (Figure 5). Two models lacking sufficient detail were excluded from this analysis. Appendix 2 reports the top three cost factors for each model, ranked by their relative impact.

Figure 18a presents the top 15 cost drivers and levers, ranked by their occurrence as the primary contributors to COP. Among these, feedstock cost, facility and capital costs, feedstock conversion costs, and raw materials costs account for over two-thirds of the primary COP drivers and levers (37 of 54 models) in the TEM landscape (Figure 18b).

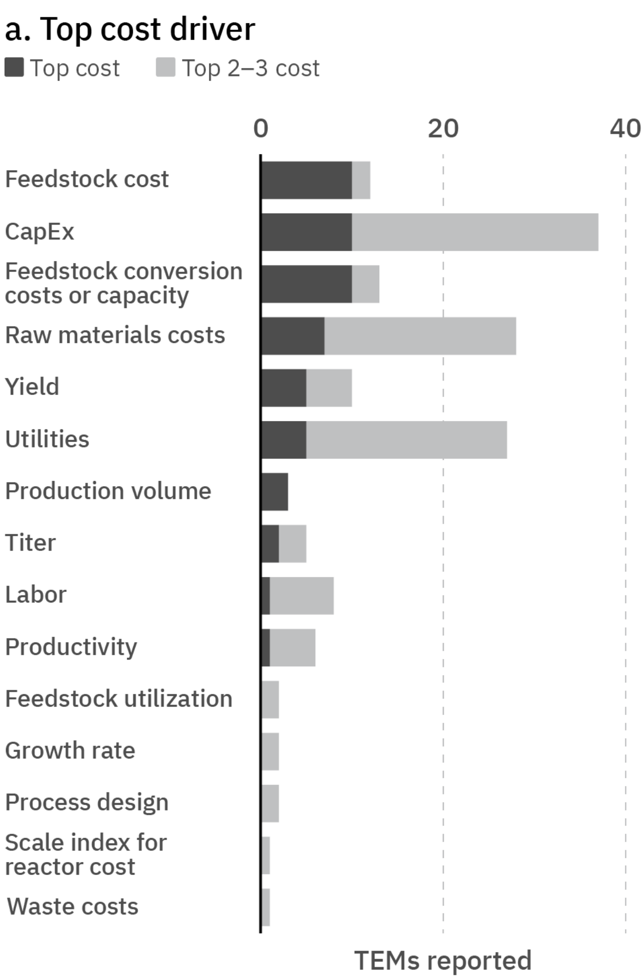


Figure 18: (a) Leading COP drivers and levers identified from published TEMs, and (b) distribution of published model primary COP drivers/levers across major categories

2.2.2 Leading COP driver and lever trends: feedstocks and raw material costs, facility and capital costs, and fermentation process metrics

Further consolidation of the primary cost factors into related areas revealed three high-level categories (Figure 18b): 1) Feedstock and raw materials, 2) Capital and facility costs, and 3) fermentation process metrics. Each of these cost categories is described in more detail below.

COP FACTOR #1:
feedstocks and raw material costs (cost drivers)

Feedstock, raw feedstock processing, and raw material costs were the primary COP drivers in just over half of the published models. These costs include the purchase price of purified feedstocks (e.g., purified sugar, glycerol, gas) as well as pretreatment and purification expenses (e.g., hydrolysis, sterilization) required for processing feedstocks and other raw material inputs.

Raw material costs also encompass media components and chemicals used throughout upstream and downstream processing, supporting microbial growth, product formation, and purification. These expenses vary based on feedstock type, process complexity, and required purity levels, all of which impact overall production economics.

COP FACTOR #2:
facility and capital-related expenses (cost driver and levers)

Facility and capital-related expenses, such as total CapEx (a cost driver realized as depreciation) and production volume (a cost lever), represented the second-largest COP driver category.

Increasing production volume reduces COP through benefits from economies of scale, whereby other fixed costs (e.g., labor, overhead) have a diminishing impact on unit costs.

Capital efficiency, expressed as the CapEx cost per total production volume ($MM/MTa), is an informative metric to evaluate how well a process utilizes its capital investment. This efficiency can be achieved by (1) increasing operational volume to increase production output, which reduces CapEx per unit through economies of scale, (2) reducing total cost of CapEx, and (3) increasing process productivity to boost output at a given scale, which is influenced by key process metrics like titer, productivity, batch failure rate, and DSP recovery.

COP FACTOR #3:
process metrics (cost levers)

Fermentation process metrics—yield, titer, and productivity—influence both variable and fixed costs by affecting raw material efficiency, energy consumption, DSP costs, and the efficiency of existing capital assets. Additionally, they influence CapEx needs by determining infrastructure and equipment requirements. Together, these factors shape overall process economics and scalability.

Yield

Yield (g-product/g-feedstock) measures the efficiency of feedstock conversion into the desired product, representing the amount of product generated per unit of carbon source consumed. It is determined by the type of microbe, its strain improvements, fermentation parameters (e.g., nutrient concentration, pH, temperature), and feedstock purity. As a lever, yield directly affects variable costs. Higher yields reduce raw material costs by decreasing the amount of feedstock required for the same output.

Titer

Titer (g/L) measures the product concentration in the fermentation system. Increasing titer means more product is concentrated within a given volume, impacting both fixed and variable costs. By producing more with the same equipment and time, fixed costs are spread over more product, lowering the cost per kg. Higher titers reduce broth volume requirements, lowering variable costs associated with water, media, and utilities. Additionally, they can reduce DSP costs, as less broth volume requires less processing, leading to lower energy consumption and recovery expenses. While higher titers can optimize per-unit production costs, titer alone does not determine total product output, as overall production is influenced by fermentation volume and productivity.

Furthermore, not all titer improvements may lead to cost savings. Some products become toxic to the microbe at high concentrations, requiring process modifications that increase fixed costs. Other products may cause higher viscosity or lower solubility, complicating DSP and potentially offsetting cost benefits.

Productivity

Productivity (g/L/day), which measures the rate of product formation over time, directly affects operational efficiency and costs, making it a prime lever of overall COP. Higher productivity may shorten fermentation time, reducing variable costs associated with energy use. Increased productivity may improve coordination with DSP, minimizing bottlenecks that can otherwise increase costs due to delays or inefficient resource and labor use.

Beyond OpEx reductions, increasing productivity improves CapEx efficiency by maximizing fermenter utilization. If higher productivity allows greater output per fermenter, fewer or smaller bioreactors may be needed to achieve production targets, reducing the required capital investment in fermentation infrastructure. Additionally, improved productivity spreads fixed CapEx across a larger product volume, lowering per-unit capital costs. However, if DSP capacity does not scale accordingly, additional processing equipment or facility upgrades may be necessary, which could offset CapEx savings and introduce new operational constraints. The following section examines opportunities to reduce these primary COP drivers across different process types and production scales.

2.3 Cost reduction insights from published TEMs: opportunities by production type

Published TEMs give a consistent overview of the main cost drivers in microbial protein and oil production. Although the fraction each cost category contributes varies by product and fermentation type, three areas consistently contribute to overall costs: capital efficiency, feedstock processing, and bioprocess performance. This section explores each of these cost categories and highlights approach-specific opportunities to reduce COP. It is important to note that the trends developed here are based on published TEMs that do not fully reflect current commercial practice.

Opportunity 1: reduce capital expenses and improve capital efficiency

Increasing production volume to achieve economies of scale is a way to reduce COP across all production processes. This can be seen in current commercial practice.

Published TEM data reflects the significant reduction in COP that comes with economies of scale, particularly above ~2,000 MTa (Figure 19a). This reduction in COP with increased facility size is mainly due to improvements in capital efficiency, the ratio of CapEx to production volume (Figure 19). Figure 20a highlights the relationship between lower COP and higher capital efficiency.

The economies of scale are an important lever driving down costs.

While achieving economies of scale is an essential step to producing a cost-competitive product, other levers to improve capital efficiency should be considered before scaling, such as improving process efficiency or reducing complexity to lower overall capital expenses. Below, we explore opportunities to reduce capital expenses and improve CapEx efficiency across different production and feedstock types.

Focusing on improving capital efficiency in alternative feedstock processes can lower costs and expand access to more sustainable inputs

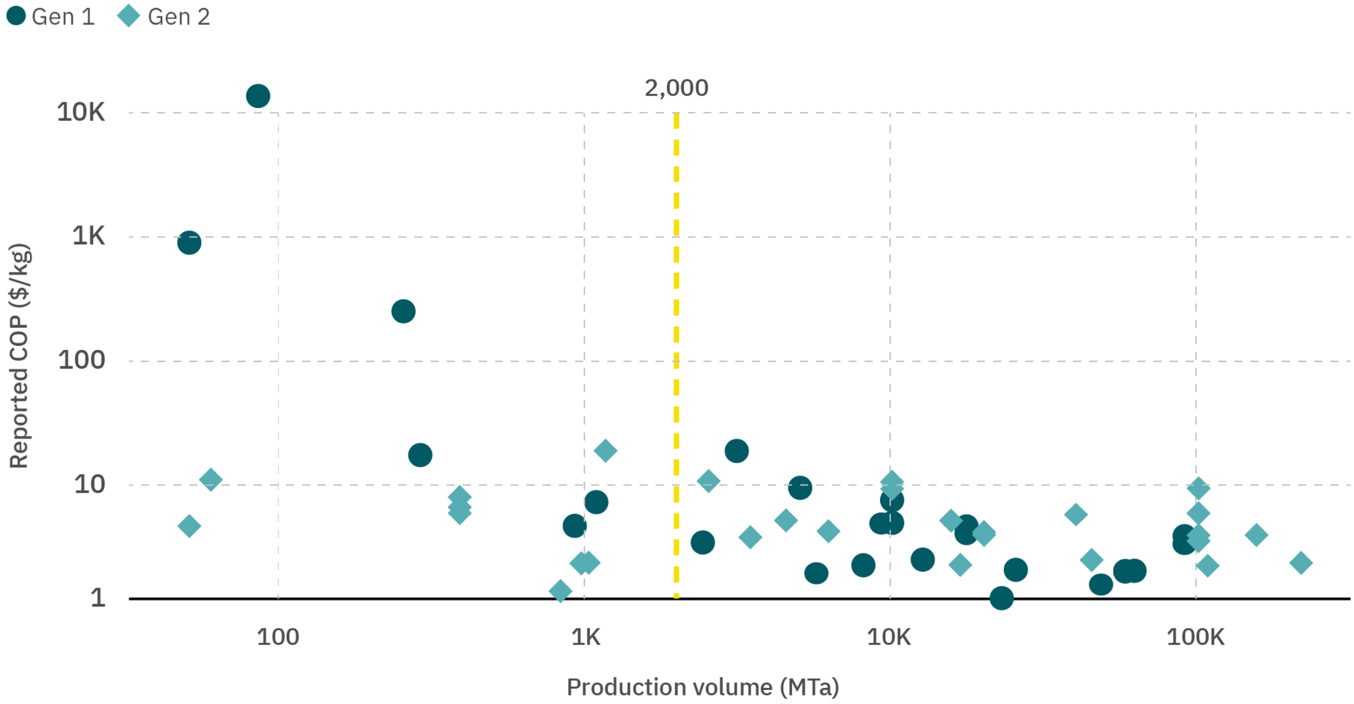
While refining feedstocks like lignocellulosic biomass or food/agricultural sidestreams enables the use of lower-cost, nonpurified carbon sources, it also adds complexity and reduces capital efficiency at commercial scale. Aerobic fermentation models that include equipment for processing these feedstocks tend to be more capital intensive than those using refined sugars, resulting in CapEx inefficiencies (Figure 20b, Figure 21).

Several published TEMs for syngas-based fermentation (IDs 93, 94, 96, 112) and aerobic fermentation using sugars from rice straw hydrolysates (ID 85) highlight CapEx as the primary driver of COP. These cases illustrate the trade-off between feedstock cost and capital requirements: using low-cost or waste-derived feedstocks often demands additional infrastructure for pretreatment or gas handling, reducing capital efficiency compared to Gen 1 (refined sugar-based) systems.

