Plant molecular farming: Industry overview and developments

Plant molecular farming (PMF) uses plants to produce functional ingredients, like the proteins found in dairy or eggs. By introducing precise genetic instructions, plants are guided to produce specific proteins—like whey or casein—using the sun's energy and traditional agricultural practices. This approach leverages well-established farming systems to grow crops that serve as sustainable biofactories for alternative proteins.

Overview

Molecular farming has long been used to develop pharmaceutical end products like insulin, antibodies, and vaccine antigens. While not a new technology, applying plant molecular farming (PMF) to alternative protein production comes with its own opportunities and challenges.

Since it does not require some of the capital-intensive equipment associated with some other forms of alternative protein production (such as bioreactors), PMF may offer cost and scalability benefits over other production processes. However, as with any novel ingredient solution, the sector will need to successfully navigate regulatory pathways, processing, and purification to establish itself as a viable, scaled technology for alternative protein production. No protein ingredient made in this way has yet been greenlit or approved for commercial sale by a national food safety regulatory body. However, in 2024 progress towards commercialization has seen approvals for the cultivation of PMF crops.

This fact sheet summarizes recent key developments in the PMF sector.

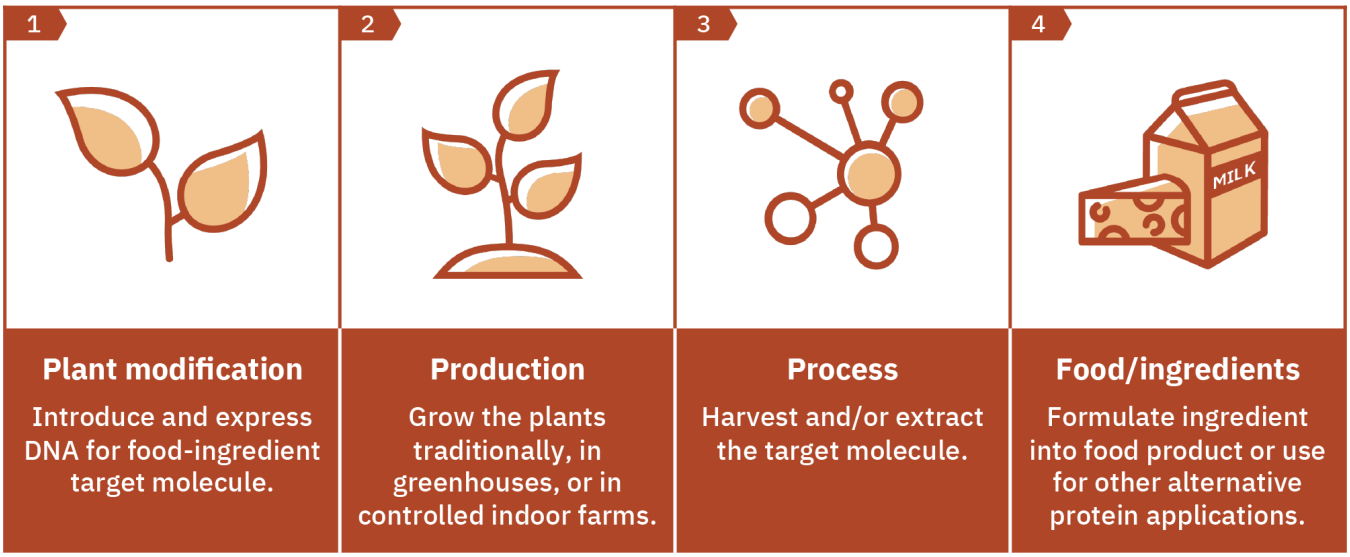

Figure 1: How plant molecular farming works

Commercial landscape

Currently, 17 known companies are primarily focused on advancing this technology for the alternative protein sector. According to GFI's company database, 34 are involved in the space, including diversified companies and companies primarily focused on technologies other than PMF. There are a variety of product approaches:

Dairy proteins

- **Alpine Bio** (formerly Nobell Foods)**, Aspyre Foods**, **Finally Foods**, **Miruku**, **Mozza**, **Plantopia,** and **Veloz Bio** produce animal-free dairy proteins for use in products like cheese, ice cream, and yogurt.

