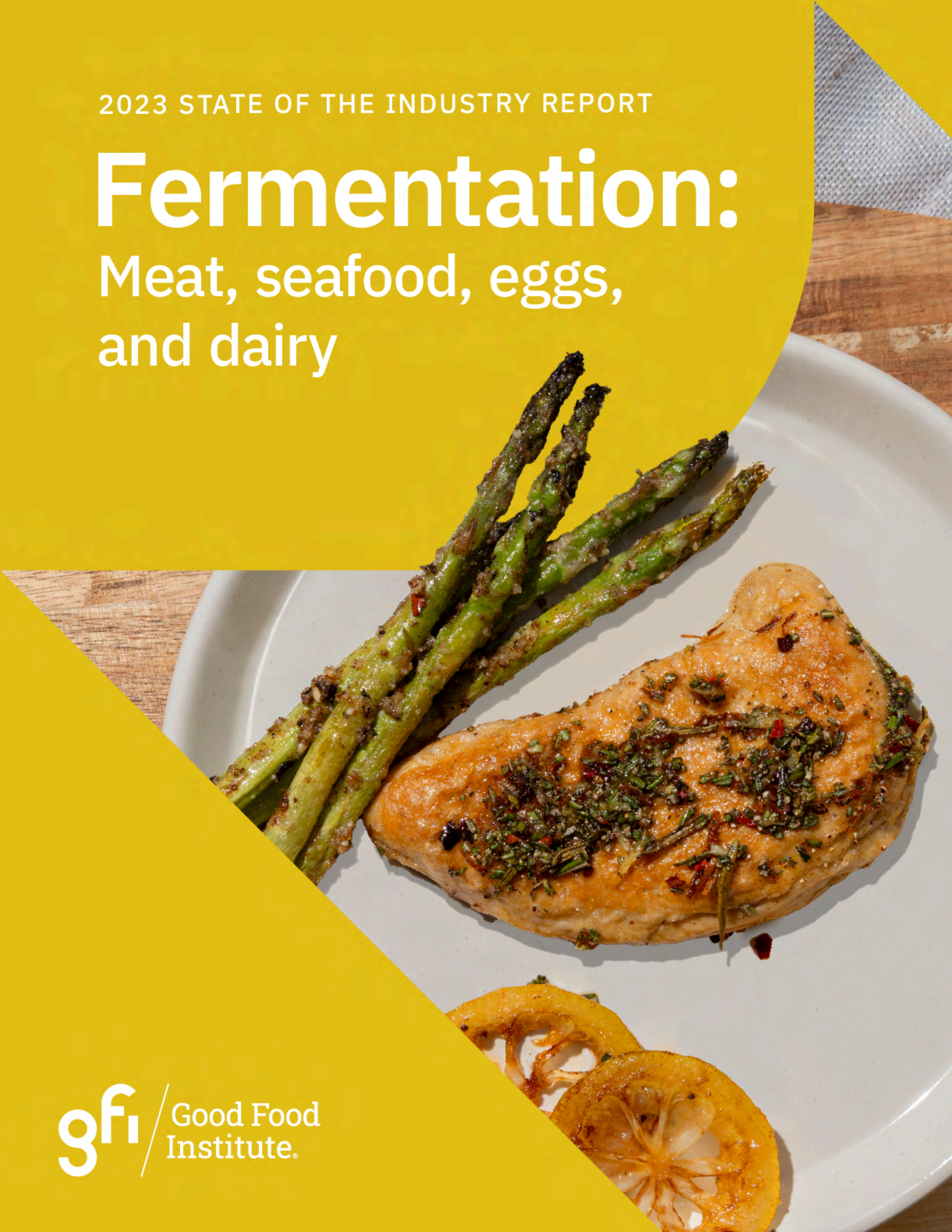
2023 STATE OF THE INDUSTRY REPORT

Fermentation:

Meat, seafood, eggs, and dairy



Good Food Institute

Table of contents

Editor's note

Fermentation is a nature-inspired technology with powerful current-day applications. In 2023, access to fermentation-enabled alternative proteins expanded, with products from bacon to crab cakes and beyond launching at diverse venues from global fast-casual restaurants to your local grocery store.

Yet the year was not without its challenges. Funding constraints and difficulties with scaling posed two of the biggest bottlenecks for fermentation. Consumer education, understanding, and adoption are still in the early stages. And the work to secure government and private investment continues. Despite these headwinds, the stark realities of our food system remain: Global meat consumption is projected to rise significantly by 2050, and animal agriculture alone accounts for between 11 and 20 percent of greenhouse gas emissions. Taken together, these projections point to the urgent need for the kinds of solutions provided by alternative proteins.

If the world is to achieve our climate, biodiversity, public health, and food security goals, reimagining the way meat is made will be as essential as the global transition to renewable energy. When compared to conventional meat, alternative proteins reduce emissions, feed more people with fewer resources, reduce pandemic and antibiotic-resistance risks, and free up lands and waters around the world for restoration and recovery.

GFI's annual State of the Industry reports equip food system stakeholders with an in-depth understanding of the alternative protein market, with its challenges and opportunities. These reports also serve as a global call to action:

Alternative proteins are agricultural innovations that, with proper levels of government and private support, will help ensure planetary and public health, transforming our global food system for the better.

Fermentation is a powerful tool for tackling such challenges. At scale, alternative proteins made via fermentation could enable a shift toward less resource-intensive ways of producing protein. But first, the industry must overcome hurdles such as increasing manufacturing capacity and reaching cost parity to satisfy the next generation of consumers, who are signaling enthusiasm for fermentation as a solution to eating protein made with fewer resources and less harm to the environment.

This report details the innovations and developments that moved the field of fermentation-enabled alternative proteins forward in 2023. But there is still much to be done. As a nonprofit and international network of organizations, GFI is accelerating alternative protein innovation and bringing more people into the field. Policymakers and governments, scientists and students, industry leaders and global citizens can all ensure that the sector of nature-positive proteins continues to progress, offering the world a far more sustainable food future.

With gratitude and deep respect to all those on this journey, we invite you to dig deep into our 2023 State of the Industry report.

Best,

Caroline Bushnell
SVP of Corporate Engagement

Liz Specht, PhD
SVP of Science and Technology

Jessica Almy
SVP of Policy and Government Relations

About GFI's State of the Industry Report series

GFI's State of the Industry Report series serves as our annual alternative protein sector deep-dive. The series compiles business developments, key technologies, policy updates, and scientific breakthroughs from around the world that are advancing the entire field. This year's reports include:

Cultivated meat and seafood

Plant-based meat, seafood, eggs, and dairy

Fermentation: Meat, seafood, eggs, and dairy

Global policy: Public support, regulation, and labeling

The *Fermentation: Meat, seafood, eggs, and dairy* report synthesizes 2023 updates across the global fermentation industry focused on animal-free alternatives to conventional proteins. This report focuses on developments across the commercial, investment, policy, and scientific landscape related to the use of fermentation in the production of alternative proteins—meat, seafood, eggs, and dairy made via microorganisms. For a primer on the emerging role of microbial fermentation in building the next generation of alternative proteins, please visit GFI's science of fermentation deep dive.

Symbols to look for

Throughout the 2023 State of the Industry Report series, look for symbols highlighting how developments in the past year advanced the alternative protein sector in the areas of health and nutrition, sustainability, and path-to-market progress. Dig deeper and Opportunity icons are calls to action for researchers, investors, and others seeking to learn more and advance the field.

Health

Sustainability

Opportunity

Path-to-market

Dig deeper

Please note that The Good Food Institute is not a licensed investment or financial advisor, and nothing in this report is intended or should be construed as investment advice.

About the Good Food Institute

As a nonprofit think tank and international network of organizations powered by philanthropy, GFI works alongside scientists, businesses, and policymakers to make alternative proteins as delicious, affordable, and accessible as conventional meat. In Asia Pacific, Brazil, Europe, India, Israel, and the United States, our teams are mobilizing the international community to use markets and technology to replace harmful practices with ones that are better for the climate and biodiversity, for food security, and for global health.

We focus on three programmatic priorities:

1. ***Cultivating a strong scientific ecosystem***

   GFI's science and technology teams map out the most neglected areas that will allow alternative proteins to compete on taste and price. We produce open-access analyses and resources, educate and connect the next generation of scientists and entrepreneurs, and fund research that benefits alternative protein development across the sector.

2. ***Influencing policy and securing government investment***

   GFI's policy teams ensure that alternative proteins are a part of the policy discussion around climate chang mitigation and global health. In every region where we have a presence, we advocate for government investment in alternative proteins and educate regulators on novel proteins such as cultivated meat.

3. ***Supporting industry to advance alternative proteins***

   GFI's corporate teams are replicating past market transformations and partnering with companies and investors across the globe to drive investment, accelerate innovation, and scale the supply chain—all faster than market forces alone would allow.

Stay connected

Newsletters | GFI's suite of expertly curated newsletters puts timely news, insights, and opportunities right in your inbox. Check out gfi.org/newsletters to find the ones most suitable for your interests.

Monthly seminar series | Each month, we host online seminars with leading experts from around the world: The *Business of Alt Protein* series is geared toward a commercially focused audience on topics related to starting and scaling a good food business. The *Science of Alt Protein* series addresses a technical audience and focuses on cutting-edge research developments that enable alternative protein innovation.

This State of the Industry Report series, as well as all of GFI's open-access insights and data, are made possible by gifts and grants from our global community of donors. If you are interested in learning more about giving to GFI, please visit here or contact philanthropy@gfi.org.

Executive summary

Executive summary

The global fermentation industry continued to innovate on animal-free alternatives to conventional proteins in 2023.

In 2023 alone, the number of fermentation companies grew by 16 percent, seven new fermentation-focused facilities opened their doors, and funding milestones were reached in Europe and Africa.

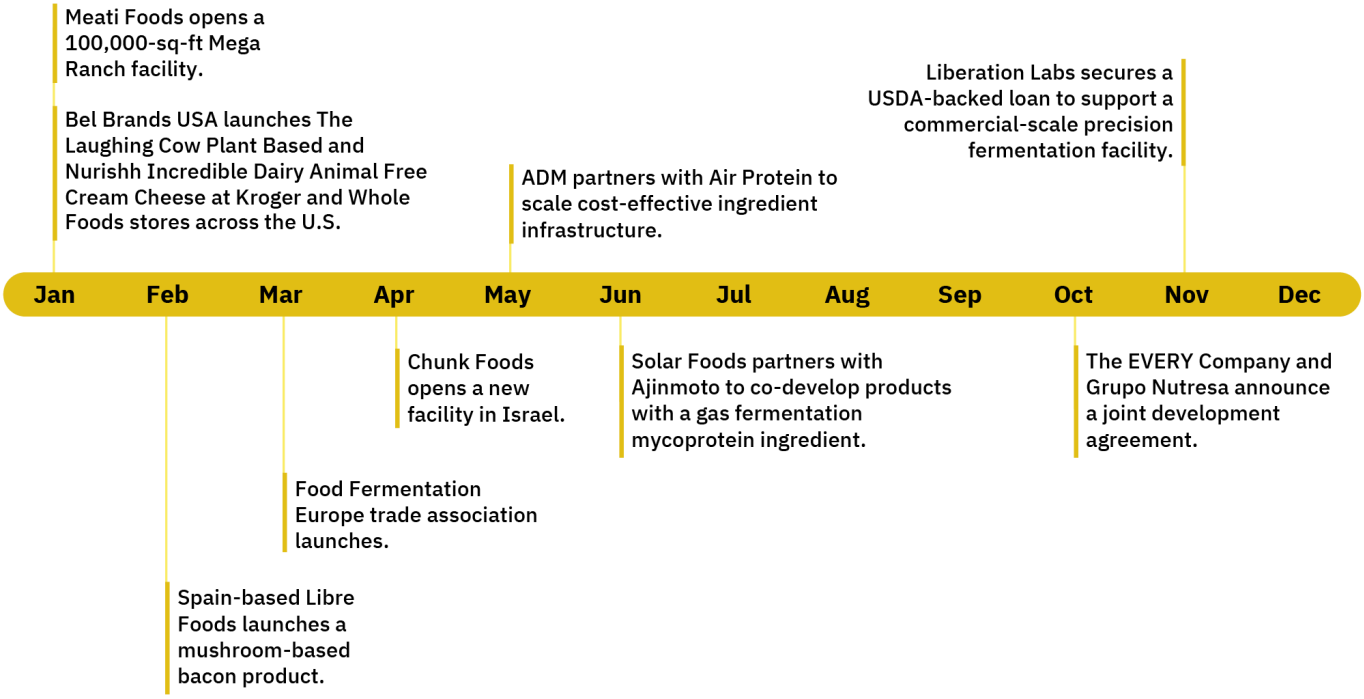
The year also delivered scientific advances, new products, more manufacturing facilities, and notable partnerships. All this progress brought the world more meat, seafood, eggs, and dairy made via microorganisms than any previous year. While challenges in manufacturing capacity and reaching cost parity remain, this nature-inspired technology is primed to transform the future of food.

Table 1: Invested capital in fermentation

Category	2023	2022	All-time (since 2013)	2023 highlights
Total invested capital	$515MM	$758MM	$4.1B	72% of fermentation investment occurred in the last three years alone.
Invested capital deal count	81	118	493	2023's largest investment was $75 MM (Air Protein).
Unique investors	205	238	693	The number of all-time unique investors increased by 22%.
Growth stage deals (Series B and above)	7	3	31	These included Meati, Enough, Prime Roots, and Solar Foods.
Liquidity events	$1MM	$504MM	$2.1B	Superlatus acquired the Urgent Company, Perfect Day's consumer-facing subsidiary.

Source: GFI analysis of data obtained from Net Zero Insights platform

Figure 2: Timeline of key fermentation updates in 2023



Commercial landscape

New industry associations

In early 2023, nine precision fermentation companies cofounded the **Precision Fermentation Alliance**, which will focus on regulatory engagement and consumer messaging. **Food Fermentation Europe**, working to address several issues, including labeling and nomenclature for animal-free proteins, also formed in 2023.

Known companies

The number of companies focused on fermentation for alternative proteins rose to 158, an increase of 16 percent over the number of known companies in 2022, according to GFI's alternative protein company database.

New fermentation facilities

Seven new fermentation facilities opened globally in 2023, and several more were announced or began construction. Notable examples include **Meati Foods**' facility in Colorado and **Liberation Labs**' facility in Indiana.

Partnerships and capacity building

In 2023, 19 new partnerships focused on end products and bioprocess scaling were formed, adding to the 21 partnerships established in 2022. For example, **Alpha Foods** partnered with **The EVERY Company** to develop hybrid plant-based and precision-fermentation-derived products.

Products

In 2023, companies applied fermentation technology to develop end products and ingredients to enhance plant-based products across categories:

Significant expansion in dairy

Several companies utilized fermentation to launch animal-free cheese products including **Bel Brands USA** launching **The Laughing Cow** Plant Based and **Nurishh** Incredible Dairy Animal Free Cream Cheese. **Nature's Fynd** also launched a fungi-based yogurt product made from their Fy protein.

Eggs

An egg white replacer made from upcycled spent brewer's yeast was introduced from Netherlands-based **revyve**. It can be used as a binder in plant-based meats and adds an umami flavor. **The EVERY Company** also launched The EVERY Egg, a liquid egg product made with precision fermentation-derived proteins and plant-based ingredients.

Meat

New fermentation-enabled meat products, including a microalgae-based meat line from **Umani** and a mushroom-based bacon product from **Libre Foods**, launched in 2023.

Investments

According to GFI's analysis of data obtained from the Net Zero Insights platform, fermentation companies raised $514.7 million in 2023, a year-over-year deceleration mirroring similar trends across markets amid challenging macroeconomic and other global factors. Still, there was some bright investment news in 2023: funding grew in Europe, totaling $179.4 million, a 22 percent increase from 2022 (and the highest annual total for the region to date). Additionally, the number of unique investors in fermentation globally grew by 22 percent to 693 unique investors.

Science and technology

Research and development

- The **EVERY Co**. unveiled the world's first precision fermentation liquid egg product in December 2023 on the heels of patent protection on recombinant protein purification strategies and precision fermentation-derived recombinant ovomucoid**.**
- Biotech company **Melt & Marble** was awarded several patents for strain improvements to increase fatty acid and protein production in fungi.
- **Mycorena AB** was granted two patents in Sweden for a dairy replacement and dry food product formulation containing their fungal biomass ingredient. Mycorena has developed a patent-pending method for a printable food product comprising their fungal biomass ingredient.
- **Koralo Foods**, an alternative seafood startup, received a patent for their novel alternative seafood product produced through the co-cultivation of fungal mycelium and microalgae that imparts the taste and texture of seafood while also providing the nutritional benefits of both the fungal protein and microalgae omega-3-fatty acids in a single process.

Environmental and social impact

- The startup **Essential Impact** has begun commercializing a fermentation-derived low-cost, high-quality protein source for low- and middle-income countries.
- **King's College London** modeled the opportunity for feedstocks from agricultural leftovers, forestry residues, and other reliable starch streams and identified almost 4,000 megatonnes of glucose and xylose sugars potentially available as feedstocks for the biomanufacture of food via fermentation.

- Gas fermentation, where microorganisms convert greenhouse gas feedstocks into microbial protein-rich biomass, has received attention as a viable production pathway for food even in the absence of agricultural feedstocks like sugars and starches. **Synonym Bio** was awarded Open Philanthropy funding to explore gas fermentation processes for food production to help understand the current and future techno-economics of gas fermentation approaches.

Government and regulation

Investments and funding

- The White House released "Bold Goals for U.S. Biotechnology and Biomanufacturing," which proposed supportive policies for the domestic biotechnology sector and called for more research on alternative proteins, public-private partnerships, and an ecosystem of agriculture-focused biomanufacturing facilities.
- The White House released a Building the Bioworkforce of the Future report that named precision fermentation explicitly as a growing sector in the American bioeconomy that will benefit from government investment.
- In the United States, precision fermentation startup **Liberation Labs** received a $25 million loan guarantee from USDA to accelerate the construction of a facility in Indiana.
- GFI estimates total Defense Advanced Research Projects Agency (DARPA) funding for fermentation at around $40 million over four years—nearly matching the United States' all-time investment in alternative proteins before 2023.
- The government of South Africa allocated what may be the first public investment in precision fermentation on the continent, with a grant of ZAR 11 million ($700,000) to South African startup **De Novo FoodLabs**.

Introduction

Introduction

Several forms of fermentation are being harnessed for alternative protein solutions.

Fermentation, in the alternative protein industry, refers to utilizing microbial organisms for food. Here is an overview of how alternative protein companies use fermentation in three primary ways.

Understanding fermentation

Traditional fermentation has been used for thousands of years to produce familiar products such as bread and beer. It uses intact, live microorganisms to modulate and process plant-derived ingredients, resulting in products with unique flavors, nutritional profiles, and textures. Examples include using the fungus *Rhizopus* to ferment soybeans into tempeh and using various lactic acid bacteria to produce cheese and yogurt. Traditional fermentation can improve the sensory, functional, and nutritional attributes of many alternative protein ingredients.

Since traditional fermentation is widely used across the conventional and alternative protein sectors, companies that effectively tailor the fermentation process to their unique ingredients and end products are most likely to differentiate themselves in the alternative protein space. Companies like **Chunk Foods** and **Planetarians** use traditional fermentation or its byproducts to create unique, whole-cut plant-based meat products. Differences in proprietary fermentation processes can affect both their cost and scalability.

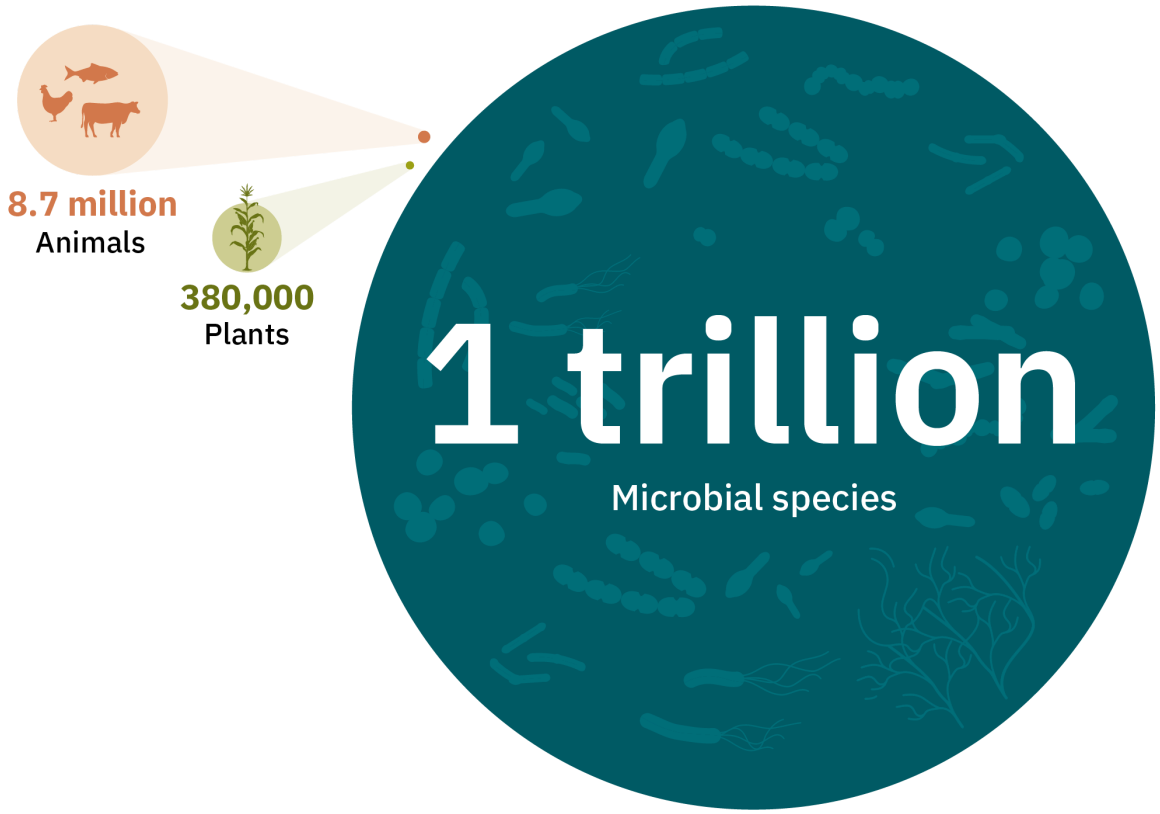
Biomass fermentation leverages the high-protein content and fast growth of microorganisms to produce large quantities of protein efficiently. Biomass fermentation offers the greatest opportunity to produce protein at scale owing to the ability of many microorganisms to grow quickly, often doubling their weight in just a few hours. The microbial biomass itself can serve as an ingredient, with the cells intact or minimally processed. 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 is being explored for their applications in biomass fermentation, from yeast to filamentous fungi to microalgae. An increasing number of biomass companies are focusing on microalgae that are grown with sugar, a process known as heterotrophic growth, instead of sunlight. Heterotrophic growth of algae is typically faster and leverages standard bioreactors as compared to phototrophic growth where a light source or sunlight is required.

Biomass fermentation has been used at scale since the 1980s by companies like **Quorn**, and others in the space, like **Meati**, have also achieved national and international product distribution. Variations in processes, feedstocks, and target microorganisms serve as the primary differentiators across companies and can impact the affordability and scalability of a given end product.

Precision fermentation is a form of specialized brewing that uses microbes as “cell factories” for producing specific functional ingredients. Capable of producing proteins, vitamins, enzymes, natural pigments, and fats, precision fermentation is well-positioned to create high-value ingredients that improve the sensory characteristics and functional attributes of plant-based products or cultivated meat. It can be used to make products like egg proteins, dairy proteins, pepsin, animal-free meat proteins including heme, and fats. Proteins like myoglobin give meat its signature taste and aroma, and incorporating these proteins into plant-based foods can impact sensory experience to more closely resemble conventional products.

Precision fermentation has been used in food production since the 1990s when chymosin, the major enzyme in rennet (a cheese coagulant), was first created via precision fermentation. A handful of key alternative protein ingredients derived from precision fermentation, such as **Perfect Day**'s whey protein and **Impossible Foods**' soy leghemoglobin, are also widely distributed. That said, the ingredient of interest—whether it's chymosin, leghemoglobin, whey, casein, or palm oil—can significantly affect the complexity of the production process, making the product development and scale-up stages especially ingredient-dependent.

Figure 3: Comparative diversity of animal, plant, and microbial species



Microbial diversity offers countless possibilities for fermentation-derived food products.
Source: (Mora et. al, 2011) (World Flora Online, 2024) (Locey & Lennon, 2016)

Commercial landscape

Commercial landscape

Overview

In 2023, fermentation-enabled alternative proteins continued to advance as viable solutions to meet the demand for sustainable food sources.

The year saw pivotal developments, including the opening of at least seven new fermentation facilities, the debut of several new products and companies, and continued commitment to the sector from large meat and consumer packaged goods (CPG) companies—all of which signaled the industry's resilience and potential for long-term growth.

