Research funding priorities for plant-based and fermentation-enabled protein ingredient optimization

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About the workshop conveners

About the Foundation for Food & Agricultural Research

FFAR builds public-private partnerships to fund bold research addressing big food and agriculture challenges. FFAR was established in the 2014 Farm Bill to increase public agriculture research investments, fill knowledge gaps and complement the U.S. Department of Agriculture's research agenda. FFAR's model matches federal funding from Congress with private funding, delivering a powerful return on taxpayer investment. Through collaboration and partnerships, FFAR advances actionable science benefiting farmers, consumers and the environment.

About the Good Food Institute

GFI is a nonprofit, science-driven think tank working to make the global food system better for the planet, people, and animals. As an international network of organizations, GFI advances alternative proteins to help meet climate, global health, food security, and biodiversity goals. GFI is known for producing a wide range of technical reports on plant-based and fermentation-enabled proteins, funding global scientific research on meat and other high-protein foods produced by plants, microbes, and via cell cultivation, and growing the scientific ecosystem fueling this work.

Executive summary

As global demand for protein continues to rise, advancing ingredient innovation can help diversify protein sources, create a safer and more resilient food system, meet nutritional needs, contribute to farmland health, and drive economic growth in communities around the world. To drive such innovation, the Foundation for Food & Agriculture Research (FFAR) and the Good Food Institute (GFI) have joined forces to identify research funding priorities for plant-based and fermentation-enabled protein ingredient optimization.

Ingredient optimization is essential to achieving taste and price parity between plant-based and fermentation-enabled protein and conventional protein. This taste and price parity is necessary to achieve consumer adoption at the scale required to realize the real-world environmental, public health, and food security potential of these innovative proteins.

From May through July 2025, FFAR and GFI conducted a global survey and co-convened an in-person workshop aimed at gathering input—in total, from 87 respected experts representing different disciplines and regions around the world—to focus the research agenda on the most promising research funding opportunities. (See appendices for more details about the survey and workshop.)

Primary objectives of the FFAR-GFI partnership

- Identify and prioritize promising research opportunities to improve plant-based or fermentation-derived ingredients that can enhance functionality, nutritional value, sensory attributes, processing efficiency, and food safety.
- Understand what time, funding mechanisms, research infrastructure, and collaborations are necessary to accelerate innovation.

Key research areas identified

- ingredient sourcing
- protein enrichment innovation
- multifunctional ingredients
- strategic research catalysts that can improve efficiency, reproducibility, and impact across the value chain

Specific research areas and recommendations

Ingredient sourcing optimization	• Upcycle sidestreams into food ingredients • Develop regional crops • Breed crops for improved quality and yield • Tailor cell lines for fermentation and plant cell culture
Low cost, mild processing protein enrichment innovation	• Upcycle sidestreams into fermentation feedstock • Streamline downstream processing of fermentation products • Tailor bioreactors for food development • Reduce off-flavors, antinutrients, and other undesirable compounds in plant protein ingredients • Scale low-energy plant protein extraction • Create value-add, small-scale processing technologies
Multifunctional, palatable, nutritious ingredients	• Create nutritious formulations • Leverage hybrid ingredients for complementary functions • Design desirable flavors and colors • Engineer proteins for optimal function and taste • Texturize plant proteins using low-energy, reproducible methods • Incorporate fat and nutrients into texturized food matrices
Strategic research catalysts	• Standardize procedures and methods • Control variability • Relate structure-function of plant- and fermentation-enabled ingredients and their sensory evaluation • Leverage neural networks, artificial intelligence, and machine learning for next generation protein development • Develop high-throughput analytics techniques to expedite R&D • Optimize commercially-relevant technoeconomic analyses and life cycle assessments

Cross-sector calls to action

Across these research areas, topline calls to action emerged—each underscoring the importance of greater cross-sector collaboration in moving the entire field forward:

Optimize products with the consumer in mind

Find and advance solutions that improve taste, nutrition, and affordability through targeted research that resolves persistent technical and sensory challenges.

Improve open-access data and infrastructure availability

Make it easier for scientists to learn from and build on each other's work, and have the tools, facilities, and support to do so.

Build public-private partnerships

Creatively leverage strengths, systems, assets, and expertise that exist across sectors.

Leverage existing systems

Tap into established agricultural supply chains, processing infrastructure, distribution networks, and regulatory frameworks, so the industry can reduce costs, shorten development timelines, and increase market reach.

Support systems-level agriculture

Seek opportunities to integrate plant-based and fermentation-enabled protein ingredient innovation into farmland health and vibrancy to deliver environmental and economic benefits.

Ensure food safety and regulatory compliance

Pursue research that prioritizes public health and a safer, more secure supply chain.

What's at stake and what's needed

Protein innovation—spanning plant-based and fermentation-derived ingredients—is recognized by leading experts as essential to addressing challenges in agriculture, climate, biodiversity, food security, and global health. Critical research investment is needed to accelerate breakthroughs in the field and ensure that we meet consumer needs, lower costs, and reduce environmental impacts. Addressing these challenges will enable larger-scale production and commercialization, create new economic opportunities and benefits for farmers and others on the frontlines of food production, and contribute to a safer, more secure, and resilient food system.

Introduction

Healthy food systems make high-quality, nutritious, affordable food accessible while minimizing environmental impacts and supporting a thriving economy. As the global population grows, the incumbent food system will likely struggle to meet this challenge. Additionally, drought, flood, fire, geopolitical conflict, and urbanization challenge our current food production supply chains.

Developing more efficient, sustainable ways to produce protein-rich, nutrient-dense foods will be essential in diversifying our food system. Meat consumption worldwide is projected to rise by at least 50 percent by 2050. More protein options are required to meet those anticipated demands. Ingredient-optimized proteins from plants and microbial fermentation offer scalable, market-based solutions that can help diversify our protein sources and create a safe and resilient food system while driving economic growth.

While the potential is huge, significant barriers exist regarding the taste, price, and scalability of plant-based and fermentation-enabled protein products. Global investment estimates suggest that an annual $4.4 billion of public research and development (R&D) investment will be needed for innovative protein solutions.

Consider how current funding levels compare to this target:

- U.S.-based public and nonprofit funders have supported over $136 million in plant-based and fermentation-enabled protein research between 2020 and 2023. The top three U.S.-based funders of plant-based and fermentation-enabled protein research are the U.S. Department of Agriculture's (USDA) National Institute of Food and Agriculture (NIFA), the U.S. Department of Defense (due to DARPA Cornucopia), and the National Science Foundation.

- In 2024, global private investment in plant-based and fermentation-derived proteins was $960 million, nearly triple the $350 million in global public funding, demonstrating the opportunity for public funding to complement private investment momentum.

While estimates vary on the economic return on public agricultural research spending (with ranges between 10x and 20x returns in the United States), it's clear that such public investments advance pre-competitive, fundamental research in ways that derisk the time lag between research and its impacts, and serves as an essential foundation for privately funded R&D, market development, and economic opportunities. Although the research field has seen increasing public support over recent years with funding from a range of organizations globally, there have been few targeted funding opportunities to address the critical technical bottlenecks facing widespread commercial production and adoption of plant-based and fermentation-enabled proteins.

To inform their research funding work, in 2024, GFI analyzed the most critical research needs with subject matter experts and scientists from across the globe. GFI identified research areas with potential impact on taste, price, and/or scalability and evaluated the research urgency, researchers' skills and availability to respond, budget needs, and collaboration opportunities. Following this analysis, GFI and FFAR partnered and collaborated, identifying ingredient optimization as a critical need.