Egg proteins

- **PoLoPo** and **Veloz Bio** are developing egg proteins like ovalbumin.

Meat proteins

- **IngredientWerks, Kyomei Proteins,** and **Moolec** produce bovine and porcine proteins for use in alternative protein products.

Growth factors and enabling technologies

- **Biobetter**, **Bright Biotech**, and **ORF Genetics** produce growth factors for cultivated meat media and medicine.
- **Asterix Foods** and **NewMoo** (formerly Imagene) are applying the technology to ingredient optimization for the alternative protein industry.

Diversified

- **Forte Protein** uses plants to produce proteins like lactoferrin, casein, albumen, collagen, and myosin.

Recent developments

Facilities

- **PoLoPo** is scaling their lab operations to increase their capacity to produce protein-rich potatoes via plant molecular farming.
- **BioBetter** opened a new facility that will use tobacco plants to produce growth factors for cultivated meat.

Product development

- **Plantopia** switched their production platform from lettuce to sprouted oats to deliver higher expressions of all four casein proteins.
- **Finally Foods** announced the start of field trials of their potatoes modified to produce casein.
- **New Moo** developed a soy plant capable of producing liquid casein that mimics the functionality of milk in cheese production.
- **Alpine Bio** said they harvested their first large-scale crop of soybeans containing casein.
- **Moolec Science** developed a soy plant able to grow pork protein at an expression level of up to 26.6% total soluble protein.
- **IngredientWerks** developed a strain of corn that can express high levels of bovine myoglobin, a heme protein important to the sensory experience of beef products.

Nomenclature

The language used to describe plant molecular farming, as with any emerging industry, may shift and evolve as the industry grows. For consistency, we refer to this technology as "plant molecular farming" or "PMF" for short, but some companies use different terms to describe their technique and products. For example, **Alpine Bio**, which makes casein using soybeans, describes their process as using "plant-grown proteins" and refers to their final product as "animal-free cheese." **Mozza** refers to their products as "cheese made from milk proteins grown in plants (not cows)," whereas **Miruku** refers to their PMF-derived products as "plant-based dairy proteins."

Future research into consumer perceptions of PMF nomenclature and messaging may inform how to best communicate the category to consumers and differentiate it from the plant-based category.

Investments

Table 1: Investments in plant molecular farming
(2017–2024)

Year	Investments in privately held companies	Investments in publicly traded companies
2017	$25MM	
2018		
2019		
2020	$8.5MM	
2021	$106MM	$30MM
2022	$35MM	
2023	$7.8MM	
2024	$14.4MM	
TOTAL	**$196MM**	**$30MM**

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

Privately held companies primarily involved in plant molecular farming have raised $196 million since 2017, while publicly traded companies have secured $30 million.

In 2024, the plant molecular farming sector attracted $14.4 million in total funding, all of which was raised by privately held companies.

Key investment highlights from across the plant molecular farming ecosystem include:

- **Significant deals:** The two largest plant molecular farming deals in 2024 were **Mozza Foods'** $5.2 million Series A-1 and **Miruku**'s $5 million pre-Series A rounds.
- **The long-view context:** The investment environment of the past two years has been fundamentally different from the low-interest-rate period of 2020 to 2022, when the vast majority of capital in the sector was raised.
- **Notable mergers and acquisitions:** In April 2025, **Moolec Science** announced a strategic merger with **Bioceres Group Limited** and affiliated companies to expand Moolec's technology platforms and global reach across the biological inputs, ingredient production, and synthetic biology sectors.