- The number of publicly announced companies focusing primarily on fermentation inputs or end products for alternative proteins rose to 158 in 2023.
- Seven new fermentation facilities opened in 2023, and several more were announced or began construction. Notable examples in the United States include **Meati Foods**' 100,000-square-foot commercial facility in Thornton, Colorado, and **Liberation Labs**' 600,000-liter facility that broke ground in Indiana.
- Large food companies continued their involvement in the fermentation industry. Global dairy companies like **FrieslandCampina** and **Danone** increased their involvement in precision fermentation, and **Thai Union**, one of the world's largest seafood companies, invested in microalgae-based ingredients.

Company landscape

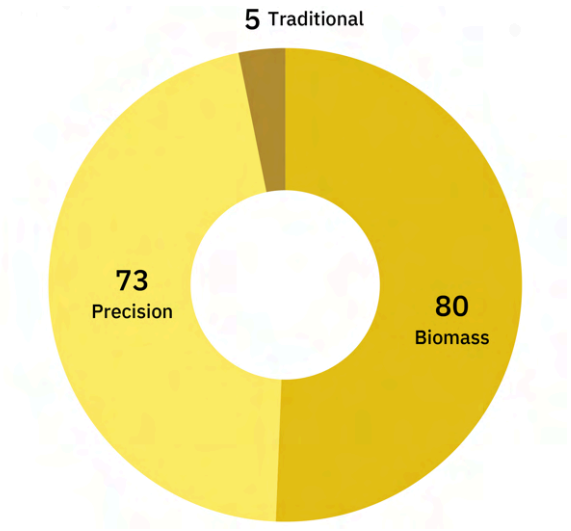
In 2023, GFI's company database identified 158 companies focused primarily on fermentation for alternative proteins, increasing from 153 in 2022. Additionally, at least 123 diversified companies to date have joined the industry through investments, partnerships, or business-to-business (B2B) product/service offerings.

These figures likely do not fully capture the actual count of companies involved in the fermentation space, as several startups may still be in stealth mode. Additionally, while GFI's company database is intended to be as comprehensive as possible, it is not exhaustive.

Do you know of an alternative protein company that's not on our list? Request to add it here. Likewise, if you see a company in our database that has been acquired, closed, or rebranded, please let us know by requesting an update.

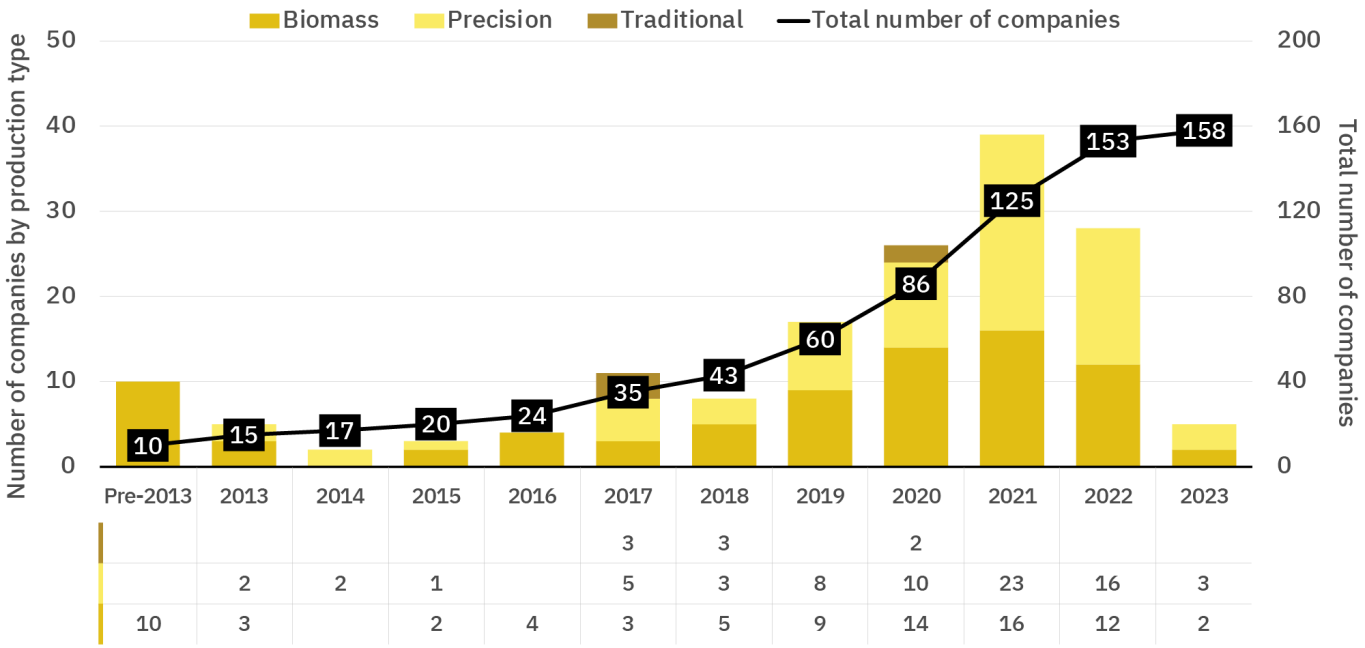
While the majority of fermentation companies remain focused on end-product formulation and manufacturing, there has been an uptick in activity in other areas of the fermentation value chain, like ingredient optimization and bioprocess design. We expect to see more companies specialize in stages of the technology stack as the industry matures.

Figure 4: Number of companies by technology focus



Source: GFI company database.

Figure 5: New and total publicly announced companies by year founded



Source: GFI company database.

Figure 6: Distribution of companies by country and region

1–9 companies | 10–19 companies | 20+ companies

Africa and Middle East *Count 15*					
Ethiopia	1	Israel	13	South Africa	1
Asia Pacific *Count 27*					
Australia	4	New Zealand	4	Vietnam	1
China	6	Singapore	8		
India	3	Thailand	1		
Europe *Count 61*					
Austria	2	France	6	Spain	6
Belgium	5	Germany	10	Sweden	4
Denmark	2	Lithuania	1	Switzerland	2
Estonia	2	The Netherlands	6	Turkey	1
Finland	3	Norway	1	United Kingdom	10
Latin America *Count 5*					
Brazil	3	Chile	2		
Canada and U.S. *Count 50*					
Canada	4	United States	46		

Source: GFI company database.

Facilities

The market for fermentation-enabled alternative protein products has expanded in recent years, and growth means that more and larger fermentation facilities are essential.

But, as GFI and Integration Consulting's 2023 fermentation manufacturing capacity analysis reveals, most existing fermentation facilities in the pharmaceutical, industrial enzyme, fuel, and beverage industries are ill-suited for alternative protein production. **This creates a barrier to growth for the fermentation-enabled alternative protein industry. While manufacturing capacity remains a challenge for some companies in the fermentation industry, 2023 brought several encouraging developments.**

Facilities that opened in 2023

- **Meati Foods**, which creates products made primarily from mushroom root, opened their 100,000-square-foot Mega Ranch facility in Thornton, Colorado, in January. The facility is capable of producing 45 million pounds of product per year—enough to supply more than 7,000 retailers and restaurants.
- **Motif FoodWorks** opened their second facility, a market development and research center in Northborough, Massachusetts. The company, which makes plant-based meat and alternative protein ingredients, announced they would add fermentation and bioprocessing services to its business.
- Swedish fungi-based food company **Mycorena** announced it scaled their food science development facility to feature increased fermentation equipment and a full production kitchen.
- **Chunk Foods**, which uses fermentation to create whole-cut plant-based meat products, opened a new facility in Israel that can manufacture millions of steaks each year.
- Austrian startup **Arkeon Biotechnologies**, which uses fermentation to produce protein from carbon dioxide, successfully opened a new pilot production plant in Vienna.
- German biomass fermentation company **MicroHarvest** opened a pilot facility in Lisbon, Portugal. The facility can produce 25 kilograms of the company's single-cell proteins per day.
- **Nosh Biofoods**, a biomass fermentation company based in Germany, opened a pilot facility inside **Berliner Berg**, a brewery in Berlin.

Facilities that broke ground in 2023

- **Aqua Cultured Foods**, a Chicago-based fermentation-enabled alternative seafood producer, began construction on a new manufacturing facility. The facility is located in Chicago and will be nearly three times larger than the company's current base.
- Precision fermentation company **Liberation Labs** broke ground on their first commercial-scale facility in Richmond, Indiana. In November 2023, they secured a $25 million government-backed loan—a strong example of the U.S. federal government leaning into building a thriving bioeconomy. The plant will have a capacity of 600,000 liters to supply to CPG companies and other industrial manufacturers. Commercial production is expected by the end of 2024.

Groundbreaking event at Liberation Labs commercial precision fermentation facility in Richmond, Indiana.
Photo credit: Liberation Labs

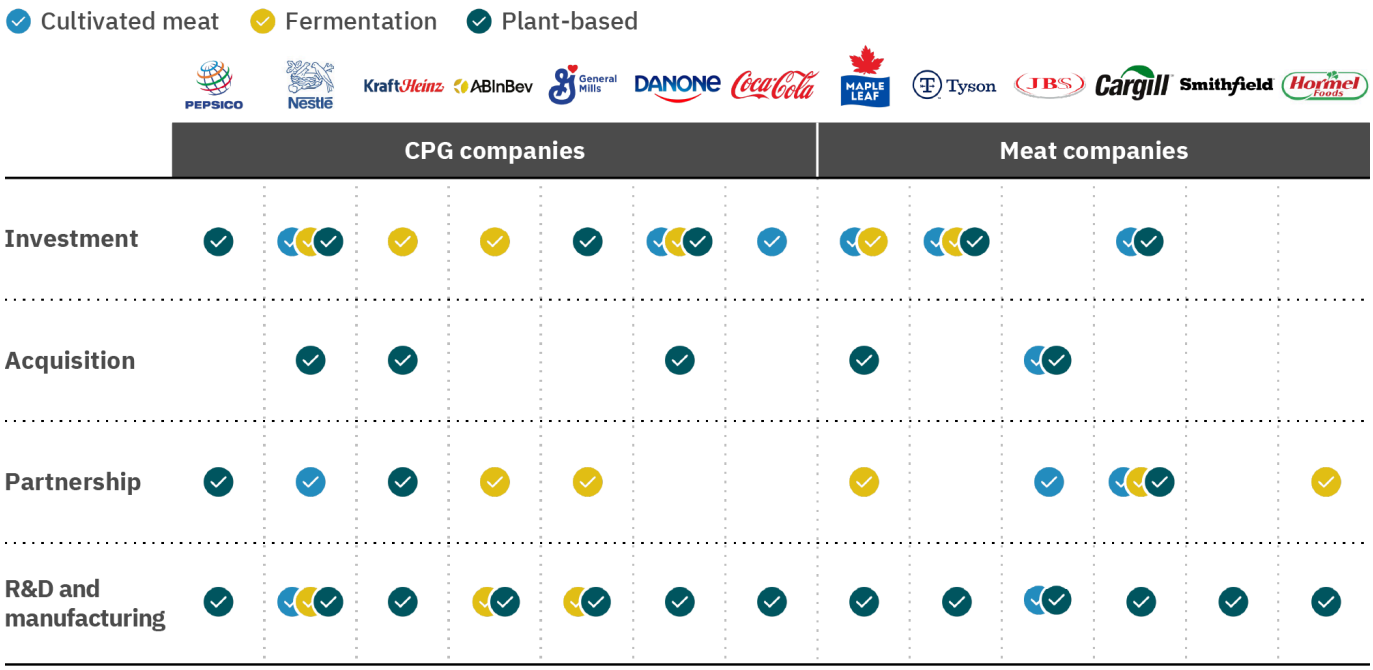
Involvement from diversified companies

Many of the leading meat and food companies around the world are involved in the fermentation industry through investments, acquisitions, partnerships, and/or research, development, and manufacturing.

Involvement from existing meat and food producers can serve as a force multiplier for the industry. These companies already have funding, infrastructure, and distribution access. Multinational companies like **Nestlé**, **Kraft Heinz**, **Cargill**, and **Tyson** are involved in the fermentation industry. New activity from diversified companies in 2023 indicates a growing commitment to the sector:

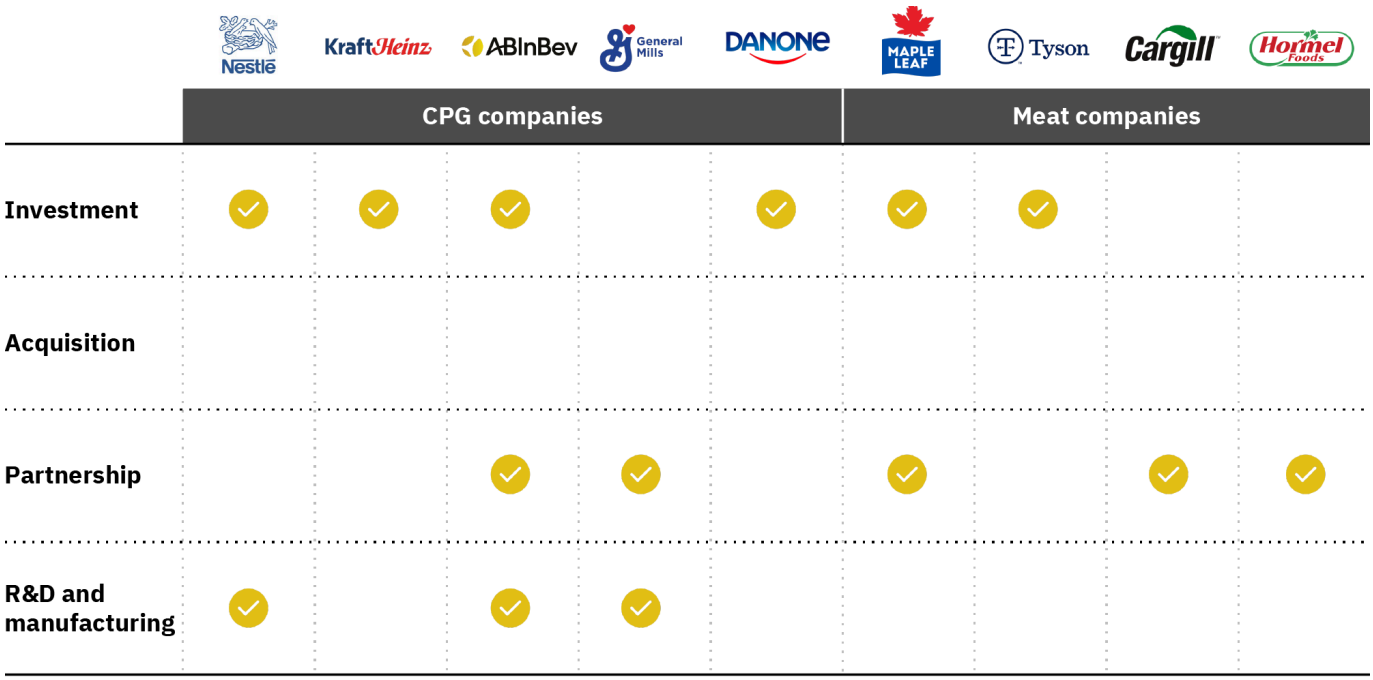
January	**FrieslandCampina Ingredients**, a branch of global dairy company **FrieslandCampina**, announced a strategic partnership with biotechnology firm **Triplebar** to develop and manufacture precision fermentation-derived proteins for various applications. The venture capital fund of global seafood company **Thai Union** led a €13 million Series A funding round for Paris-based microalgae producer **Algama Foods**.
April	**Danone Manifesto Ventures**, **Danone**'s corporate venture arm, took a minority stake in Israeli precision fermentation startup **Imagindairy**.
October	U.S.-based precision fermentation ingredient producer **The EVERY Company** and Colombia's largest CPG food company, **Grupo Nutresa**, announced a joint development agreement to use EVERY's ingredients in Nutresa's existing line of plant-based products.

Table 2: Diversified companies with involvement in alternative proteins



Source: GFI analysis of publicly reported industry news and events

Table 3: Diversified companies with involvement in fermentation



Source: GFI analysis of publicly reported industry news and events

Partnerships

Collaborations among research, production, and distribution partners are crucial for accelerating the mainstream adoption of fermentation-enabled products.

The number of announced collaborations in 2023 increased slightly from 2022. Partnership activity in 2023 largely centered on end-product development and distribution, two critical components to the mainstream adoption of fermentation-enabled products. Here are some of the publicly announced partnerships from 2023.

Table 4: Partnerships table

Product development partnerships

Companies/organizations	Details
Air Protein and ADM	Developing products for commercialization
Alpha Foods and The EVERY Company	Developing hybrid plant-based and precision-fermentation-derived products
Fermify, CREMER, and Interfood	Developing animal-free cheeses
FrieslandCampina and Triplebar	Developing and manufacturing precision-fermentation-derived proteins
Mycorena, Nybergs Deli, and ICA	Developing blended meat and mycoprotein products
MycoTechnology and IFF	Developing mycelium-based alternative proteins
Nosh Biofoods and Ginkgo Bioworks	Creating a mycoprotein ingredient to give alternative proteins a more meat-like flavor
Prime Roots and Fabrique Délices	Developing a line of fungi-based koji-pâtés and koji-foie gras
QL AG and Ginkgo Bioworks	Creating fermentation-derived dairy proteins with identical nutritional profiles to conventional dairy
SimpliiGood and Haifa Group	Creating and scaling spirulina products
Solar Foods and Ajinomoto Group	Using Solar Foods' Solein product to create new products
The Better Meat Co. and Greenleaf Foods, SPC.	Developing new products with Rhiza mycoprotein
Nelson-Jameson, Vaess, and Lallem and Specialty Cultures	Producing mycoprotein-based meat alternatives

Scale-up partnerships

Companies/organizations	Details
Cauldron and Boston Bioprocess	Supporting third-party companies scaling from lab to industrial production
EGGcited and revyve	Scaling up revyve's technology for extracting new ingredients from spent brewer's yeast
Fermbox Bio and BBGI	Establishing precision fermentation facilities in Thailand and Southeast Asia
Fermbox Bio and Dyadic International	Developing, manufacturing, and commercializing animal-free proteins
Ginkgo Bioworks and Vivici	Advancing the production of animal-free dairy proteins
LiDestri Foods and Drinks and Fermentum	Building a commercial-scale precision fermentation facility

Distribution partnerships

Companies/organizations	Details
Marlow Ingredients and Tempty Foods	Introducing Tempty Foods products made with Marlow's mycoprotein ingredients
Mycorena, RIP Foods, and Meeat Food Tech	Launching joint products and expanding Mycorena's market reach
Perfect Day and Unico	Launching a protein powder made from milk protein, egg whites, and Perfect Day's whey protein
Quorn and Prime Roots	Creating market expansion opportunities and collaborating on new product offerings
The EVERY Company and Grupo Nutresa	Using EVERY's ingredients in Nutresa's existing plant-based products

Equipment partnerships

Companies/organizations	Details
Ecovative and Limbraco	Developing specialized farming equipment for Ecovative's AirMycelium crops
Quorn and Karakuri	Collaborating to ensure Karakuri's equipment in quick-service and fast-casual kitchens is optimized to prepare Quorn's products

Product launches

Fermentation-enabled products increased in variety and availability in 2023. Consumers are now more likely than ever to find alternative proteins made with fermentation on retail shelves and restaurant menus.

Fermentation for alternative protein products typically means creating either: 1) individual ingredients that replicate the sensory properties of meat, seafood, dairy, or eggs (typically via precision fermentation) or: 2) the protein base for a standalone product, like mycelium-based products (typically via biomass fermentation).

Exciting innovations across the plant-based meat, seafood, dairy, eggs, and ingredient categories launched in 2023, positioning the category for long-term growth.

Meat and seafood

February	Spain-based **Libre Foods** unveiled a mushroom-based bacon product, which the company claims is the first of its kind to launch in the European Union. Israel's **Mush Foods** introduced its mycelium protein ingredient solution, **50CUT**, which is tailored for use in blended animal- and mycelium-based meat products.
March	Mycoprotein pioneer **Quorn** rolled out a mycoprotein-based chicken and leek family pie at **Sainsbury's** stores in the United Kingdom. Swiss upcycling startup **brewbee**, which creates food products from spent brewer's yeast, began selling their plant-based meat and other food products in co-op retailers throughout Switzerland.
April	**Quorn** released new mycoprotein-based chicken Katsu Fillets that are now available at **Tesco**, **Morrisons**, **Waitrose**, and **Asda** in the United Kingdom.
May	California-based mushroom meat producer **Shroomeats** launched three new mushroom-based products: meatballs, burgers, and ground beef. Each product contains only six ingredients. Colorado-based **RollinGreens** debuted a new shelf-stable chicken fajita product made with a blend of fermented shiitake mushrooms, pea protein, and rice.
October	**Meati Foods** debuted new shelf-stable jerky products with a mycelium base in original, peppered, and sweet chile flavors.
November	**Meati Foods** launched four new mycelium-based meat products.

Dairy

January	**Bel Brands USA** launched **The Laughing Cow Plant Based** and **Nurishh Incredible Dairy Animal Free Cream Cheese** at **Kroger** and **Whole Foods** stores across the United States. The Nurishh Incredible Dairy Animal Free Cream Cheese was Bel Brands USA's first animal-free product created in partnership with **Perfect Day**.
May	Shanghai-based **Changing Bio** debuted the company's first line of microbial-based dairy products, including whipped cream and grated parmesan.
June	Singaporean restaurant **Fico** was the first to serve gelato made from Finnish food tech company **Solar Foods**' fermentation-derived **Solein** protein.
August	**Puretrue** debuted an animal-free casein using a traditional yeast-based fermentation process. The company says that their casein ingredient undercuts the price of its conventional counterpart.
December	**Nature's Fynd** introduced a line of yogurts made with their fermentation-enabled **Fy** protein.

Eggs

March	Netherlands-based **revyve** introduced an egg white replacer made from upcycled spent brewer's yeast. The egg replacer can be used as a binder in plant-based meats and adds an umami flavor.
December	**The EVERY Company** launched the EVERY Egg, a liquid egg created with precision fermentation-derived ovalbumin that can be used as a 1:1 replacement for conventional eggs.

Ingredients

March	Boston's **Motif FoodWorks** released a texture ingredient for plant-based meat developed in partnership with **Rhizome Network**. The ingredient recreates the texture of animal connective tissue by using a combination of plant proteins and plant-based carbohydrates.

Pet food

March	Plant- and fungi-based pet food company **Wild Earth** unveiled new dog food products as part of the company's new Core and Performance collections.

Industry associations

Collaboration is key to supporting market growth for fermentation-enabled products. Industry associations and alliances can play important roles in driving regulatory transparency, conducting consumer research, and aligning on nomenclature.

In addition to the two groups formed in 2022 (the Fungi Protein Association and Precision Fermentation Alliance), a new industry group called Food Fermentation Europe was formed in 2023. It addresses issues including labeling and nomenclature for animal-free proteins, capacity challenges in industrial-scale fermentation, and regulatory pathways for approving novel foods in the European Union.

Associations like these will be crucial to the success of the industry. **For more information on industry collaboration, check out this blog post and database of alternative protein trade organizations.**

The Better Meat Co.'s chicken breast made with Rhiza mycoprotein. Photo credit: The Better Meat Co.

Consumer insights

Consumer insights

In 2023, dozens of innovative fermented alternative proteins hit the market, from mushroom-based bacon to microalgae-based crab cakes.

Consumers are finding more fermentation-derived products on grocery store shelves and traditional fermented food categories like kimchi and kombucha experienced retail growth over recent years. Yet despite these milestones, consumer awareness of fermented foods remains low.

Research published in 2023 points to emerging opportunities and challenges across the fermentation industry.

Nomenclature and messaging appeal

Research on product nomenclature and terminology for and consumer perceptions of fermentation-enabled products was released in 2023. This research suggests a bright future for fermentation-enabled proteins as consumers learn more. It also reveals insights on how to introduce this category in an appealing and informative way.

Category diversity

Studies in the last few years have tested many variants of names and descriptions for product types and technologies. While some research focuses on specific terms or combinations, other research takes a comparative approach to learn what resonates with consumers.

Consumer education

To clarify the benefits and tradeoffs of naming options, GFI and Accenture conducted research in 2023 on nomenclature for precision-fermented dairy and eggs with consumers in France, Germany, the United Kingdom, the United States, and Spain, testing dozens of naming variants in four languages (see figure 7).

Among the options tested, modifiers translating as "animal-free" (Spanish: "sin origen animal," French: "non-animal(e)," German: "tierfrei") were most appealing in most markets; consumers also reported that they could see themselves using these terms socially.

While process-focused terminology including words like "fermentation" and "brewing" performed well in some markets and contexts, they were polarizing in others. "Fermentation" had positive health connotations in France and Spain, but was relatively lower in appeal to respondents in the United States and the United Kingdom. Variants of "brewing," which were tested in English and German for translation reasons, were seen as familiar and made the products seem innovative, but were similarly reported as less appealing by respondents compared to other terms.