Ingredient optimization is essential for achieving taste and price parity in plant-based and fermentation-enabled proteins with conventional proteins and, in some cases, ensuring consumer adoption. Developing plant-based and fermentation-enabled protein products requires high-quality functional ingredients that enhance taste, texture, and appearance. These ingredients must serve specific roles, such as emulsification, gelation, water and oil retention, color enhancement, salt content regulation, and allergen management. However, the isolation and extraction of ingredients is time-consuming, costly, and complex. Integrating crops or microbial biomass directly into end products with minimal steps may help retain their original organoleptic profiles, while innovative enrichment steps can improve overall production efficiency and reduce resource use and cost.

The survey and workshop co-convened by GFI and FFAR aimed to gather stakeholder input and define key funding priorities in ingredient optimization for plant-based and fermentation-enabled proteins, with the goal of accelerating their public benefits. For more information about the survey and workshop, please see the Appendix. The following essential research areas emerged:

Area 1:
Ingredient sourcing optimization

Area 2:
Low cost, mild protein enrichment innovation

Area 3:
Multifunctional, palatable, nutritious ingredients

Area 4:
Strategic research catalysts

Beyond ingredient optimization research opportunities, participants also helped identify funding mechanisms, research infrastructure needs, and cross-sector, cross-disciplinary partnerships with the potential to accelerate innovation and progress by closing priority research gaps before they become bottlenecks to scale and adoption.

A set of cross-sector calls to action were identified:

1. Optimize products with the consumer in mind.
2. Improve open-access data and research infrastructure.
3. Build and sustain public-private partnerships.
4. Leveraging existing systems.
5. Support systems-level agriculture.
6. Ensure food safety and regulatory compliance.

Leveraging these insights, FFAR and GFI have outlined which research opportunities can most effectively advance the taste, cost, functionality, and scalability of innovative protein ingredients.

	Area 1: Ingredient sourcing optimization	**Area 2:** Low cost, mild protein enrichment innovation	**Area 3:** Multifunctional, palatable, nutritious ingredients	**Area 4:** Strategic research catalysts
Optimize products with the consumer in mind	✔	✔	✔	✔
Improve open-access data and research infrastructure	✔	✔	✔	✔
Build and sustain public-private partnerships	✔	✔	✔	✔
Leveraging existing systems	✔	✔	✔	✔
Support systems-level agriculture	✔	✔		✔
Ensure food safety and regulatory compliance	✔	✔	✔	✔

Box 1.

Contextualization of research, infrastructure, and partnership recommendation time scales.

Advancing ingredient sourcing optimization for plant-based and fermentation-enabled proteins requires a phased approach in which short-, medium-, and long-term activities build upon one another to deliver scalable, impactful solutions. Each research area detailed below provides insight into research, infrastructure, and partnership recommendations needed to commercially translate innovations based on these time scales.

Short-term recommendations—such as exploratory methods development or pilot-scale demonstrations—are well-suited for smaller, targeted grants that de-risk early concepts and generate critical baseline data. Medium-term recommendations, which typically involve multi-year research programs to refine technologies, expand datasets, and validate scalability, align with medium-sized grants that can support sustained investigation. Long-term recommendations, such as establishing regional hubs, open-access databases, or advanced breeding and processing infrastructure, require the scale and stability provided by large grants, such as research centers or centers of excellence. While recommendations may often be sequenced from short-term to long-term, a different ordering may sometimes be more effective. For example, a data repository may be needed, requiring a large initial investment, to be followed by short term grants to contribute needed data to the repository.

Area

1

Ingredient sourcing optimization

Background

To meet the challenge of delivering plant-based and fermentation- derived protein foods that match taste and cost expectation of consumers, optimizing ingredient sourcing is a critical upstream strategy. It can alleviate challenges across the protein value chain by improving input quality, availability, and production costs. Common plant protein sources, such as soy, pea, and wheat, remain dominant due to their global abundance and use familiarity, but there are significant opportunities to enhance these protein ingredients as well as to discover and develop novel sources with superior traits.

For a crop or microbial input to serve as an optimal protein source, several characteristics are desirable, developed with cost-efficiency and scalability at the forefront to accelerate market adoption:

- High total protein content
- Optimal protein fraction composition
- Food safe with low allergenicity potential
- Bland protein flavor or low levels of off-flavor compounds
- Good protein digestibility
- High micronutrient concentration
- Minimal anti- and non-nutrient factors
- Suitable protein functionality (e.g., emulsification, gelling, foaming)
- Ability to enrich protein fraction with minimal steps

For novel ingredient sources, these traits should be identified, optimized, and tailored to regional agricultural, environmental, and cultural contexts. Promising sources will then need to be developed for commercialization, including navigation of regulatory approvals.

Challenges and opportunities

Unlocking the full potential of plant-based and fermentation-enabled protein production requires investment in diversified, local, and adaptive sourcing strategies. Compelling research opportunities exist with ingredient sourcing optimisation that, if addressed, can have a transformative impact on diversifying and optimizing plant and microbial protein sources. Table 1 summarizes the challenges and opportunities identified by expert input.

Table 1. Summary of ingredient sourcing optimization challenges and opportunities

Opportunity	Insights
Upcycling sidestreams into food ingredients	Upcycling sidestreams presents an opportunity to reduce waste and unlock new value from underutilized resources. Valorization of sidestreams is a common practice in agricultural systems to increase the value of harvested crops. Current uses are often already cost-effective, so diverting them into food requires a compelling value proposition. Transforming these residues into food ingredients can unlock their economic potential while supporting circular bioeconomies (da Silva et al. 2024, GFI, 2023). The novelty of these sources brings regulatory, technical, scaling, and equipment-related challenges. Key challenges include navigating food safety and developing effective, mild protein fractionation methods.
Developing regional crops	Regional crops represent possible new sources of proteins with other desirable properties for ingredients. Enriching underused regional crops can support biodiversity, improve food security, and bolster local economies (TNC, 2021). These crops may also improve cultural acceptance and be resilient to the environmental conditions where they are found. To compete with well-established commodity ingredients, these novel inputs must be optimized for their protein extraction, nutritional content, and sensory quality. Key challenges for developing regional crops include lack of information and a need for new cooking and enrichment methods.
Breeding crops for improved quality and yield	Mainstream efforts today are typically narrowly focused on overall crop yield, disease- and weather-resistance, or strain development for non-food applications. There is significant potential to advance value-added traits with breeding efforts (Cordoba et al. 2025). However, competing with industrial-scale production is costly, highlighting the urgent need for risk reduction to advance crops and microbial strains with improved protein density and quality. Crop breeding research is often costly and time-consuming, requiring multiple growing cycles and years of data. Efforts should consider using new techniques and tools to shorten timelines for breeding efforts. For example, integrating speed breeding techniques can significantly shorten development timelines. Opportunities exist to breed for protein quality and quantity, improved flavor, and reduced allergenicity.
Tailor cell lines for fermentation and plant cell culture	Microbes, as efficient converters of multiple carbon feedstocks to protein and high-value molecules, are positioned to valorize current low-to-no value farm, processing, and food sidestreams into food ingredients. Most of the microbes used currently have a longstanding history in foods, like *S. cerevisiae, Lactobacillus sp., Aspergillus sp.,* and *Neurospora sp.* There is a pressing need to expand the repertoire of microbes and processes that can grow effectively and economically on the yet-to-be-valorized carbon sidestreams already present in our food processing systems. These organisms and processes must also be safe and produce high-concentration protein, flavoring, and additional high-value ingredients (Graham and Ledesma-Amaro, 2023).