Even when modeled at equivalent production scales, Gen 2 systems are consistently less capital efficient due to added processing steps. To close this gap, there is an opportunity to improve the conversion of sidestream feedstocks into media-grade sugars, especially as demand for purified sugars increases (Lips 2022). Strategies could include novel refining methods, integrating other carbon conversion technologies, or sourcing easier-to-process waste streams.

Finally, for nongaseous Gen 2 aerobic fermentation to achieve cost competitiveness with Gen 1 sugar-fed or Gen 2 gas-fed systems, higher production volumes may be required to offset capital inefficiencies—an approach already modeled in several Gen 2 gas fermentation studies (Figure 20b, Figure 21). Reducing system complexity while scaling production remains a key opportunity for improving techno-economic performance in these pathways.

a. Reported COP *($/kg)* by production volume *(MTa)*



b. Total CapEx *($MM)* by production volume *(MTa)*

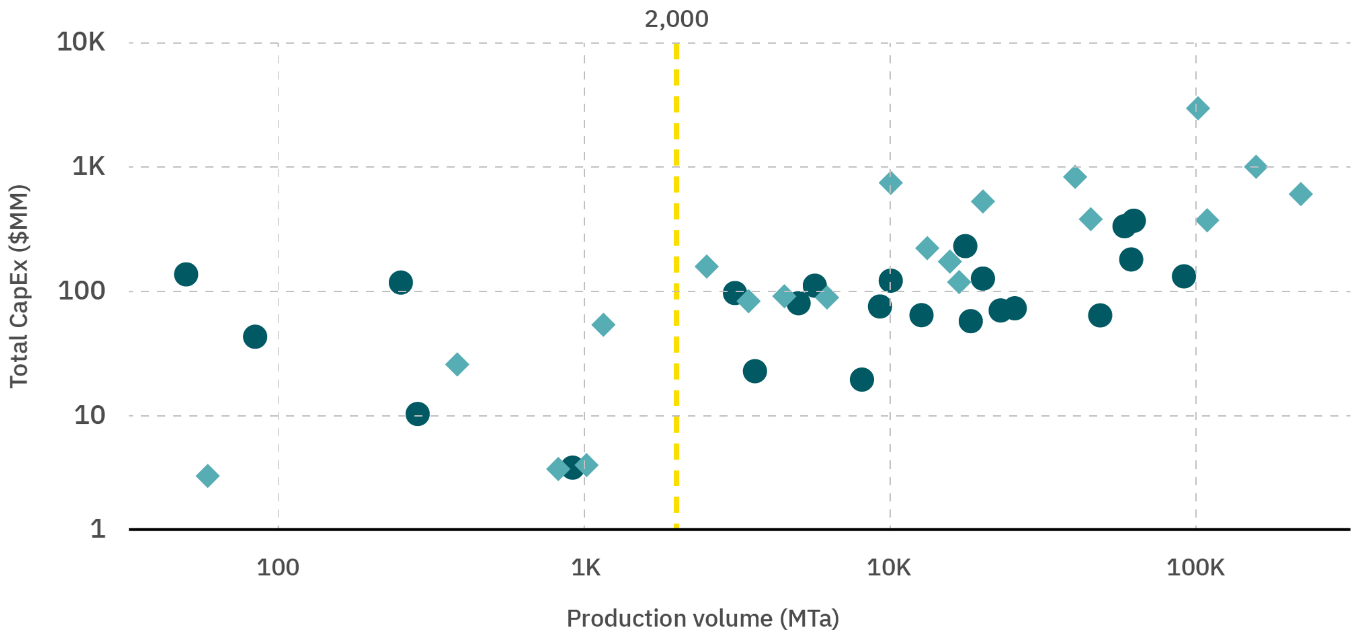
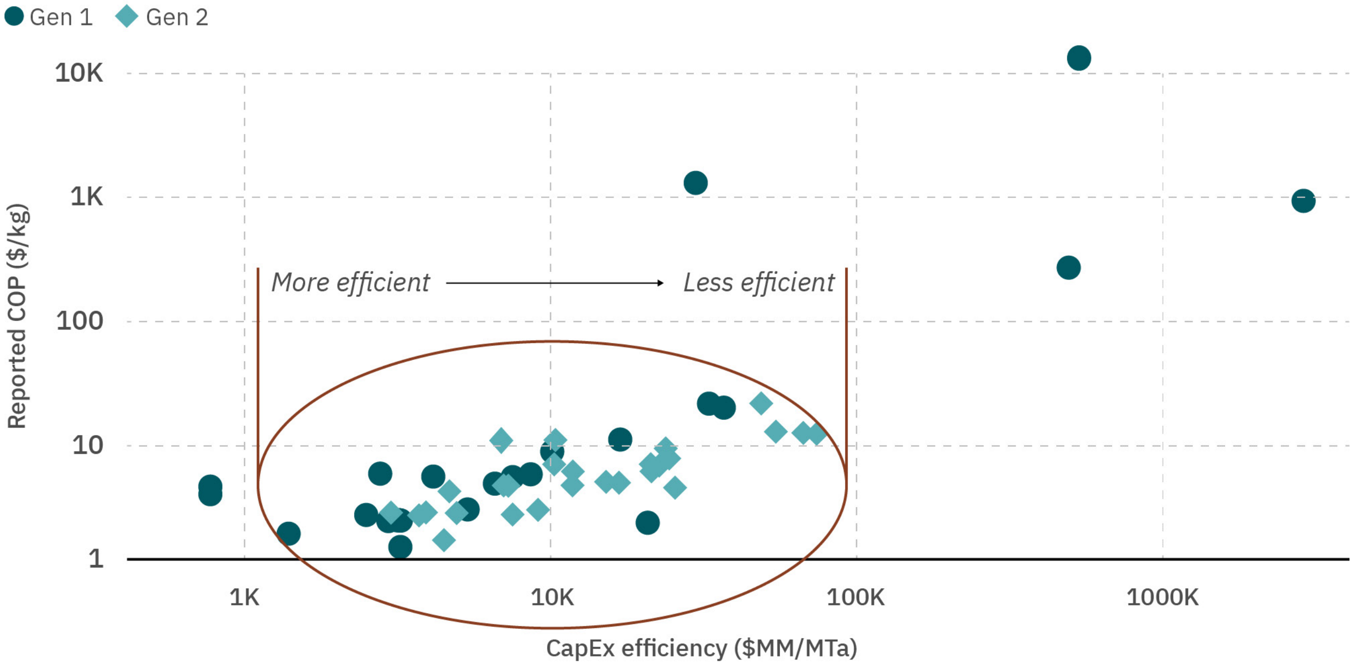


Figure 19. TEMs landscape by production volume its impact on (a) COP ($/kg) and (b) total CapEx costs. Yellow line denotes 2000 MTa production volume.

a. Reported COP *($/kg)* by CapEx efficiency



b. Fermentation approach and reported COP by CapEx efficiency

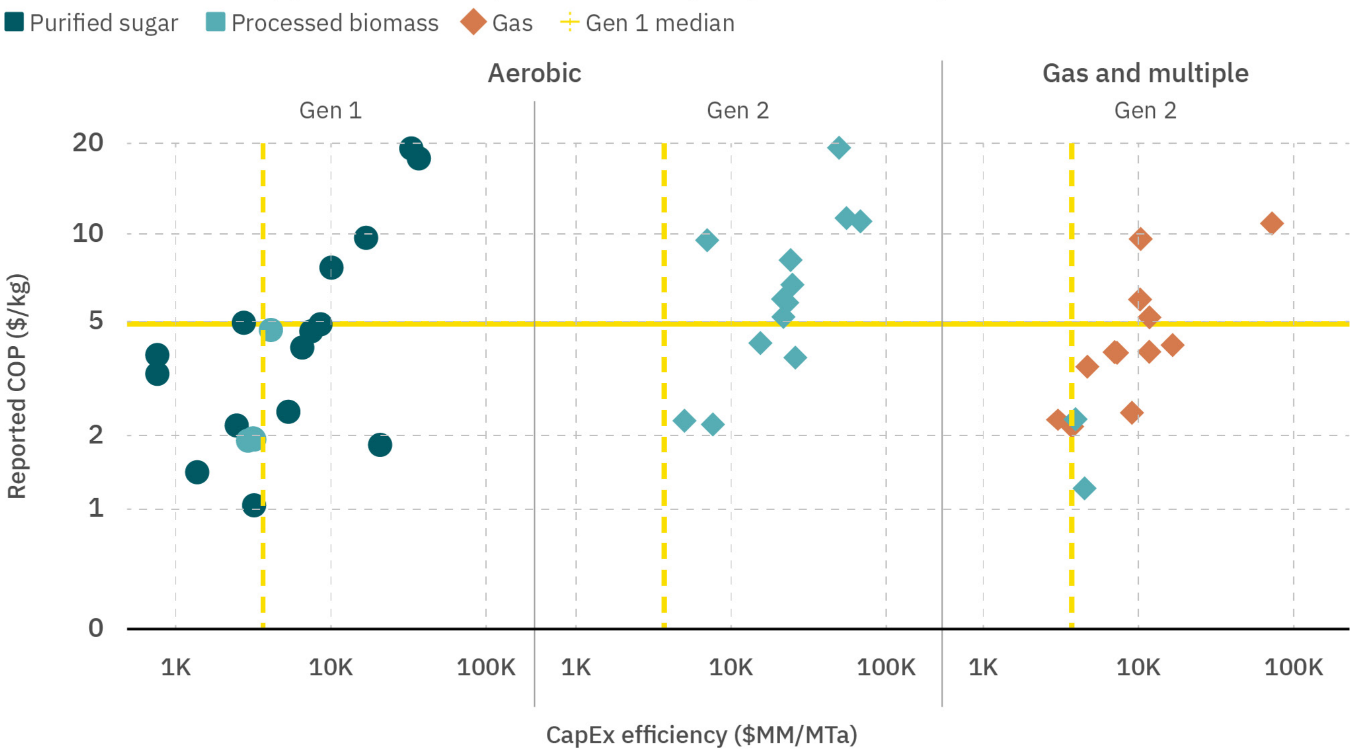


Figure 20. (a) Reported COP ($/kg) plotted against CapEx efficiency across the published TEM landscape, segmented by feedstock approach. Higher COP values are generally associated with higher capital efficiency values (more capital intensive). (b) A zoomed-in view (red circle) highlights trends by fermentation type—specifically aerobic Gen 1, aerobic Gen 2, and gas fermentation TEMs. A shift to the right at a given COP indicates reduced capital efficiency, illustrating trade-offs between capital-intensive and capital-efficient processes across different fermentation strategies. Yellow reference line represents Gen1 feedstock median values

Gas fermentation presents opportunities to reduce cost through CapEx optimization at commercial scale

Published TEM models using very high production volumes demonstrate favorable COP for gas fermentation-derived production. While gas fermentation facilities have not been built at these scales to date, the low-modeled COP highlights the potential for economies of scale to enable cost-effective protein production using this approach. Compared to Gen 1 sugar-based systems, gas fermentation is often more capital intensive (Figure 21), due to the need for specialized bioreactors, gas handling systems, and purification equipment. This results in lower capital efficiency, though it enables the use of lower-cost feedstocks (Figure 20b, Figure 21). Published models of large-scale syngas- and methane-based fermentation report CapEx ranging from $232MM (ID 93) to $1079MM (ID 190), reflecting the infrastructure required at industrial scale.

Reducing CapEx for gas fermentation may be achievable through bioreactor optimization, standardization of designs, and adoption of new materials or technologies for carbon and hydrogen gas handling.