When describing the process by which ingredients are produced, it's clear that people desire detail, but not a lengthy scientific explanation. The GFI and Accenture research tested explanations of the precision fermentation process that went into different levels of detail, and the most favored explanation included:

- A light walkthrough of the process.
- Relatable examples of host microorganisms.
- Relatable examples of the ingredients produced.
- Confirmation that the produced ingredient is the same as the conventionally produced ingredient.
- The messaged benefit of the ingredient being produced without animals.

The explanation most preferred by respondents:

Just like brewing beer, this fermentation process uses microorganisms like yeast. In this case, microorganisms are programmed to produce specific proteins during fermentation, when they are fed sugars, which they convert into dairy or egg proteins, like whey or casein. These proteins are identical to what we'd find in milk or eggs but made without animals.

Similarly, a 2022 study by Hartman Group and **Perfect Day** found that reported purchase likelihood for precision-fermented dairy (as well as plant-based meat) increased after a short description, showing that messaged descriptions can help introduce consumers to the category.

> *In our work across multiple aspects of the transition towards sustainable and nutritious diets, we see precision-fermented food and drink as an exciting and critical solution. With this new, data-driven perspective on nomenclature and messaging, the global Food Industry can now position these emerging products and ingredients in ways that appeal to mainstream audiences, helping to ensure widespread, global uptake. What comes through loud and clear is the importance of communicating in ways that feel familiar and everyday, majoring on mainstream benefits that truly resonate with consumers – like taste, price and convenience – while differentiating through more unique health and sustainability benefits.*
>
> **Fiona Bennie**
> *Managing Director, Accenture Song – Sustainability, Future of Food & Circularity*

Consumer awareness and familiarity

While most consumers are not familiar with precision fermentation as a process, a significant minority are aware of product categories made with it. Many are already using products made with fermentation, such as cheese, vitamins, and supplements.

- A November 2023 study conducted by Morning Consult on behalf of GFI evaluated U.S. adults' perceptions of and openness to emerging alternative protein technologies (including precision-fermented dairy products and meat made from mycoprotein). The same survey detailed that 30 percent claimed to be aware of meat products made with mushrooms and fungi while 27 percent of all consumers claimed to be very or somewhat familiar.
- A 2023 study by the International Food Information Council (IFIC) found that 29 percent of U.S. consumers had heard of "fermented protein," and 16 percent had heard of "mycoprotein."
- A 2022 study by Hartman Group and **Perfect Day** in the United States found 29 percent reported being familiar with precision-fermented dairy.

Similar rates have been seen in other countries for related technology.

- A 2023 study in Canada by Powell et al. on consumer perceptions of yeast-derived dairy found that 56 percent of participants responded that they had heard of cellular agriculture (defined for participants as "a set of technologies used in the production of agricultural products like meat, dairy, eggs, and other animal products using cell cultures rather than relying on animals"), vs. 44 percent who had not; 35 percent said that they understood it. While this seems high given the novelty of the technology, these consumers were able to identify cellular agriculture's use in meat, dairy, leather, and pharmaceutical production.
- A 2022 survey by BCG and Blue Horizon found that 47 percent of consumers globally reported having heard of fermentation-based proteins, and as high as 73 percent in the United Kingdom.

While awareness of most precision-fermented product categories is low, consumers are already using many products made with fermentation (sauerkraut, miso), which suggests a moderate learning curve. New launches and marketing will likely increase awareness and understanding in the coming years.

Product appeal

When consumers are informed about the definition of fermentation-derived products and asked about product appeal, many rate them positively in terms of appeal and interest.

- In a November 2023 survey conducted by Morning Consult on behalf of GFI, 42 percent of consumers rated animal-free dairy as appealing after reading a brief description, including the term "fermentation"; 35 percent rated mycoprotein as appealing after reading a brief description. GFI and Accenture found 47 percent of consumers in France, Germany, Spain, the United Kingdom, and the United States found precision-fermented dairy appealing.
- IFIC's 2023 study found that 37 percent of U.S. consumers reported being interested in products made with fermented protein, which was a notable increase from their 2021 survey where 27 percent reported interest. A comparable number (33 percent) were interested in trying mycoprotein products.
- Powell et al. found that 46 percent of Canadian respondents indicated positive feelings toward the term: "yeast-derived agriculture."

Precision fermentation description

Consumers saw this description of precision fermentation after reporting awareness and before reporting perceptions and likelihood to purchase.

"As you may know, fermentation is used to make foods like beer, bread, and yogurt. We can also use a type of fermentation to convert sugars into dairy or egg proteins like whey or casein. These proteins are identical to what we'd find in milk or eggs, but made without animals and can be used to make animal-free dairy products like ice cream, milk, protein powder, and more. Some examples include brands like Modern Kitchen and Nurishh."

Consumer willingness to try

Many consumers express willingness to try and purchase precision-fermented products, likely because of expectations around taste, health, and sustainability. This is notable for a category that most consumers are not familiar with, and suggests many consumers will be interested in trying and purchasing as they learn more about precision fermented products.

Try and purchase

Consumers' expected purchase rates for precision-fermented products are difficult to determine and vary widely due to the diversity of products, limited consumer access, and varied consumer understanding. But most studies show that either a significant minority or slight majority of

consumers are willing to try or purchase various fermentation-enabled products.

Perfect Day, inc. produces milk proteins using fermentation. Photo credit: Perfect Day, Inc.

- GFI and Accenture found that 51 percent of consumers on average across France, Germany, Spain, the United Kingdom, and the United States were willing to try precision fermented dairy.
- A 2023 study by Thomas et al. in the United States, Germany, and Singapore found high levels (greater than 50 percent) of willingness to try precision-fermented eggs in all three countries. GFI and Accenture found comparable levels with 50 percent willing to try precision-fermented eggs on average across France, Germany, Spain, the United Kingdom, and the United States.
- A November 2023 study conducted by Morning Consult on behalf of GFI found 23 percent of consumers reported they would be likely to purchase animal-free dairy, and 20 percent reported they would be likely to purchase mycoprotein meat.
- In a 2022 study by Hartman Group and Perfect Day in the United States, 43 percent of consumers reported that they would be likely to purchase precision-fermented dairy products. Additionally, the study found that purchase likelihood was strong across multiple categories and formats where consumers were told precision fermentation could be used, including protein powder, drinkable yogurt, protein bars, energy drinks, sports drinks, and even flavored water.

A November 2023 study conducted by Morning Consult on behalf of GFI asked consumers to compare animal-free dairy products head-to-head with their conventional counterparts on key descriptors based on their understanding of the technology (after a brief description, shown above in "Consumer awareness & familiarity"). For both animal-free dairy and mycoprotein, most consumers are likely to believe that these products are equally or more sustainable and healthy than conventional proteins. Only around 25 to 30 percent see the products as more processed than conventional meat.

Other studies have suggested that health benefits will play a key role in category receptivity:

- **GFI and Accenture found 41 percent of consumers across France, Germany, Spain, the United Kingdom, and the United States who reported willingness to try precision-fermented dairy cited health as a top reason.**
- A 2022 study by Hartman Group and Perfect Day in the United States found that consumers' top criterion for willingness to purchase is whether precision-fermented dairy products were safe (60 percent), followed by taste (59 percent), and health (53 percent), with other factors like cost value, allergens, endorsement by authority, and non-GMO being of lower importance.
- In a multinational 2023 analysis, Dean et al. found consumer willingness to try and buy meat made using mycoprotein slightly higher than for plant-based meat on average, though willingness to pay was slightly lower. This is likely due to consumers being less familiar with fermented proteins than plant-based meat but is a positive signal for future trial and adoption. Their earlier analysis in 2018-19 found that perceptions of health were most predictive of willingness to try and buy meat made using mycoprotein, while perceptions of taste would be more predictive of a willingness to pay a premium for mycoprotein vs. conventional products.

- A 2021 study by Thomas and Bryant found consumers in five countries (Brazil, Germany, India, the United Kingdom, and the United States) expect animal-free cheese to be tastier than plant-based cheese and comparable to basic, non-premium animal-based cheeses. Animal-free cheese was also perceived in all five countries as more ethical and sustainable than vegan and conventional cheese, and comparably as healthy and nutritious as vegan cheese.

- A focus group study by Broad et al. in 2022 in the United States, Germany, and Singapore found consumers were more likely to associate "animal-free" and "fermented" dairy (both terms were introduced to participants) with animal welfare benefits than environmental, individual health, and public health benefits. While this may have been prompted because the product description that participants reviewed emphasized the concept of making "the same proteins" without using animals, it does suggest that positioning products as animal-free successfully conveys benefits that would lead them to try or buy.

Overall, these studies suggest that once messages are shared with consumers, they readily associate ethical, environmental, health, and taste benefits with products made via precision fermentation, and that health may play an important role alongside taste and price in driving purchase consideration.

Tomorrow Farms' Bored Cow milk made with milk protein from fermentation. Photo credit Tomorrow Farms

Consumer research and demographic insights from around the world

Consumer research on fermented proteins and mycoprotein has been global in scope, and researchers in the past few years have released various studies showing strong expected responses to these products in many countries.

- A 2023 analysis by Dean et al. of survey data from 2018-19 on consumer perceptions of mycoprotein in 12 countries representing over 33 percent of the estimated global population (China, United States, Indonesia, Pakistan, Brazil, Mexico, France, United Kingdom, Spain, Netherlands, Dominican Republic, and New Zealand) found consumers overall reported being probably willing to try and buy "fungal-based" meat products, and that consumers in Indonesia, Mexico, Netherlands, Spain, and the United Kingdom were most willing to buy them.

- A 2021 study by Thomas and Bryant of consumers in the United States, Brazil, United Kingdom, Germany, and India (summarized in our 2022 State of the Industry Report) found strong majorities of consumers (around 50 to 75 percent in the United States, United Kingdom, and Germany) and as high as 90 percent (in Brazil and India) are willing to try and buy an animal-free cheese product after reading a detailed explanation of precision fermentation and the sensory properties of resultant ingredients/products.

While each of these studies took different approaches to nomenclature and category explanation that prevent direct comparison, it is clear that attitudes toward fermentation-enabled alternative proteins likely vary widely by culture, making local research crucial for companies considering introducing products to new markets.

Figure 7: Ranking of potential precision fermentation category descriptions in five countries

	US	UK	Germany	France	Spain
Animal-free	#1	#1	#1 Tierfrei	#4 Non-animal(e)	#1 Sin origen animal
Non-animal	#2	#2	#2 Ohne Tierhaltung	#1 Sans élevage animal*	#4/5 *tie* Sin ganadería*
Cultivated	#3	#3	#3 Hergestellt durch Fermentation	#6 Obtenu(e) par fermentation*	#6 Cultivado/cultivada*
Made from precision fermentation	#4	#4	#5 Hergestellt durch Präzisionsfermentation	#3 Obtenu(e) par fermentation de precision	#3 Elaborado por fermentación de precisión
Made from fermentation	#5	#5	#4 Hergestellt durch präzises Brauen	#2 Obtenu(e) par brassage de precision	#2 Elaborado por fermentación
Made with microflora	#6	#6	#6 Hergestellt aus Mikroflora	#5 Élaboré(e) à partir de microflore	#4/5 *tie* Elaborado a partir de microflora

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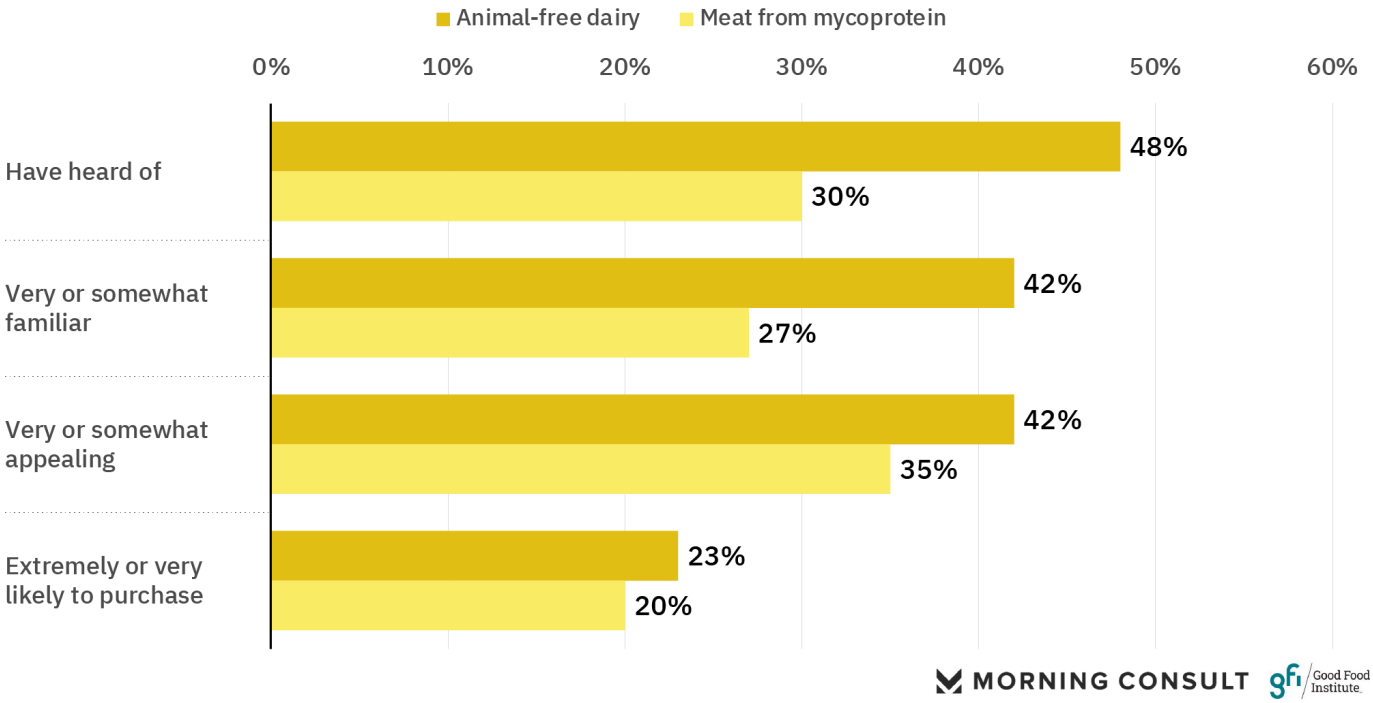
Source: GFI and Accenture survey of n=5,128 consumers in 5 countries, September 2023
Rankings are shown among 6 names tested across all countries; additional local names tested are not factored in ranking; additional names were not #1 on net in any country
* = carries an additional connotation vs. the English terminology; tested names were translated by native speakers

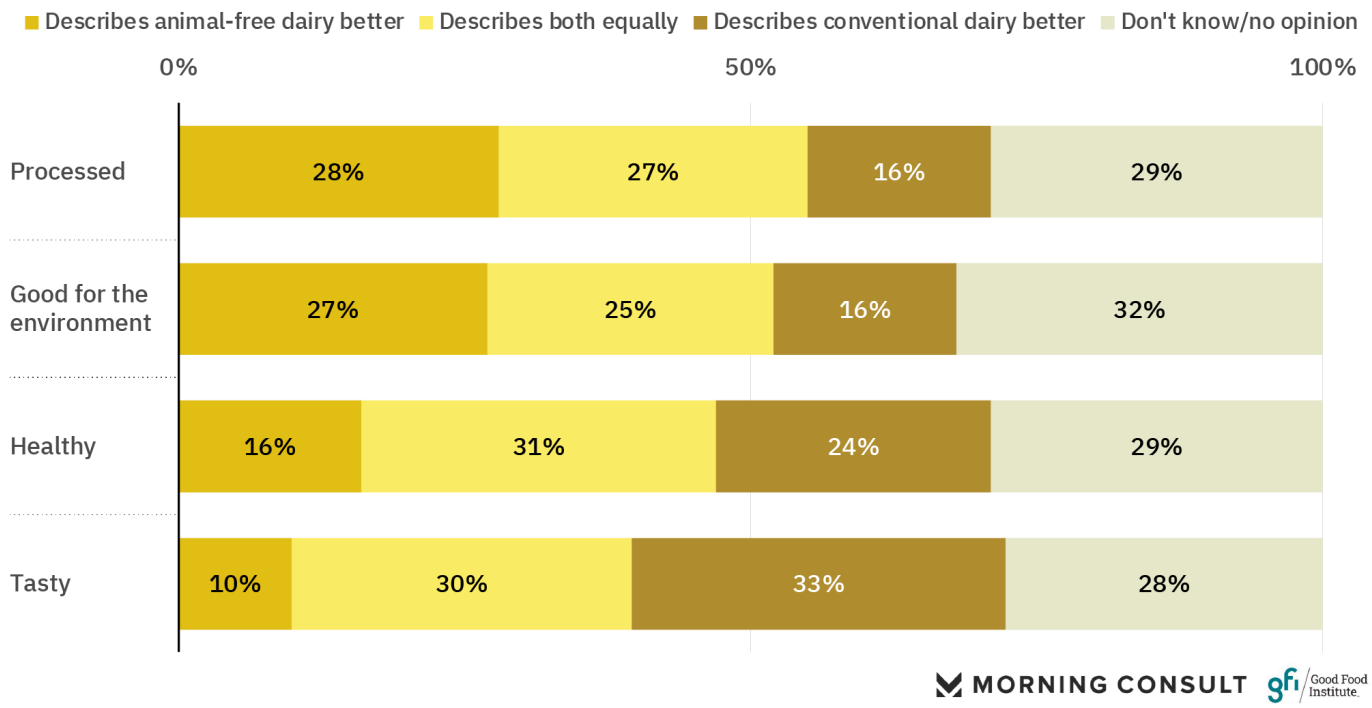
Figure 8: Consumer metrics for fermentation-enabled products



MORNING CONSULT gfi Good Food Institute

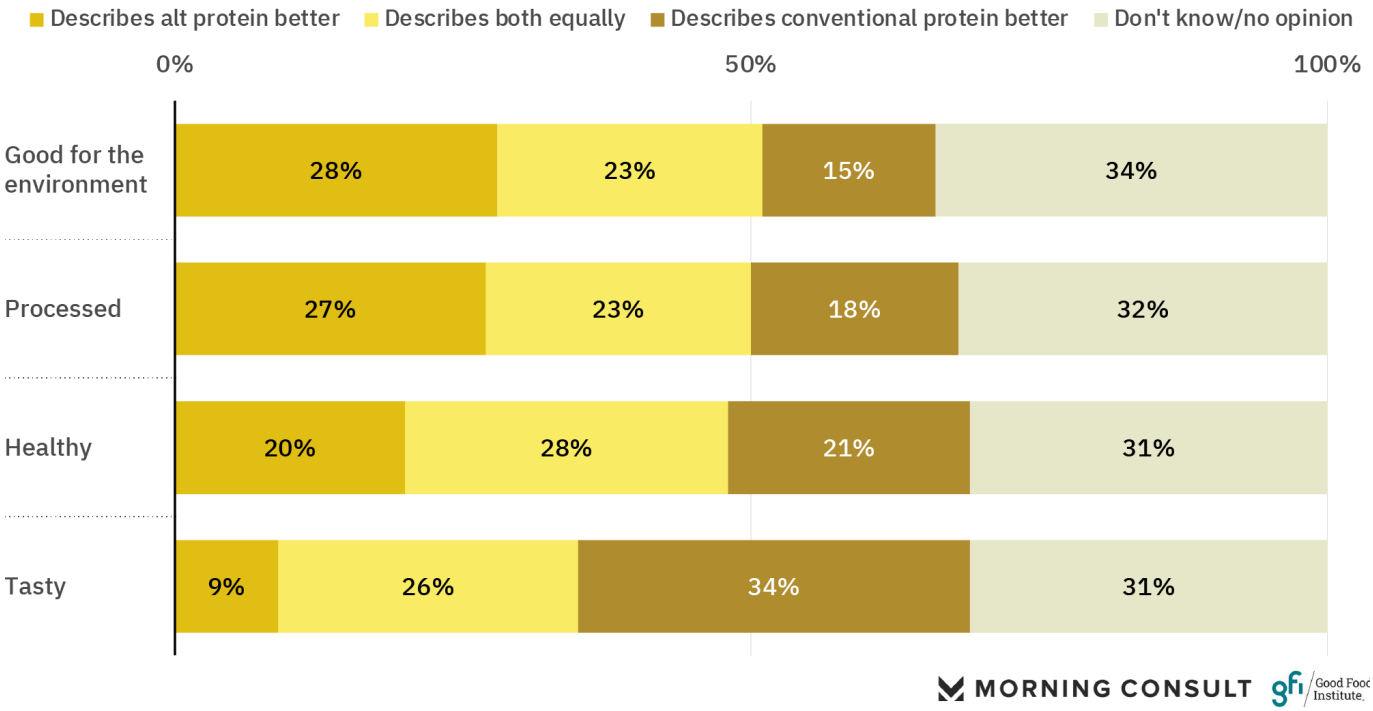
Source: Poll by Morning Consult on behalf of GFI, n=2.203 U.S. adults November 2023

Figure 9: Do each of the following attributes describe animal-free or conventional dairy better?



Source: Poll by Morning Consult on behalf of GFI, n=2,228 U.S. adults December 2023

Figure 10: Do each of the following attributes describe mycoprotein or conventional meat better?



Source: Poll by Morning Consult on behalf of GFI, n=2,228 U.S. adults December 2023

Investments

Investments

Overview

Following the first disclosed investment in a fermentation company in 2013, companies primarily involved in the fermentation space have raised a total of $4.1 billion to date, with 95 percent of invested dollars in the last five years alone. While 2023 fundraising totals marked a decline from 2022 levels, other primarily venture-backed sectors like fintech also experienced funding declines of around 50 percent year-over-year (YOY).

Fermentation companies raised $514.7 million in 2023, representing a 32 percent decrease from the $758.5 million raised in 2022. Similar declines were seen across global venture funding and benchmark segments like climate tech and food tech.

Fermentation remains a relatively nascent sector with fewer than 200 companies worldwide. As a result, a minority of deals can significantly impact annual investment totals for the sector. For example, in 2022, nearly half—$355 million—of the year's total investment dollars were raised from just three deals: **Meati Foods**' $150-million Series C round, **Remilk**'s $120-million Series B round, and **Mycotechnology**'s $85-million Series E round. Since advanced companies generally do not raise large rounds two years in a row, there is a degree of randomness in any single year's funding totals.

The fermentation sector lacked similarly sized rounds in 2023, in which the largest three deals totaled $168.7 million. This made it difficult for the industry to meet 2022's funding levels. That said, not all regions saw declines in fermentation investments. Fermentation funding in Europe in 2023 totaled $179.4 million in 2023, a 22 percent increase from 2022, and the highest annual total for the region to date.

The wider alternative protein industry also saw private funding fall in 2023. While alternative protein companies raised $15.7 billion from 2014 to 2023—over half of which was raised in 2020 and 2021—investments dipped from $2.9 billion in 2022 to $1.6 billion in 2023. That said, these totals—and those for fermentation companies—are likely underestimated. Some companies raised funds that were not publicly reported under simple agreements for future equity (SAFE) or bridge rounds to increase financial runway. While certain deals, in general, are not publicly disclosed, we suspect an increased frequency of under-reporting this year based on the larger number of SAFE and bridge rounds and our conversations with market participants. Some of these investments may eventually be reported as investments in 2024.

Various industries contended with a tepid private funding environment in 2023 driven by rising interest rates, elevated inflation, and a mixed economic outlook. As a result, global venture funding across all sectors fell 42 percent YOY in 2023 to its lowest level since 2017. Climate tech equity investments decreased by as much as 40 percent YOY, despite the sector receiving significant government support through the Inflation Reduction Act and other policies that helped to de-risk and fuel investment. Investments in food tech startups declined by 61 percent YOY.

Even in the face of these challenges, the fermentation industry continued to advance in 2023. Fermentation companies around the world hit key product development, distribution, and scaling milestones. All the while, companies continued to innovate their processes and products.