Recommendations

Research recommendations

Upcycle sidestreams into food ingredients.

Fundamental research is needed in order to improve the quality and usability of sidestreams at the source through mild fractionation methods that preserve nutrition and reduce costs and technologies for feedstock development from low-to-no value sidestreams, as well as technologies that offer better storage and transport options for high-moisture streams to prevent spoilage. Research programs focused on addressing these lay the groundwork for regional hub(s) that aggregate and share data on composition, availability, transport, and utilization. Such hub(s) would connect producers, processors, and buyers, enabling coordinated markets and increasing adoption. Over time, sidestreams could become consistent, competitive inputs in a circular bioeconomy.

Develop regional crops.

Open-access crop germplasm banks and open-access omics databases are a key intervention needed in order to ensure that the full value of regional crops are realised. To address the significant gap in data, early work should focus on creating regional crop database(s), with a focus on connecting with producers to identify high-potential, underutilized crops. These connections support targeted cultivation trials. The next stage is an open-access library of crop varieties and their protein functionalities, enabling selection and optimization for nutrition, functionality, and sensory performance. Long-term, open-access germplasms and omics databases would allow breeders, scientists, and entrepreneurs to accelerate improvement globally. This pathway strengthens resilience and diversity in agricultural systems while supplying high-quality, regionally adapted ingredients.

Breed crops for improved quality and yield.

Crop quality and yield are foundational to ingredient optimization, yet significant gaps in research exist. In the long term, breeding programs should co-optimize ingredient quality with yield and resilience, integrate plant molecular farming for native animal proteins, and apply omics to refine protein quality. These innovations ensure new varieties meet both food industry needs and agronomic performance standards. Traditional crop breeding demands years of field trials to untangle the complex interplay between genetics and shifting environmental conditions, making it inherently slow and resource-intensive.

By harnessing speed breeding techniques and advanced omics tools, researchers can compress breeding cycles, generate richer datasets faster, and dramatically accelerate the path from genetic insight to high-performance, market-ready varieties. Profiling crops for protein content, allergenicity, and nutrition to build a dataset for selection will help to speed breeding efforts and enable more advanced work using omics tools. Fundamental research can improve plant breeding's pace, including developing non-destructive, rapid phenotyping methods, new greenhouse methods, and photosynthesis optimization. These advances will enable researchers to target high protein content, minimal off-flavors and antinutrients, and reduce allergenicity.

Tailor strains for fermentation and cell lines for plant cell culture.

Fundamental advances are needed in order to address key challenges in the effectiveness of cell lines. The ultimate goal is consistent, cost-effective ingredient production that expands the functional, nutritional, and sensory options available for plant-based and fermentation-enabled foods. Immediate priorities include identifying novel targets for genetic improvement of food-producing species and developing metabolomic maps and dynamic models for fermentation microbes and their production parameters to predict and control cellular behavior. Medium-term work can adapt innovations from non-food sectors and establish stable plant and microbial cell lines that efficiently produce target proteins at scale.

Table 2. Examples of research recommendations for ingredient sourcing optimization in the short-, medium-, and long-terms

Recommendations			
Opportunity	**Short-term: Shorter projects with quick results**	**Medium-term: Projects that take more time but can start now**	**Long-term: Longer projects with larger scope or complexity**
Upcycling sidestreams into food ingredients	Mild fractionation methods for sidestreams New technologies to address improved storage and transport conditions for high-moisture sidestreams Technologies for feedstock development from low-to-no value sidestreams	Regional hub for data collection and sharing concerning sidestream composition, availability, transport, and utilization	Replicate regional hubs across new geographies using technologies and principles developed
Breeding crops for improved quality and yield	Protein, allergenicity, and nutrition profiling of novel crops Non-destructive phenotyping methods	High-quality protein crop phenotyping Speed breeding techniques, including using omics, greenhouse methods, and increased photosynthesis Breed for optimal protein content Breed for minimal off-flavors and anti-nutrients Breed for reduced allergenicity	Breed for co-optimization of ingredient quality and overall crop yield/resilience Plant molecular farming for production of native animal proteins Omics for protein quality

Recommendations (cont.)			
Opportunity	**Short-term: Shorter projects with quick results**	**Medium-term: Projects that take more time but can start now**	**Long-term: Longer projects with larger scope or complexity**
Developing regional crops	Regional crop database along with funding to connect to local producers	Open-access library of crop varieties and protein functionalities Agronomic studies to improve regional crop production	Open-access crop germplasm banks Open-access omics databases
Tailoring strains and cell lines for fermentation and plant cell culture	Metabolomic maps and dynamic models for fermentation microbes and production parameters Identify novel targets for genetic improvement of food-producing species	Apply non-food innovations to explore novel inputs in the food context Stable plant cell lines to efficiently culture and produce plant proteins Demonstrate and scale-up novel tailored strains, cell lines, and trait stacks for food production	Continuous strain improvement, disseminating state of the art chassis strains and cell lines for R&D and enhanced performance

Infrastructure recommendations

Plant-based protein:

- Research infrastructure investments are needed to advance crop breeding and regional crop development. While these efforts require agronomic research fields, greenhouse space, and phenotyping resources needed for many breeding efforts, there is a specific need for data and germplasm infrastructure to advance crop breeding and regional crop development for plant-based protein-rich foods.
- Open access proteomic and metabolomics databases were repeatedly identified as a need. Reliable databases exist for only a couple of species (e.g., soy and wheat), requiring researchers to resort to homology studies to offset the lack of such databases for other species. Such databases require concerted efforts for time and number of samples, but have the potential to speed research necessary for improved ingredient sourcing.
- Regional crop databases, as well as open access germplasm resources, would also be impactful. There is a paucity of resources for most regional crops, which limits the ability to identify and use more regional crops for ingredient sourcing.

Fermentation-enabled protein:

- Strain banking and biorepository systems would improve sharing and utilization of fermentation-relevant organisms and expand the repertoire of food producing, high-protein microbes.
- Proteomic, metabolomic, and genomic research infrastructure would also help advance research into relevant microbial organisms for ingredient sourcing, as well as engineering of microbial organisms for use in biomanufacturing.

Partnership recommendations

Ingredient sourcing optimization requires a multi-disciplinary and multi-sector approach, engaging partners across academia, industry, and the public sector.

- Efforts to upcycle sidestreams into food ingredients will draw on food science, process engineering, postharvest technology, and microbiology to improve extraction, storage, safety, and quality of ingredients. Support from large consumer packaged goods (CPG) and beverage companies supplying feedstocks, regional hubs managing aggregation, laboratories ensuring safety and functionality, and government and regulatory agencies would enable strong frameworks.
- Developing regional crops will focus on crop science, agronomy, molecular biology, and data science, with regional agricultural cooperatives, hubs, and commodity groups linking producers to open-access crop and functionality databases. Many of these same disciplines and stakeholders could also advance breeding crops for improved protein quality and yield.
- Integrating plant breeding, physiology, genomics, and biotechnology subject matter expertise will be necessary, and leveraging partnerships with seed companies, government, and commodity groups will help fund infrastructure and align varieties with market needs.
- Tailoring strains for fermentation and cell lines for plant cell culture will involve fermentation science, metabolic engineering, biotechnology, and bioinformatics with food innovation labs providing pilot-scale capabilities, large CPGs supporting commercialization, and regulatory agencies streamlining approvals.