Methodology

To more accurately reflect investment trends in the cultivated meat and alternative protein sectors, GFI updated our reporting methodology for the 2024 "State of" reports to differentiate alternative protein funding according to whether a company is publicly traded or privately held. Find an overview of our investment data methodology here and take a look at previous editions of the investor newsletter here for a deeper dive into this year's activity.

Unless otherwise cited, all investment data reported in this Investments section was derived from GFI's analysis of data from the Net Zero Insights platform.

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

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Science and technology

Plants are a compelling platform for recombinant protein production, with years of crop breeding, trait stack development methods, and molecular tools available to produce specific protein products, both recombinant and endogenous (Tusé et al. 2024).

Further, by harnessing photosynthesis, there is the opportunity to use atmospheric carbon and sunlight (or renewable-powered grow lights) as the principal drivers of ingredient production. Plant molecular farming approaches are an opportunity to produce a variety of alternative proteins using myriad methods, crops, and even plant tissues. Once produced, these specific proteins can be efficiently isolated from plant proteins or even handled in tandem with bulk plant protein to provide a nutritional or sensory boost to plant proteins. Key opportunities include:

- High-yield, tissue-specific expression of target proteins
- Inexpensive protein isolation
- Low-cost inputs (water, light, fertilizers)

Advancements across these areas can propel PMF to commercial-scale, low-cost, and sustainable production of proteins capable of elevating the taste and functionality of alternative proteins.

Research across the technology stack

In the past few years, the R&D and scale-up environment for the PMF ecosystem has grown, and progress has been reported on a range of alternative proteins.

Meat proteins from soybeans

For many companies, soybeans are a compelling development platform for PMF. The soybean plant, *Glycine max*, is a nodule-forming legume that concentrates nitrogen-fixing bacteria in its roots and produces a high-protein bean. As a major global food system crop, soybean crop breeding and modification strategies are mature, making it a well-studied crop for PMF applications. In 2024,

Moolec Science's Piggy Sooy soybeans express porcine proteins at levels up to 26.6 percent of the protein content and which can be used as an ingredient in alternative protein products. Moolec Science also applied to patent their technology that produces animal heme proteins in transgenic plants, including in soybeans. See the "Government and regulatory" section below for more information about the United States Department of Agriculture's (USDA) Animal and Plant Health Inspection Service's (APHIS) completed regulatory review of Piggy Sooy. **Kyomei Ltd** is using soybeans, among other plants, to produce myoglobin proteins for the plant-based meat market, with a stated goal of increasing myoglobin protein yields.

Dairy proteins from soybeans

Dairy proteins remain a compelling target for alternative protein producers. Adding animal-free dairy proteins to plant-based milk and cheese enables products to provide a "complete protein" containing essential amino acids and high digestible indispensable amino acid scores (DIAAS). Whey proteins can provide important texturization to foods, such as foaming, gelation, and improved mouthfeel.

In cheese, casein proteins are complexed with fats and calcium salts in structures called micelles that coagulate to form curds. The functionality of this complex helps make cheese melt and stretch. **Mozza Foods** has been awarded a U.S. patent for their Cheesebeans™, soybeans that express casein proteins that can be isolated as micelles and used in animal-free cheese formulations (in a patent-pending process).

In 2024, **Alpine Bio** harvested its casein-containing soybeans at a large scale for the first time. Prior, they were granted dependent claims to their 2021 U.S. patent, further articulating their technology where proteins, potentially a whey protein (beta-lactoglobulin) and a casein protein (kappa-casein), are expressed as one fusion protein for later downstream processing and formulation. Alpine Bio was also granted additional patent protection on other recombinant fusion proteins in various dicotyledonous plants, demonstrating their focus on novel fusion proteins for use in the alternative protein space, as well as on optimized gene expression methods. Startup **NewMoo** is focused on creating a liquid-form casein base from soybeans (patent pending) to avoid time- and capital-intensive downstream processing.