The challenging private funding environment for fermentation and alternative proteins may continue in the year ahead, especially as interest rates in the United States, Europe, and elsewhere are likely to remain elevated in 2024. At the same time, alternative proteins and fermentation continue to be critical tools for producing protein in more efficient, secure, and sustainable ways. **This also makes fermentation an important ESG opportunity, providing potential upside for investors and the industry.**

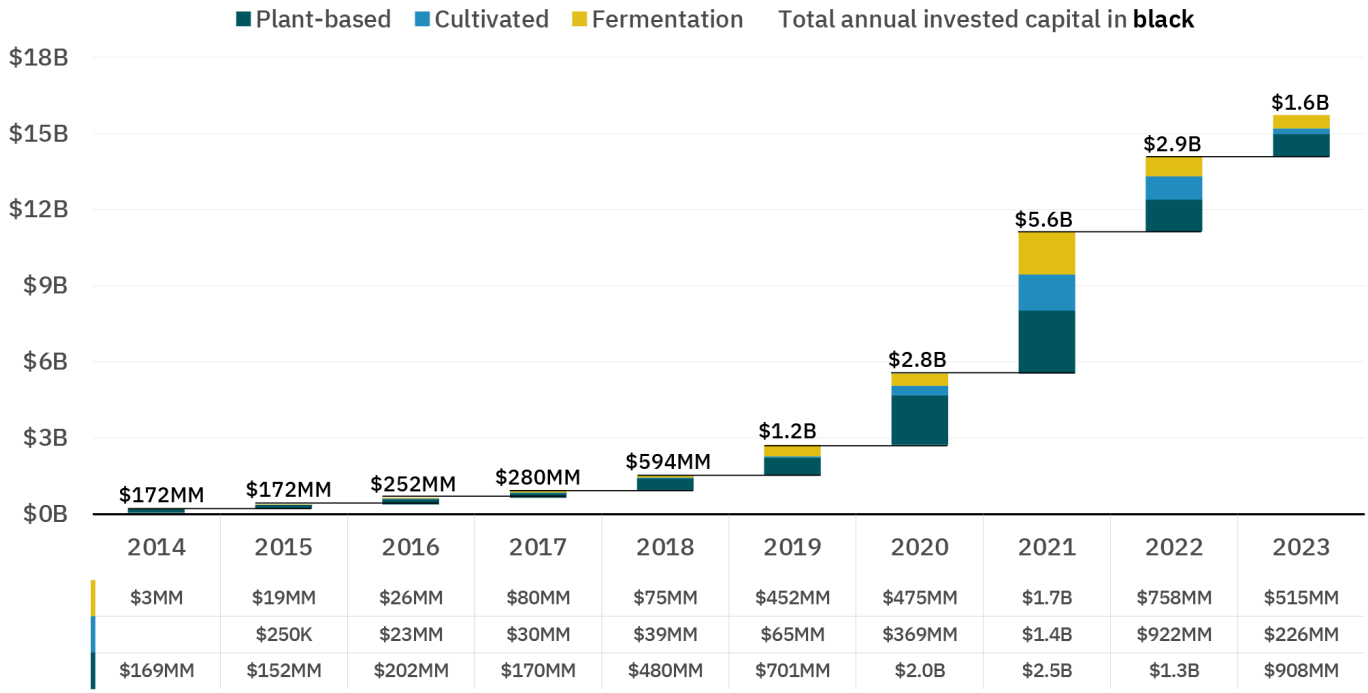
With this backdrop, we expect alternative protein and fermentation investments to evolve in the coming years. Since 2023 was a year of major transition, the industry is likely to settle on an adjusted, more realistic path in 2024. In light of the tighter private funding environment that is expected to persist into 2024, we expect the alternative protein companies best positioned to attract equity investment will be those that can demonstrate clear pathways to revenue and profitability. At the same time, long-term debt, grants, and government incentives are essential for companies to lower their production costs and achieve price parity as they scale production. **To enable alternative protein companies to access such funding, they will need creative solutions in areas such as product off-take and leveraging government and philanthropic funding.** Fortunately, there are replicable solutions already being implemented (e.g., school districts procuring alternative proteins for lunch menus) as well as those that have been successfully used in other industries (e.g., government loan guarantees and blended philanthropic financing for renewable energy). Through multi-stakeholder collaboration, these solutions can facilitate the flow of capital into alternative proteins.

Regardless of external market forces, if governments and companies are serious about improving food security, reducing emissions, and achieving their climate goals, more alternative protein funding is needed to help companies scale, improve their products, and reduce their costs.

Source: Unless otherwise cited, the investment data reported above was derived from GFI's analysis of data from Net Zero Insights.

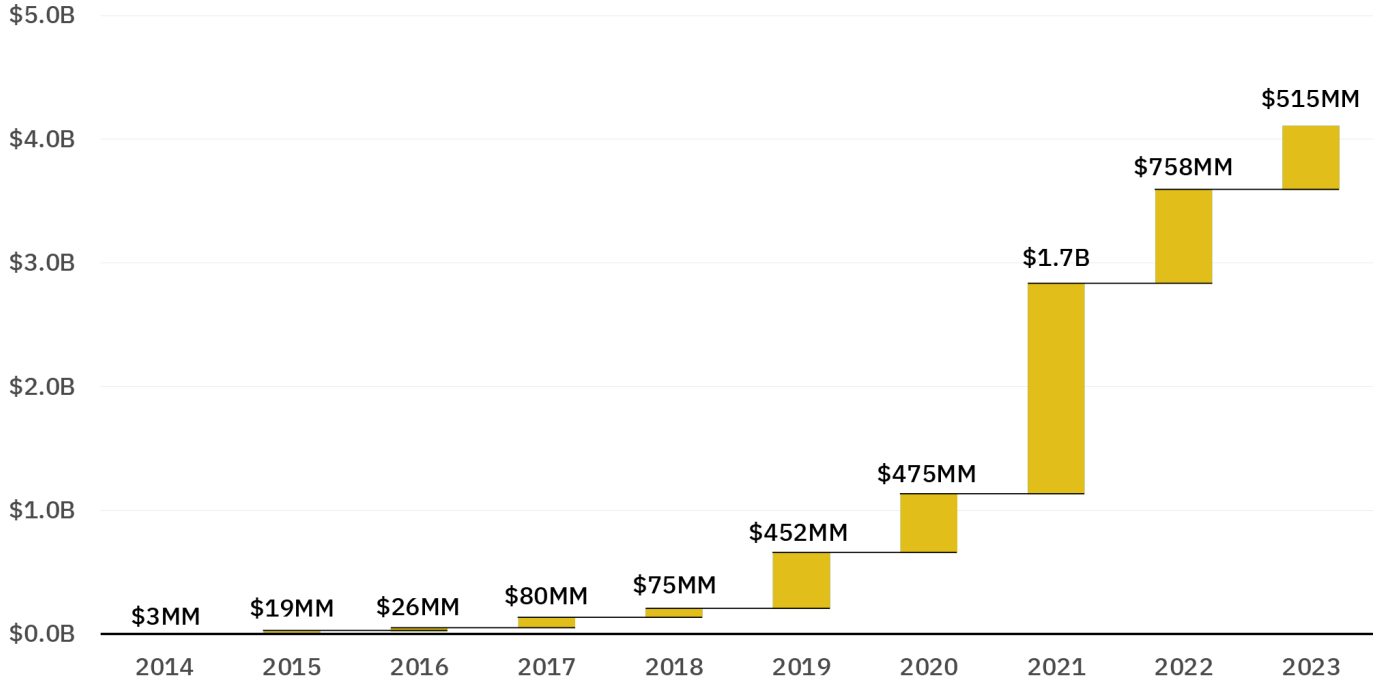
Note: Aggregated data has not been reviewed by Net Zero Insights analysts. Total deal counts include deals with undisclosed amounts.

Figure 11: Cumulative and annual alternative protein invested capital, by pillar



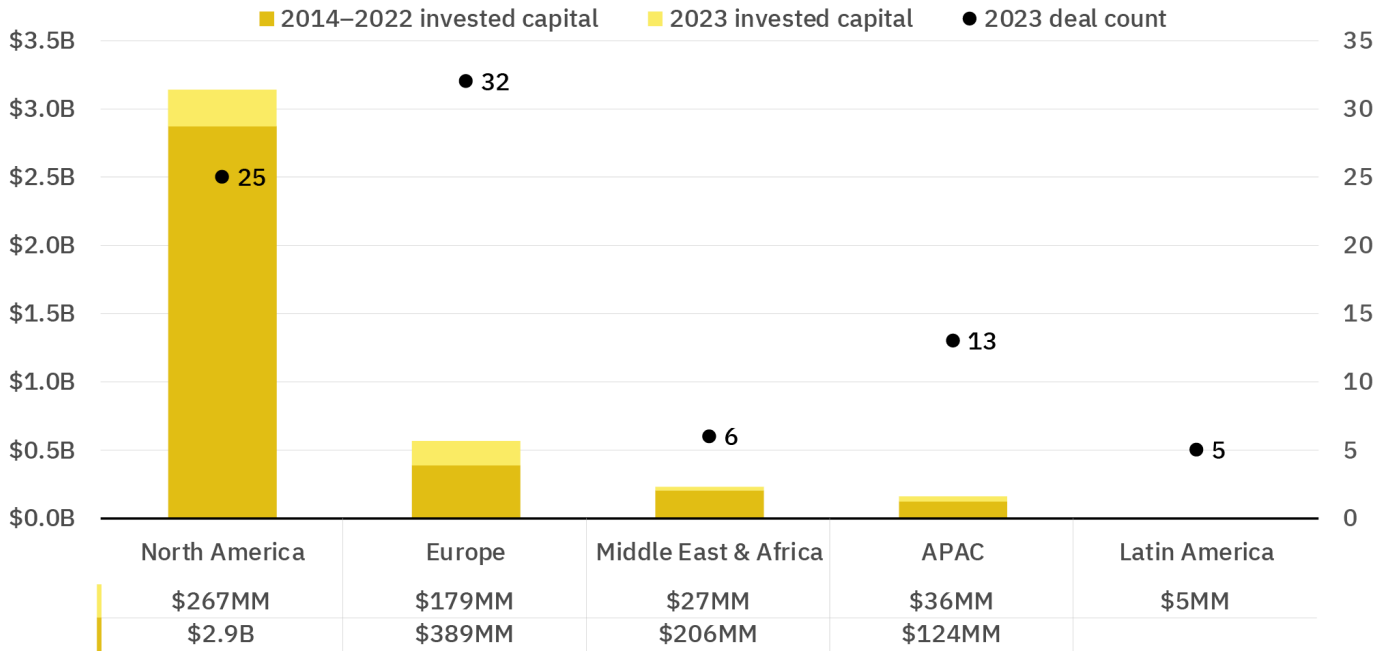
Source: GFI analysis of data from Net Zero Insights.
Note: Data has not been reviewed by Net Zero Insights analysts.

Figure 12: Cumulative and annual investment in fermentation companies (2014-2023)



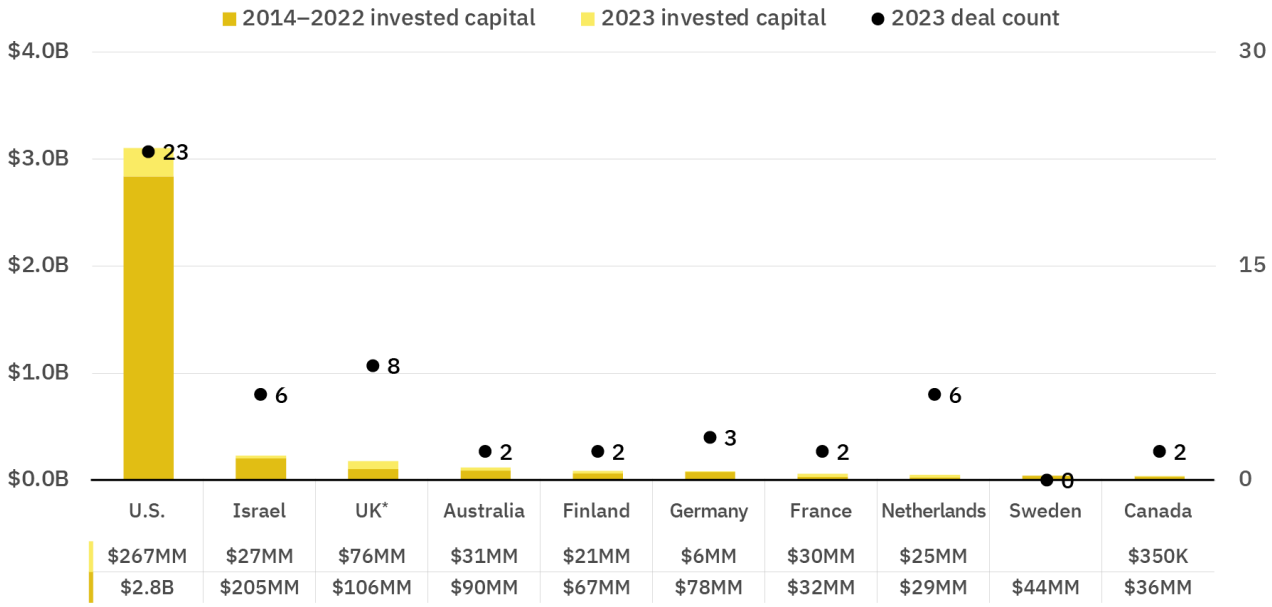
Source: GFI analysis of data from Net Zero Insights.
Note: Data has not been reviewed by Net Zero Insights analysts.

Figure 13: Investments in fermentation by region (2014-2023)



Source: GFI analysis of data from Net Zero Insights.
Note: Data has not been reviewed by Net Zero Insights analysts. The total deal count includes deals with undisclosed amounts.
Note: Fermentation totals include investments in companies focused primarily on plant molecular farming due to similarities in the types of ingredients they produce and in the downstream processing to obtain those ingredients from the host organisms.

Figure 14: Investments in fermentation: Top 10 countries (2014-2023)



Source: GFI analysis of data from Net Zero Insights.
Note: Data has not been reviewed by Net Zero Insights analysts. The total deal count includes deals with undisclosed amounts.
*Fermentation totals include investments in companies focused primarily on plant molecular farming due to similarities in the types of ingredients they produce and in the downstream processing to obtain those ingredients from the host organisms.

Table 5: Deal type summary statistics

Deal type	Median (2023)	Median (2022)	Median (all years)	Maximum (all years)	Deal count (all years)
Accelerator/incubator	$0.15MM	$0.10MM	$0.06MM	$3.39MM	157
Convertible note	$30.00MM	$0.75MM	$5.48MM	$30.00MM	7
Debt	$27.50MM	$15.00MM	$1.09MM	$45.00MM	17
Debt crowdfunding			$0.02MM	$0.02MM	1
Early VC	$2.98MM	$9.38MM	$4.15MM	$75.00MM	91
Equity crowdfunding	$0.16MM		$0.16MM	$0.36MM	4
Pre-seed	$1.53MM	$1.43MM	$1.31MM	$6.30MM	35
Private placement			$8.10MM	$8.10MM	1
Seed	$5.00MM	$3.55MM	$3.00MM	$25.00MM	110
Series A	$14.03MM	$14.70MM	$17.00MM	$90.00MM	39
Series B	$19.33MM	$120.00MM	$37.47MM	$226.00MM	15
Series C	$43.65MM	$150.00MM	$95.00MM	$350.00MM	11
Series D			$55.00MM	$350.00MM	3
Series E		$85.00MM	$87.50MM	$90.00MM	2

Source: GFI analysis of data from Net Zero Insights.
Note: Data has not been reviewed by Net Zero Insights analysts. These figures represent summary statistics of invested capital rounds with disclosed deal amounts. Deal count includes rounds with undisclosed amounts. Due to their limited number and size, this table excludes angel, bridge, convertible note, corporate, convertible debt, general crowdfunding, equity, growth equity, late VC, private equity, product crowdfunding, and series F, G, and H rounds. It also excludes uncategorized rounds.

Figure 15: 2023 key funding rounds

Series C/extension	Series B	Series A
meati $72MM	ENOUGH $44MM	prime roots $30MM	SOLAR FOODS $9MM	Eden Brew $24MM	MyFOREST foods $15MM

Seed	Pre-seed	Early VC
Bon Vivant $16MM	Chunk $15MM	BREVEL a new era for algae $10MM	Cauldron $7MM	Wild MICROBES $3MM	ADAMO FOODS $2MM	AIR PROTEIN™ $75MM	phycom $10MM

Debt	Convertible note
Liberation LABS $30MM	Liberation LABS $25MM	Moolec SCIENCE IN FOOD INGREDIENTS $30MM

Source: GFI analysis of data from Net Zero Insights.
Note: Data has not been reviewed by Net Zero Insights analysts. "2023 key funding rounds" includes investments in the 75th percentile or higher by dollar amount for each funding round category that includes more than three deals. For funding round categories that include three deals or fewer, all deals are included.

For a list of investors who have expressed interest in funding fermentation-enabled alternative proteins, companies can request access to GFI's investor directory.

Methodology

GFI conducted a global analysis of fermentation investments using data from Net Zero Insights. Our analysis uses a list we custom-built in Net Zero Insights' platform of companies that focus primarily on fermentation-enabled meat, egg, and dairy products or on providing services to those who produce them.

Types of companies included and excluded

- We excluded the many companies that are involved in fermentation but not as their core business, such as **Kerry**, as the funding these companies devote to fermentation is undisclosed.
- We also exclude companies that are more focused on plant-based or cultivated meat than fermentation—we instead include those companies in the area they are most involved in (e.g., plant-based, cultivated).
- Some companies use another alternative protein production platform to produce inputs for cultivated meat, for example using precision fermentation to produce growth factors. Those companies were categorized as fermentation companies and were excluded from our cultivated meat dataset.
- Companies focused primarily on plant molecular farming are included in overall fermentation investment totals owing to similarities in the types of ingredients they produce and in the downstream processing to obtain those ingredients from the host organisms.

The Net Zero Insights platform contained 171 companies primarily focused on fermentation, 151 of which had disclosed deals. Of these, 128 had deals with publicly disclosed amounts. Net Zero Insights primarily tracks deals from publicly disclosed sources unless companies claim their profiles on the platform and provide their own investment information. Because our aggregate calculations include only companies with deals and deal sizes available to Net Zero Insights, they are conservative estimates.

Types of funding included

For this report, invested capital/investment comprises accelerator and incubator funding, angel funding, bridge funding, convertible debt, corporate venture, equity and product crowdfunding, general debt completed deals, debt crowdfunding, seed funding, early-stage venture capital, late-stage venture capital, private equity growth/expansion, capitalization, joint venture, and private placements. Liquidity events comprise completed mergers, acquisitions, reverse mergers, buyouts, leveraged buyouts, spinoffs, and IPOs, while other financing comprises completed subsequent public share offerings and private investment in public equity. We do not include capital raised through a SPAC IPO until the entity has merged with or acquired a target company.

Data provider

Please note that the figures published in this report may differ from prior figures published by GFI as we are now using Net Zero Insights as our investment data provider and are continually working to improve our dataset. To verify your company's data on the Net Zero Insights platform, claim your company's profile here and help us ensure we have access to the fullest, most up-to-date information.

Liquidity events

Liquidity events represent the sale of an equity owner's interest in a company typically through a merger, acquisition, buyout, or IPO. In a developing category like the fermentation sector, certain liquidity events such as mergers and acquisitions are more common components of industry development, while others, such as IPOs, are less common at this stage. Mergers and acquisitions (M&A) allow companies with stronger financial footing to acquire firms with valuable technologies, manufacturing processes, and talent. That said, liquidity event activity is also highly dependent on the broader economic context.

A handful of liquidity events, also known as exits, took place in 2023.

- Perfect Day, a precision fermentation company, sold their consumer-facing subsidiary **The Urgent Company** (which includes brands Coolhaus and Brave Robot) to U.S. food tech company **Superlatus** for $1.3 million.
- Additionally, technology and bioproducts developer **Solar Biotech** acquired biomass fermentation company **Noblegen** for an undisclosed amount.

In a year when global M&A activity fell to its lowest level in over a decade, the relatively small number of fermentation liquidity events was representative of the larger funding and M&A environment. The same conditions that led to fundraising difficulties—like economic concerns and a tight financing environment—also contributed to limited M&A activity.

While we expect fermentation liquidity event activity to accelerate in the coming years, the rate at which it does so will also hinge on conditions like interest rates, economic sentiment, and views of the sector.

Note: Unless otherwise cited, all of the information presented in this Investments section is from GFI's analysis of data from the Net Zero Insights platform. Please note that aggregated data has not been reviewed by Net Zero analysts.

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Science and technology

Science and technology

Overview

Innovative companies and food scientists are exploring exciting new ways to use fermentation to create delicious alternatives to meat, seafood, eggs, and dairy.

This nature-inspired technology is behind mycoprotein-based meats, precision fermentation-enabled casein and whey proteins for cheese, and microbial oils and fat. The field is growing, but there's still untapped potential in the vast diversity of microbes and fungi. While fermentation-derived foods have become well-established in recent years, price and taste parity have yet to be realized.

In the past year alone, notable advances in fermentation science and technology took place. **These advances focused on how microbes can: improve taste, texture, and nutritional profiles; reduce waste and enable upcycling; contribute to food safety; and add much-needed diversification to vulnerable food supply chains.** Research this year demonstrated how microbes are capable of feeding more people in far more efficient ways. The impact of fermentation expands beyond food system transformation and into helping build a resilient circular bioeconomy.

Innovation in this field is largely driven by private-sector research and development. What began as a trickle of applications in the first half of the 2010s has led to nearly 178 awarded patents from 2021 to 2023, with 417 and 319 patent applications in 2022 and 2023, respectively (see the "Scientific ecosystem" section for more). These protected innovations and intellectual property applications represent processes, compositions, and designs that will continue to contribute to the fermentation ecosystem.

While much of this tracked innovation is in the private sector, there's also a continuous need for open-access research to democratize knowledge and pave the way for affordable, delicious alternative proteins and fats. In the public research realm, fermentation for food proteins and oils is one of many potential applications for microbial cell factories.

Many of the research developments in the following sections highlight these public and private sector R&D endeavors in 2023. While most of these highlights are alternative protein- and food-focused, some research highlights include enabling fermentation technologies across sectors.

Check out our research grants page to explore grant opportunities and meet the scientists leading open-access fermentation research for applications in meat, eggs, and dairy.

Ingredient trends and highlights

Biomass

Protein products—including center-of-plate options like patties, steaks, and cutlets—are being produced through biomass fermentation from microorganisms like fungi, yeast, microalgae, and bacteria. Mycoprotein and mycelial sources continued to expand in 2023 due to their market familiarity, techno-economics, and taste and texture properties. **Much of the mycelium and fungal biomass research this year focused on producing improved strain and processes for taste, texture, and price. There was also an increase in research around formulation and nutritional attributes of fungal biomass, signaling a transition to more mainstream end-product development.**

In 2023, there was also progress on novel biomass protein sources, like single-cell protein (SCP) from bacteria, microalgae, gas-fed microbes, as well as previously unexplored fungi. **Much of this research focused on improving the techno-economics and developing novel processes to leverage more sustainable feedstocks through upcycling waste biomass or sequestration of carbon dioxide as a feedstock.** Research on SCP sources also focused on end-product formulation to improve hybrid and standalone microbial formulations.

Precision fermentation targets

Proteins produced via precision fermentation (PF) are often selected to replicate the taste and texture of dairy and meat or to improve the flavor and nutritional profile of various food formulations. Certain proteins enhance food products even in small concentrations, such as leghemoglobin for meat protein enhancement (<2 percent concentration), alternative protein sweeteners (<0.1 percent), or bioactive nutrient proteins (<1 percent). In contrast, egg and dairy proteins are frequently added to the final product in much larger quantities, ranging from five percent to 35 percent, to contribute to both functionality and sensory properties. These PF targets continued to gain interest in 2023.

Dairy

PF-produced dairy proteins, like whey and casein, remain a prime area of interest for attributes like emulsification, gelation, and foaming, along with being nutritionally complete proteins. A review and overview of commercial precision fermentation dairy production, published by researchers at **Jiangnan University**, provides a succinct overview of PF-enabled dairy proteins and their techno-economic feasibility, indicating that they are economically viable for industrial production. In 2023, whey protein research, patent protection, and regulatory approval continued to expand.

- A 2023 patent was awarded to **Perfect Day** for their recombinant β-lactoglobulin protein product and methods for food formulations
- A 2023 patent was awarded to **Perfect Day** for their recombinant β-lactoglobulin protein product and methods for food formulations containing the company's whey protein including sweet proteins, fats, and other nutrients.
- **ImaginDairy Ltd.**, which has pioneered the use of *Asperigullus orzyae* for the production of β-lactoglobulin, submitted a Generally Recognized as Safe (GRAS) dossier to FDA.
- **Bon Vivant** published a detailed life cycle assessment of their animal-free fermentation-derived (FD) whey protein.

Lactoferrin, a multifunctional iron-binding whey protein valued as a nutraceutical in food, infant formula, and supplements, continued to garner research and commercial interest in 2023. **Its low concentration in bovine milk and costly extraction make PF production of lactoferrin proteins commercially compelling and a sustainable alternative.**

- Researchers at **Hanoi University** developed upstream cultivation strategies to produce bovine lactoferrin in a high cell-density cultivation of *K. phaffii*. Their cultivation strategy was demonstrated at the two-liter, 10-liter, and 100-liter scales with intracellular expression of lactoferrin.
- **TurtleTree**, who is producing bovine lactoferrin through a comparable bioprocess, debuted their LF+ product in 2023.
- **Helaina,** who is commercializing a human lactoferrin for infant formula and adult nutrition, continued to scale their product, perform safety assessments, and launched a clinical study of their lactoferrin dietary ingredient, Effera™. They also released an extensive characterization of their precision lactoferrin expressed in *K. phaffii.*

Progress in precision caseins was notable with much-anticipated product launches, patent applications, and open-access research elucidating precision casein cheese formulations.

- In 2023, **New Culture** was granted a patent for their animal-free non-micellar mozzarella cheese alternative formulated with dephosphorylated precision alpha-casein.
- Additionally, researchers at **Wageningen University** evaluated the formulation of artificial casein micelles in several publications for PF-derived cheese formulation.