Area 2

Low cost, mild protein enrichment innovation

Background

Commercial strategies to convert crops and microbe inputs into food ingredients have historically prioritized the extraction of oils, carbohydrates, and small molecules. To make plant-based and fermentation-enabled proteins viable in mainstream foods, optimizing raw ingredients for protein enrichment is increasingly critical to achieving functionality, taste and cost targets.

Current enrichment techniques often rely on harsh chemicals or high-energy inputs, can yield low protein recovery, or are designed for non-food applications, limiting their scalability and relevance in food production. To be commercially viable for food applications, protein enrichment should meet several key criteria, designed with technoeconomics and scalability in mind to improve commercialization potential:

- Enhanced protein content, composition, and yield
- Food-safe with low allergenicity potential
- Co-optimization for recovery of multiple high-value components
- Improved protein functionality (e.g., emulsification, gelling, foaming)
- Reduction of antinutrients, off-color, and off-flavor compounds
- Retention or enhancement of micronutrient content
- Low-energy use and affordable
- Mild fractionation conditions
- Minimal number of and reproducible downstream steps

Mild, efficient processing of protein ingredients can enhance quality and provide food developers with the flexibility needed to meet consumer demands. The most promising innovations will be designed with commercialization and regulatory approval in mind.

Challenges and opportunities

Lowering production costs while improving sustainability is a central challenge for scaling plant-based and fermentation-enabled protein ingredients with many innovative opportunities for ingredient producers. Table 3 summarizes the challenges and opportunities identified by expert input.

Table 3. Summary of low cost, mild protein enrichment innovation challenges and opportunities

Opportunity	Insights
Upcycling sidestreams into fermentation feedstock	Upcycling sidestreams into fermentation feedstock offers a dual benefit of improving the economics of fermentation and investing valuable agricultural and food residues from solid, liquid, and gaseous/gasified waste streams. In fermentation-enabled protein production, feedstock costs and conversion efficiencies are key levers for cost reduction (GFI, 2025). Shifting from traditional, refined sugar to low-cost, sustainable feedstocks—such as agricultural sidestreams and spent yeast—will reduce costs, but achieving reliable performance with these unconventional sources remains challenging (Lips, 2021). Microbes that can grow productively on long-chain starches and approaches that process starches and fibers to sugars could both significantly increase feedstock options available for fermentation-derived food ingredients. Food-safe supply chains and bioprocesses can be developed to add diverse protein ingredients available to consumers while increasing the value of harvested materials (e.g., stover, processing starches, peels, pomace). Programs like California's BEAM Circular highlight how regional bioeconomy hubs can transform underutilized agricultural byproducts, such as nutrient-rich almond hulls, into valuable fermentation-ready substrates. Notably, some sidestreams are more suitable as fermentation media than direct food ingredients, due to their nutrient profiles and sensory characteristics.
Streamlining downstream enrichment of fermentation products	Downstream enrichment, the act of isolating and purifying proteins and other food molecules from fermentation microbes and media, can be expensive, energy-intensive, and lead to yield loss. Efficient, food-specific approaches for ingredient purification are required for dewatering, RNA reduction, protein isolation, and storage preparation. Future downstream processing equipment and approaches should reduce cost and resource usage while preserving food functionality of isolated ingredients and ensuring food safety. Initiatives like BioMADE, a U.S. Department of Defense-funded innovation institute, are supporting the bioindustrial manufacturing ecosystem by building infrastructure and technical capability for commercial-scale fermentation, including downstream protein ingredient production.
Tailoring bioreactors for food development	Tailoring bioreactors for food development—through scalable, automated, continuous fermentation and *in situ* monitoring and simplified parameter control—can further drive efficiency as capital remains an expensive barrier to fermentation capacity expansion. Low-cost, food-grade bioreactors using novel designs or materials can significantly lower costs of production for fermentation facilities and therefore lower the cost of production. Novel bioreactors should also take into account water usage, electrical demand, and thermal efficiency to decrease operational expenses for fermentation-derived food manufacturing. Development of such technologies is critical for expanding available infrastructure for fermentation-derived food ingredients and novel proteins.

Opportunity (cont.)	Insights (cont.)
Reducing off-flavors, antinutrients, and other undesirable compounds in plant protein ingredients	Undesirable compounds often originate from complex biochemical pathways influenced by multiple genes and environmental factors, making them difficult to eliminate at the raw input selection stage (Wang et al. 2022, Sharma et al. 2025). Targeted biological, physical, and chemical treatments, including seed germination, enzyme hydrolysis, microbial fermentation, ultrasound, microwave application, and pH adjustments, and selective extraction techniques can reduce their presence without compromising overall protein quality. Understanding how these antinutrients, etc. interact with complex ingredient matrices will open new opportunities to optimize their removal, transformation, or masking. Moreover, formulation shelf stability, including resistance to oxidation, is an important consideration for preventing the formation of off-flavors.
Scaling low-energy plant protein extraction	Scaling low-energy plant protein extraction can reduce water, waste, and energy use while producing minimally processed ingredients with unique nutritional and functional profiles. Techniques like dry fractionation, aqueous separation, enzymatic treatments, and targeted pretreatments (e.g., ultrasound or protease application) can enhance extraction efficiency and functionality (Schlangen et al. 2022, Sá et al. 2022). More research is needed to better understand and control interactions between proteins and other compounds in food matrices and to optimize methods for industrial application. For example, the Novo Nordisk Foundation has funded University of Copenhagen research focused on drastically reducing energy and water consumption of plant protein production using mild, sustainable methods. Special attention is needed for high-potential but challenging feedstocks, such as oilseeds, lignin-rich biomass, and sidestreams, which are often difficult to fractionate using mild methods.
Creating value-add, small-scale equipment for rural producers	Creating value-add, small-scale equipment for rural producers can provide new income streams and lower production costs through co-located operations. Equipment such as low-footprint extruders or fermentation bioreactors must be affordable, easy to operate without advanced technical expertise, and adaptable to local feedstocks, resource constraints, and market demands. Cooperative extension programs that provide training and tools for farmers to implement new innovations in crop breeding and enrichment can reduce the barriers associated with adopting novel practices. Moreover, agricultural cooperatives, like Northern Europe's Lantmännen which produces pea and wheat protein from member-grown crops, offer a scalable model for linking farmers to regional equipment hubs and shared infrastructure.

Recommendations

Research recommendations

Upcycling sidestreams into fermentation feedstock.

Progressing from early feasibility trials to large-scale economic transformation will ensure innovative commercialization of affordable fermentation feedstocks. In the short term, research demonstrating solid-state fermentation using sidestream inputs should focus on technical viability and generate data on performance and yields. Medium-term efforts would expand into broader valorization of diverse manufacturing sidestreams, optimizing processes to unlock both functional and nutritional value. In the long term, these innovations could establish economically advantaged pathways that transform sidestreams from waste management liabilities into high-value inputs, reshaping the economics of food manufacturing within a circular system.

Streamlining downstream enrichment of fermentation products.

Highly resource-efficient recovery of high-value fermentation-enabled ingredients would further reduce production costs of innovative protein foods. Short-term priorities include upcycling wastewater, waste biomass, and other sidestreams from fermentation-enabled protein production to reduce waste streams and capture added value. Medium-term innovations should focus on food-specific protein isolation technologies that minimize water and electricity use, lowering both costs and environmental impacts. In the long term, fully integrated downstream systems will emphasize low resource usage, material recycling, and high product recovery, enabling more sustainable and affordable enrichment at commercial scale.

Tailoring bioreactors for food development.