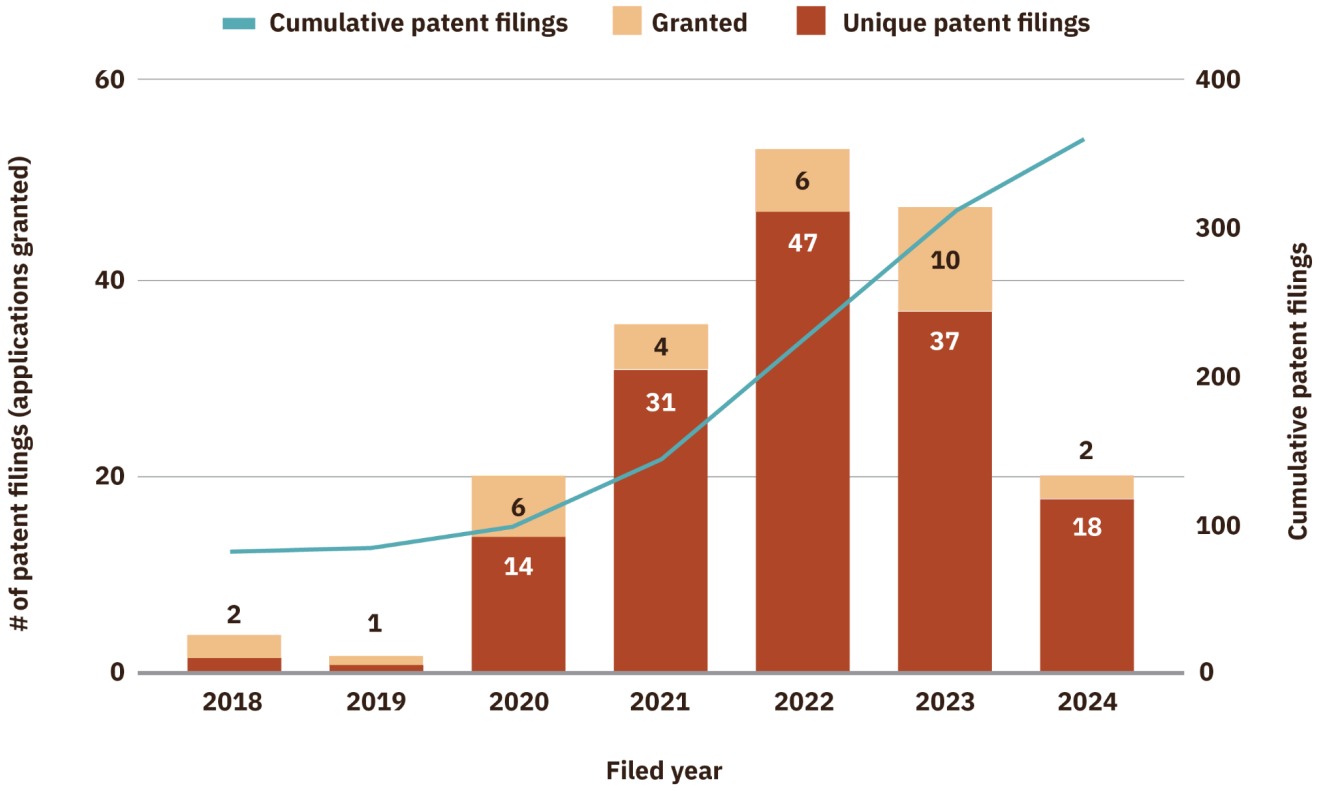

Figure 3: Annual patent filings and cumulative patent activity
by filed year and patent status, 2018–2024

Source: GFI analysis of patent data sourced from Dimensions, an inter-linked research information system provided by Digital Science.