In comparison, large-scale sugar-fed biomass fermentation models peak at around $130 MM (ID 15), reflecting the relative simplicity of these facilities. However, this lower CapEx may also result from several influencing factors, such as differences in model assumptions, cost inputs, and scaling approaches commonly found in published TEMs. The $130 MM CapEx upper bounds figure should be viewed as a conservative indicator and not directly comparable to industry benchmarks.

For more on CapEx strategies, see GFI's report on the fermentation manufacturing landscape.

GFI assessed the global fermentation-derived product manufacturing landscape as well as strategies to scale manufacturing capabilities to meet future demand. Learn more and download the report here.

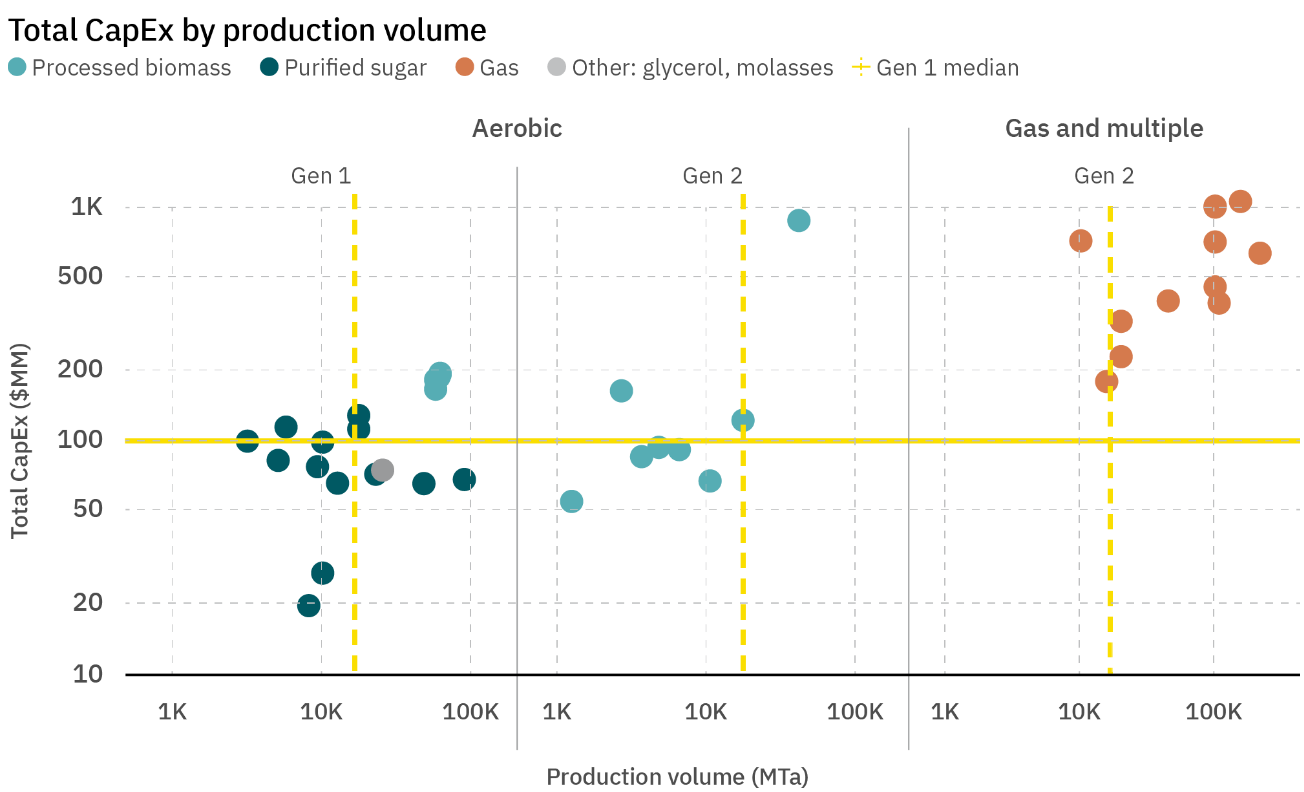


Figure 21. Total modeled CapEx costs ($MM) per facility relative to production volume. While capital efficiency generally improves with scale, total CapEx remains dependent on the fermentation process type—shown here as aerobic Gen 1, aerobic Gen 2, and Gen 2 gas fermentation. Yellow reference line represents Gen1 feedstock median values

Opportunity 2: improve Gen 2 gas and nongaseous feedstock efficiency to tap into low-cost feedstocks

Feedstock costs, raw material costs, and feedstock conversion costs are consistently identified as leading COP drivers for aerobic fermentation processes producing more than ~1,000 MTa. Figure 22 illustrates how individual TEMs align with three leading COP driver categories identified in section 2.2. These cost drivers reflect the high cost of inputs required to convert feedstocks into end products at large-scale commercial production volumes (Figure 22). Opportunities to reduce the feedstock cost category are discussed below.

Improving second-generation feedstock processing efficiency can reduce COP

Among models evaluating aerobic fermentation with Gen 1 feedstocks, feedstock costs emerged as the leading COP driver (9 of 25) (Figure 22). In contrast, for processes using Gen 2 feedstocks, feedstock conversion and processing costs emerged as the leading COP driver (7 of 22). It is worth noting that the use of nongaseous Gen 2 feedstocks, such as lignocellulosic carbon, is largely aspirational at commercial scale today. Over the past two decades, commercial-scale biorefineries, primarily for biofuels, were developed to access nongaseous Gen 2 feedstocks (Calvo-Flores and Martin-Martinez 2022). With improvements in processing technology, increased processing throughput, and a focus on food protein as an end-product, there is now an opportunity to invest in modernized feedstock conversion systems that can lower OpEx.

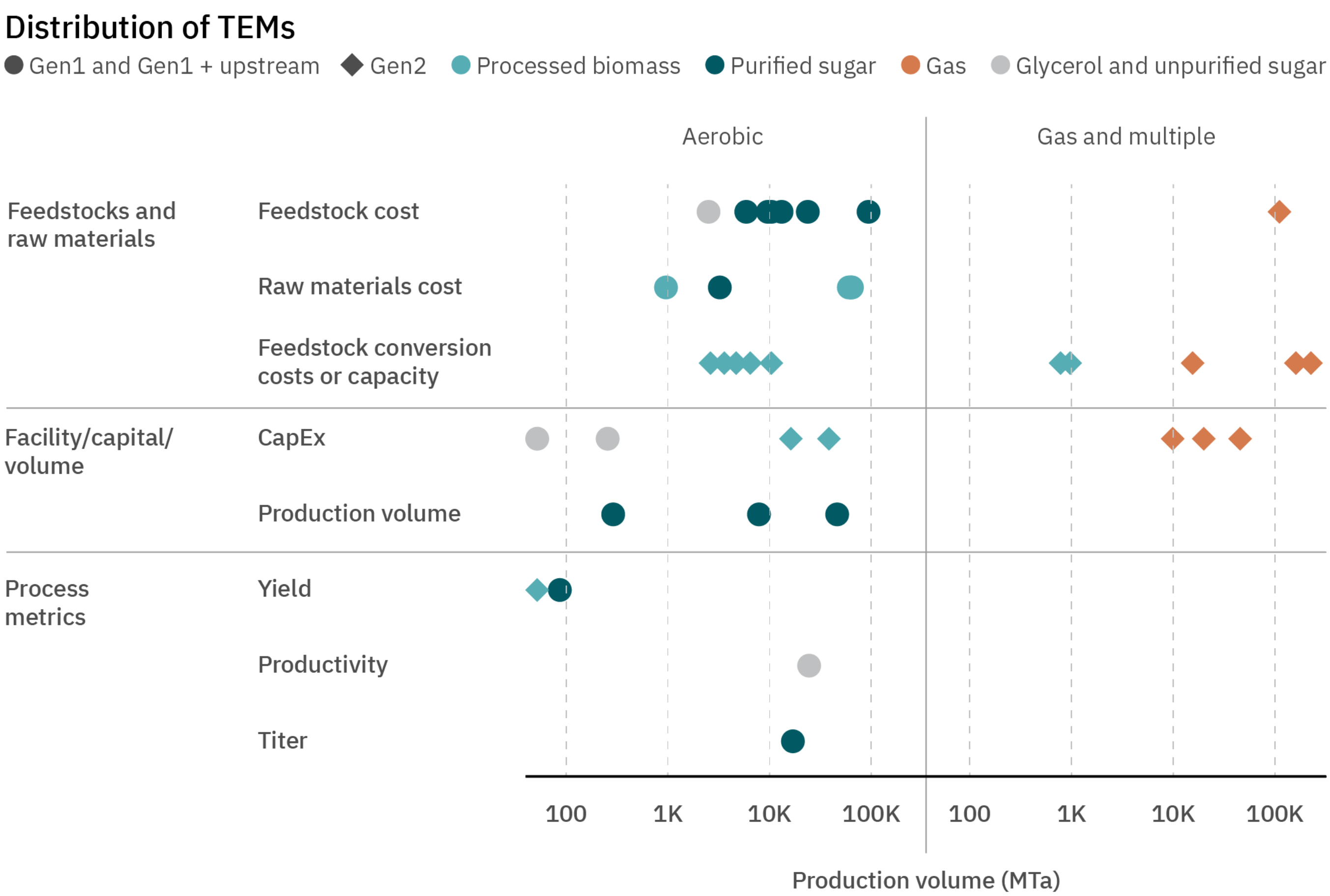


Figure 22. Distribution of individual TEMs across the leading COP driver categories shows groupings by production volume, fermentation type, and feedstock

Low-cost gas feedstock opportunity

Despite the capital intensity of gas fermentation, COP estimates from published TEMs are comparable to those of large-scale sugar-fed biomass production, suggesting that the cost advantages of low-cost gas feedstocks may offset higher CapEx requirements (Figure 20b). Gas carbon feedstocks are widely available and present growing opportunities for capture and valorization into valuable ingredients. They potentially offer a more abundant and lower-cost, lower-volatility alternative to sugar, but their use is highly dependent on the availability of specialized infrastructure. Models for gas fermentation result in low COP, but with high CapEx, due to the requirement for large facilities and high production volumes to unlock economies of scale for gaseous feedstocks.

While gas feedstocks themselves are generally inexpensive, gas fermentation models show that costs often shift toward utilities and feedstock conversion, largely due to gas delivery infrastructure, compression, and processing needs (Figure 22). Continued technology development in areas such as feedstock conditioning, renewable hydrogen production, gas capture, and plant-level optimization offers pathways to reduce costs and enable broader commercialization of gas fermentation.

Opportunity 3: improve bioprocess performance to reduce overall variable and fixed costs

Yield, productivity, and titer are emphatically cited among fermentation professionals as core cost levers, as they impact critical cost drivers in CapEx and OpEx. However, their impact on COP is unique to the process and product, making it difficult to define specific goals for these parameters across the fermentation product landscape. The impact of yield and titer on COP is best explored through TEM sensitivity analysis for a given process and product. To that end, section 2.4 presents a case study to explore the potential of yield and titer to improve COP for an average commercial-scale facility.