Eggs

Egg white proteins (EWPs) find extensive use in various food products such as baked goods, ice creams, nutritional supplements, and meat alternatives, owing to their comprehensive amino acid composition and versatile functional attributes like gelation. Thus, there were several notable developments to recreate EWP through precision fermentation:

- The **EVERY Co**. unveiled the world's first PF liquid egg product in December 2023 on the heels of their patents for recombinant protein purification strategies and PF-derived recombinant ovomucoid.
- **Onego Bio** termed their ovalbumin protein product Bioalbumin and is scaling to commercialize the product on the B2B market in 2024.

Egg whites have been a long-standing binding agent in vegetarian formulations, thus PF-derived EWPs or alternative binder proteins could enable animal-free end-product formulations.

- **Quorn Foods** and the **University of Leeds** extensively evaluated the role EWPs play in fungal protein formulations. This research also led to alternative binder formulation with potato protein.
- **Marlow Foods** was granted a patent for mycoprotein formulations using vegetable proteins, like potato, instead of EWP, unlocking improved animal-free end-products.

New Culture's mozzarella is made with animal-free casein protein derived from precision fermentation. Photo credit: New Culture

Meat/animal proteins

Plant-based meat alternatives and cultivated meat can often benefit from the addition of FD ingredients that improve sensory properties, such as texture and mouthfeel. Heme proteins like myoglobin and leghemoglobin continued to garner commercial and research interests this past year.

- **Impossible Foods** led a study further characterizing the safety of precision fermentation-derived leghemoglobin.
- Several academic research groups demonstrated a novel and improved production of leghemoglobin in different microbial hosts. As one of the pioneer PF proteins, its ingredient status demonstrates the market pull for increased public-sector research. (See more in the "Strain development" section.)

Sweet proteins

Proteins such as brazzein and monellin can be used as sweeteners at levels of volume far below those of sugar-based sweeteners. Sweet proteins don't replace animal-derived proteins, but they can provide insights and innovations in target selection, bioprocess, and formulation. **Shared development and infrastructure can benefit both FD nutritive proteins and sweet proteins. Their widespread use may reduce future competition between sugar-based feedstocks and sugar crops bound for food.**

- **Mycotechnology**, a producer of biomass protein and pea/fungal protein end-products, was awarded an Australian patent for their novel sweet protein from truffle fungi.
- **Oobli** has submitted a GRAS dossier to the U.S. FDA for the sweet protein brazzein, produced by *Komagataella phaffii* (GRN No. 1142).

Alternative fats and oils

Traditionally derived from animal or plant tissues, fats are in high demand, leading to the exploration of sustainable alternatives, with microorganisms, particularly microalgae and oleaginous fungi, emerging as promising sources. Fatty acids are an important target for the alternative protein foods industry. Fatty acids and oils can unlock flavor, functionality, and sustainability for alternative protein meats and dairy. For example, many plant-based meat formulations include oils like coconut and palm oil which could be produced more sustainably in fermentation.

- **Nourish Ingredients** identified microbes that can produce the "most potent" fats that allow for taste and sensory parity with animal fats to improve alternative protein products. Some of these targets have been identified in microbes found in wild fungi from around Canberra, Australia.
- **Melt & Marble** was awarded several patents for strain improvements to increase fatty acid and protein production in fungi, which can help maximize the production of fats and proteins from fungal species.

For a comprehensive introduction to the current state of the science in fermentation, visit GFI's science of fermentation page.

Figure 16: Precision fermentation process

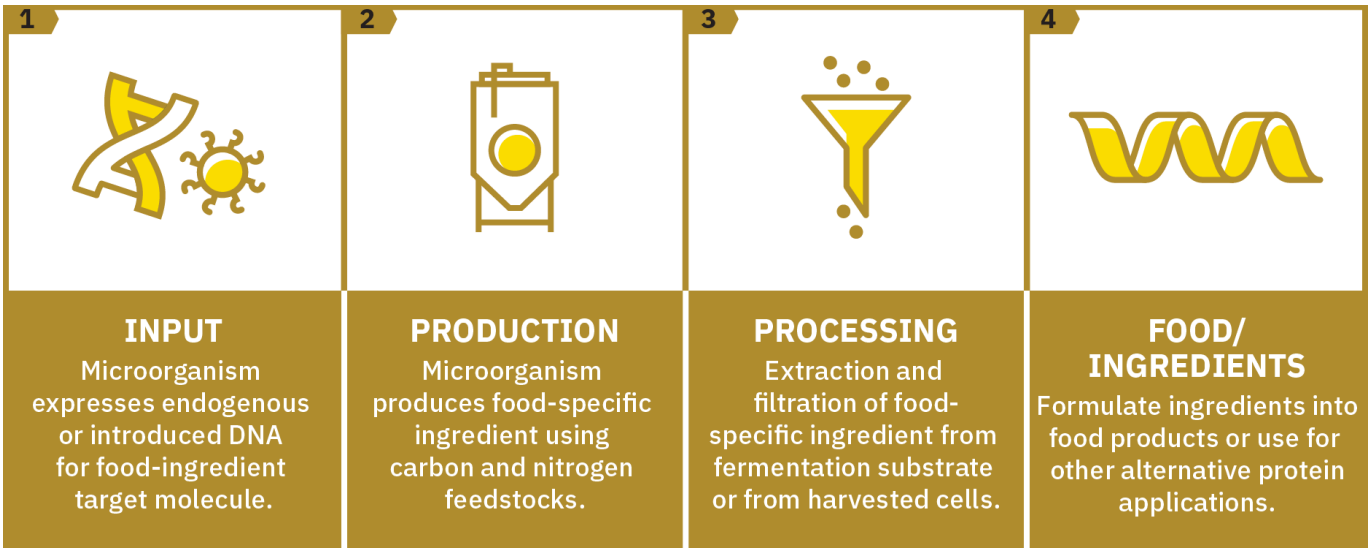
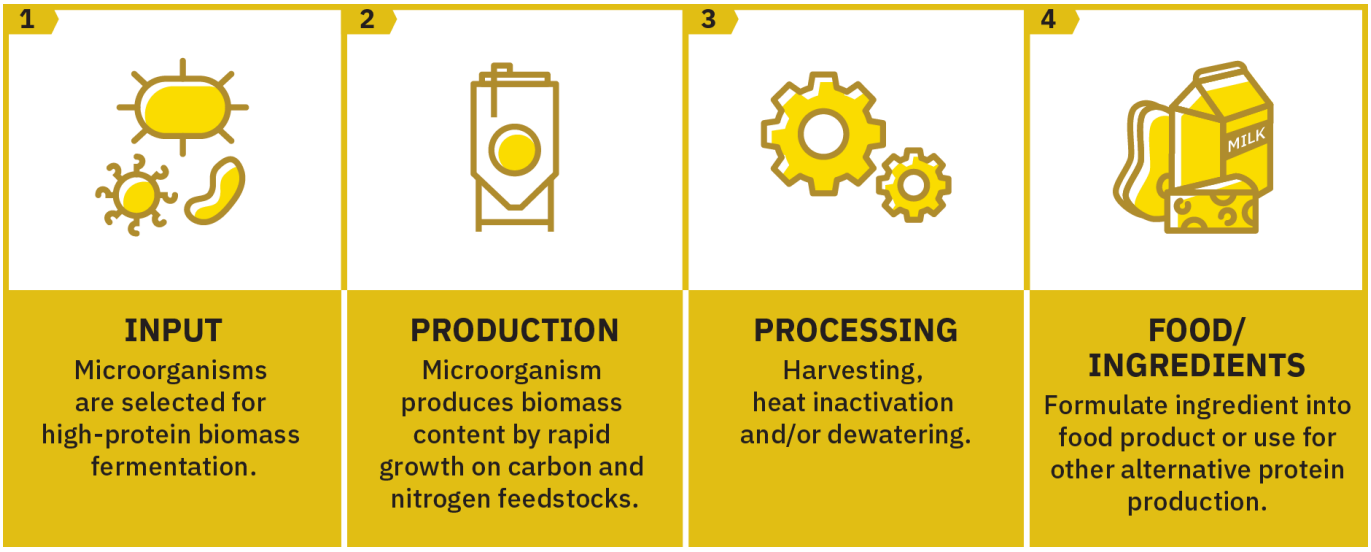


Figure 17: Biomass fermentation process



Research across the technology stack

Strain development

Definition: Strain development focuses on bringing out the best features of a particular microbial strain and minimizing undesirable qualities.

When selecting a strain, researchers account for metabolism, protein trafficking, cell morphology, cell proliferation, and the potential for genetic improvements. Research is ongoing to improve gene expression and protein production systems in workhorse organisms. In addition, improving microbes' ability to be a chassis for productivity involves many cellular pathways and mechanism enhancements. Finally, bioprospecting for novel organisms can result in the identification of novel compounds and host organisms to further increase productivity.

Research highlights

Developments in precision fermentation

In 2023, researchers demonstrated that long-standing PF organisms can be improved to increase yield/productivity/titer and robustness in the fermentation environment. This means that proteins and oils can be produced in high concentration, more quickly, and with fewer feedstock inputs.

Developing more robust organisms allows them to be grown in environments more amenable to lower costs, such as less temperature control, pH adjustment, oxygen additions, and even mixing intensity. *Komagataella phaffii* (formerly *Pichia pastoris)* has been established as a production organism for industrially relevant heme-binding proteins such as leghemoglobin. Since these proteins require the production of both heme (an important iron-binding molecule) and the protein itself, researchers have closely examined the heme biosynthesis pathway to improve its efficiency.

- The heme protein is a key target for developing meat alternatives. Researchers at **UC Berkeley** are working to significantly increase heme biosynthesis while leveraging the flexible use of various feedstocks by filamentous fungi.
- Metabolic modeling led by the **University of Latvia** suggests that the presence of methanol and glycerol in feedstocks increases the up/down regulation in heme production. In addition, extensive remodeling of the regulation and protein localization of the heme biosynthesis enzyme in *K. phaffii* resulted in impressive increases in heme availability.

In addition to its value in heme production, *K. phaffii* has been extensively employed in biomanufacturing outside of heme proteins.

- Researchers at **Tunghai University** expressed a microbial transglutaminase in *K. phaffii* and showed that once isolated, transglutaminase could be used to improve plant-based nugget texture because of the bonds it forms between proteins.
- Research led by the **Queensland University of Technology** used a biosensor to help screen strains with high secretory performance, while research at **Erzincan Binali Yıldırım University** demonstrated alternative signaling peptides from other yeast strains may increase the secretion of particular proteins. Better protein secretion by fermentation organisms simplifies protein isolation and decreases downstream processing costs.

Adapting and engineering existing microbes used in the food industry into PF workhorse strains is a worthy research goal, given that they are food-safe, familiar to researchers, and effective metabolic targets. Work published in 2023 demonstrates that these familiar microbes can be engineered to produce higher-protein titers and new protein targets to increase their industrial utility.

- Researchers at **Fudan University** showed high-level expression of leghemoglobin in *Kluyveromyces marxianus,* a yeast often found in dairy products, achieving a commercially relevant titer (7.27 g/L).
- RuBisCo is also emerging as a potentially "ideal" protein for human consumption.

Researchers at **Kyungpook National University** have demonstrated a *Saccharomyces cerevisiae* strain with high-copy, functional expression of RuBisCo for increased carbon dioxide capture during fermentation. This approach can yield improved fermentation, but also paves the way for precision RuBisCo from budding yeast.

- *Corynebacterium glutamicum*, a bacteria long used to produce amino acids and umami flavor compounds for foods, acts as an attractive chassis organism for PF Research led by the **Tianjin Institute of Industrial Biotechnology** developed a *C. glutamicum* strain capable of producing leghemoglobin to ~20 percent of total cellular protein. New molecular techniques in *C. glutamicum* may pave the way for rapid strain improvement and may lead to commercially relevant yields for multiple proteins of interest in the next few years.
- **Dyadic International** has unveiled their filamentous fungi expression platform targeting proteins such as animal-free albumin for the cultivated meat and biotech industries. Improvements to post-translational modification, protein titer/productivity/yield, and process compatibility will help expand the range of potential targets for PF.

Strain development is often associated with PF rather than biomass fermentation. However, biomass fermentation processes also benefit from strain selection, adaptive evolution, and engineering to improve strain productivity, taste, texture, and more. In 2023, researchers developed approaches to increase the iron content of biomass as well as methods to reduce the carbon dioxide outputs of microorganisms in fermentation.

- Researchers at **Tianjin Institute of Industrial Biotechnology** demonstrated that improved *Fusarium venenatum* strains emit less carbon dioxide during fermentation due to strain engineering of the ethanol metabolism and gluconeogenesis pathways. **These types of improvements can lower mycoprotein's climate impact even further.**
- In a hybrid biomass and precision fermentation process, **Calysta** has a pending patent on heme-enriched C1 metabolizing non-photosynthetic bacterium, which can improve flavor and boost iron delivery in alternative meat products.
- **Triton Algae Innovations** similarly developed strains of the microalgae Chlamydomonas, which is naturally rich in color-fast red pigment heme precursor protoporphyrin-IX, to improve meat substitute product formulation with their pigmented algal cells. Their protoporphyrin IX-rich microalgal biomass is used in their alternative pork dumpling products released in 2023.

Computational approaches to microbial strain development

Widespread computation tools such as artificial intelligence (AI) and improved machine learning (ML) algorithms took hold in many industries and within everyday life in 2023. Computational design of experimental strategies has the potential to shorten the already fast R&D cycles of microorganisms.

- A team at **Inscripta** recommends extensive use of computational design with ML approaches to accelerate and integrate facets of the design-build-test-learn cycles that are currently the paradigm in strain development for biomolecules.
- **Equii** applied for patent protection on a computational method to identify microbes with high protein quality and nutritional scores based on the organism's genome. **These approaches can help select organisms with optimal amino acid profiles and high biomass protein content.**
- **Nosh.Bio** teamed up with **Ginkgo Bioworks** to develop tastier fungal strains using an AI-led strain selection process, complementing **Ginkgo**'s partnership with **Vivici** to use AI for PF expression strain improvement.

Strain development in alternative fats and oils

With the scale of its market potential increasingly acknowledged, researchers in both academia and corporate R&D are looking at fatty acid fermentation to increase the commercial availability of the wide array of food-relevant fats.

- Biotech company **Melt & Marble** was awarded several patents for strain improvements to increase fatty acid and protein production in fungi. These approaches can help maximize the production of fats and proteins from fungal species.
- While many oleaginous microbes contain important food-relevant fatty acids, the signals that lead to maximal fatty acid biosynthesis and accumulation are not well understood. Research from the **Academy of Scientific and Innovative Research (AcSIR)** used time-series transcriptomics to observe *Rhodotorula mucilaginosa* gene expression during fermentation to determine the regulatory timing of key metabolic enzymes for fatty acid biosynthesis in this oleaginous yeast. These studies help explain the timing and regulation of the key enzymes these cells use to synthesize fatty acids.
- **C16 Biosciences**, in collaboration with **Pacific Northwest National Labs** and **Sandia National Labs**, reported on their efforts to produce mid-chain fatty acids **in the oleaginous yeast *Rhodosporidium toruloides* to replace palm oils.** These fatty acids are critical for baking and cooking applications, and their production in yeast can dramatically improve the sustainable production of palm-oil-type fatty acids.

Microalgae remains among the most promising groups of microorganisms for alternative fatty acids. Microalgaes can grow quickly, produce fats and proteins, and can use a variety of sources for energy—including photosynthesis. A review summarizing microalgal production of both lipids and proteins outlines the extensive progress in metabolic modeling and forward genetic screens, but also the need for additional study. According to a model generated by the review authors, a relatively modest 610 km^3 used for phototrophic microalgae cultivation could meet worldwide demand for microalgae-derived EPA omega-3 fatty acids. Though challenging to scale, optimizing phototrophic (sun or light-fed growth) microalgae fermentation could help increase the global supply of sustainable and nutritionally important oils.

Feedstock optimization

Definition: Optimizing feedstocks for microbes can cut costs, reduce waste, and improve the sustainability of alternative protein production. Currently, much of biomanufacturing, including alternative protein production, relies on processed fermentable sugars from crops (e.g., maize, sugarcane) and energy-intensive Haber-process-derived nitrogen (e.g., ammonium) to grow microbes. Research is underway to make more efficient use of these standard feedstocks and drive the development of alternative feedstocks.

Research in 2023 gave us a vision of microbially derived protein and nutrition moving away from highly refined and less sustainable glucose feedstocks as the primary feedstock for fermentation.

Optimizing or diversifying feedstocks

Fermentation for food represents an enormous opportunity to increase the sustainability and circularity of food production. Fermentation bioprocesses can use a diverse array of feedstocks while potentially generating sidestreams that could provide nitrogen and carbon sources for agriculture and biomanufacturing. Currently, sugar- and starch-based crops are the main carbon source for fermentation processes. **Glucose feedstocks, typically derived from corn, wheat, sugarbeets, and only a few other crops, could be diversified to add regional options and free up land for grains, cereals, and other crops for human consumption.** As the bioeconomy grows, the demand for economical sugar sources will increase, and cost will drive many companies to focus on the optimization of carbon feedstocks.

Microbes, with a diverse repertoire of metabolic pathways, can break down and use carbon sources like woody biomass, agricultural leftovers, food scraps, alcohols (e.g., methanol and ethanol), and even gaseous carbon. Additionally, new processes that better utilize common sources of carbon, like maize, are a welcome improvement to the use of refined corn sugars and syrups.

- **SuperBrewed Foods** was granted a U.S. patent for a process to efficiently convert starchy feedstock to glucose monomers. The process yields a fermentation feedstock from starchy grains with a glucose concentration of ~50 to 300 g/L that can be used in many fermentation processes.

Co-production and valorization of sidestreams as feedstocks

An attractive and sustainable alternative to sugar- and starch-based crops is the valorization of lignocellulosic biomass for single-cell protein and precision fermentation production by upcycling various sidestream raw materials.

- Mushroom mycelium and filamentous fungi have the greatest potential to use agricultural and woody residues, as they're adapted to grow on this type of material. There is enormous potential in organisms that fit this environmental niche, and research on these fungal species is gaining momentum.
- Researchers from the **University of Ioannina** demonstrated the production of mycelium mycoprotein from oyster mushrooms (*Pleurotus ostreatus)* using lignocellulosic hydrolysate of aspen wood chips. Their bioprocess was able to efficiently utilize both the glucose and xylose from woody biomass waste to produce protein-rich mycelium.

- Similarly, the start-up company **ÄIO**, founded by researchers at **Tallinn University of Technology**, is developing yeast strains capable of growing on lignocellulosic sidestreams like wood chips for the production of alternative fats by improving the xylose utilization in the oleaginous yeast *R. toruloides*. These researchers also published a genome-scale metabolic model for *R. toruloides*, which helps improve strain development.

Researchers and companies throughout the alternative protein ecosystem find many opportunities to improve sustainability and economics by upcycling and leveraging sidestreams for production.

- **This potential was highlighted in GFI's commodity crop sidestreams analysis which showed promising opportunities for alternative protein production using targeted agricultural and processing residues like spent grains and tomato pomace.**

- A collaborative team led by researchers from **King's College London**, published a comprehensive analysis and review on sustainable waste-to-protein systems to maximize waste resource utilization for developing food- and feed-grade protein solutions.

- Startup company **Hyfé** developed a patent-pending process to transform food processing wastewater into feedstocks for biomanufacturing. Their process helps unlock the valuable organic carbon in food processing waste streams and improves the sustainability of fermentation feedstocks.

- Finnish startup **EniferBio** developed a patent-pending process to continuously produce fungal biomass using wastewater sidestreams like vinasse or stillage from bioethanol production. Their PEKILO™ process uses a proprietary strain, *Paecilomyces variotii*, that can efficiently use sidestream feedstocks and run at higher temperatures, which further reduces costs.

- Many fungi can grow on a low-cost substrate such as food waste. These fungi can produce a dual-benefit protein product by lowering feedstock expenses while decreasing food waste that enters landfills and wastewater. Researchers at the **University of Borås**'s **Swedish Center for Resource Recovery** demonstrated the production of protein-rich fungal biomass when grown on carrot pomace waste and developed a process to upcycle brewer's spent grain (BSG) into fungal biomass. They found that both *Aspergillus oryzae* and *Neurospora intermedia* can effectively be grown on organosolv-pretreated BSG, resulting in fungal biomass with significantly increased protein content.

- Researchers at **Singapore**'s **A*STAR** demonstrated single-cell protein and oil production from waste cocoa fatty acid distillates. GFI research program grantee Dr. Naazneen Sofeo further improved the lipid production in *Yarrowia lipolytica,* a common oleaginous yeast, through adaptive evolution when grown on the cocoa fatty acid distillate.

- Researchers at **Cukurova University** in Turkey demonstrated the valorization of bread waste for the production of *Y. lipolytica*.

- A research group from the **Indian Institute of Engineering Science and Technology** fermented deoiled edible quality sesame flour (a waste byproduct of the sesame oil extraction process) with cultures of *Lactobacillus delbrueckii subsp. bulgaricus* and *Streptococcus thermophilus* to develop a non-dairy yogurt drink with enhanced nutritional properties.

Most fermentation companies use heterotrophic microbes that consume carbon derived from crops like corn or wheat to produce a target protein. However, production from these sugar crops can account for a significant portion of greenhouse gas emissions in a precision fermentation process. Thus, there is a growing commercial and research landscape for making food from carbon dioxide and other gas feedstocks.

- The potential of gas fermentation for food was highlighted in a research review paper from researchers at the **University of Massachusetts Amherst**, including a current GFI research grantee, Dr. Lutz Grossman. While highlighting the challenges of scaling this new technology for food protein, the review points to the sustainability improvements, especially land and water use, of gas fermentation microbes compared to traditional food production.

- **Solar Foods** utilizes carbon dioxide and hydrogen to produce protein-rich biomass for food formulations. They, along with a consortium of research organizations deemed "HYDROCOW," are working to develop gas fermentation microorganisms for the PF production of milk proteins. This technological endeavor could be a breakthrough in improving the sustainability of PF.

- **Farmless,** a Dutch start-up company, has a similar approach to utilizing CO_2 and hydrogen, rather than sugar, to produce protein-rich biomass, except they are generating a liquid feedstock from these gasses to enable improved feedstock conversion.

Researchers are increasingly looking to gas-derived feedstocks for potential cost and sustainability improvements. The biological or electrochemical conversion of gas feedstocks like carbon dioxide to liquid feedstocks like acetate and methanol is a promising way to sequester carbon for fermentation processes.

In the past several years, researchers have shown the promise of converting a variety of sources, from carbon gasses to cafeteria waste, into acetate. Acetate can be used as the sole carbon source for a range of food-producing microorganisms, including microalgae, yeast, and fungal mycelium. Acetate, as an energy-dense and safe liquid feedstock, could have an array of applications in fermentation food production or even in plant cell culture.

- Researchers at **Ghent University** and **Biobased Europe Pilot Plant** developed a comprehensive techno-economic assessment (TEA) model for a carbon-neutral two-step fermentation process where industrial furnace off-gasses are first converted to acetate by *Moorella thermoacetica*. The liquid acetate is then used as the feedstock for biomass growth of *Cupriavidus necator*, which has superior protein content, nutritious amino acid profile, and better digestibility than many common and animal-derived protein sources. The analysis points to economies of scale for unit production costs ranging from $2.78 to $4.15/kg depending on productivity.

- Similarly, researchers at the **University of A Coruña** demonstrated a two-stage process for the biological conversion of syngas to acetic acid followed by lipid and beta-carotene production in the oleaginous yeast *Y. lipolytica.*

- Methanol, recognized as a favorable one-carbon feedstock for biomanufacturing, can also be derived from significant quantities of CO_2 and hydrogen through electrocatalysis or photocatalysis. Researchers at the **Tianjin Institute of Industrial Biotechnology** demonstrated the production of single-cell protein (*K. phaffii*) from methanol at industrial pilot scale.

Bioprocess design

Definition: The bioprocess for FD ingredients involves upstream (USP) cultivation of the microorganism in large-scale bioreactors followed by downstream purification (DSP) of the target product. Whether through improvements to downstream yield, upstream medium recycling, improved system control, or novel growth strategies, innovations in bioprocess design can unlock opportunities for cost reduction, scale-up, and environmental sustainability for fermentation's use with alternative proteins.

Scaling up FD alternative protein manufacturing infrastructure is a major hurdle that ingredient producers will face going forward. This hurdle is likely to increase in the coming years as many companies approach commercialization. Good technology is necessary for a product's viability, but only if infrastructure is available and assessed at scale before commercialization. Thus, assessment of a bioprocess at scale and procurement of infrastructure are key metrics for the growth of the industry.

Alternative protein companies can either build a facility, lease a facility, or work with a contract manufacturer (CMO). Infrastructure will either arise from purpose-built new construction (greenfields) or from repurposed conversion of brownfield sites. Moreover, the majority of current fermentation capacity was not originally designed for food applications and/or does not have updated modernized control systems.