Evolution of small, proven prototypes to scaled, specialized systems will ensure bioreactor design for precision and efficiency. Short-term efforts include developing lab- and benchtop-scale prototypes optimized for batch, fed-batch, and continuous processes for fermentation-derived food proteins. Medium-term goals involve integrating digital modeling to optimize production procedures and embedding advanced sensors to monitor and control key parameters. In the long term, these advances would enable commercial bioreactors with novel designs, materials, and control systems that deliver greater consistency, higher yields, and reduced costs for large-scale protein production.

Reducing off-flavors, antinutrients, and other undesirable compounds in plant protein ingredients.

Staged progression from practical treatments to deeper biochemical and computational advances will create better tasting innovative protein foods. Short-term strategies include physical and biological treatments such as germination, enzymatic processing, or fermentation, paired with stable formulations and storage conditions to enhance quality and shelf life. Medium-term work should employ machine learning (ML) models to simulate compound interactions and map biochemical and genetic pathways, and precursors of off-flavor generation. In the long term, fully characterizing these pathways will enable breeding or engineering solutions, supported by expert sensory panels and regional research centers. Building an open-access protein structure-function database and advanced ML models will provide a global foundation for consistently palatable, nutritious ingredients.

Scaling low-energy plant protein extraction.

Moving from pretreatments to pilot- and industry-level deployment of mild fractionation methods is essential to reduce resource-intensive protein production. In the short term, targeted pretreatments can reduce downstream steps, while mild enrichment for tough plant materials, dry fractionation beyond legumes, and optimized RuBisCO extraction expand the range of viable inputs. Medium-term progress should refine aqueous fractionation methods that avoid sodium and optimize extraction to preserve native functionality while tailoring protein fractions for food applications. Long-term goals include scaling these mild methods from lab to pilot and industry levels, enabling cost-effective extraction of diverse plant proteins with reduced energy use and broadened commercial potential.

Create value-add, small-scale equipment for rural producers.

Appropriate equipment for rural producers is essential for ensuring effective ingredient sourcing, however many challenges exist. For maximum utility, it is important to create agronomic research studies that assess value-add equipment impacts on regional farmers, producers, and markets. Innovation is essential to producing a wide range of potential ingredients. This can be accomplished by pairing regional crops with appropriate equipment, creating reproducible and efficient small-scale extrusion and fermentation methods. Medium-term efforts focus on cost-effective, modular equipment designed for rural use, enabling local enrichment of crops into higher-value ingredients. These systems can reduce reliance on centralized facilities, increase farmer revenues, and strengthen regional participation in the protein market.

Table 4. Examples of research recommendations for low-cost, mild protein enrichment innovation in the short-, medium-, and long-terms

Recommendations			
Opportunity	**Short-term: Shorter projects with quick results**	**Medium-term: Projects that take more time but can start now**	**Long-term: Longer projects with larger scope or complexity**
Upcycling sidestreams into fermentation feedstock	Solid state fermentation with sidestream feedstocks	Cost-effective valorization of manufacturing sidestreams	Economically advantaged sidestream valorization that replaces profit-loss to waste disposal/treatment
Streamlining downstream enrichment of fermentation products	Upcycling wastewater, waste biomass, and other sidestreams from fermentation-enabled protein production	Food-specific protein isolation technologies that reduce water and electricity demand	Scaled downstream systems for low resource usage, material recycling, and high product recovery
Tailoring bioreactors for food development	Lab and benchtop prototype development of food-focused bioreactors for fermentation-derived food protein	Digital procedure modeling for optimizing production Integration of sensors into production steps and equipment	Scaled, commercial bioreactors of novel, design, material, and sensor/control systems
Reducing off-flavors, antinutrients, and other undesirable compounds in plant protein ingredients	Physical and biological treatments for improved plant protein ingredients Stable formulations and storage conditions	ML models to simulate compound interactions Identification of biochemical genetics, pathways, and precursors that promote off-flavor generation	Identification of biochemical pathways and genetics of precursors to off-flavor generation Trained expert sensory panelists and research centers in different regions Open-access protein structure-function database ML models to investigate biochemical pathways that enhance flavor and functionality

Recommendations (cont.)			
Opportunity	**Short-term: Shorter projects with quick results**	**Medium-term: Projects that take more time but can start now**	**Long-term: Longer projects with larger scope or complexity**
Scaling low-energy plant protein extraction	Pretreatments to reduce downstream steps Mild enrichment methods for leaves and other tough plant materials Dry fractionation beyond legumes RuBisCO extraction optimization for novel crops, leaves, other sources Explore functionality of individual protein fractions	Aqueous fractionation methods that do not require or produce sodium Optimize protein extraction for fraction functionality Optimizing for protein fractions and their native functionality	Scaling mild fractionation methods from lab-scale to pilot and industry scale
Creating value-add, small-scale equipment for rural producers	Improved reproducibility and efficiency of small-scale extrusion and fermentation	Cost-effective, modular, value-add equipment for rural producers	Agronomic research to set up and monitor regional hubs that assess impacts on farmers, producers, and markets

Infrastructure recommendations

Equipment:

Research on low cost, mild protein enrichment innovation will require research facilities stocked with equipment relevant to the specific processes being examined. Researchers would benefit from increased access to industry-relevant equipment including de-hulling machines, mills, membrane filters, spray-dryers, freeze-dryers, and downstream enrichment units. Ideally, this equipment would be usable as pilot-scale food production lines. Such facilities will also need relevant assay and testing equipment, such as chromatography equipment, particle size analyzers, and thermal property analyzers relevant for proteins.

Data and computing research infrastructure:

With the potential to advance low cost, mild protein enrichment innovation, machine learning can elucidate biochemical pathways for enhancing flavor and functionality of protein ingredients. Developing these models will require data, which could be enabled by creating an open-access protein structure-function database.

Partnership recommendations

Progress in low-cost, mild protein enrichment innovation depends on close collaboration across academia, industry, and public partners to advance a set of interconnected research opportunities.

- Upcycling sidestreams into fermentation feedstocks will require food science, process engineering, microbiology, and fermentation science to design methods that preserve nutritional quality while reducing costs.
- Microbial biotech companies and large CPGs can supply strains and sidestream inputs, while regional biomanufacturing hubs enable scaling and integration of local agriculture.
- Streamlining downstream enrichment of fermentation products will draw on analytical chemistry, process engineering, and biotechnology to reduce water and electricity use, supported by analytical equipment manufacturers and ingredient companies validating outcomes.
- Tailoring bioreactors for food development involves engineering, fermentation science, and molecular biology to design food-focused prototypes, optimize production with sensor integration, and scale new systems; governments and regulatory agencies will provide essential oversight and funding.
- Reducing off-flavors, antinutrients, and undesirable compounds requires molecular biology, bioinformatics, food science, and nutrition science, in partnership with research innovation engines and regulatory agencies to ensure safety and adoption.
- Scaling low-energy plant protein extraction will depend on food science, biotechnology, and process engineering, with governments and ingredient companies supporting infrastructure development and commercialization.
- Developing small-scale, value-add equipment will require mechanical and process engineering, food science, and agronomy, with agricultural cooperatives, regional hubs, and extension programs driving local adoption.

Together, these disciplines and partners can advance protein enrichment methods that are affordable, mild, and industrially scalable, reducing reliance on harsh chemicals and enabling a more circular, resource-efficient bioeconomy. Across all these opportunities, capacity-building through fellowships and training, public-private and international partnerships, and infrastructure grants will be essential to connect expertise, resources, and markets—ensuring that innovations move efficiently from early-stage research to scalable, commercially viable solutions.