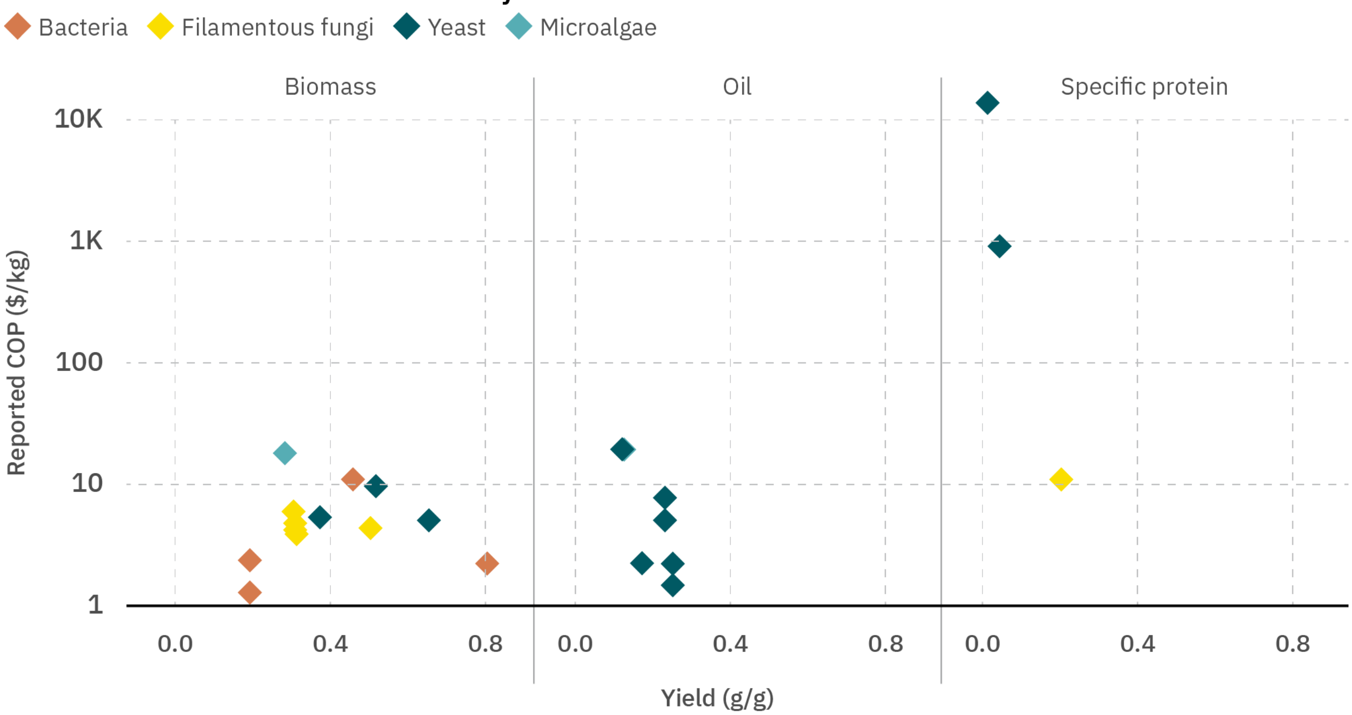
While the published TEMs are not robust enough to assess yield and titer impact at a meta-level, understanding yield and titer ranges is essential for understanding individual process performance.

Yield and titer landscapes provide a snapshot of bioprocess diversity

Figures 23 and 24 show how yield and titer vary across product classes and fermentation strategies. These values tend to cluster by both product type and microbial host, as theoretical yield is determined by the chosen microbes' metabolic pathways. This clustering may reflect a combination of other factors: there may also be a degree of historical or technological bias, where certain organisms are favored due to prior development, regulatory requirements, or platform availability. In general, higher titers and yields are associated with lower COP. This is especially evident in PF. Fungal processes have lower COP than yeast-based systems with more modest titers and yields (Figure 23 "Specific Protein"; Figure 24).

Biomass models are more difficult to interpret as a group, given the wider range of organisms, processes, and fermentation modes they encompass. Unlike protein or oil models, they do not show consistent trends in yield or titer across the dataset. In these systems, the mode of operation, batch versus continuous, has a greater influence on overall productivity and COP than titer or yield alone. Most biomass TEMs analyzed here reflect continuous fermentation (e.g., gas-based SCP or fungal protein processes), which operate at lower titers but benefit from higher overall productivity through reduced downtime and improved equipment utilization. Direct comparisons across fermentation modes are limited due to a lack of published models representing high-titer batch SCP processes. This may be as much due to limitations of the models as the processes. This suggests an opportunity for TEMs to be built with the explicit aim of comparing different processes.

a. COP as a function of feedstock yield



b. COP as a function of product titer

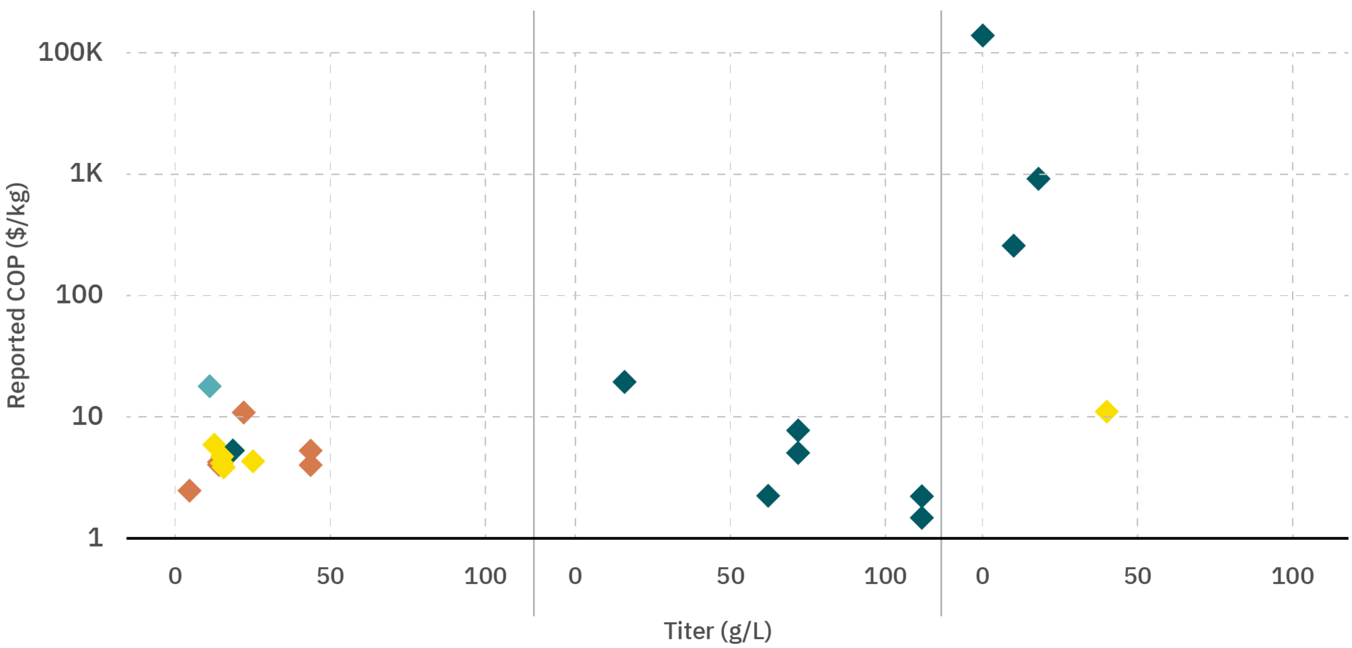


Figure 23. COP as a function of (a) yield and (b) titer for select product classes. Yield is defined as grams of product per gram of carbon feedstock, while titer is expressed as grams of product per liter of fermentation volume.

Process metrics by product class for yield and titer

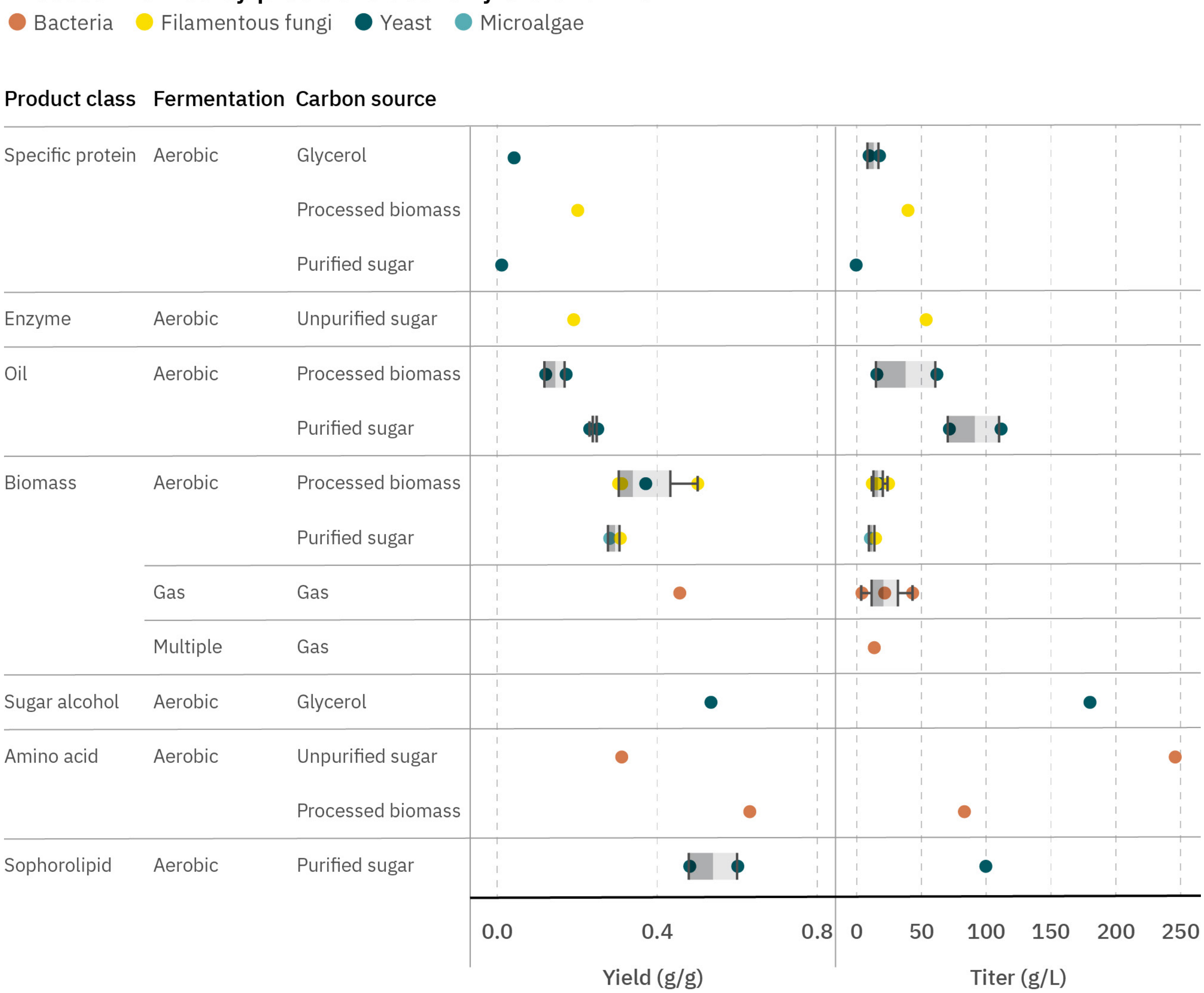


Figure 24. Reported yield and titer ranges from published TEMs, segmented by product, process, and feedstock type. Yield is defined as grams of product per gram of carbon feedstock, while titer is expressed as grams of product per liter of fermentation volume

Reporting maximum theoretical yield would improve comparisons across product and fermentation landscapes

Comparing absolute yields across products is challenging, as each has a unique maximum theoretical yield, dictated by the biological conversion pathways of the microbe. For example, triglyceride oils have a lower theoretical yield (~0.3 g/g glucose) than some forms of microbial biomass (>0.5 g/g glucose). Since absolute yields do not necessarily reflect efficiency differences, comparing processes relative to a product's maximum theoretical yield can be more meaningful and provides a ceiling for which an entire system can operate. However, unfortunately, most published TEMs lack theoretical yield estimates, limiting efficiency benchmarking.

Downstream product recovery is often overlooked in published TEMs, yet it represents important opportunities for cost improvement

DSP can be a major cost driver, as it often requires multiple unit operations, each introducing potential product losses. DSP recovery yield—how much of the product is retained after purification—represents a significant opportunity for cost improvement, one that is often overlooked in published models. Many DSP technologies involve trade-offs: achieving higher recovery may increase energy consumption, raw material use, and overall process complexity, all of which can drive up costs. However, commercial operators have long experience in optimizing these trade-offs to minimize COP.