The patent landscape includes PMF alternative protein companies included in the GFI company database and this factsheet from 2018 to 2024. Company names and legal filing company names often differ, so these were manually adjusted if available. Duplicate patents were filtered by application number, family ID, and jurisdiction to provide total unique patents across jurisdictions, including WO patent applications. Companies searched included Alpine Bio (Nobell Foods), Aspyre Foods, Asterix Foods, Azargen Bio, BioBetter, Bright Biotech, Core Biogenesis, Finally Foods, Forte Protein, Elo Life Systems, Greenlab, Inc., New Moo (Imagene Foods), IngredientWerks, Kyomei Proteins, Leafycoll, Miruku, Moolec Science, Mozza Foods, New Moo, Nutriterra, ORF Genetics, Plantopia (Pigmentum), PoLoPo, Seedling Biosystems, Tiamat Sciences, Union Haus, and Veloz Bio. 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.

Alternative proteins from corn

An additional major row crop gets (justifiable) attention in the PMF space. Corn, *Zea mays*, is planted across more than 80 million acres in the United States, with much of the current crop going to animal feed or biofuel production as a sugar feedstock. Unlocking the agricultural know-how and existing value chain for corn farming and processing could be a major enabling lever for PMF in maize.

IngredientWerks, a 2022 spinoff from **AgriVida**, uses corn to express myoglobin. IngredientWerks plans to isolate the myoglobin from corn for use in alternative meat products and return the cornstarch to the value chain where it can be used as a fermentation feedstock. Recognizing the importance of feedstock efficiency in fermentation, **GreenLab** has developed a corn-produced cellulase using PMF to increase glucose yields from corn feedstocks. Additionally, **GreenLab** has partnered with **Gingko Bioworks** to develop maize strains and downstream processing approaches to produce the sweet protein Brazzein from corn. These proteins taste much sweeter than sugar, potentially reducing the need for sugar as a food sweetener. **Greenlab** also partnered with **Shiru** to commercialize food proteins using Shiru's AI-powered ingredient discovery expertise and Greenlab's proprietary corn expression system. **Shiru** is also active in precision fermentation efforts and plans to continue unlocking ingredient scaling via microbes and crops. Corn growers also saw a new variety of corn appear on the market—**Bayer Crop Sciences** and **Corteva Agriscience** have unveiled their commercial short-stature corn. This advancement can help eliminate some of the biomass waste from corn stover (stalks, leaves, etc.), which has proven difficult for the agriculture industry to valorize.

Alternative proteins from tobacco plants

Tobacco leaves may not be the first crop to come to mind when one thinks of food; however, *Nicotiana tabacum* is a fast-growing and large-leafed plant, where *Agrobacterium*-mediated gene transfer has enabled smaller-scale recombinant protein production for decades. Israeli-based **BioBetter** has opened a pilot facility to produce recombinant growth factor proteins in tobacco for the cultivated meat industry. This net-house growth facility is built with sustainable engineering designed to minimize water and nitrogen production inputs while lowering the cost of growth factors for the cultivated meat industry. BioBetter uses a purification process that removes tobacco plant impurities, including nicotine, from growth factor proteins.

Elo Life Systems, a **Precision Biosciences** spinoff, announced their monk fruit sweetener derived from *N. tabacum* last year. Unlike sweet proteins like Brazzein or Monelin, monk fruit sweet flavor compounds are triterpene glycoside molecules called mogrosides. Mogrosides are zero-calorie and can be used at very low concentrations because they are 100–250x sweeter than sugar. Using PMF to also produce non-protein food products will help to further develop R&D, production technology, and the regulatory space for ingredients made in this way.

Alternative proteins from potatoes

Israel-based **PoLoPo** completed their first outdoor field cultivation of their high-protein potatoes and expanded their lab operations, enabling them to grow and process five tons of protein-rich potatoes. They apply molecular farming techniques to produce patatin, native to potatoes, at higher concentrations. **PoLoPo** also secured funding to develop potato-derived chicken egg ovalbumin.