Area 3

Multifunctional, palatable, nutritious ingredients

Background

To drive adoption of plant-based and fermentation-enabled foods, formulations must supply more than just good protein content, they must offer multifunctionality that supports appealing texture, flavor, and nutrition.

Currently, many food formulators rely on multiple individual components—such as binders, flavor maskers, and nutrient fortifiers—to create palatable and nutritious products. Developing multifunctional proteins and other ingredients that can serve several roles reduces the need for multiple additives, simplifying formulations and making production more efficient and cost-effective. This is especially important for scaling plant-based and fermentation-enabled protein food globally, where cost, supply chain constraints, and consumer expectations must all be considered. Desirable traits for multifunctional, food-grade ingredients include:

- High-quality protein content with balanced amino acid profile
- Strong gelation, emulsification, and/or foaming capabilities
- Low levels of off-flavors and/or presence of appealing flavor compounds
- Appropriate color for the intended end-product application
- Food-safe with low allergenicity potential
- Compatibility with fats, vitamins, minerals, and other ingredients
- Stability during enrichment, transport, and storage

Designing ingredients that combine functionality, palatability, and nutrition in a single input will allow food developers to reduce formulation complexity and lower production costs, thus paving the way for more accessible and appealing protein products across diverse markets.

Challenges and opportunities

To drive consumer demand, plant-based and fermentation-enable protein foods must rely on ingredient systems that combine strong sensory performance and robust nutrition with formulation simplicity. Producing ingredients that simultaneously deliver texture, flavor, nutrition, and costs is a complex task, but one with high impact for improving product quality and reducing formulation time and costs. Table 5 summarizes the challenges and opportunities identified by expert input.

Table 5. Summary of multifunctional, palatable, nutritious ingredients challenges and opportunities

Opportunity	Insights
Creating nutritious formulations	For plant-based and fermentation-enabled proteins to play a significant role in improving global diets, they must provide essential nutrients such as iron, omega-3 fatty acids, and complete, digestible protein. Plant-based and fermentation-enabled protein already offer promising nutritional benefits (GFI Europe, 2025) with areas to further improve nutrition by balancing amino acid profiles and incorporating bioavailable micronutrients. Ingredient optimization research will be key to develop nutritious formulations that do not degrade taste, texture, or cost competitiveness. Multifunctional ingredients that can contribute to nutrition while retaining key functional properties are critical targets for innovation.
Leveraging hybrid ingredients for complementary functions	Hybrid ingredients, those that bring together components from plant-based, fermentation-derived, and cultivated sources, offer a promising strategy to overcome the tradeoffs between nutrition, taste, functionality, and cost of plant-based foods (Kaleda et al. 2025). For example, HealthFerm, funded by the European Union under Horizon Europe, is investigating the health effects and consumer perceptions of innovative pulse and cereal-based food fermentations. However, this approach comes with research challenges beyond optimizing individual ingredients, especially deepening the understanding of how proteins and other components interact within complex, hybrid matrices. Unlocking the promise of hybrid ingredients and formulations for plant-based foods depends on advancing tools like predictive modeling and next-generation ingredient libraries.
Designing desirable flavors and colors	While plants and microbes can produce all the necessary building blocks, replicating the umami-rich flavors and vibrant colors of animal meat remains a key challenge compounded by plant-protein off-notes and colors. As a result, there is growing interest in designing desirable flavors and colors (NECTAR, 2025). These flavor and color innovations can eliminate the need for masking agents or additional components while enhancing consumer acceptance. Overcoming this requires integrated solutions across the value chain, including breeding, processing, formulation, and sensory science, guided by high-quality data and predictive modeling of ingredient and process interactions.

Opportunity (cont.)	Insights (cont.)
Engineering proteins for optimal function and taste	Protein functionality and organoleptic properties can be modulated by altering the peptide chain length, post-translational modifications, or amino acid substitution. Currently, proteins engineered for heterologous expression are codon optimized and tagged for proper protein trafficking, but are not optimized for food functionality and processing ease. Future changes to protein sequence and structure should lower the demands of processing by altering the overall pH, salt, or solvent interactions of the protein. Additionally, these changes can effectively increase food functionality (e.g., solubility, clarity, foaming, gelation). Lastly, modifications can boost the digestibility and essential amino acid content of proteins. Computational approaches can be developed and deployed to survey potential protein sequences for allergenicity.
Texturizing plant proteins using low-energy, reproducible methods	Fibrous protein ingredients are essential for enhancing the mouthfeel and structure of plant-based foods, but texturizing plant proteins presents technical challenges. Current methods require moderate-to-high energy inputs and can suffer from poor reproducibility. There is a growing opportunity to scale lower-energy, more consistent techniques that improve protein fiber alignment, enhance final product structure and quality, and require less refined inputs (Allan et al. 2025). Methods such as innovative high-moisture extrusion, shear cell, spinning, and combinations with enzymatic treatments offer scalable pathways to fibrous, appealing products, while reducing energy use and improving process control.
Incorporating fat and nutrients into texturized protein matrices	Incorporating fats and nutrients into texturized protein matrices offers an opportunity to enhance mouthfeel, juiciness, and nutritional value in plant-based foods. However, extrusion texturizinging poses challenges, as fats are difficult to integrate and both fats and nutrients are prone to degradation under heat and shear. Innovations such as fat encapsulation, the use of more stable fat substitutes (Soleimanian et al. 2024), redesigning extruder dies, and formulation layering can help overcome these hurdles and enable the creation of more sophisticated, stable food matrices.

Recommendations

Research recommendations

Creating nutritious formulations.

Progressing from building foundational datasets to predictive design tools, research can enable healthy, nutritious formulations for innovative protein foods. In the short term, priorities include compiling a library of protein ingredient nutrition, optimizing extraction methods for digestibility, and developing protein formulations with complete essential amino acid profiles. Efforts that leverage fermentation as a pre-treatment for plant proteins should focus on improving digestibility and nutrient quality. Medium-term work will focus on food matrix design that better incorporates nutrients into plant-based products, while also identifying compounds with desirable thermal properties that can survive processing. In the long term, predictive modeling will help uncover viable formulations and illuminate ingredient–processing interactions, enabling the design of foods that maximize nutrition, stability, and consumer appeal.

Leveraging hybrid ingredients for complementary functions.

There is value in combining plant and fermentation-enabled ingredients. In the short term, blending ingredients with complementary properties can improve nutrition and texture. Medium-term work will require deeper structure-function studies to understand how hybrid ingredients interact within food matrices and influence performance. Ultimately, the long-term goal is to establish an open-access ingredient library that quantifies functionality, nutrition, and flavor data. Such a resource would give researchers and product developers a powerful tool for designing next-generation formulations that are both efficient and high-performing.

Designing desirable flavors and colors.

Advancing from practical processing to targeted biochemical insights will ensure appealing foods for consumers. Short-term efforts include extracting natural flavor compounds from crops, applying enzymes to substrates to reduce off-notes, and testing processing methods to both mitigate undesirable flavors and enhance desirable ones. At the same time, a more integrated understanding of flavor development along the value chain is needed. Medium-term work should focus on training sensory panels to provide reliable evaluation. In the long term, regional research centers that focus on developing new assays and equipment that evaluate sensory traits in ways consistent with consumer experience, while mapping biochemical pathways and genetic precursors of off-flavors will create avenues for precise flavor and color design.

Engineering proteins for optimal function and taste.