The current TEM landscape highlights categories, such as gas-based biomass protein and sugar-fed yeast fermentation, where USP performance (e.g., yield and titer) is already high and likely approaching biological limits (Figures 23 and 24). In these cases, further USP optimization may yield diminishing returns. Instead, targeted improvements in DSP, especially for PF proteins, offer more targeted cost savings. Techniques like filtration or precipitation, though highly product-specific, can reduce the cost per unit of recovered protein.

For biomass protein produced by filamentous fungi, DSP steps such as drying and nucleic acid removal require significant energy input and can result in product loss, simultaneously increasing costs and reducing final titer. Advancing DSP technologies for both proteins and microbial oils is key to improving COP. In commercial production, advances in DSP design and implementation are often motivated by techno-economic pressures. Low-resource, high-recovery DSP systems can reduce utility demands while increasing overall recovery and process efficiency.

2.4 Case-study insights: exploring cost drivers and levers through sensitivity analysis

Overview

TEMs provide insights into the cost structure and process parameters of FD ingredients; however, most published TEMs are static, limiting their usefulness for dynamic sensitivity analyses. Additionally, inconsistencies in TEM reporting—including variability in data transparency for key process metrics—make it difficult to derive insights across models.

These limitations underscore the need for better comparisons between published and private sector TEMs (see section 1.2), as well as a deeper analysis of cost drivers in commercial case studies. In particular, private sector aerobic fermentation SCP models indicate more favorable COP trends for large-scale protein production. To address these gaps, we analyzed commercial-scale TEMs from Hawkwood Biotech to benchmark published TEM estimates and explore cost-driver sensitivity under real-world assumptions. The following case study provides this perspective, offering a deeper analysis of cost drivers within commercial-scale aerobic submerged sugar-based fermentation for SCP.

2.4.1 Case study: a pro forma commercial SCP biomass production model

Hawkwood developed a TEM representing a hypothetical case for commercial-scale aerobic fermentation SCP production. This model combines assumptions and process parameters from several proprietary Hawkwood FEL-1 TEMs of SCP production. These models use either *Saccharomyces sp.* (budding yeast) or microalgae, assume a Midwest USA location, and use corn glucose (dextrose 95/ DE95) as the carbon source. The resulting model allows us to carry out sensitivity analyses to evaluate how specific factors affect COP.

Tables 3 and 4 summarize the key process assumptions and parameters used to build the hypothetical case model. The cost basis for all cost drivers—including feedstock, utilities, labor, capital, and installation—is shown in Table 1 (section 1.2). Additional details on assumptions and modeled cost outputs from the pro forma are presented in Tables 3, 4, and 5.

Table 3. Modeled parameters in Hawkwood SCP TEMs and the pro forma SCP model

Area	Detail
Product	Dried, single-cell protein, 50%–57% protein by weight
Processes	Aerobic submerged stirred tank fed-batch fermentation, spray drying
Microbes	Budding yeast or different microalgal species
Feedstock	Corn glucose (DE95)
Location	Midwest, USA

Table 4. Modeled production and fermentation metrics from Hawkwood FEL-1 TEMs

Area	Units	Lower bounds	Upper bounds	Hypothetical commercial case values
Production volume	MTa	18,000	48,000	32,000
Yield	g/g	0.45	0.50	0.47
Titer	g/L	100	150	142
Protein content	%	50	57	54

Table 5. Modeled economic output ranges from Hawkwood FEL-1 TEMs

Area	Units	Lower bounds	Upper bounds	Hypothetical commercial case values
Unit COP	$/kg	$2.25	$2.90	$2.53
CapEx	$MM USD	$139	$324	$237
OpEx	$MM USD/yr	$47.1	$101.4	$80.8

Hawkwood's TEMs are a front-end loading 1 (FEL-1) estimate to evaluate the cost and scalability of fermentation processes

A TEM workflow begins with data collection and assumption validation, reviewing process details, incumbent technologies, and market benchmarks. A process flow diagram and mass balance are developed, equipment sized, and cost estimates made. Cost estimates are derived from Hawkwood's proprietary database, incorporating quotes from manufacturers and EPC firms.

CapEx estimations are +40% / -25% accuracy (Smanski et al. 2022). Utility costs for electricity, water, wastewater, and steam are input to the model. The final output is a flexible, spreadsheet-based model, allowing key assumptions to be adjusted and scenarios tested for comprehensive economic assessment.

2.4.2 Baseline cost drivers: feedstock costs and CapEx are major drivers of SCP COP

To focus the sensitivity analysis, we first identified the biggest COP drivers. Figure 25 shows a breakdown of fixed and variable costs for the hypothetical case. Feedstock costs and CapEx together make up 51% of COP, while utilities, including electricity, natural gas, water, and wastewater, account for 16%. Other fixed costs (accounting for 20% of COP) are comprised of four components (labor, maintenance, property taxes, and insurance).

Next, sensitivity to variation in key cost drivers and levers was evaluated, including feedstock price, utility costs, and total equipment installed costs (TEIC), along with process metrics yield, titer, batch time, and DSP recovery efficiency.

2.4.3 Sensitivity analysis: exploring cost driver sensitivity under real-world assumptions

Sensitivity analyses were conducted by adjusting each factor one at a time within a defined parameter range to evaluate its impact on COP. Values for upper and lower bounds were chosen based on proprietary Hawkwood data and literature reports. Since DSP recovery efficiency (96%) was deemed optimized, further improvements were not considered. The extent of positive and negative variation was not always equal. For instance, feedstock costs were increased by 40% but were only decreased by 10% for this evaluation. This approach allowed for the assessment of more extreme scenarios for specific factors. Table 6 summarizes the baseline, improved, and reduced values for each factor, along with the percentage variation applied and the resulting impact on COP (expressed as a percentage). Figure 26 shows how each of the nine factors was varied across a specific range and how those changes affected COP.

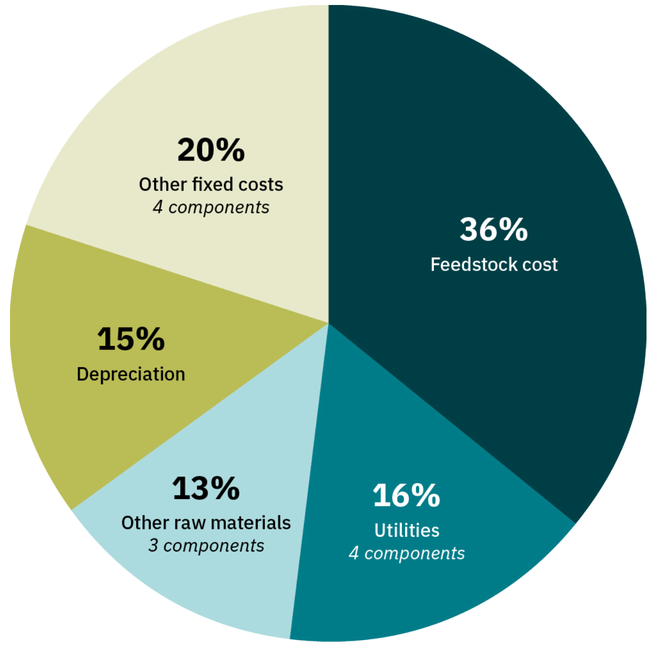


Figure 25. Proportional distribution of COP components. Variable costs = Feedstock, utilities, and raw materials. Fixed costs = Depreciation and other fixed costs

Table 6. Sensitivity analysis of SCP COP drivers

		Value			% Variation		% Impact on COP	
Cost driver	**Unit**	**Base**	**Improved**	**Reduced**	**Improved**	**Reduced**	**Improved**	**Reduced**
Titer	g/L	142	185	99	30	-30	12.2	-22.6
Feedstock cost	$/kg	$0.40	$0.35	$0.56	10	-40	3.5	-14.3
DSP Recovery	%	96	-	87	-	-10	0.0	-11.1
Batch time	h	57	43	71	25	-25	8.6	-8.6
Yield	g/g	0.47	0.56	0.36	20	-20	5.2	-8.0
TEIC	$MM	$139	$104	$173	25	-25	6.2	-6.2
Electricity cost	$/kWh	$0.08	$0.07	$0.11	10	-20	1.1	-4.5
Water cost	$/m3	$1.50	$1.35	$2.10	10	-40	0.2	-1.1
Natural gas cost	$/MMBTU	$6.00	$5.40	$8.40	10	-40	0.2	-1.0

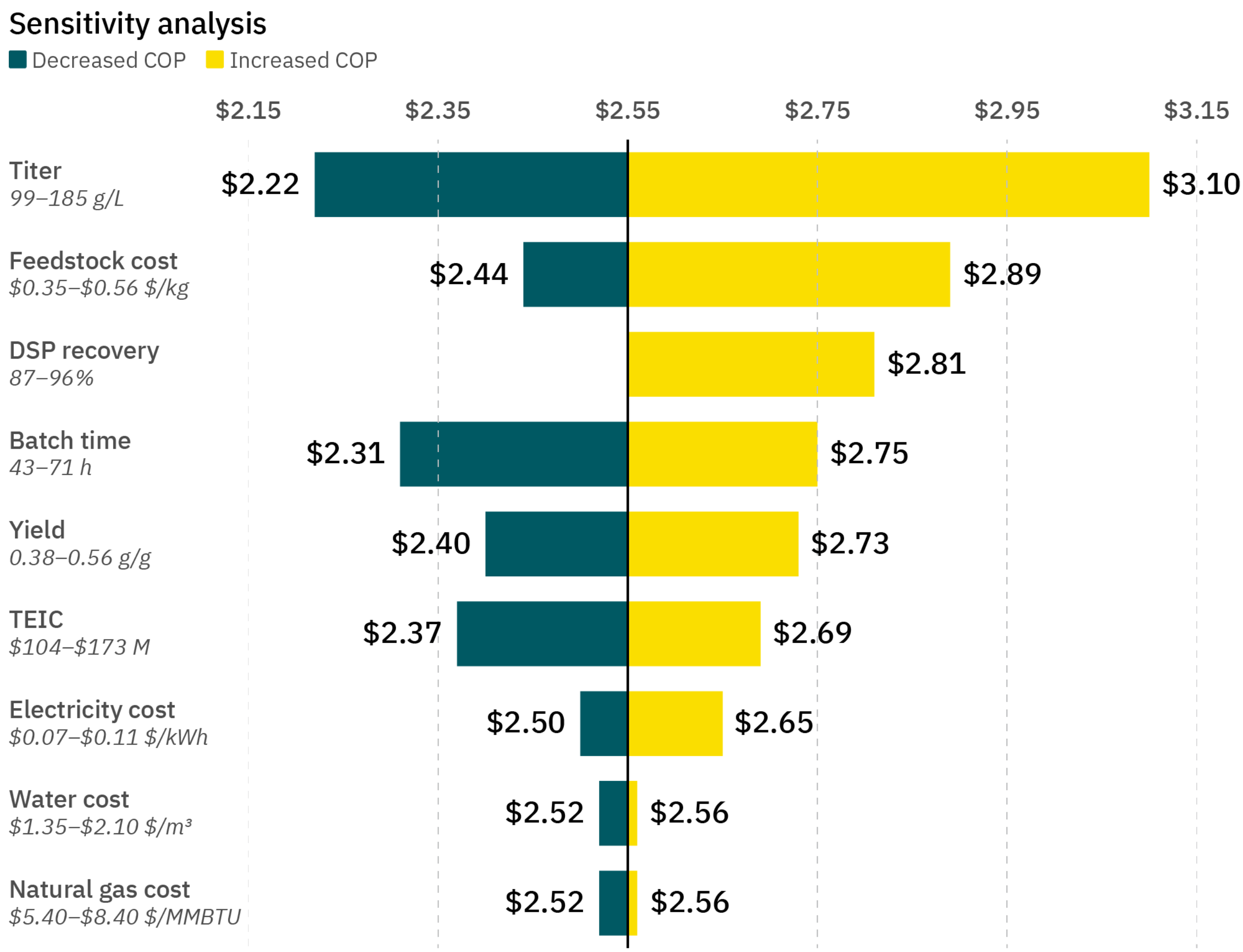


Figure 26. Sensitivity analysis: SCP COP (USD/kg) is most sensitive to process metrics and feedstock and equipment costs. Each factor was varied according to the value range shown on the y-axis. Reduced COP = positive impact (green). Increased COP = negative impact (yellow)

Process metrics are primary cost levers

The titer, yield, batch time, and DSP recovery all affect COP. In this analysis, changes to the titer had the biggest impact.