Research highlights

Upstream bioprocess developments across pillars

Continuous fermentation processes are considered the holy grail of bioprocessing due to their potential to significantly enhance efficiency, productivity, and cost-effectiveness in an upstream bioprocess. However, the continuous process is operationally complex with constant processing needs, which can increase contamination risk and create genetic drift over the long-term operation. In 2023, a handful of startups worked to control fermentation and mitigate microbial contamination in continuous bioprocesses:

- Startup **Pow.Bio** has developed a continuous upstream bioprocess that counteracts contamination concerns and strain genetic drift for precision fermentation processes.
- Australian startup **Cauldron**'s comparable upstream bioprocess enables more continuous operation and increased volumetric productivity at a smaller scale. Their "scale out" strategies can mitigate batch failure risks and increase the control of fermentation conditions within bioreactors.

Improvements to media usage can also greatly improve bioprocesses by reducing costs, diversifying potential sources, and opening the door to more sustainable and circular media formulations:

- Highlighting the potential of fermentation processes to operate in extreme settings, **Mycorena** has developed a circular food production system using microalgae and fungi to produce a mycoprotein. Their process was advanced to phase 3 in NASA's deep space food challenge.
- **Air Protein** and **Solar Foods** were also chosen as winners and invited to advance to Phase 3 by NASA for their low-resource sustainable gas fermentation processes.
- Demonstrating the potential for serum-free cultivated meat production, researchers in Japan further improved their circular, closed-loop bioprocess using microalgae and mammalian myoblast by improving lactate utilization in the cyanobacteria strain. Their research demonstrates the fermentation-enabled potential for serum-free cultivated meat processes by using the lactate waste stream as a feedstock for fermentation.

Bioprocesses for PF require optimization and demonstration at different scales. Often the conditions optimized in a lab or a small bioreactor do not scale beyond the pilot stage. Working to understand, optimize, and demonstrate bioprocesses at increasingly larger scales (up to cost-effective production) is a key progress marker for the industry.

- **Nourish Ingredients** partnered with **Boston Bioprocess** to help scale their microbial fat processes from bench to 1500-liter scale with improvements to the bioprocess.

Microbial bioprocess conditions are complex and often defy intuitive pattern recognition and systematic optimization by bioprocess scientists. ML approaches in bioreactor monitoring and control can be powerful tools when coupled with advanced process controls and a skilled workforce.

- Researchers led by a group at **Dompé Farmaceutici SpA** used neural network-based ML algorithms to predict outcomes for fermentation yields from critical process parameter data during fermentation, a step forward in observing strain-dependent fermentation responses that could improve strains and bioprocesses for better fermentation outcomes.
- Similarly, **The EVERY Company** has developed a patent-pending ML upstream bioprocess system for the optimization of precision fermentation animal proteins, which helps improve fermentation titer, glucose utilization, and productivity. And the startup **Pow.Bio** developed a patent-pending ML process to optimize culture conditions in upstream bioprocesses.

Downstream processes can be as cost- and resource-intensive as the fermentation process itself. Therefore, more efficient downstream processes can significantly improve the costs to separate and isolate precision proteins, an important R&D focus for the industry.

- Researchers at the **Federal University of Rio de Janeiro** developed an aqueous two-phase downstream process to selectively separate enzymes from the fermentation broth of *Y. lipolytica.*
- A simple precipitation purification process for recombinant β-lactoglobulin was demonstrated by researchers at **Wageningen University.** Their process uses the food-grade salt sodium hexametaphosphate to precipitate and isolate the whey protein.
- A U.S. patent was granted to **The EVERY Company** for a downstream purification process that removes cellular byproducts from the precision-produced EWP, resulting in a higher-quality end-product. Filamentous fungi production strains are efficient protein producers; however, they also tend to produce excessive exopolysaccharides (EPS). Their patent demonstrates methods to separate the EPS byproducts for higher-purity protein, while also enabling potential valorization of the EPS for other applications.

Bioprocess developments in biomass fermentation

Microbe-derived single-cell protein is typically grown in traditional submerged fermentation, while mycelial biomass can be generated through submerged fermentation or low moisture solid-state fermentation.

- A patent was granted to the **Protein Brewery** for an upstream bioprocess to produce a fungal single-cell protein. Their process uses a thermophilic fungus, *Rhizomucor pusillus*, capable of improved growth at high temperatures and low pH, which allows for a cost-effective fermentation process that can be run under non-sterile conditions and without additional cooling requirements.

- **Nature's Fynd** has developed a patented continuous or semi-continuous surface fermentation bioreactor system to produce their fungal protein Fy. The process uses a roller to harvest the fungal biomats when mature, which provides increased automation and throughput over a more simplified tray-based air-liquid surface fermentation process.
- Elsewhere, researchers at **Ningbo University** developed a solid-substrate fermentation with a consortium of microorganisms to produce a plant-based meat analog with improved color, texture, and flavor.
- Researchers at **Ghent University** found that the nutritional composition of microbial biomass for food applications can be altered by the growth conditions. The researchers evaluated the single-cell protein quality of *C. necator* and *K. phaffii* under varying growth regimens. A key finding showed that increased productivity can affect the nutritional quality of the biomass.

Understanding the techno-economics of any bioprocess can guide process improvements and market viability. In 2023, publication of various mycoprotein TEAs filled an open-access research gap:

- Researchers at **UC Davis** published an open-access TEA for mycoprotein production that is based on the **Quorn** mycoprotein production process. Many TEAs utilize process simulation software that can require significant economic investment and require additional training for effective use. Their open-source Excel model overcomes this challenge, which allows users to model possible scenarios, such as food grade vs. pharmaceutical grade inputs, and explore innovation areas for mycoprotein production.
- The process simulation company **Intelligen** also published a mycoprotein TEA, developed using their SuperPro Designer software, which provides another detailed process description for mycoprotein production.

Gas fermentation continues to gain interest for alternative protein applications, and its applications continue to expand. Commercially scaled gas fermentation will enable the capture of stovepipe emissions from high-carbon emitting industries and food protein production in austere environments and will help diversify feedstock options for producers. These fermentation processes use gaseous feedstocks, which require improved mixing to efficiently deliver gasses to the microorganisms.

- Originally pioneered by the **Danish Technical University** and patented by **Unibio**, loop bioreactors are gas-liquid contactors often used in gas fermentation to improve gas mass transfer to the microorganism. The process deployed by **Calysta** implements the U-loop style bioreactor. The company was awarded a patent for their novel improvements to these loop bioreactors.
- A patent was granted to **Solar Foods** for strains and processes for single-cell protein using gas-fed fermentation. They were also granted another patent for a bioreactor design comprising multiple chambers and provisions for gas feedstocks for growing microbes.

Microbial oils bioprocess developments

If microbes could make more lipids in the most nutritious, well-digested, and flavorful forms, then fermentation-derived fats could replace fats and oils from a variety of conventional animal sources. Currently, economical food-grade lipid downstream processing can be a major obstacle to the commercialization of microbial lipids. In 2023, several researchers advanced the science of making oils and fats using microbial fermentation:

- Researchers in China developed an artificial neural network soft sensor to monitor microbial lipid production by *Y. lipolytica,* which provides online monitoring of lipid production during a process.

- A team of researchers at **Nanjing Agricultural University** optimized and demonstrated a two-stage process for single-cell oil production from *Cryptococcus curvatus* using glucose and N-acetylglucosamine derived from food wastes. The researchers note that the oil composition was similar to that of vegetable oil.
- Researchers at the **Institute of Chemical Technology** (India) developed a more efficient oil extraction process directly from the fermentation broth of *Aurantiochytrium limacinum.* Their acid-assisted extraction directly from the fermentation broth had a >90 percent oil recovery with significantly less energy input than traditional dry biomass solvent extraction methods.
- Researchers at **KU Leuven** provided a comprehensive overview and case study for enzyme-assisted extraction of microbial oils from the oleaginous microalgae *Nannochloropsis.*
- GFI research program grantee **Connectomix Bio** is developing techno-economic models for transforming waste into microbial lipids like triacylglycerols and phospholipids for food applications via common oleaginous yeast. Their models will inform techno-economic challenges and opportunities for waste to microbial lipid bioprocesses, providing pathways for process optimization.

Polyunsaturated fatty acids (PUFAs), such as the omega-3s docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), play a pivotal role as essential nutrients for humans.

- A comprehensive review of microorganisms, the patents landscape, and commercial bioprocesses for omega-3s was published by researchers at the **Federal University of Paraná**. The review highlights the growing demand for omega-3s and the need for increased microbial oil production.
- Researchers at the **National Kaohsiung University of Science and Technology** demonstrated enhanced production of PUFAs at high glucose concentrations from the commonly used marine protist, *Aurantiochytrium sp.* They further evaluated and increased PUFA production in another marine protist, *Thraustochytrium sp.*, through upstream cultivation condition optimization.
- The commercial microbial production of PUFAs is increasing, with many companies offering microbially derived omega-3 and omega-6 alternatives. In 2023, **Hubei Fuxing Biotechnology Co** received GRAS status for arachidonic acid, an omega-6 fatty acid, produced from an oleaginous yeast (*Mortierella alpina)* for use in animal- and plant-based milk. **The addition of PUFAs to plant-based milks offers a nutritional upgrade to an increasingly large group of products.**
- The **Jiangsu Grand Xianle Pharmaceutical Company** submitted a new GRAS application for docosahexaenoic acid, an omega-3 fatty acid, produced from *Schizochytrium* sp., a common oleaginous algal protist. The algal oil DHA is intended as a replacement for menhaden (fish) oil in several food categories.

See GFI's solutions database for more information on omega-3 PUFA production potential.

End-product formulation

Definition: Product formulation is a complex process that includes ingredient interactions and testing for desired texture and sensory attributes. With FD products still an emerging category in alternative proteins, they can achieve even greater sensory and textural breakthrough innovations in formulation and manufacturing. At the same time, FD ingredients are commonly used in the food industry. As new ingredients and products emerge, companies need to assess formulation and demonstrate manufacturing at scale.

End-product formulation also informs target selection and design if a target molecule's functionality affects the final formulation or desired functionality. **Partnerships with established food companies can enable rapid development given the long-standing expertise in formulation**. Finally, much of the development in recent years has been food-tech-centric, though 2023 demonstrated an influx of end-product food science, formulation, and nutritional assessments of fermentation-derived alternative proteins and fats.

Research highlights:

End-product formulation

New research elucidating and improving public understanding of mycoprotein formulation emerged in 2023, including several patents and publications involving end-product formulation with mycoprotein and other fungal biomass proteins like mycelium. These products continue to enter the market, along with **Quorn's** long-standing offerings and new animal-free formulations.

Developing a formulation with optimal ingredient binding plays a crucial role in the texture and taste of an end product. Often, food formulations come from longstanding recipes without a mechanistic understanding as to "why" an ingredient combination is effective.

- EWP has long been used as a binding agent in mycoprotein formulations. Researchers at the **University of Leeds** and **Quorn Foods** described fungal hyphae interaction with EWP and its moderating effect on the mycoprotein paste's properties under varying conditions. Their microscopic imaging confirmed that EWP covered the fungal hyphae, supporting the idea that EWP-coated surfaces play a vital role in enhancing interactions and could be essential for effective binding in the system.
- This research team followed up by evaluating the use of potato protein (PoP) as a substitute for EWP, as well as fortification formulations with calcium and iron to improve the micronutrient bioavailability in fungal-based meat alternatives. They found that PoP coated the fungal hyphae similarly to EWP, but resulted in a significant reduction in stiffness, suggesting potential benefits for fortifying an egg-free mycoprotein formulation with micronutrients. Likely in conjunction with this research, **Marlow Foods (Quorn Foods)** was granted a patent for fungal food formulations without EWP.
- There are many ways to develop a food formulation with improved taste and texture. Researchers at the **Iran University of Medical Sciences** and **Halal Research Center of IRI** evaluated mycoprotein nugget formulas with soy protein isolate, carrageenan, or phosphate additions and developed a formulation with similar or better characteristics compared to a control ground chicken breast formulation.
- Though often grouped together, whole biomass and protein isolates can offer vastly different functionality options for alternative protein products. Researchers from **Lund University** and the startup company **Mycorena** co-evaluated methods for efficient mycoprotein extraction from filamentous fungi, focusing on cell wall

degradation and protein functionalities resulting in a high-yield process for protein isolates with improved emulsifying and foaming properties compared to the fungal biomass alone.

- While fungal biomass is valued for its high protein content and nutritional protein quality, it also contains insoluble dietary fiber (IDF), which plays a crucial role in gastrointestinal health. Researchers at **Tianjin Institute of Industrial Biotechnology** evaluated the extraction of IDF from mycoprotein and its functional properties such as emulsification and water-holding capacity for applications as a separate functional food ingredient.

With the increased fungal protein product formulation and products on the market, it is no surprise to see a number of secured patents for these companies.

- **Meati (Emergy Inc.)** was awarded a U.S. patent for edible compositions including fungal mycelium protein. The commercial term for their *Neurospora crassa* biomass ingredient is MushroomRoot.
- Similarly, **Mycorena AB** was granted two patents in Sweden for a dairy replacement and dry food product formulation containing their fungal biomass ingredient. **Mycorena** has developed a patent-pending method for a printable food product comprising their fungal biomass ingredient.
- A patent was also granted to **Nature's Fynd** for their surface fermentation-produced fungal protein. Their patent provides descriptive manufacturing processes for harvesting, deactivation, size reduction (grinding, chopping, etc.), and end-product formulation claims for food products produced using their FD protein.

Food formulation chemistry can be modified through various ingredient mixtures, and PF has the opportunity to further improve desired end-product characteristics through fermentation-enabled production of animal-origin proteins or through targeted protein modification. The use of specific proteins, protein fragments/peptides, or alternative post-translational modifications can change protein properties and formulation characteristics and open new opportunities to improve flavor, texture, aroma, and nutrition.

- This year, **The EVERY Company** was granted a patent for microbial-produced EWP (ovomucoid) that is highly soluble and able to form an optically clear, high-protein liquid. Animal-free EWP will be a choice ingredient for many food formulations.
- Researchers at **Wageningen University** and **Technische Universität Braunschweig** demonstrated that the aggregation behavior of recombinant β-lactoglobulin (whey protein) can be modified through the removal of cysteine to induce more amyloid-like linear fibril protein structures. Examining the impact of the cysteine removal site on the overall protein structure provides valuable insights into the specific modulation of the protein's structure.
- A 2023 patent was awarded to **Perfect Day** for their recombinant β-lactoglobulin protein product and methods for food formulations containing the company's whey protein, including sweet proteins, fats, and other nutrients. This patent filing underscores the various potential applications for a single protein.

In milk, caseins are localized to large globular aggregates called casein micelles. Their main biological function is to transport and deliver proteins, calcium, and phosphate to young mammals. In traditional cheese production, these micelles stick to each other to form curds through acid coagulation and enzyme rennet cleavage of kappa casein. Understanding and developing formulations for precision dairy products is essential for the development of cheese formulations that may contain both fermentation-derived and plant-based ingredients.

- This past year, researchers from **Wageningen University** evaluated formulations of artificial casein micelles in several evaluations, including the influence of temperature, pH, and calcium

concentration on micelle formation. In one, they assessed the importance of casein phosphorylation in casein micelle formation, which has been one of the challenges surrounding PF-derived caseins. Their research found that the phosphorylated casein is crucial to micelle formation and sufficient curd formation.

- In contrast, **New Culture** formulated a non-micellar mozzarella cheese using various bacterial strains of dephosphorylated precision alpha-casein (patent granted) and combinations of alpha and kappa casein (patent pending). Their innovative formulations had highly comparable firmness, stretch, and melt characteristics to animal-based mozzarella, highlighting the importance of thinking creatively about end-product formulation to achieve desired characteristics without strictly mimicking traditional cheese production.

Microalgae have long been touted as a production microorganism for food protein and lipids. Advances in cultivation and end-product formulation into final products have increased their commercial applications. In 2023, startups and researchers achieved success in formulating EWP and seafood, two food applications where achieving the right organoleptic properties is challenging.

- Researchers at the **Singapore Institute of Technology** investigated the impact of incorporating different amounts of the microalgae *Nannochloropsis* into plant-based fishcakes, comparing them to surimi- and pea-protein-based fishcakes. The study revealed that the addition of microalgae improved texture and protein digestibility, bringing the product closer to animal-based surimi than pea protein alone. The findings underscore the significance of hybrid products and thorough end-product characterization in the development of new food items.

- A patent was granted to **Noblegen**, acquired by **Solar Biotech** this past year, for a dry egg replacement product formulated with single-cell protein flour derived from the microalgae *Euglena gracilis*. The egg formulation uses a *Euglena* protein-rich flour that has a beige-yellow color closely resembling egg yolk products. This color match is achieved through heterotrophic cultivation of this microalgae, which reduces the green chlorophyll content and improves downstream product coloration. **Achieving appropriate color is among the factors that increase the appeal of fermentation-derived ingredients to manufacturers.**

- Researchers at **Shenzhen University** also demonstrated heterotrophic cultivation of *Euglena* for protein production. *Euglena* biomass is already added to foods to boost their nutritional profiles and expanded, high-efficiency production would continue this trend.

- Elsewhere, a patent was granted to **Koralo Foods**, an alternative seafood startup, for their novel alternative seafood product produced through the co-cultivation of fungal mycelium and microalgae that **imparts the taste and texture of seafood while also providing the nutritional benefits of both the fungal protein and microalgae omega-3-fatty acids in a single process.**

Environmental and social impact

Scientific and technological progress in fermentation-derived protein production leads to benefits in food production sustainability and food security. Fermentation technology can improve quality of life worldwide by producing proteins with less environmental impact and create production opportunities where few had previously existed. By thoughtfully planning and integrating fermentation for protein with other biomanufacturing, there is the potential to further reduce the environmental footprint of production.

- A review from **Microbiogen** describes potential scenarios for coupling clean energy, innovative feedstocks, and integrated bioprocesses to produce food and fuels via fermentation. A collaborative review describes the potential for fermentation to decarbonize chemical manufacturing. Of note, and especially exciting, is the potential for biogenic carbon dioxide off-gas from these processes to be sequestered or valorized as feedstock for other bioprocesses, further reducing biomanufacturing's footprint and increasing production circularity.

The fermentation ecosystem has enormous potential to elevate the sustainability of food manufacturing, but without good models and quantitative insights, it would be difficult to understand the most strategic implementations of the technology or where improvements could be made. Life cycle assessments (LCAs) survey the input materials, resources, and energy required for production to assess the categories and magnitude of environmental impact.

- In alternative protein fermentation, the categorical assessment of impacts can guide process improvements, material resourcing, and waste management. An LCA/nutritional assessment from the **University of Helsinki** on a variety of alternative proteins demonstrated the sustainability advantage of fermentation-derived protein for nutrition compared to animal-derived proteins. However, the report also highlighted areas where particular types of FD products could improve their environmental footprint.
- Individual companies have chosen to scrutinize their ingredient production using an LCA framework. **Bon Vivant** published a detailed LCA for their animal-free whey protein. By publishing LCAs, FD ingredient producers can demonstrate environmental benefits to consumers, distributors, investors, and government stakeholders.

Other sustainability models can show opportunities for further research in microbial fermentation. Pentose sugars, a primary building block of cellulosic materials like plant stems and woody biomass, have long remained a feedstock development goal for bioprocessors.

- A report from **King's College London** modeled the opportunity for feedstocks from agricultural leftovers, forestry residues, and other reliable starch streams and identified almost 4,000 megatonnes of glucose and xylose sugars potentially available as feedstocks for the biomanufacture of food via fermentation. Analyses such as this and GFI's sidestreams analysis highlight the challenging but promising opportunities in waste biomass feedstocks for fermentation.

Gas fermentation has received attention as a viable production pathway for food even in the absence of agricultural feedstocks like sugars and starches. Commercialization of these technologies can bring protein to regions where producing feedstocks or protein by traditional means is challenging (e.g., deserts, tundras, and highly urbanized areas). Broadly, gas fermentation approaches take advantage of microbial fixing of gasses like carbon dioxide, methane, carbon monoxide, and nitrogen while using hydrogen as an electron donor. As these microbes, typically bacteria, do not require sugar as a carbon source, the production of food and nutrients by these organisms can be decoupled from agriculture.

- **Synonym Bio** was awarded Open Philanthropy funding to explore gas fermentation processes for food production to understand the current and future techno-economics of gas fermentation approaches. This work will complement earlier assessments of the potential for gas fermentation during potential global food crises (**ALLFED**) and reviews of the current state of the gas fermentation ecosystem (GFI grantee, Dr. Lutz Grossman) highlighting its sustainability promise.

Sustainable food production is an advantage of FD protein. Biomass products like mycoproteins from mycelium and other fungi are also increasingly recognized as protein sources for those under threat of malnutrition or hunger. With demonstrated commercial-scale production, global distribution, a well-characterized bioprocess, and a favorable nutrition profile, mycoprotein is poised to be a part of the solution that ends global hunger within sustainability mandates.

The startup **Essential Impact** shares this vision and has begun commercializing an FD, low-cost, high-quality protein source for low- and middle-income countries.

Nutrition

As more fermentation-derived products enter the market, both consumers and researchers are increasingly interested in their health and nutrition benefits. Nutrition studies can take the shape of biochemical analyses, human subject studies, or digestion analyses, all of which lend evidence to the nutritional benefits and drawbacks of any food.

Marlow Foods, the makers of **Quorn**, continue to fund peer-reviewed, university-led, human-subject research into mycoprotein health and wellness benefits:

- Researchers at the **University of Exeter** showed that a vegan diet containing mycoprotein biomass protein supported muscle growth and maintenance for athletes. This research addresses a consumer concern regarding protein intake for athletes and exercise. Mycoprotein helps support athlete nutrition and provides a high-quality protein source.

- At the **University of Northumbria**, a study demonstrated that men consuming mycoprotein improved several markers of gut microbiome and digestive health compared to red and processed meats. Additional studies by the authors demonstrated improvements in biochemical markers of cardiovascular disease risk.

Many studies have set out to capture the potential health benefits associated with alternative protein-based diets (which can include fermentation-enabled proteins) compared to predominantly animal-based diets. To assess these studies at large, a team at the **University of Warwick** performed a meta-analysis of available evidence to examine the potential changes to cardiometabolic health in those consuming a plant-based and mycoprotein diet. **The authors found that consumption of these alternative proteins, as opposed to an omnivorous diet, had statistically significant improvements in total cholesterol, LDL, and triglycerides levels.**

While "mycoprotein" is typically associated with *F. venenatum* biomass protein exclusively, researchers are delving into other sources of fermentation-derived biomass protein to examine their health and nutrition properties. These results suggest that fermentation-derived proteins, and not only mycoproteins, are highly nutritious, digestible, and safe.

- A team from **Chalmers University of Technology** and the **University of Borås** evaluated the digestibility, nutrient, and amino acid content from *Aspergillus oryzae*, *Neurospora intermedia*, *Fusarium venenatum*, *Rhizopus delemar*, and *Rhizopus oligosporus*. The results indicated that edible fungi are a sustainable and nutritionally sound protein source.

- Microalgae has also gained interest and enthusiasm from nutrition researchers. Plant-based fishcakes offer an alternative protein product in an important market sector. Scientists at the **Singapore Institute of Technology** demonstrated improved functionality along with better protein digestibility in alternative fishcakes with the addition of *Nannochloropsis oceanica* biomass.

- GFI research grantee Jasper Zwinkels of **Wageningen University** published a paper on improving the protein digestibility of plant-based feedstocks through solid-state fungal fermentation. The research demonstrates improved protein digestibility of barley and rice using the fungal strains *Rhizopus microsporus* and *A. oryzae*, which are commonly used in tempeh and koji production, respectively.

- Researchers from **Henan University of Technology** and **Kansas State University** developed a solid-state fungal fermentation process to upcycle and remediate cereal grains contaminated with aflatoxin, a naturally occurring toxin produced by certain crop-contaminating molds. The fermentation organisms are equipped with mechanisms to metabolize the aflatoxin and detoxify the feedstock. This technology has the promise to mitigate the risk of aflatoxins, reduce food waste, and improve the nutritional content of grains.

- Understanding the mechanisms that have led to the adoption of particular fermentation microbes in traditional fermentation will pay dividends in improving the nutrition, digestibility, and sensory properties of FD alternative proteins. A report from the **University of Saskatchewan** revealed proteomic changes in *A. oryzae* during fermentation on pea protein isolate, to shed light on the process by which the fungus diversifies the amino acid content of the end product and improves the availability of sulfur-containing amino acids.

Scientific ecosystem

Supporting the complete value chain–from research and development through commercial biomanufacturing of fermentation-derived alternative proteins and oils–requires a varied set of efforts from granting support, safety validation, equipment innovations, and feedstock supplies to capital facility projects. The complexity of the space often makes it difficult to see year-over-year progress.

- **In 2023, GFI released a report and associated action papers to call for additional fermentation capacity devoted to alternative protein fermentation. Synonym,** curators of the Capacitor database and Scaler TEA tool released their 2023 State of Global Fermentation that identifies trends in fermentation capacity, as well as key needs for the industry, such as improved yield, productivity, and titer for microbes and bioprocess alike. **BioP2P** launched their biomanufacturing facilities directory in July, with annotated capacity, downstream processing equipment, cell type compatibility, and feedstock selection for users looking for fermentation and bioprocessing sites.