More exact innovation will create optimized proteins, progressing from computational prediction to microbial and crop-based innovation. Short-term efforts will use computational modeling of protein structure, sequence, and organoleptic properties to anticipate taste and functionality. Medium-term opportunities include engineering microbial strains such as

Lactobacillus to generate umami compounds, identifying the native functionality of protein fractions, and valorizing co-products of fractionation. In the long term, researchers will aim to understand how both mechanical and biological activities modify functionality, paving the way for engineered proteins with optimized taste, nutrition, and performance.

Texturizing plant proteins using low-energy, reproducible methods.

Scaling accessible technologies for meat-like structures will be critical to create foods with desirable mouthfeels. Short-term work includes improving reproducibility in extrusion, optimizing hardware for scalable texturization, developing dies for fat and oil inclusion, and diversifying gelling agents. Medium-term efforts will redesign equipment for continuous texturization, focus on achieving high-aspect ratio protein fibers, and optimize extrusion parameters for protein flours, reducing the need for upstream enrichment steps. In the long term, commercial-scale high-aspect texturization methods must be made affordable and widely available, not only to industry but also to R&D labs seeking to innovate new product concepts.

Incorporating fat and nutrients into texturized protein matrices.

For juicy, nutritious protein foods, it is essential to consider how fats and nutrients interact with proteins. In the short term, encapsulation technologies can stabilize nutrients, while fat substitutes with greater stability can be explored. Medium-term work will focus on embedding fats and nutrients directly into protein matrices without compromising structure or flavor. Long-term success will require integrating these stabilized components into continuous texturization methods, producing protein-rich foods that combine desirable mouthfeel with balanced nutrition.

Table 6. Examples of research recommendations for multifunctional, palatable, nutritious ingredients in the short-, medium-, and long-terms

	Recommendations		
Opportunity	**Short-term: Shorter projects with quick results**	**Medium-term: Projects that take more time but can start now**	**Long-term: Longer projects with larger scope or complexity**
Creating nutritious formulations	Create a library of protein ingredient nutrition Optimize protein extraction methods for digestibility Provide protein formulations with complete essential amino acid profiles Utilize fermentation as a pre-treatment for protein extraction	Food matrix design for better incorporation of nutrients in plant-based products Identifying nutrients with desirable thermal properties	Predictive modelling to find viable formulations and uncover ingredient-processing interactions
Leveraging hybrid ingredients for complementary functions	Leveraging hybrid product formulation synergies	Integrating structure-function relationships to understand how hybrid ingredients interact	Open-access ingredient library with quantified functionality, nutrition, cost, and flavor data
Designing desirable flavors and colors	Flavor compounds extracted from crop sources Integrated understanding of flavor along the value chain Apply enzymes to plant-based substrates to improve flavor Explore processing techniques to mitigate off-flavors and generate desirable flavors	Trained expert sensory panelists	Sensory research centers in different regions that focus on new assays and equipment to assess sensory attributes that are consistent with consumer experience Identify biochemical pathways and genetic precursors related to off-flavors

Recommendations (cont.)			
Opportunity	**Short-term: Shorter projects with quick results**	**Medium-term: Projects that take more time but can start now**	**Long-term: Longer projects with larger scope or complexity**
Engineering proteins for optimal function and taste	Computational modeling of protein organoleptics and structure/sequence	Microbial strains (e.g., *Lactobactillus sp.*) that can generate umami compounds Identifying the fractions of different plant proteins and their native functionality Valorizing co-products of fractionation	Understanding of how mechanical and biological activities modify functionality
Texturizing plant proteins using low-energy, reproducible methods	Extrusion die development for fat/oil inclusion Improved reproducibility for plant protein extrusion Extrusion hardware optimization for scalable plant protein texturization Diversifying gelling agents	Product equipment redesigning for protein texturization Continuous texturization techniques achieve high-aspect ratio protein fibers Extrusion of protein flours to reduce number of upstream enrichment steps	Commercial-scale high-aspect texturization techniques are affordable and accessible for R&D labs
Incorporating fat and nutrients into texturized protein matrices	Encapsulation of nutrients for improved stability Fat substitutes with improved stability	Incorporating fat and nutrients into protein matrix	Stable fat and nutrient formulations are incorporated into continuous texturization methods

Infrastructure recommendations

Advancing multifunctional, palatable, nutritious ingredients will require robust research infrastructure:

- Research-scale production and formulation facilities, sensory evaluation facilities, analysis equipment, and pilot and commercial texturization technology facilities. Such facilities should be equipped with feeders, cutting systems, breaker plates, cooling dies, and other other industry-relevant equipment.

- Formulation kitchens will be necessary to explore potential formulations in a data-intensive manner. Researchers would benefit from sensory evaluation facilities, such as trained panels and consumer testing, which integrate lab measures and sensory evaluations.
- Researchers will need analysis equipment to ensure they can collect data necessary to improve ingredient functionality, with a need for rheological and texture analysis, spectroscopy, chromatography, nutrition analysis, and other functionality assessment equipment.

Partnership recommendations

Developing multifunctional, palatable, and nutritious ingredients calls on diverse expertise and cross-sector collaboration to advance several opportunities.

- Creating nutritious formulations requires food science, nutrition science, biochemistry, and process engineering to build protein nutrition libraries, optimize digestibility, and design matrices that retain nutrients; partnerships with lab analysis firms and large CPGs can accelerate translation into products.
- Leveraging hybrid ingredients for complementary functions will rely on bioinformatics, food science, and plant breeding to explore synergies and ultimately build an open-access ingredient library; commodity groups and breeder organizations are essential to ensure supply alignment.
- Designing desirable flavors and colors draws on sensory science, molecular biology, and process engineering to extract natural compounds, improve off-flavors, and establish regional sensory research centers; governments, regulatory agencies, and sensory research firms can support consistency and consumer trust.
- Engineering proteins for optimal function and taste leverages computational biology, fermentation science, and biotechnology to design proteins with improved functionality and taste, with ingredient companies and business-to-consumer partners testing market fit.
- Texturizing plant proteins using low-energy, reproducible methods requires process engineering and mechanical engineering to optimize extrusion and continuous texturization; regional hubs and CPGs will be crucial for scaling.
- Incorporating fats and nutrients into texturized matrices draws on food science, encapsulation, and sensory science, with regulatory agencies and ingredient companies ensuring products are both safe and appealing.

This coordinated, collaborative approach ensures that new ingredients meet consumer expectations for nutrition, flavor, texture, and affordability.

Area

4

Strategic research catalysts

Background

For plant-based and fermentation-enabled proteins to become more affordable, functional, and appealing to consumers, accelerating innovation will require strategic research catalysts that improve efficiency, reproducibility, and impact across the value chain.

The complexity of food systems presents a major bottleneck for scaling novel protein products, including the inherent variability of crop and microbial inputs and extraction techniques. Essentials for accelerating progress and scaling across the entire field include:

- Open-access data
- Standardized methods and high-throughput analytic techniques
- Structure-function understanding of ingredients
- Thorough economic models
- Leveraging AI, ML, and neural networks

Shared research infrastructure and open-access databases will enable level playing fields for innovation and reduce duplication of effort across the entire industry, from startups to academic labs and global producers. By focusing on these foundational research needs, the sector can more rapidly overcome technical bottlenecks, de-risk product development, and unlock a new generation of high-performance protein food ingredients.

Challenges and opportunities

Unlocking the full potential of plant-based and fermentation-enabled protein ingredients requires a robust foundation of scientific research tools, methods, and infrastructure. There are many opportunities to accelerate discovery, de-risk development, and improve reproducibility across innovative protein value chains. To move the field forward, greater investment in open-access, collaborative, and applied research infrastructure is essential. Shared resources will not only reduce duplication and lower barriers to entry, but also foster greater alignment across the ecosystem, from academic and government labs to startups and multinational companies. Investing in these foundational tools will be key to accelerating innovation protein food development. Table 7 summarizes the challenges and opportunities identified by expert input.