Titer has a nonlinear impact on COP as it influences multiple cost drivers asymmetrically. Higher titers improve asset utilization, reducing per-unit fixed costs by increasing output per fermentation cycle, while also lowering DSP burdens by reducing the volume of broth that must be processed. However, the benefits of titer improvements are constrained by facility and process limitations, leading to diminishing returns at higher concentrations. In contrast, lower titers significantly increase COP, as fixed costs are spread over a smaller output, feedstock is used less efficiently, and DSP costs increase. This asymmetry is reflected in modeled results: a 30% titer increase led to a 12% COP reduction, while a 30% titer decrease resulted in a 22% COP increase, highlighting the compounding effects.

DSP recovery efficiency is also a critical regulator of COP. This modeled process assumes a relatively low-complexity DSP workflow, with significantly fewer steps than many PF processes. As a result, it represents a high-end recovery efficiency scenario. The finding that a 10% decrease in recovery efficiency (from 96% to 87%) led to an 11% increase in COP underscores the substantial impact of DSP recovery on production costs.

While less impactful than titer and DSP recovery in this analysis, batch time and yield also influenced COP. A 25% increase in batch time raised COP by 8.7%. Provided that yield and titer are maintained, a longer batch time means fewer batches per year, depressing the overall annual output and utilization efficiency of equipment. Shortening batch time increases the number of production cycles per year, improving equipment utilization and reducing COP by spreading fixed costs across a greater total output.

Yield has a direct effect on feedstock requirements. In this analysis, a 20% reduction in yield increased COP by 8.1%, highlighting the importance of maximizing conversion efficiency. Like titer, yield affects costs disproportionately in this analysis—lower yield means more feedstock is needed to produce the same amount of product, increasing variable costs. At the same time, fixed costs such as equipment and labor are spread over a smaller output, driving up the per-unit cost of production.

SCP COP is sensitive to feedstock and capital costs

A 40% increase in DE95 glucose price (from $0.40/kg to $0.56/kg) caused a 14.3% rise in COP. As feedstock is the largest variable cost in this modeled process, even small price changes can strongly affect overall production costs.

With respect to capital costs, varying TEIC had a more moderate impact on COP: a 25% increase led to a 6.3% rise in costs. Unlike feedstock, which drives variable costs, TEIC contributes to fixed costs—these make up a smaller share of COP and demonstrate capital efficiency at volumes of scale in this model.

Utility costs have a smaller COP impact in this model

Among utility costs, electricity had the greatest influence, increasing COP by 4.5% with a 20% increase in electrical costs. This points to the importance of electricity as an operational expense, particularly in aerobic fermentations where power-intensive processes such as agitation, aeration, and cooling drive overall energy consumption. Conversely, a 40% increase in water and natural gas costs resulted in only a 1.2% and 1.0% COP increase, respectively.

Summary and considerations

This analysis highlights the primary cost drivers in a hypothetical model of SCP production and quantifies their relative impact on COP. Among the factors and variations evaluated, titer and DSP recovery efficiency emerged as the most influential cost levers. Titer showed the most asymmetric effect on COP, with decreases having a disproportionately negative impact due to compounding effects on output, feedstock efficiency, and downstream processing. Yield and batch time also played important roles, especially through their influence on feedstock usage and equipment utilization. Beyond process parameters, feedstock price was the most significant external cost driver, reinforcing its central role in biomass-based production systems. Capital and utility costs had more moderate effects, with TEIC contributing less due to its impact on fixed costs, which comprise a smaller proportion of COP in this model.

While these findings provide insights into the economics of SCP production, it is important to recognize that they are based on a hypothetical case built from an optimized process with specific assumptions around feedstock, technology, and geographic location. Other SCP processes in different geographies may have different utility, labor, and other costs. Nonetheless, this analysis reveals the most important cost levers for this study and demonstrates where process improvements or cost mitigation strategies are likely to have the greatest impact on economic viability.

Summary of cost driver insights

Published TEMs identify feedstock and raw material costs, capital expenses, and core process performance metrics as leading drivers of COP. These findings are supported by a case study sensitivity analysis, which also highlighted downstream recovery efficiency as a significant cost lever.

1. Among published models, raw materials costs and costs associated with feedstock processing dominate as primary COP drivers for processes at volumes of scale. Depending on the process, feedstocks are often the largest variable expense for fermentation-based production. Utilities were largely raised as a second-level COP driver.

- **Landscape trend:** Transitioning from Gen 1 to Gen 2 feedstocks shifts the cost burden from raw materials to feedstock processing costs. This shift highlights the need for improved preprocessing technologies and integrated facility designs that can manage the added complexity and cost of handling less refined inputs.
- **Sensitivity analysis** demonstrated the impact of feedstock costs on SCP COP as a primary cost driver in a specific case study.

2. Facility and capital-related expenses, such as equipment, construction, and infrastructure, are highly influenced by production volume and process productivity. Among published TEMs, these costs emerged as the second-largest driver of COP.

- **Landscape trend:** Among large-scale second-generation feedstock processes, CapEx and facility-dependent costs drive COP, reflecting a processing approach choice that moves toward higher capital investment to access lower-cost feedstocks.
- **Landscape trend:** Among published TEMs, facility-dependent costs are also a major driver of COP in low-volume process models, such as those for precision fermentation protein production.

3. Process metrics impact COP both directly and indirectly. As cost levers, process metrics define many aspects of both CapEx and OpEx, impacting both fixed and variable costs. Their combined effect shapes process economics and viability.

- **Improving techno-economics in the private sector:** The case study SCP model highlighted the impact of titer, yield, and batch time on SCP costs, while also revealing DSP recovery as an important cost lever. The private sector model shows a COP of $2.5 per kg, a 42% reduction from the median landscape SCP cost of $4.3 per kg.
- **Landscape gap:** Data gaps and process differences, especially in biomass fermentation, limit insights into how published TEMs link process metrics (YTP) to COP. Evaluating yield and titer impacts on COP was only possible within a narrow range of oil and PF protein products, while productivity reporting was limited across the TEM landscape.

Photo credit: Formo

Section 3. Key insights and recommendations

Overview

This report evaluates the current state of techno-economics for fermentation-derived ingredients through a meta-analysis of published techno-economic models, alongside comparisons to private industry data. This section summarizes key findings, including the state of published TEM literature, major cost drivers and levers for reducing COP, research gaps, and recommendations based on these insights.

3.1 The state of publicly available fermentation-derived techno-economic data

As of 2024, there are 165 fermentation-focused alternative protein companies, each with the goal of producing nutritional and organoleptically satisfying protein at a competitive price (GFI SOTIR 2024). Over 200 additional companies have a business line in fermentation-derived APs. Despite this interest, there are relatively few TEM publications of FD proteins and oils in the published literature. A better understanding of their techno-economics can help identify where improvements will have the greatest impact on reducing costs.

The state of published fermentation TEM coverage was variable across three ingredient categories: biomass, precision protein, and microbial oils. Only four precision fermentation protein TEMs and seven microbial oil ingredient TEMs were identified in the published literature. These models reported a COP range of $11 to $15,000 per kg and $1.85 to $19.64 per kg, respectively. The paucity of models and data therein makes it difficult to gauge the competitiveness of these products and processes. This highlights a critical need to increase the number of TEMs available to the public.

In contrast to the limited PF protein and oil TEMs, the biomass protein TEM landscape is more developed. It includes models for established processes for mycoprotein and yeast using Gen 1 feedstocks, as well as emerging approaches like gas- or acetate-fed bacteria. Across 25 biomass TEMs, COP estimates range from $1.27 to $18.00 per kg, with a median under $5 per kg. These biomass costs are conceivably within the range to compete with some incumbent protein prices.

Many biomass production models are precommercial and do not benchmark against Gen 1 feedstocks. This is despite widespread use of Gen 1 feedstocks in current commercial production. As a result, today's commercial feedstocks are underrepresented in the public biomass TEM landscape. Overall, SCP appears to be an economically attractive approach for producing sustainable, commodity-level protein, especially in high-volume and private-sector model scenarios. These findings should support greater confidence in planning, investment, and commercialization of SCP products.

3.2 Insights from the fermentation-deived TEM landscape

Biomass proteins are closing the price gap with several incumbent proteins, based on published techno-economic data and a private data case study.

Developing microbial biomass protein production today will provide new protein sources at competitive production costs. Published biomass TEMs, with a median COP of $4.3 per kg, suggest that SCP production has the potential to compete with some incumbent protein ingredients. A private case study, based on real-world process parameters, demonstrated a significantly lower COP of $2.5 per kg. This model assumed an annual production volume of 32,000 MTa, nearly triple the average in published studies, underscoring the importance of scale. The improved economics were driven by higher titer and yield values, highlighting the critical role of high-performance microbial strains in achieving low-cost production at scale.

Photo credit: Perfect Day, Inc.

Together, the public and private data indicates that cost parity with incumbent proteins such as beef and pork is within reach. The opportunity for low-cost SCP production, especially using aerobic fermentation with Gen 1 feedstocks, is not just theoretical, but now. Poultry remains a tighter cost benchmark, indicating the need for further cost reductions. Competing with commodity plant proteins is even more challenging, as average biomass COP meets or exceeds current soy and pea prices on a per-protein basis. Certain high-purity plant protein isolates do command premium prices, suggesting they could be viable targets for biomass-based alternatives.

Some data gaps remain. For example, SSF is frequently cited as a promising, low-cost method for protein production. Despite its commercial adoption in biomass applications, no published TEMs exist to assess the current state of SSF technology or to identify opportunities for improving COP.

Limited PF TEMs obscure progress toward price parity with commodity ingredients.

The reported COP range of $11 to $15,000 per kg for PF-derived proteins spans several orders of magnitude, making it difficult to assess cost-competitiveness. The small number of published TEMs, with no coverage of high-interest proteins such as egg white and dairy proteins, also limits insights for PF.

Therefore, we recommend increasing the publication of TEMs for precision fermentation, with a focus on food proteins relevant to ingredient markets and consumers. These models should use industrially representative parameters to generate commercially relevant COP estimates. To position PF proteins such as whey, casein, and egg white competitively in the market, pricing must align with high-volume applications in dairy, baking, confectionery, and food service.

Microbial oils are competitive with some high-value incumbents, but cannot compete on price with commodity oils.

Publishing TEMs based on commercial conditions will improve cost assessments and support more informed decision-making.

We identified seven fermentation-derived oil TEMs. These modeled a COP range from $1.8 to $19.6 per kg, which demonstrates promise against specialty oils. However, models reflecting larger-scale production are needed to more accurately assess the potential of microbial oil production across various food fat and oil applications.

We recommend greater transparency and expanded development of published TEMs for large-scale microbial oil production. As microbial biomanufacturing becomes increasingly vital to a more sustainable and resilient food system, for both proteins and oils, robust modeling will play a critical role. Expanding the scope of microbial oil TEMs beyond commodity applications and incorporating commercially relevant scales will better inform R&D priorities and guide bioprocess development needed to accelerate production of these essential ingredients.

Published TEMs highlight cost production drivers of feedstock costs, capital expenses, and process performance.