In 2023, consortia from university education and workforce development have shown the transformative potential of fermentation biomanufacturing.

- The Circular Bioeconomy Innovation Collaborative (CBIO) by BEAM Circular in California was established to bring biomanufacturing to the agricultural region.

- In October, the Illinois Fermentation and Agriculture Biomanufacturing Hub (iFAB) was established. Led by the Integrated Bioprocess Research Laboratory (IBRL) pilot facility at the **University of Illinois Urbana-Champaign**, iFAB has several goals including securing funding for workforce development, fermentation capital expansion, and attracting and incubating fermentation companies of all sizes. Large, multipartner consortia such as these leverage stakeholders from across the fermentation ecosystem and value chain to create solutions and drive innovation.

In 2023, several facilities progressed from groundbreakings to operational starts.

- In June, **Liberation Labs** broke ground and began construction on their dedicated food precision fermentation facility in Richmond, Indiana.
- **LiDestri Foods** and **Fermentum** announced a fermentation partnership to operate an existing 510,000-liter fermentation facility in Rochester, New York for food ingredients.
- In September, **MycoTechnology** unveiled their FermentX contract manufacturing services, using their Aurora, Colorado facility to offer fermentation capacity from pilot through to 90,000-liter fermentations.
- **ScaleUp Bio**, an **ADM** and **Nurasa** joint venture contract development manufacturing organization (CDMO), announced their first commercial customers in November, with **Nourish Ingredients** and **C16 Biosciences** among their first users.

These facilities represent a massive push forward for the industry to allow producers to leverage contract manufacturing for their innovative microbes and products.

The highlighted progress in the sector demonstrates the abundance of public and private researchers around the globe who are developing new fermentation-derived ingredients. Often, researchers report progress in peer-reviewed manuscripts, like the many reported in this section. **Additionally, patents allow for the disclosure of scientific progress with added intellectual property protection. The patent activity in the space represents the maturation of the global fermentation value chain across universities, institutes, and companies of all sizes. The progress in company innovation, while often a lagging indicator of investment return, can be a leading indicator of product development and pending entrance to the market.**

Following innovation and scaleup, a remaining hurdle to the marketplace is regulatory approval for fermentation-derived proteins and fats. Globally, several ingredients were approved or greenlit in this past year.

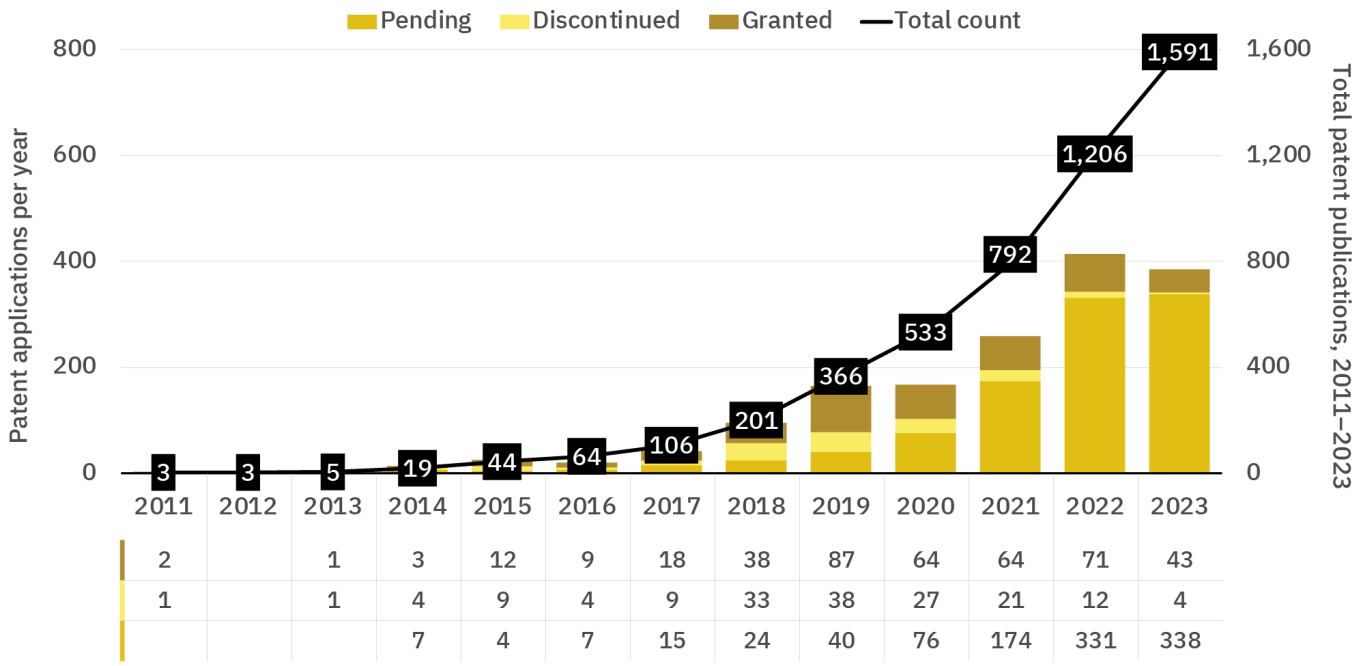
- U.S. FDA issued a letter indicating it had no questions regarding a submission from **The EVERY Company** demonstrating that the company's egg white protein produced by *K. phaffii* is generally recognized as safe (GRAS).
- **ReMilk Ltd.** received a no-questions letter from FDA for their submission demonstrating that β-lactoglobulin protein produced in *K. phaffii* is GRAS.
- Several fermentation-derived ingredients for food use are submitted for GRAS notification and are pending FDA response, potentially in 2024. Examples include **Mycotechnology**'s pea protein fermented by shiitake mycelium, **Oobli**'s brazzein sweet protein from *K. phaffii*, **ImaginDairy**'s β-lactoglobulin from *A. oryzae*, and **the Better Meat Co.**'s mycelial biomass from *N. crassa*.

Additional information on safety and potential regulatory progress comes from peer-reviewed toxicology studies.

- *C. necator,* a bacteria capable of fixing atmospheric gasses for metabolism, has been shown to have no adverse toxicological effects upon consumption up to 3g/kg of body weight per day, the highest tested dietary consumption. This paves the way for food formulations with *C. necator*, which has a superior protein content, nutritious amino acid profile, and better digestibility than many common and animal-derived protein sources.
- **The Protein Brewery** led a published safety assessment of the filamentous, biomass protein-producing fungal strain *Rhizomucor pusillus* CBS 143028, demonstrating safety for its pasteurized end product.
- **Impossible Foods** led a study characterizing the safety of precision fermentation leghemoglobin.

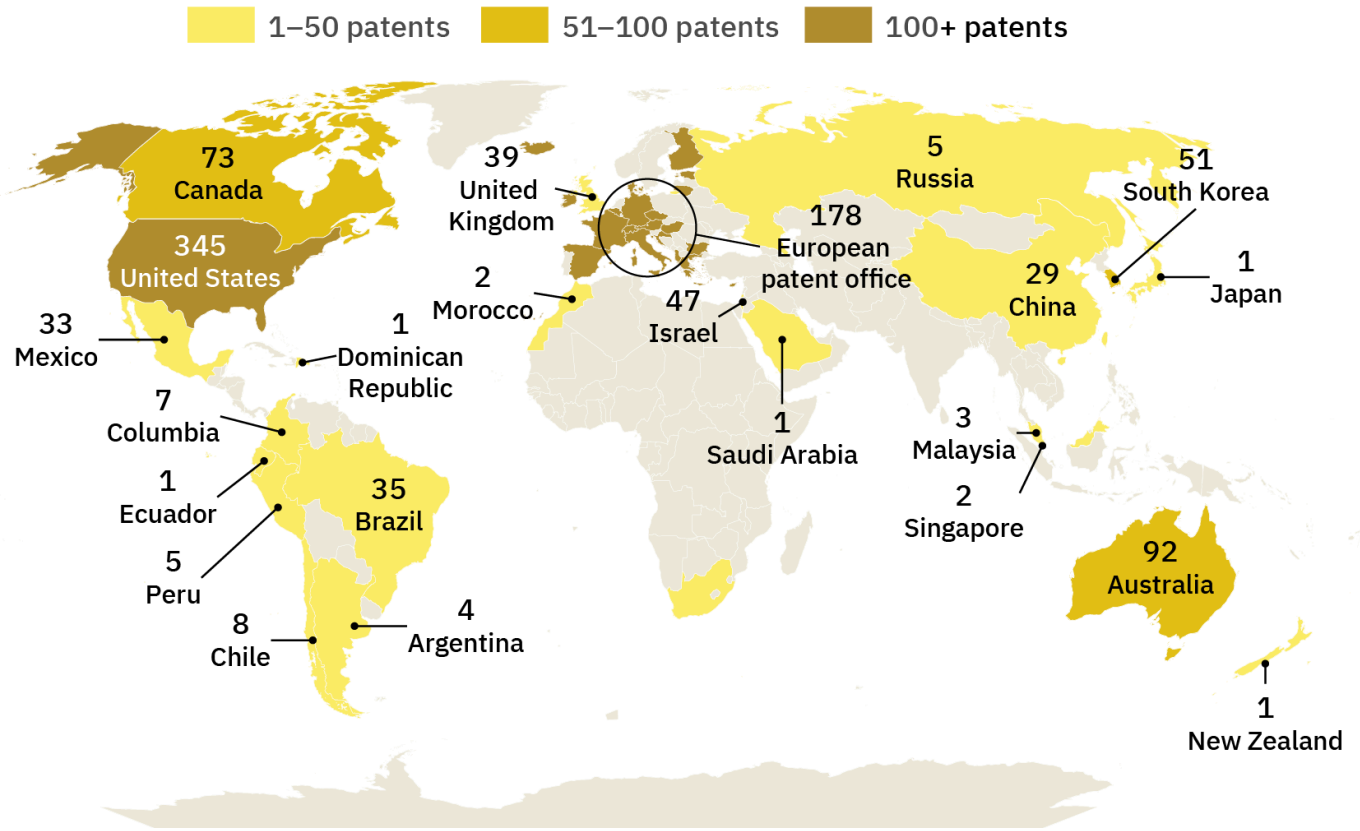
These peer-reviewed studies demonstrate the multipronged approach to ascertaining the safety of fermentation-derived products.

Figure 18: Patent landscape: Number of patents, by status



Source: GFI analysis of patent landscape from The Lens - https://www.lens.org.
The patent landscape includes alternative protein companies focused on biomass and precision fermentation who are included in the GFI company database. It does not include larger diversified corporations. Company names and legal filing company names often differ, so these were manually adjusted if available. Unique patents were filtered by application number and jurisdiction to provide total patents across jurisdictions. Thus, some unique patents will have additional counts across jurisdictions. Note that applicant jurisdictions represent the filing location for protection, not where the intellectual property was developed. Patents were further downselected for a specific focus on food and enabling technologies (e.g., bioreactor design), and by further removing patents strongly associated with biofuels/bioindustrials, healthcare, cosmetics, textiles, and animal feed applications. You can learn more about many of these companies in the GFI company database. Are we missing something? Let us know by filling out our company database edits form or contact us at corporate@gfi.org.

Figure 19: Patent applications by jurisdiction (2021-2023)



Source: GFI analysis of patent landscape from The Lens - https://www.lens.org.

Table 6: Number of patents by company (past 36 months)

89	The Every Company	**13**	Impossible Foods Inc	**4**	Aquacultured Foods Inc
85	Solar Foods	**13**	New Culture	**4**	Bond Pet Foods
82	Nature's Fynd	**12**	Melt&Marble	**4**	Helaina
68	Perfect Day	**11**	Enough (3f Bio)	**4**	Smallfood Inc
53	Corbion	**11**	Nourish Ingredients	**3**	Koralo
52	Mycotechnology	**11**	Revyve (Fumi Ingredients)	**3**	Zero Acre Farms
47	Air Protein	**11**	Yeap Ltd	**2**	Changing Biotech
39	Marlow Foods (Quorn)	**10**	Triton Algae Innovations	**2**	Eighth Day Foods
35	Algama	**9**	Infinite Roots (Mushlabs)	**2**	Eniferbio
32	Geltor Inc	**8**	Arkeon Gmbh	**2**	Equii (Cella Farms)
31	The Protein Brewery	**8**	Brevel	**2**	Fybraworks Foods
28	Calysta	**8**	Paleo B.V.	**2**	Nobell Foods
24	Noblegen	**8**	Planetarians (Usarium Inc)	**2**	Prairie Aquatech (Houdek)
22	C16 Biosciences	**8**	Standing Ovation	**2**	Wild Earth Inc
22	Mycorena	**7**	Ecovative Design Llc	**1**	All G Foods
21	Meati Foods	**7**	Kinoko-Tech	**1**	Better Dairy
20	Superbrewed Food, Inc.	**7**	Motif Foodworks	**1**	Change Foods
19	Formo Bio Gmbh	**7**	Turtletree	**1**	Imagindairy
18	Nextferm	**6**	Deep Branch Biotechnology Ltd.	**1**	Innomy
18	Prime Roots (Terramino Inc)	**6**	Yemoja	**1**	Kynda Biotech Gmbh
14	Checkerspot Inc	**5**	Shiru, Inc.	**1**	Nosh.Bio
14	Sophies Bionutrients Pte Ltd	**5**	The Better Meat Co.	**1**	Phyx44

Source: GFI analysis of patent landscape from The Lens - https://www.lens.org.

Government and regulation

Government and regulation

Overview

Governments around the world increased support for fermentation technology in 2023, recognizing that transitioning toward these new technologies could simultaneously create jobs, reduce emissions, and feed more people with fewer resources.

Governments increasingly invested in fermentation as an economic driver, especially through initiatives supporting biotechnology as a whole. The governments of the United States, the European Union, and China have announced initiatives to accelerate biotechnology development, and all three have noted fermentation technology–especially precision fermentation–as an area of interest. In 2023, the United States and the European Union (and likely China) made significant public investments in fermentation R&D, with countries including the United Kingdom, South Korea, Germany, Israel, and Thailand not far behind.

Fermentation-derived alternative proteins are also a promising solution for reducing greenhouse gas emissions from food systems, a fact recognized in governments' 2023 climate spending, some of which went to developing fermentation-enabled dairy, seafood, and functional proteins. **At COP28 in Dubai, a report from the UN Environment Programme was released confirming the technology's potential to benefit the climate, environment, and global health and providing a comprehensive list of supportive policies governments might adopt to speed its development and deployment.**

Overall, fermentation became increasingly recognized as benefiting the economy and the environment, and governments kicked off new strategies to build fermentation capacity and develop the science in 2023.

Global public funding

North America

Public support for fermentation-enabled alternative proteins increased globally in 2023, but especially in the United States, where government investment in alternative proteins had previously lagged.

In February 2023, the Defense Advanced Research Projects Agency (DARPA) of the U.S. Department of Defense announced that work had begun through their Cornucopia program, which seeks to "create a variety of healthy new microbial-based foods using three ingredients—air, water, and electricity—with minimal or no supplementation." With one of the four projects funded at $10.4 million, GFI estimates the total DARPA funding at around $40 million over four years–nearly matching the United States' all-time investment in alternative proteins.

In March 2023, the Biden Administration released a report titled Bold Goals for U.S. Biotechnology and Biomanufacturing that proposed supportive policies for the domestic biotechnology sector. Alternative proteins were included in submissions from the Department of Agriculture (USDA) and the Department of Energy, both of which called for more research on alternative proteins, public-private partnerships, and an ecosystem of agriculture-focused biomanufacturing facilities.

In July 2023, the White House subsequently released a Building the Bioworkforce of the Future report that called out precision fermentation explicitly. The plan affirmed the Administration's commitment to ensuring that "cutting-edge products resulting from biotechnology invented in the United States are manufactured in the United States."

The administration's promises were followed by increased public investment in fermentation capabilities in multiple forms, including much-needed support for increasing U.S. fermentation capacity. Precision fermentation startup Liberation Labs received a $25 million loan guarantee from USDA to accelerate construction of a facility in Richmond, Indiana, which is expected to create local jobs and a new market for the state's corn crop.

The Department of Commerce, meanwhile, designated the Illinois Fermentation and Agriculture Biomanufacturing (iFAB) Tech Hub as one of 31 Regional Innovation and Technology Hubs to receive a $400,000–500,000 Strategy Development Grant and the opportunity to apply for a further grant of up to $75 million. Led by the University of Illinois Urbana-Champaign, the **iFAB Tech Hub** aims to scale precision fermentation to convert underutilized corn feedstocks into alternative proteins and food ingredients.

Finally, in late 2023 the Department of Energy's Industrial Efficiency and Decarbonization Office announced plans to issue a funding opportunity on decarbonizing critical industries (which it did in January 2024), listing alternative protein production as a specific area of interest.

The United States also continued to fund precision- and biomass-fermentation research and development, announcing several new grants for companies and researchers. A research project at the **University of Massachusetts Amherst** received a New Innovator Grant from the Foundation for Food & Agriculture Research (FFAR) to develop a new protein derived from hydrogen-consuming bacteria, while California-based **Air Protein** and Finland-based **Solar Foods** made it to the final round of NASA's Deep Space Food Challenge, each receiving $150,000 toward their work on gas fermentation in closed-loop environments. U.S.-based biomass and precision fermentation startups received small business grants from the Department of Energy and the National Science Foundation, while USDA's National Institute for Food and Agriculture funded a workforce development project intending to draw more students to careers in food technology.

In Canada, the government supported a research project at the **University of Saskatchewan** evaluating canola meal, a sidestream of Canada's robust canola sector, as a feedstock in fermentation applications.

Asia Pacific

Governments in the Asia Pacific region continued research projects in fermentation, though new initiatives among the region's top alternative protein funders were few.

Singapore, by far the regional leader, continued to invest in fermentation technology R&D through the well-funded Singapore Food Story 2.0 research program. **Nurasa**, a company owned by the country's sovereign wealth fund, continued to support Singapore's development of bench- and demonstration-scale fermentation capabilities through their Food Tech Innovation Centre, which includes **ScaleUp Bio**, a contract development manufacturing organization (CDMO) co-founded by Nurasa and U.S.-based food company **ADM**.

In February 2023, South Korea's North Gyeongsang Province led a 28-member Memorandum of Understanding calling for the advancement of the cellular agriculture ecosystem in South Korea and informally creating a cellular agriculture cluster comprising companies, universities, and city governments. The province also proposed establishing a regulation-free zone in which companies can showcase proof-of-concept prototypes, as well as a nine billion won ($6.7 million) North Gyeongsang Cellular Agriculture Industry Support Center, which opened in March 2023 in a ceremony at which the world's largest meat prototype, weighing in at 10 kilograms (22 pounds), was unveiled by **Tissen Biofarm**, a cluster member.

Europe

Europe, which led the world in alternative protein public investment in 2022, maintained or possibly extended its lead in 2023 with a series of strategic government investments across the continent.

The European Union, which has been a leading supporter of fermentation technology, continued to support the industry with a €14 million ($15 million) grant from the public-private Circular Bio-based Europe Joint Undertaking to a company building an alternative protein biomass fermentation facility in France, a €5.5 million ($6 million) grant from the European Innovation Council's (EIC) Pathfinder program to a consortium led by Finnish food tech company **Solar Foods** to produce whey protein from hydrogen via precision fermentation, and the announcement of €50 million ($54.9 million) to assist startups in scaling up the production of food from precision fermentation and algae as part of the EIC's Work Programme 2024.

On the national level, the United Kingdom became a major player in alternative proteins, particularly in cellular agriculture, with an allocation of £12 million ($15 million) for a new Cellular Agriculture Research Hub at the University of Bath followed by an estimated £2.9 million ($3.7 million) for six research projects on fermentation through a program supporting low-emission food production systems. Two fermentation technology companies were selected through Innovate UK's Better Food for All competition as well.

Further boosting the United Kingdom's collaboration across the research and business ecosystems, the Biotechnology and Biological Sciences Research Council teamed up with Innovate UK to announce up to £15 million ($19 million) for an Alternative Proteins Innovation and Knowledge Centre to be established over the next five years. Finally, in December 2023 the United Kingdom released a National Vision for Engineering Biology which outlines a £2 billion ($2.2 billion) investment in research, development, and infrastructure in the bioeconomy. The strategy highlights the cultivated meat and fermentation sectors specifically, stating that alternative proteins can address climate and food security goals.

Germany announced €38 million ($41 million) in federal funding for a sustainable protein transition in 2024, including funding for innovating in alternative protein production, promoting the nutritional value of alternative proteins, and aiding farmers and companies to transition from animal agriculture to plant-based, cultivated, or fermented protein production. Additionally, Germany's Ministry of Food and Agriculture awarded a €500,000 ($547,000) grant to **Kynda**, a German mycelial biomass fermentation company. The Netherlands awarded €1 million ($1.1 million) to a group of companies and academics to research the scalability and cost-effectiveness of producing collagen and elastin for food and health care through precision fermentation, while Spanish startup **Libre Foods** was awarded a €335,000 ($368,000) grant to develop low-cost mycelium biomass as a meat alternative through a public-private partnership supporting research on new technologies.

On the sub-national level, the state of Catalonia in Spain invested €7 million ($7.32 million) in a Center for Innovation in Alternative Proteins (CiPA), which will help alternative protein businesses scale up production. The government of Wales supported a project to examine hydrogen-based biomass fermentation, with the Welsh head of Smart Living noting: "It is hoped that the development of this project will increase the economic prospects of Wales and improve the environmental wellbeing through the transition into a greener economy."

Finally, as part of a growing trend of international collaboration on alternative proteins, the research and innovation agencies of Sweden and Austria cofunded a €1.5 million grant to Austria-based **Revo Foods** and Sweden-based **Mycorena** to jointly develop a 3D-printed mycoprotein prototype. This emerging model of bilateral research partnerships helps develop not only individual products but also research and business ties between participants and their governments.

Israel

Israel maintained leadership in its support for fermentation technology through innovative new funds, investments, and initiatives.

In June 2023, the government awarded previously announced funding of NIS 50 million ($14 million) to build a precision fermentation CDMO, lowering the cost of pilot- and demonstration-scale equipment and expertise for emerging startups. Additionally, a new human capital program will cultivate expertise in alternative proteins and food technology, fueling the country's research ecosystem and developing a workforce for a future food system.

Additionally, Israel championed international alternative protein collaborations, embarking on multiple bilateral and multilateral efforts to co-develop new products and technologies with other nations. Among these, the Binational Industrial Research and Development (BIRD) Foundation, a collaboration between Israel and the United States, jointly awarded $1 million to Israel's **Oshi** and the United States' **The Better Meat Co.** to produce mycoprotein-based salmon filets.

Africa

In 2023, the government of South Africa allocated what may be the first public investment in precision fermentation on the continent, with a grant of ZAR 11 million ($700,000) to South African startup **De Novo Foodlabs** toward their development of precision-fermented dairy proteins.

Regulation by country

Microbial fermentation has long been used as a processing method in the food industry, and to create ingredients derived from microbial cultures. Fermentation can also be used to create natural flavors and sweeteners found in many foods and beverages. Given its long history, most governments have well-established regulatory systems to govern the use of microbial fermentation in food systems. Some countries evaluate new fermentation products under novel food regulations, which typically require pre-market authorization. Others, like the United States, apply a more complex regulatory framework.

Australia/New Zealand

In December 2022, the Food Ministers' Meeting (FMM) accepted that the existing Food Standards Code and labeling requirements in place across Australia and New Zealand are well-equipped to regulate precision fermentation products. These foods will require pre-market approval under the novel foods standard. The FMM will continue to monitor the need for additional standards based on the number and types of applications for premarket approval received.

Brazil

In December 2023, the National Health Surveillance Agency (Anvisa) published RDC 839/2023, updating Brazil's regulations for novel foods and ingredients. This regulation includes the procedures to be followed by companies to assess the safety of products obtained from the cultivation of cells and tissues and those obtained through innovative fermentation processes. Anvisa's publication was a prerequisite for the next stages of the regulatory process, which will define the product registration regulations, comprising the labeling rules, the identity and quality standards to be met, and the rules for inspecting manufacturing units, all of which are the responsibility of the Ministry of Agriculture.

Canada

Health Canada is the Canadian federal department responsible for national health standards and policy. Health Canada has evaluated precision fermentation products as novel foods, requiring manufacturers to submit detailed scientific data for review before such foods are authorized for sale. The Guidelines for the Safety Assessment of Novel Foods Derived from Plants and Microorganisms outlines the specific

criteria for the safety assessment of novel food. In August 2023, Chicago-based company **Nature's Fynd** received authorization from Health Canada to commercialize their alternative meat and dairy products. Nature's Fynd makes a novel protein fungi called "Fy" through fermentation.

European Union (EU)

In the European Union, companies must secure pre-market authorization for new fermentation-derived ingredients under the European Union's novel food regulation. Products produced with genetic modification are covered under the European regulation on genetically modified food and feed, EC 1829/2003. The procedure includes a risk assessment conducted by the European Food Safety Authority. Pre-market authorization is handled centrally at the EU level, meaning that once the European Commission and representatives from EU member states approve a product, the approval applies across all 27 EU countries.