Given potato cultivation's global popularity and patatin's and ovalbumin's in-demand emulsification and gelation functionalities, these systems have encouraging potential pending USDA approval. In 2024, **Finally Foods** began its first field trial for potatoes that produce multiple variations of casein, noting the appeal of potatoes due to their high yields and ease of protein extraction. **ReaGenics** is taking an interesting approach, plant cell culture, by growing potato cell cultures with a high protein content of 31 percent, compared to the two percent protein content in traditional potatoes. Growing plant cell cultures in bioreactors, rather than the full crops in fields or greenhouses, could have supply chain security benefits, e.g., not being as affected by unpredictable weather, disease, and more.

Other crops

Other crops, in addition to soybean, corn, tobacco, and potatoes, can also function well as PMF platforms, and crop breeding and ingredient targets could be co-optimized to reduce the cultivation and downstream processing costs and generate high-yielding functional ingredients. **Moolec Science** gained USDA approval to grow their peas, which can produce iron-rich bovine myoglobin. **Kinish** is exploring casein production in dwarf rice crops using vertical farming practices. These crops can be harvested in less than half the time of traditional rice.

Sustainability

Plant molecular farming can take advantage of indoor production, such as in greenhouses and vertical farms, to avoid the higher regulatory requirements of field-grown crops and to optimize plant growth and protein production. **ORF Genetics** grows barley for cultivated meat growth factor production in greenhouses sited to take advantage of Iceland's geothermal power and heat generation, a leading example of renewable energy for the space. The recent attention on vertical farming has led to a push for crop breeding and genetic improvement optimized for the vertical farm environment. Further, both greenhouses and vertical farms could benefit from the valorization of carbon dioxide off-gas and biomass fertilizers produced as sidestreams of the alternative protein industry, which could guide co-location and partnering decisions in the future.

Government and regulation

To date, no protein ingredient made in this way has been greenlit or approved for commercial sale by a national food safety regulatory body. However, in 2024, **Moolec Science** reached a regulatory milestone in the U.S. when USDA-APHIS completed its Regulatory Status Review (RSR) of the company's new soybean variety that incorporates pork protein, called Piggy Sooy. The RSR determined that Piggy Sooy is unlikely to pose an increased plant pest risk relative to non-engineered soybeans, meaning it would not be subject to a USDA-APHIS regulation that governs the movement of genetically engineered organisms or products. Moolec also completed the RSR process for its garden pea plant that incorporates bovine myoglobin. Moolec is currently engaging the U.S. Food and Drug Administration (FDA) to bring its products to market.

Since that determination, the APHIS regulation that established the RSR process was vacated by a federal court, for reasons unrelated to PMF. The rule was remanded to APHIS for further consideration, which means the agency may amend and re-publish the rule, although it is unclear whether or when APHIS will do so, or how such amendments might change the RSR process. In the interim, PMF companies may work with APHIS to determine whether they are regulated by the agency under the Am I Regulated (AIR) process. This court decision only applies prospectively and does not affect the status of products previously reviewed under the RSR process.

Also of note, in 2023, the FDA Office of Food Additive Safety published an open letter to "Manufacturers and Developers of New Plant Varieties" regarding the production of potentially allergenic proteins within plant platforms. The letter emphasized the need for proper consumer notification of a potential allergen or the combination of plant and recombinant protein allergens and encouraged companies to engage with FDA early in their development process to discuss the steps they plan to take to ensure compliance with FDA's regulatory requirements related to allergens and otherwise prevent the unintentional transfer of allergens to foods. Additionally, the letter calls for special care and consideration for the entire value chain with which the target protein(s) may share equipment, transport, or storage systems. FDA also emphasized the need to ensure that allergen information is adequately conveyed throughout the supply chain.

Although focused on pharmaceutical products, a thorough review was published identifying potential sources of toxicological safety risks associated with products manufactured via PMF, along with solutions through processing technology, plant breeding, and plant growth environments. These solutions demonstrate awareness of potential hazards for producers and the ability to safely mitigate these risks.