AI generated image showing cane sugar feedstock processing. NEXT-Ai/stock.adobe.com.

Section 2 of this report summarizes key cost drivers for fermentation-derived proteins and oils as identified in the published literature. These included feedstock costs, CapEx, and raw material or feedstock processing inputs. Production volume and feedstock type also emerged as important levers influencing overall COP.

Feedstocks: For many processes, feedstock cost is the primary COP driver. Reducing COP across the sector will require optimizing low-cost feedstocks (both Gen 1 and Gen 2) and achieving high conversion efficiency. Improvements in bioprocess performance, such as higher yields and downstream recovery, can increase output per unit of feedstock and enhance overall conversion efficiency.

Feedstocks requiring extensive refining or upstream processing, such as long-chain starches or cellulosics, will benefit from continued innovation in low-cost preparation technologies. Similarly, for gas fermentation, reducing the costs associated with gas capture, purification, and delivery is critical to improving feedstock processing efficiency. **Efforts to optimize feedstock utilization, identify novel low-cost feedstocks, and improve sourcing strategies will be essential for minimizing feedstock-related impacts on COP.**

CapEx: The type and scale of a bioprocess significantly influence how CapEx contributes to COP. This analysis found that gas fermentation, despite favorable COP in some cases, involves higher CapEx and fixed costs due to the need for specialized equipment, especially when using Gen 2 feedstocks to access lower-cost inputs. In general, more complex systems with gas feedstocks or intensive DSP carry greater capital burdens. In contrast, SSF tends to be lower-cost, while submerged fermentation spans a wide range of capital requirements. Understanding these trade-offs is essential for aligning process design with financial strategy.

Strategies for identifying and committing to the ideal capital outlay and investment structure for a particular production project can maximize CapEx efficiency through design, planning, and support. Additional technological improvements can decrease the impact of CapEx by driving efficient production on lower-cost equipment. High-titer bioprocesses can further increase CapEx efficiency by increasing production volume.

TEM standardization can increase the value of modeling as a tool for the industry.

Publish TEMs that reflect the current state of the science and technology, with parameters that reflect the state of the art. Despite the growing commercial and functional potential of PF-derived proteins, there is a notable lack of published TEMs that reflect modern, industrial-scale processes. Published TEMs often rely on conservative assumptions for key parameters like yield and titer, sometimes underestimating current performance by orders of magnitude. In many cases, these parameters are not explicitly reported and must be inferred. As yield and titer are critical performance indicators in biomanufacturing, these models may not accurately represent the current realities of PF-derived alternative protein production in 2025.

For example, many papers reference Humbird et al. (2011), a foundational bioethanol biorefinery model constructed nearly 15 years ago, but whose performance metrics and design assumptions do not fully reflect the current state of food-grade biomanufacturing. Other models use lab-derived parameters from unoptimized strains (e.g., low titers) that would not be brought to commercial scale production.

Develop best practices for biomanufacturing techno-economic assessment by establishing frameworks that make TEMs readily comparable, report model inputs, and standardize model outputs. Techno-economic modeling is a valuable tool for evaluating biomanufacturing processes, but the utility of published TEMs is limited by deficiencies in the published models. Few published models reflect today's commercially relevant scenarios for production volume and feedstock use. Many lack transparency in key inputs and assumptions. For example, DSP details are often underdefined or omitted, despite their major influence on recovery yield, purity, and resource use. Finally, reporting units differ wildly across publications.

Taken together, it is difficult to adapt or benchmark these models, which can limit their application to real-world decision-making.

The literature also shows heavy reliance on a small number of software tools with built-in assumptions and a limited set of reference publications for process simulation and cost modeling. This uniformity risks reinforcing shared assumptions across much of the literature, potentially misrepresenting costs and perpetuating uncertainties that could affect the accuracy of viability assessments.

Recognizing this gap, BioMADE, a USA Manufacturing Innovation Institute, recently called for research to establish “Standardization of TEA Guidelines” as a part of their Fall 2024 Project Call 5. Similarly, the Engineering Biology Research Council (EBRC) report, Engineering Biology Metrics and Technical Standards for the Global Bioeconomy, highlights the need for standardization of TEA tools to accelerate biomanufacturing progress and product commercialization. This expansion should be thoughtfully constructed, using frameworks that allow for updates to model inputs and parameters, easing comparison between independent model results, and standardizing units for modeled parameters.

Additionally, the sector should develop mechanisms for sharing aggregated industrially relevant cost and process parameters with the research community to support translational research and strengthen stakeholder confidence in its commercial viability. These mechanisms should be designed with an awareness of the need to protect commercially sensitive information.

Conclusion

This analysis compiled and normalized published TEMs for fermentation-derived production of food proteins and oils. The relationship between production cost and the underlying biotechnology is complex and this report presents published cost estimates, commercial benchmarks, and key cost drivers that influence competitiveness. Some biomass models show potential to compete with incumbent protein ingredients, while microbial oils are not currently cost-competitive with commodity oils. Additional published TEMs on PF proteins are needed to better understand cost dynamics.

Taking full advantage of high volume production requires production efficiency that drives down the cost of production across the production landscape. Additionally, improvements such as increasing production titers and feedstock use efficiency will improve production costs for alternative proteins.

Techno-economic improvements are a high priority for fermentation-derived food and microbial oil producers. Together with consistently delivering on taste and food functionality, lowering the cost of production can unlock the sustainability benefit and protein supply advantages that fermentation-derived protein offers to producers, regions, consumers, and the world.

Photo credit: Kinoko-Tech

Appendix 1

Materials and methods

Scope

The initial scope focused on studies modeling the production of FD proteins for food and feed. This included specific proteins and biomass. The paucity of publications led to expanding the scope to food-stuffs and ingredients for food or feed. This included fats and oils, saccharides, and other edible ingredients. Models of nonfood ingredients (e.g., pigments, fragrances, and nonpharmaceutical building block molecules) were collected to serve as comparative benchmarks but were not further analyzed in this study. Publications modeling pharmaceutical targets were excluded.

Literature searches

Public and private databases were accessed to retrieve English-language studies published within the last 15 years. Databases searched included Google Scholar, ResearchGate, ScienceDirect, SpringerLink, and open-access repositories arXiv and bioRxiv. AI-assisted search tools were employed to increase search comprehension. All literature searches were conducted between August 5, 2024 and February 10, 2025. A total of 190 publications were cataloged, including peer-reviewed articles, theses, and industry white papers.

Scale and processes

Aerobic, anaerobic, gas, and solid-state fermentation TEMs were considered for evaluation, provided they utilized at least one microbial fermentation step. This excluded studies of only plant-based or photosynthetic microalgal processes. Only models evaluating processes beyond bench-scale were considered.

Publication data quality

Publications that lacked sufficient detail on process parameters, model assumptions, calculations, key outputs, or process steps were excluded, as were those focused solely on software development: 48 publications met data quality boundaries (33 focused on food-related ingredients, 15 on nonfood ingredients).

Data extraction

The 33 publications describing 55 TEMs were harvested for key information, including product and process details, system boundaries, feedstock type, fermentation metrics, techno-economic cost elements, and financial metrics. The cost-basis year was recorded. Information regarding specific engineering software used and references for cost estimates and scaling factors was collected.

Calculated data and cost allocation assumptions

In cases where publications failed to report key outcomes, data were calculated provided that sufficient information was given. For normalization purposes, OpEx was assumed to exclude marketing and administrative costs.

Incumbent price landscape and normalization

Prices for 2024 plant proteins (pea, soy), animal meats (fish, beef, pork, chicken, turkey), and fats and oils were sourced from public datasets, including those from the Federal Reserve Economic Data (FRED), Organisation for Economic Co-operation and Development (OECD), U.S. Department of Agriculture Agricultural Marketing Service (USDA AMS), USDA Economic Research Service (USDA ERS), and U.S. International Trade Commission (USITC). Private data sources were used where indicated. All prices were standardized to $USD/kg and further normalized by protein content. Oil content was not normalized. Protein concentration data was sourced from American Dairy Products Institute (ADPI), IRA-CIRAD-AFZ Feedtables, USAID, USDA AMS, and USDA FoodData Central.

View and download the full incumbent price dataset here.

Year and currency normalization

Cost, CapEx, and OpEx data were first normalized to U.S. dollars where necessary and then adjusted to 2024 dollars using year-by-year inflation and Chemical Engineering Plant Cost Index rates.

COP drivers

The top three COP drivers or levers were identified for each TEM. For publications that did not explicitly report cost drivers, the largest contributors to OpEx were used. If OpEx breakdowns were unavailable, cost drivers were determined based on the publication's sensitivity analyses.

Appendix 2 / Overview and extracted data from the landscape of published alternative protein, oils, and other relevant food ingredient TEMs.

Listed by publication is a brief description followed by process details and modeled outputs, including COP, CapEx, and OpEx normalized to 2024 USD. Some publications report on multiple TEMs. View and download the full dataset here.

	Publication	Product class	Specific product	Fermentation	Microbe info	Production volume (MTa)	Reported COP ($/kg) - Normalized to 2024 USD	Reported OpEx ($MM/yr) - Normalized to 2024 USD	Reported total CapEx ($MM) - Normalized to 2024 USD
10	A Process Model for Approximating the Production Costs of the Fermentative Synthesis of Sophorolipids	Sophorolipid	Sophorolipids	Aerobic	Yeast	90700	3.4	307.66	68.88
10	A Process Model for Approximating the Production Costs of the Fermentative Synthesis of Sophorolipids	Sophorolipid	Sophorolipids	Aerobic	Yeast	90700	3.95	359.12	68.88
12	A Simplified Techno-Economic Analysis for Sophorolipid Production in a Solid-State Fermentation Process	Sophorolipid	Sophorolipids	Solid state	Yeast	384	6.12	2.28	8.04
12	A Simplified Techno-Economic Analysis for Sophorolipid Production in a Solid-State Fermentation Process	Sophorolipid	Sophorolipids	Solid state	Yeast	384	6.84	2.88	9.24
12	A Simplified Techno-Economic Analysis for Sophorolipid Production in a Solid-State Fermentation Process	Sophorolipid	Sophorolipids	Solid state	Yeast	384	8.28	8.16	9
15	A techno-economic model of mycoprotein production: achieving price parity with beef protein	Biomass	Mycoprotein	Aerobic	Filamentous fungi	17520	4.19	63.81	113.4
15	A techno-economic model of mycoprotein production: achieving price parity with beef protein	Biomass	Quorn® like product	Aerobic	Filamentous fungi	17520	4.76	72.94	129.68
39	Development of an economically competitive Trichoderma-based platform for enzyme production: Bioprocess optimization, pilot plant scale-up, techno-economic analysis and life cycle assessment	Enzyme	Cellulase cocktail	Aerobic	Filamentous fungi	2400	3.5	8.39	
47	Economic and Environmental Comparison of the Monosodium Glutamate (MSG) Production Processes from A-Molasses in an Integrated Sugarcane Biorefinery	Amino acid	MSG	Aerobic	Bacteria	58000	1.96	25.3	168.3
47	Economic and Environmental Comparison of the Monosodium Glutamate (MSG) Production Processes from A-Molasses in an Integrated Sugarcane Biorefinery	Amino acid	MSG	Aerobic	Bacteria	58000	1.98	27.5	184.8