In early 2023, the European Commission approved **MycoTechnology**'s novel food application and authorized their pea and rice protein fermented by shiitake mushroom mycelia, which the company calls FermentIQ. **Nature's Fynd**, **Solar Foods**, **Perfect Day**, and **The Protein Brewery** have also submitted novel food applications to the European Union. Additionally, the EU has been assessing **Impossible Foods**' soy leghemoglobin both as a genetically modified food and as a food additive. As part of this assessment process, the European Union required Impossible Foods to conduct a dietary study, the results of which were made publicly available on October 10, 2023. It is expected that each of these companies will continue to move forward with the regulatory process.

Israel

In April 2023, **Remilk** received the first regulatory approval of its kind in Israel to market and sell products containing the company's precision fermentation-derived milk protein. The regulatory approval was granted by Israel's Ministry of Health, and came after Remilk had already received regulatory approvals in the United States and Singapore.

Singapore

In October 2022, Singapore became the first nation to grant approval of a gas-fermented microbe-based protein called Solein, created by Finnish startup **Solar Foods.**

Singapore regulates new foods created via fermentation as novel foods that must be approved by the Singapore Food Agency (SFA) before they are allowed for sale. Food manufacturers that wish to sell such foods must conduct safety assessments of their products for SFA review. As with all foods in Singapore, new foods derived from fermentation that are approved will be subject to market monitoring to ensure manufacturers continue to abide by high safety standards.

United Kingdom

While the United Kingdom is no longer a member of the European Union, it has largely retained the substance of the EU's novel food regulations. Some fermentation companies seeking to sell products in the United Kingdom will need to apply for authorization from the UK Food Standards Agency (FSA), depending on whether the product and process have an established history of production and consumption. The FSA provides general guidance on how to submit novel food applications. At present, the United Kingdom is considering changes to its novel food regulations that could speed up precision fermentation product approvals.

A 2023 report from Deloitte commissioned by the FSA outlined a roadmap for UK regulators to improve the regulatory processes for products of precision fermentation and cultivated meat. The UK government's response to this report was positive, acknowledging that technological advances are accelerating the development of novel foods (including products of fermentation) and that this industry represents a commercial and economic opportunity for the United Kingdom.

United States

The U.S. Food and Drug Administration (FDA) has regulatory authority over fermentation-enabled foods, and there are two potential regulatory pathways that companies can follow to ensure their novel fermentation-derived foods and ingredients can be sold in the United States.

The first is a food additive petition, which is a lengthy process that involves a consultation with FDA and a petition to the agency requesting the issuance of a regulation that would allow specific uses of the ingredient or additive. The second pathway is a GRAS notice, which is used for ingredients that the food producer believes are already "generally recognized as safe" among qualified experts under their conditions of intended use.

In recent years, the majority of fermentation companies in the United States have elected to take this second pathway. These companies have obtained no-questions letters from FDA in response to their GRAS submissions:

- In March 2020, **Perfect Day** received a no-questions letter from FDA in response to their GRAS notice for β-lactoglobulin, the major protein in whey.
- In March 2021, **Nature's Fynd** (formerly Sustainable Bioproducts) received a no-questions letter from FDA in response to their GRAS notice for a fungi-derived protein.
- In September 2021, **EVERY** received a no-questions letter from FDA in response to their GRAS notice for a soluble egg-white protein produced by yeast.
- In December 2021, **Motif FoodWorks** received a no-questions letter from FDA in response to their GRAS notice for a heme protein derived from yeast, which the company calls HEMAMI™.
- In April 2022, **ENOUGH** (formerly 3F BIO Ltd.) received a no-questions letter from FDA regarding their ABUNDA® mycoprotein.
- In February 2023, **Remilk Ltd.** received a GRAS no-questions letter from FDA regarding their production organism, *Komagataella phaffii*.

Global cooperation and coordination

Codex Alimentarius Commission

In April 2023, the Codex Secretariat issued a circular letter seeking comments from member countries and observers on specific topics that would require the development of a Codex standard related to new food sources and production systems (NFPS), which includes novel foods created via fermentation.

The circular letter also sought comments about the appropriate procedural methods within Codex to address NFPS. Members and observers, including GFI, commented on whether the current Codex procedural mechanisms were appropriate to address NFPS issues and raised aspects relevant to NFPS standard-setting that had not yet been considered by the Commission.

The topic of NFPS was discussed at the 46th convening of the entire Commission (CAC46) in December 2023, and it was decided that current Codex procedural mechanisms were sufficient to address any future NFPS issues that may arise.

Several Codex members indicated an interest in submitting specific proposals for new work related to NFPS in the future, including a potential discussion paper on the application of existing Codex tests to precision-fermentation-derived ingredients.

Food and Agriculture Organization (FAO)

In November 2023, the United Nations Food and Agriculture Organization (FAO) hosted the Food Safety Foresight Technical Meeting on New Food Sources and Production Systems in Rome. The main objective of the meeting was to evaluate the food safety issues associated with innovative food sources, including new applications of precision fermentation.

The meeting's conclusions described how precision fermentation is a technology that has been around for decades, yet it is now being used to produce innovative food technology. As such, the safety considerations and regulatory landscape for new products created with precision fermentation should be continuously monitored by companies to keep up with evolving regulatory requirements.

COP28

The year 2023 also brought new ideas on how governments might collaborate on alternative protein development, not only for their mutual gain but also to advance the common good.

A report from the United Nations Environment Programme, released at COP28 in Dubai, assembled a strong list of potential actions governments could take individually and in concert. **In a section on multilateral cooperation, the report suggests that governments embark on bilateral and multilateral research efforts, evaluate and revise trade policy to be more supportive, develop international food safety standards, and collaborate with development finance institutions to build capabilities worldwide.**

Also at COP28, 134 countries/regions, including the United States, China, the European Union, and Brazil, signed the Emirates Declaration on Sustainable Agriculture and Food Systems, committing to addressing emissions from food systems in their 2025 Nationally Determined Contributions (NDCs). Since, 25 more signatories have also endorsed the declaration. While the declaration does not mention alternative proteins outright, supporting alternatives to animal agriculture will be necessary to keep the world within 1.5°C of warming.

Outlook

Outlook

Overview

The sub-pillars of traditional, biomass, and precision fermentation are distinct in their production methods and end-use applications. Consequently, it can be difficult to discuss the technologies collectively. They each face unique challenges and opportunities in manufacturing, scaling, funding, consumer messaging, and governmental regulation.

Although biomass, precision, and traditional fermentation exist at distinct stages of industry development, key trends held across the fermentation and food sectors in 2023.

The private capital environment moderated. It was negatively impacted by rising interest rates and an uncertain economic outlook.

The fermentation category experienced funding difficulties similar to the broader startup landscape on the back of elevated interest rates and an uncertain market backdrop. The slowdown was far from unique to the fermentation sector, as global venture funding declined by 42 percent year-over-year from 2022 to 2023. Although the fermentation category was not immune to 2023's subdued fundraising environment, there were notable exceptions: **Air Protein**'s $75 million, **Meati**'s $50 million, and **ENOUGH**'s $43.7 million fundraising rounds. Similarly, there were advancements in public support for fermentation-enabled alternative proteins, as evidenced by USDA's $25 million loan guarantee on **Liberation Labs**' new facility, and the European Union's €50 million commitment to supporting precision fermentation scale-up.

Manufacturing capacity grew but remained at modest levels, contributing to elevated production costs relative to those of conventional counterparts.

Companies across the fermentation landscape worked to scale their processes in 2023, with multiple industrial-scale facilities either opening or starting construction. However, globally, there is still only somewhere between 0.4 and 2.8 million metric tons (MMT) of fermentation capacity that could be used for alternative protein production. These relatively small volumes mean that many ingredients and end products remain at price premiums, much like the average plant-based meat and dairy products. Given that higher-priced protein products struggled to stimulate sales demand in 2023, fermentation-enabled products likely experienced similar impacts at the industry level.

Some individual companies enjoyed year-over-year sales increases, but consumers had less room in their wallets for premium-priced protein products in 2023.

Just as select companies in the fermentation sector fell short of forecasts in 2023, several large conventional meat companies also underperformed relative to expectations. Tenuous consumer financial standing depressed demand for many animal protein types, particularly in U.S. retail. Plus, supply-side pressures, like Highly Pathogenic Avian Influenza (HPAI), mixtures of over-and-under supply in various markets, and elevated input costs squeezed meat producers' margins. According to SPINS data, animal meat volume sales at U.S. retail declined in 2023—likely a consequence of these and other factors. As a result, conventional meat leaders like **Tyson Foods**, **Hormel Foods**, **JBS USA**, **Smithfield Foods**, and others took cost-cutting actions and/or lowered their 2024 forecasts in reaction to 2023's financial performance. Specific sectors, like the U.S. pork market, saw retail dollar sales fall by roughly 10 percent from 2022 levels, largely in response to elevated prices. Last year's struggles weren't unique to the meat sector, as dairy companies and even grocery chains also shifted their strategies to respond to the current environment.

Despite some of the challenges of 2023, the FAO projects global meat consumption to rise by at least

50 percent from 2012 levels by 2050. Fermentation-enabled foods can play a crucial role in addressing the growing demand for protein while improving personal, public, and planetary health outcomes. To do so, the category needs to make a clear and convincing value proposition to consumers while navigating the current economic headwinds.

So, what does the future hold for the fermentation industry? The remainder of this section will explore the category's near- and long-term outlooks, along with expert insights and external forecasts.

2024 outlook

Phrases such as "shakeout," "normalization," and "stabilization" were frequently used to describe the dynamics of the alternative protein sector in 2023. While the fermentation-enabled food category exists at a relatively early stage of development, it was not immune to the broader market trends discussed in the previous section. Those factors that shaped the environment in 2023 are likely to extend into 2024.

The funding difficulties that were prevalent across the startup landscape in 2023 will continue to affect the fermentation sector in 2024. Though there's optimism for some relief in 2024, interest rates remain elevated, meaning it will be difficult for startups to access free-flowing funding. Investors and stakeholders will expect the capital that companies do raise to go further and last longer.

With the fermentation category still populated by a large share of early-stage and pre-revenue companies, the fundraising environment is important for the health of the category. Startups rely on fundraising to provide a financial runway and, crucially, to help them weather the pre-revenue stage as they scale from pilot to commercial production.

Some fermentation companies will access the financing they need to grow their businesses, but they'll do so in a less conducive environment than in years past. As a result, it will be increasingly important for governments around the world to continue to support the growing fermentation sector through investments in R&D, grants, loans and loan guarantees, and other forms of financing. On that front, the progress made in 2023 with governments recognizing that fermentation-enabled foods as climate and food security solutions bodes well for the future of the sector. However, more work needs to be done to close the gap between investments in alternative proteins and other climate solutions, which have received many multiples more funding.

The funding environment will also affect another looming bottleneck for the fermentation category: manufacturing capacity. The fermentation industry sits at a crossroads in 2024. On one hand, the growing global demand for healthy, sustainable food means the fermentation sector is well-positioned for growth. On the other hand, impending manufacturing capacity limitations paired with a more cautious private funding environment means some companies may struggle to meet rising consumer demand.

Even moderate growth in the fermentation industry could mean a capacity squeeze, but with capital harder to access, startups will need to look for expansion opportunities beyond building new facilities. Two solutions of growing importance include partnering with contract manufacturing organizations (CMOs) and retrofitting brownfield facilities. Both approaches typically require less time and money than building greenfield sites, making them attractive options for growing capacity in the current market environment. We expect to see an increased prioritization of these types of initiatives in 2024.

Finally, the fermentation category is rapidly evolving. New and innovative products frequently come to market, but the fermentation sub-pillars exist at different stages of development.

- Many biomass fermentation companies hold the potential for significant, near-term market upside in the meat and dairy categories. Several companies in the space have achieved widespread distribution, and some biomass fermentation products are sold at relatively competitive price points. On the other hand, biomass fermentation companies pursuing more

novel products and processes—like those creating food from carbon dioxide—are likely to be further from broad market penetration.

- Some alternative protein ingredients made with precision fermentation have also achieved widespread distribution. But while a handful of new products—like cheese made with fermentation-derived casein or eggs made with fermentation-derived ovalbumin—may hit the market in a limited capacity in 2024, the path to both scale and cost-competitiveness is likely longer for precision fermentation companies.
- Traditional fermentation is already widely used in alternative proteins, especially in the plant-based dairy category. Improvements in fermentation processes can help plant-based dairy products close the taste and texture gap with their conventional counterparts. Many traditional fermentation processes, once refined, are cost-effective and scalable, positioning traditional fermentation products for near-term growth. Other traditional fermentation processes—like those used to create whole-cut beef products—may be further from the commercial scale on account of their novelty but also hold significant upside potential over the medium term.

Long-term outlook

About half of the world's habitable land is used for agriculture, which means that global food system change is necessarily an enormous, intensive, and lengthy pursuit.
Scaling a sector from virtually nonexistent to commercial volumes is a monumental task. Precision fermentation for chymosin and other ingredient production took 10 to 20 years to achieve maturation. Replicating the same market penetration with a growing list of increasingly complex target end products while remaining cost-competitive is no small feat. For products made with biomass and traditional fermentation, ever-higher standards around taste, texture, nutrition, and price also mean that achieving widespread adoption will be a long, challenging process.

Meeting the challenge of producing affordable, accessible, and tasty fermentation-enabled products will require continued innovation and investment from companies, governments, and investors. By making products consumers want in a way that's better for the planet, fermentation companies can chart the path toward long-term growth. Plus, continued innovations in strain development, equipment, and feedstock sourcing in the biomass fermentation, precision fermentation, and cultivated meat industries are poised to both increase manufacturing capacity and lower operational costs. This will make the entire industry more competitive within the broader food sector.

But progress is not linear, and it is not guaranteed. The fermentation-enabled meat, seafood, eggs, and dairy industries still face hurdles on the path to robust, long-term growth. Companies must continue to refine their processes to achieve maximum efficiencies that create delicious food to generate demand, and brands need to reach consumers about the unique benefits of their products. Companies will have to do so in what looks to be a tighter private capital funding environment than in recent years. They'll also need to contend with global regulatory obstacles and likely manufacturing capacity bottlenecks.

Considering these factors, plus the size of the $1 trillion global meat market, the opportunity for the fermentation sector remains immense. This category is in its early stages, and there exists a sizable runway for expansion as consumers discover both existing products improved with fermentation-derived ingredients and entirely new fermentation-enabled products. In the coming years, companies can refine their processes, communicate their benefits to consumers, and capture market share. Doing so will require investment, collaboration, and commitment. Given the challenges facing our planet and global food systems, progress is not only possible—it is necessary to meet international goals.

External projections

External forecasts of the alternative protein and fermentation-enabled meat, seafood, eggs, and dairy markets from consulting firms, think tanks, and research organizations vary widely in their estimates of the potential future of the industry, but they all project robust growth from today's market size.

Forecasts for 2030 range from ambitious estimates of $15 billion to $74 billion for the fermentation-enabled meat, seafood, eggs, and dairy markets alone, though some of these forecasts were published several years ago and no longer reflect probable outcomes for 2030. That would represent a significant increase from today's market size, which is currently only capable of producing 0.4–2.8 MMT of fermentation-enabled alternative protein products per year. Combined alternative protein (plant-based, fermentation, and cultivated) market forecasts for 2030 range from $58 billion to $570 billion. Such market growth would demand unprecedented investment and innovation in the sector.

Will the fermentation market achieve these projections by 2030? Meeting even the low-end estimate would require notable advancements in production efficiency, costs, and—most importantly—capacity. Robust contract manufacturing infrastructure would need to quickly develop, and a large number of fermentation facilities from the beer, wine, and biofuel industries would need to be retrofitted for alternative protein production.

Given the current environment, these estimated market sizes are possible, though they would necessitate levels of public and private investment many times higher than today's norms.

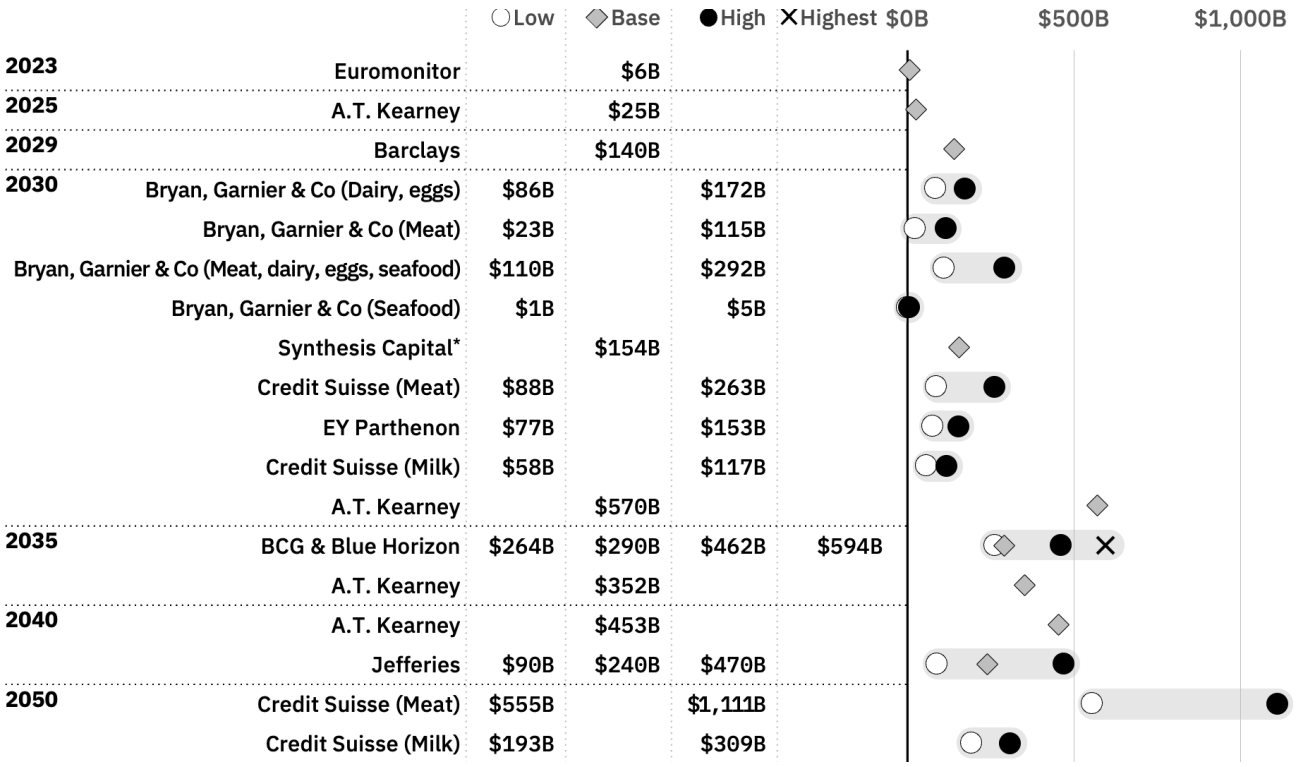
Vast increases in support for alternative proteins are justified by their potential climate, public health, and food security benefits. Companies need to continue to innovate to meet consumers' wants and needs while bringing costs down.

While consumers' financial standing, the health of individual alternative protein companies, and the media's sentiment regarding alternative proteins are constantly changing, the challenge before us is not. Animal agriculture alone, including the crops and pastures to feed those animals, accounts for between 11 and 20 percent of all emissions (FAO, Nature Food). If governments and investors around the world are serious about meeting key climate benchmarks, they must step up to position the sector for long-term success.

Figure 20: Forecasts for global fermentation industry market size from Bryan, Garnier & Co

Source: Bryan, Garnier & Co

Figure 21: Total alternative protein industry forecasts



*Some forecasts projected a share of the total meat market rather than the industry in dollars. For those forecasts, we estimated the dollar size of the alternative protein sector using EY's forecast for the total 2030 meat market.

Source: A.T. Kearney, Barclays, BCG & Blue Horizon, Bryan, Garnier & Co, Credit Suisse, Euromonitor International Limited 2023 © All rights reserved., EY Parthenon, Jefferies, Synthesis Capital

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Conclusion

More meat, seafood, eggs, and dairy products were made via microorganisms in 2023 than any year before. Milestones throughout the year included landmark investments in Europe, the launch of appealing new products including animal-free cheeses, and the continued expansion of fermentation facilities.

Despite this progress, fermentation faced economic headwinds as the global economy continued to slow and private investments tailed off their previous highs. Despite the sobering economic landscape, we remain optimistic about the future of fermentation as a promising agricultural innovation with far-reaching implications for planetary and public health, strong bioeconomies, and more resilient global security. In that spirit, we offer these reflections on the year ahead:

A global protein transformation will require strong, system-wide participation.

Where do you see yourself?

By delivering delicious, affordable alternative protein products to mainstream consumers, companies can realize a significant market opportunity to satisfy a growing consumer interest in healthy, sustainable protein sources that meet their foundational needs on taste and price. The research community can lean in by encouraging more scientists, from varied disciplines and at different points in their careers, to jump into the alternative protein field. The world's governments can invest in critical R&D to advance alternative protein science, manufacturing incentives to help scale up, and policies that level the playing field to allow alternatives to compete on taste, price, and convenience. And philanthropy can advance the alternative protein ecosystem by unlocking early breakthroughs and greater investment from governments and the private sector. System-wide participation can address the industry's biggest technical challenges, inspire research, create growth opportunities, and ensure these sustainable foods can benefit everyone.

We always keep the long view in sight.

What steps can you take toward a long-term goal?

The alternative protein industry is still developing, and yet we see the growing recognition that fermentation-derived foods and other alternative proteins are a solution for reducing greenhouse gas emissions from food systems and feeding more people with fewer resources. Advances in fermentation technology are escalating, and the policy and regulatory landscape is looking brighter as more governments and agencies look to alternative proteins to offer solutions to serious global issues like food safety and security and environmental degradation. Consumers want sustainable options, but they don't want to compromise on taste, price, or convenience. Navigating and building the path to scale and adoption will take years. Staying on this path while overcoming obstacles and headwinds will be critical to success.

Believe change is possible.

What inspires your vision?

At GFI, we bring determination and informed optimism to our work because we know a better food future is achievable. We see these same traits in those who pushed fermentation forward this year, many of them highlighted in this report. Across sectors and regions, there is a growing understanding of the importance of finding viable alternatives to conventional animal agriculture and huge opportunities for companies who get involved in this space. Just as the world is changing how energy is produced, we need to change how meat is made. Alternative proteins can satisfy growing demand, reduce pressure on the planet, and create jobs. Alongside other advances and innovations, alternative proteins can help write the next chapter for food and agriculture around the world.

To those who are in this work already, we hope GFI's 2023 State of the Industry Report, *Fermentation: Meat, seafood, eggs, and dairy*, gives you a detailed look at this rapidly evolving sector. For those new to the field, welcome. Stay a while, grow with us, and change the world.

Expert predictions

Rodrigo Ledesma Amaro

Professor of Nutritional Physiology, Imperial College London

Advances in tools and applications of engineering biology will lead to development in the fermentation industry, breaking down the price and quality barriers. In the long term, our capacity to design and engineer complex microbial communities, an area of research that is emerging, will enable the creation of the next generation of fermentation-based processes, making them more efficient, robust, and affordable.

Nicki Briggs

Founder/Principal, Here/There Strategic Communications

Precision fermentation will continue to transform food—both how it is made and the very products we eat. The hallmark of this transformation won't be sheer disruption but adaptation and collaboration. Precision fermentation will provide existing companies and industries with critical tools to accelerate their ability to adapt to rapidly shifting consumer demands while meeting ambitious sustainability goals and regulations.

Alan Hahn

Executive Chairman MycoTechnology, Inc.

I anticipate slight shifts toward improved commercialization, while in the long term, I am optimistic that increased government investments will pave the way for an ideal environment that promotes sustainable food production through fermentation.

Beth Conerty

Associate Director of Business Development, University of Illinois Urbana-Champaign

In the short term, I think there will be a consolidation of startup companies because there are quite a few working on the same target molecule or ingredient. I believe the ones with the most compelling techno-economic analyses will come out on top, while the others will need to pivot and consider alternative end-product targets. In the long term, I think that the fermentation industry will continue to expand the markets impacted, find niches where price parity can be achieved, and become more sustainable through technologies like gas-fed fermentations or waste streams as feedstocks.

Dr. Louise Durrant, RD

Nutrition Communications Manager, Quorn Foods

In the short term, we would anticipate continued innovation and market growth in the fermentation industry, with new products and applications emerging. Long term, the industry is poised for significant expansion as it becomes a cornerstone of sustainable protein production, addressing global challenges and redefining our approach to nutrition and the environmental impact of our food.

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The Good Food Institute is a nonprofit think tank working to make the global food system better for the planet, people, and animals. Alongside scientists, businesses, and policymakers, GFI's teams focus on making plant-based and cultivated meat delicious, affordable, and accessible. Powered by philanthropy, GFI is an international network of organizations advancing alternative proteins as an essential solution needed to meet the world's climate, global health, food security, and biodiversity goals. To learn more, please visit gfi.org.

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