47	Economic and Environmental Comparison of the Monosodium Glutamate (MSG) Production Processes from A-Molasses in an Integrated Sugarcane Biorefinery	Amino acid	MSG	Aerobic	Bacteria	61000	1.99	36.3	189.2
47	Economic and Environmental Comparison of the Monosodium Glutamate (MSG) Production Processes from A-Molasses in an Integrated Sugarcane Biorefinery	Amino acid	MSG	Aerobic	Bacteria	62200	1.99	44	196.9
47	Economic and Environmental Comparison of the Monosodium Glutamate (MSG) Production Processes from A-Molasses in an Integrated Sugarcane Biorefinery	Amino acid	MSG	Aerobic	Bacteria	62200	2	45.1	194.7
49	Economic comparison of food protein production with single-cell organisms from lignocellulose side-streams	Biomass	SCP	Aerobic	Filamentous fungi	3434	3.87	13.69	86.35
49	Economic comparison of food protein production with single-cell organisms from lignocellulose side-streams	Biomass	SCP	Aerobic	Filamentous fungi	6190	4.34	11.17	92.57
49	Economic comparison of food protein production with single-cell organisms from lignocellulose side-streams	Biomass	SCP	Aerobic	Yeast	4495	5.33	13.67	94.64
49	Economic comparison of food protein production with single-cell organisms from lignocellulose side-streams	Specific protein	Recombinant protein	Aerobic	Filamentous fungi	2507	11.16	19.68	165.56
55	Evaluation and Identification of Key Economic Bottlenecks for Cost-Effective Microbial Oil Production from Fruit and Vegetable Residues	Oil	Microbial oil	Aerobic	Yeast	1153	19.64	14.55	55.44
64	Methane Single Cell Protein: Potential to Secure a Global Protein Supply Against Catastrophic Food Shocks	Biomass	SCP	Gas	Bacteria	108000	2.21	220.32	394.8
67	Omega-3 Fatty Acids Production via Microalgal Fermentation – Process Modeling and Techno-Economic Assessment (TEA) using SuperPro Designer.	Oil	Omega-3 oil	Aerobic	Microalgae	3100	19.55	57.92	100.64
81	Production of Human Collagen via Fermentation (Bio-Collagen) – Process Modeling and Techno-Economic Assessment (TEA) using SuperPro Designer.	Specific protein	Collagen peptide	Aerobic	Yeast	50	938.96	46.95	142.94
85	Protein from renewable resources: mycoprotein production from agricultural residues	Biomass	SCP	Aerobic	Filamentous fungi	40000	5.95	147.5	892.08
92	Scale-up of the erythritol production technology – Process simulation and techno-economic analysis	Sugar alcohol	Erythritol	Aerobic	Yeast	1075	7.52	8.07	
93	Single-Cell Protein (SCP) Production via Gas Fermentation – Process Modeling and Techno-Economic Assessment (TEA) using SuperPro Designer.	Biomass	SCP	Multiple	Bacteria	20000	4.05	81.02	232.29

94	Single-Cell Protein Production from Industrial Off-Gas through Acetate: Techno-Economic Analysis for a Coupled Fermentation Approach	Biomass	SCP	Multiple	Bacteria	20000	4.27	86.52	329.6
96	Solar-Powered Carbon Fixation for Food and Feed Production Using Microorganisms—A Comparative Techno-Economic Analysis	Biomass	SCP	Gas	Bacteria	10000	10.98	109.79	730.32
99	Stochastic techno-economic analysis for the co-production of alternative sweeteners in sugarcane biorefineries	Specific protein	Thaumatin	Aerobic	Yeast	84	14347.95	48.94	44.28
99	Stochastic techno-economic analysis for the co-production of alternative sweeteners in sugarcane biorefineries	Sweetener	Allulose	Aerobic	Bacteria	12600	2.5	46.11	66.42
99	Stochastic techno-economic analysis for the co-production of alternative sweeteners in sugarcane biorefineries	Sweetener	Isomaltulose	Aerobic	Yeast	22850	1.07	38.13	72.57
99	Stochastic techno-economic analysis for the co-production of alternative sweeteners in sugarcane biorefineries	Sweetener	Short-chain fructooligo-saccharides	Aerobic	Yeast	5650	1.89	42.5	115.62
100	Sustainable Co-Production of Xylanase, Cellulase, and Pectinase through Agroindustrial Residue Valorization Using Solid-State Fermentation: A Techno-Economic Assessment	Enzyme	Enzyme cocktail of xylanase (majority), cellulase, and pectinase	Solid state	Filamentous fungi	960	2.32	3.47	4.66
103	Techno-economic analysis for probiotics preparation production using optimized corn flour medium and spray-drying protective blends	Biomass	Probiotic	Aerobic	Bacteria	914	4.81	4.4	3.72
112	Techno-Economic Analysis of Gas Fermentation for the Production of Single Cell Protein	Biomass	SCP	Gas	Bacteria	45000	2.48	56.9	403.2
125	Techno-economic assessment of DHA-rich <i>Aurantiochytrium</i> sp. production using food industry by-products and waste streams as alternative growth media	Biomass	DHA biomass	Aerobic	Microalgae	285.161	18.11	5.16	10.35
153	Using techno-economic modelling to determine the minimum cost possible for a microbial palm oil substitute	Oil	Microbial palm oil	Aerobic	Yeast	8053	2.23	18.21	19.78
153	Using techno-economic modelling to determine the minimum cost possible for a microbial palm oil substitute	Oil	Microbial palm oil	Aerobic	Yeast	48315	1.48	71.54	66.16
164	Comprehensive assessment of the l-lysine production process from fermentation of sugar-cane molasses	Amino acid	Lysine-HCL	Aerobic	Bacteria	25411	2.03	51.69	75.57
165	Design and techno-economic evaluation of microbial oil production as a renewable resource for biodiesel and oleochemical production	Oil	Microbial oil	Aerobic	Yeast	10000	7.81	77.82	99.68
176	Techno-economic analysis and life cycle assessment of heterotrophic yeast-derived single cell oil production process	Oil	Microbial oil	Aerobic	Yeast	10000	5.09	50.94	27.29

177	Lactoferrin Production via Precision Fermentation – Process Modeling and Techno-Economic Assessment (TEA) using SuperPro Designer..	Specific protein	Lactoferrin	Aerobic	Yeast	251.304	262.43	65.95	122.53
178	Towards a Biorefinery Processing Waste from Plantain Agro-Industry: Process Design and Techno-Economic Assessment of Single-Cell Protein, Natural Fibers, and Biomethane Production through Process Simulation	Biomass	SCP	Aerobic	Yeast	58.8	11.44	2.43	3.16
178	Towards a Biorefinery Processing Waste from Plantain Agro-Industry: Process Design and Techno-Economic Assessment of Single-Cell Protein, Natural Fibers, and Biomethane Production through Process Simulation	Biomass	SCP	Aerobic	Yeast	10000	9.65	135.33	67.9
184	Single cell oil production integrated to a sugar-cane-mill: Conceptual design, process specifica-tions and economic analysis using molasses as raw material	Oil	Oil	Aerobic	Yeast	16720	2.25	37.62	123.67
185	Assessing the potential for up-cycling recovered resources from anaerobic digestion through microbial protein production	Biomass	SCP	Gas	Bacteria	1015.11	2.35	3.17	3.91
185	Assessing the potential for up-cycling recovered resources from anaerobic digestion through microbial protein production	Biomass	SCP	Gas	Bacteria	820.91	1.27	0.83	3.62
187	Xanthan Gum Production via Fermentation - Process Modeling and Techno-Economic Binder Ingredient	Xanthan gum	Aerobic	Bacteria	5000	9.83	50.05	83.2	
188	Process model economics of xanthan production from confectionery industry wastewaters	Binder Ingredient	Xanthan gum	Aerobic	Bacteria	50	4.79	0.24	
189	Yeast Extract Production - Process Modeling and Techno-Economic Assessment (TEA) using SuperPro Designer	Biomass	Yeast extract	Aerobic	Yeast	9223	5.03	46.32	78.17
190	Global potential of sustainable single-cell protein based on variable renewable electricity	Biomass	SCP	Gas	Bacteria	15600	5.31	11.09	181.67
190	Global potential of sustainable single-cell protein based on variable renewable electricity	Biomass	SCP	Gas	Bacteria	156000	4.04	64.47	1078.75
190	Global potential of sustainable single-cell protein based on variable renewable electricity	Biomass	SCP	Gas	Bacteria	218400	2.34	51.04	646.33
192	Potential of microbial protein from hydrogen for preventing mass starvation in catastrophic scenarios	Biomass	SCP	Gas	Bacteria	100800	3.6	362.88	463.2
192	Potential of microbial protein from hydrogen for preventing mass starvation in catastrophic scenarios	Biomass	SCP	Gas	Bacteria	100800	4.02	405.22	722.4
192	Potential of microbial protein from hydrogen for preventing mass starvation in catastrophic scenarios	Biomass	SCP	Gas	Bacteria	100800	6.1	614.48	1020
192	Potential of microbial protein from hydrogen for preventing mass starvation in catastrophic scenarios	Biomass	SCP	Gas	Bacteria	100800	9.74	982.2	1029.6

Appendix 3 / Top three reported COP drivers and levers from the published TEM landscape.

View and download the full dataset here.

Fermentation	Publication ID	Reported COP driver 1	Reported COP driver 2	Reported COP driver 3
Aerobic	10	Feedstock cost	Raw material cost (ex feedstock)	Utilities
Aerobic	15	Titer	Yield	Scale index for reactor cost
Aerobic	39	Feedstock cost	CapEx	Electricity costs
Aerobic	47	DSP chemicals	Utilities	Raw materials
Aerobic	47	DSP chemicals	Utilities	Fermentation raw materials
Aerobic	47	DSP chemicals	Yield	Titer
Aerobic	49	Raw feedstock conversion capacity	CapEx	Utilities
Aerobic	49	Raw feedstock conversion capacity	CapEx	Raw material costs
Aerobic	55	Utilities	Yield	Raw material costs
Aerobic	67	Raw material costs	Facility-dependent costs	Labor
Aerobic	81	Facility-dependent costs	Raw material costs	Labor
Aerobic	85	CapEx uncertainty	Saccharification yield	Potential for xylose utilization
Aerobic	99	Feedstock cost	Utilities	
Aerobic	99	Feedstock cost	Waste removal	Raw material costs (ex feeedstock)
Aerobic	99	Yield	Utilities	Feedstock cost
Aerobic	103	Raw material costs (inulin)	Growth rate	Drying time
Aerobic	125	Production volume	Raw material costs	Productivity
Aerobic	153	Production volume	Eliminating DSP steps	Electricity cost
Aerobic	164	Productivity	Yield	Utilities
Aerobic	165	Feedstock cost	Titer	Productivity
Aerobic	176	Feedstock cost	Titer	Productivity
Aerobic	177	Facilitiy-dendent costs	Raw material costs	Labor
Aerobic	178	Feedstock processing costs	Utilities	

Aerobic	178	Utilities	Feedstock processing costs	Labor
Aerobic	184	Capital associated with fermenter	Feedstock cost	Productivity
Aerobic	187	Utilities	Facility-dependent cost	Labor
Aerobic	188	Yield	Utilities	Labor
Aerobic	189	Feedstock cost	Facility-dependent costs	Labor
Gas	64	Methane costq	Electricity cost	Project lifetime
Gas	96	CapEx tied to electricity strategy	Productivity	Project lifetime
Gas	112	Product recovery	Electrolyzer capital cost	Wind electricity cost
Gas	185	Biogas production costs	Ammonia recovery cost	
Gas	185	Hydrogen gas production costs	Ammonia recovery costs	Growth rate
Gas	190	Electricity supply	Production volume / CapEx (WACC)	Utilities/Raw Materials (non-energy H2 & CO2 supply)
Gas	190	Electricity supply	Utilities/Raw Materials (non-energy H2 & CO2 supply)	Productivity
Gas	192	CapEx	Interest on loan	Taxes
Gas	192	CapEx	Interest on loan	Costs associated with coal gasification
Gas	192	Electricity costs	CapEx	Interest on loan
Multiple	93	Facility-dependent costs	Utilities	Raw material costs
Multiple	94	Facility-dependent costs for gas-acetate	Facility-dependent costs for SCP	Utilities
Solid state	12	Yield	CapEx associated with solvent recovery	Raw material costs
Solid state	100	Labor	Consumables	Raw materials for innoculum (ex-feedstock)

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