Table 7. Summary of strategic research catalyst challenges and opportunities

Opportunity	Insights
Standardizing procedures and methods	Standardizing procedures and methods across the value chain is essential to accelerate innovation, improve reproducibility, and enable meaningful data comparisons. Without consistent protocols for measuring functionality and sensory attributes, it is difficult to benchmark progress or translate lab-scale findings into commercially-viable products. While the development of foundational methods is often perceived as lacking novelty and, thus, less competitive for traditional research funding, these tools are critical to the success of the industry. Prioritizing standardized, open-access method development will unlock more equitable and faster progress across the ecosystem.
Controlling variability	Variability presents a major concern throughout the lifecycle of plant-based and fermentation-enabled ingredients. Genetics, environmental conditions, and enrichment factors can affect crops, microbes, and the ingredients created from them. This can make it difficult to relate traits in crops and microbes to final ingredients. Opportunities exist to reduce performance variability in crops, microbes, and processing between users or applications to reliably predict performance. Standardization pairs well with predictive modeling to understand variability, and production flexibility to embrace variability, all while ensuring predictable behavior in food formulations.
Relating structure-function of plant- and fermentation- based ingredients and their sensory evaluation	Relating structure-function of plant- and fermentation-based ingredients and their sensory evaluation remains a major opportunity (Zhang et al. 2025). While traditional product development relies on empirical approaches, there is growing interest in applying artificial intelligence (AI), physics-based models, and polymer chemistry to better predict and control texture, appearance, and flavor. However, the complexity of food systems makes it difficult to map inputs to sensory outcomes. Advancing this field requires deeper understanding of physico-chemical transformations, as well as efforts to connect molecular characteristics with consumer preferences across diverse markets. The Periodic Table of Food Initiative, led by The Rockefeller Foundation, and the protein database project led by Fraunhofer IVV are examples of an open source initiative to democratize tools, data, and training, by leveraging food composition data and for an ecosystem of scientists, practitioners, consumers, and policymakers.
Levering neural networks, AI, and ML for next generation protein development	Levering neural networks, AI, and ML for next generation protein development can support the development of useful models. These methods may improve understanding of protein properties, designing proteins with desirable properties (Dahl et al. 2025), improving methodologies, refining formulations, and processing -omics data. Key challenges persist in the availability of large-scale, high-quality, standardized datasets, workforce development, and encouraging collaborations between food scientists and ML researchers.

Opportunity (cont.)	Insights (cont.)
Developing high-throughput analytics techniques to expedite R&D	Developing high-throughput analytics techniques to expedite R&D will enable rapid screening of ingredient candidates across multiple variables, such as extractability (Ratanpaul et al. 2025, Rijken et al. 2025), solubility, gelling, digestibility, off-flavor content, allergenicity, and fibrousness. These tools can drastically reduce R&D timelines and allow researchers to more efficiently navigate the vast space of possible inputs and downstream enrichment parameters. However, their implementation requires cross-disciplinary collaboration and research infrastructure that many startups or small labs struggle to access. R&D could be accelerated through development of high-throughput analytical techniques such as new taste sensor assays, gut-on-chip systems, bioprocess sensor development for fermentation, and predictive modeling based on omics data.
Optimizing commercially-relevant TEAs and LCAs	Optimizing commercially-relevant technoeconomic analyses (TEAs) and life cycle assessments (LCAs) is similarly crucial to supporting innovations across the value chain as they are crucial for guiding innovation toward commercially viable and environmentally beneficial outcomes. When designed with food industry relevance in mind, these tools can help developers prioritize methodology improvements, communicate impact to stakeholders, and make informed decisions about scale-up, regional development, and investment (GFI 2024, GFI 2025). Current efforts are constrained by limited access to high-quality, open-source data, standardized modeling approaches, and lack of social science integration. Collaborative consortia focused on shared data infrastructure and robust modeling tools can accelerate progress.

Recommendations

Research recommendations

Standardizing procedures and methods.

Standardization across research is a critical starting point, as lack of consistency in protein characterization and sensory evaluation slows progress and prevents cross-study comparisons. Short-term efforts should include establishing a consortium to harmonize protein characterization methods. Medium-term work will focus on developing standardized protocols and a shared lexicon for expert sensory panels, as well as publishing open-access, reproducible models for broader use. In the long term, a global network of international labs can collaborate on developing, validating, and maintaining standards to ensure alignment across the industry.

Controlling variability.

Ingredient performance often differs by crop variety, plant fractionation and fermentation conditions, or geography, making downstream formulation challenging. In the short term, collaborations between universities and companies can begin building the infrastructure needed to generate relevant datasets. Medium-term investments in equipment and facilities will allow for systematic data collection across geographies, helping researchers better predict and control variability. Ultimately, long-term progress will rely on predictive modeling tools that can anticipate variability in ingredient and product performance, reducing risk in formulation and manufacturing.

Relating structure-function of plant- and fermentation- based ingredients and their sensory evaluation.

Bridging the gap between molecular properties and consumer experience will require a deep understanding of how ingredient structure relates to food function. In the short term, this requires generating protein function datasets across geographies and ensuring researchers have the equipment needed to characterize structure-function attributes. Medium-term work should explore human-computer interfaces that accelerate product development by linking structure-function insights directly to design. Long-term, these efforts can culminate in an open-access database capturing cross-geography structure-function relationships, linking ingredient properties to final product performance and sensory outcomes.

Levering neural networks, AI, and ML for next generation protein development.

Taking advantage of modern neural networks, AI, and ML tools will transform how the field develops next-generation proteins. In the short term, ML can be applied to understand basic structure-function relationships, supported by pipelines of student and post-doctoral researchers contributing to dataset growth. These efforts will require data infrastructure, like open-source databases and data repositories, to ensure data is findable and available. Convenings between food scientists and AI researchers can also establish a common language. Medium-term efforts will expand into physics-informed neural networks designed specifically for protein structures. In the long term, a Center of Excellence and data consortium will be needed to house models, databases, and collaborative platforms. Open-access AI models capable of analyzing complex food matrices will allow the industry to predict ingredient performance before costly physical trials.

Developing high-throughput analytics techniques to expedite R&D.

Shortening R&D cycles will help fast-track innovative protein foods for commercial success. Short-term work can focus on building early-stage high-throughput analytics platforms, including "mouth-on-a-chip" devices to assess multimodal sensory attributes. Medium-term validation of these approaches against traditional analytics will help establish credibility and reliability. Long-term goals include scaling these methods into commercially viable, affordable tools accessible to R&D labs worldwide, allowing rapid screening of ingredients and formulations.

Optimizing commercially-relevant TEA and LCAs.

It is critical that the industry ensures that innovations are both financially viable and environmentally sound. Short-term priorities include establishing best practices for cross-study comparison and results standardization. In the medium term, open-access environmental and technoeconomic databases will give researchers and funders a shared foundation for decision-making. In the long term, real-world process data and comparative modeling frameworks will enable dynamic models for continuous process improvement, ensuring sustainability and competitiveness in parallel.

Table 8. Examples of research recommendations for strategic research catalysts in the short-, medium-, and long-terms

	Recommendations		
Opportunity	**Short-term: Shorter projects with quick results**	**Medium-term: Projects that take more time but can start now**	**Long-term: Longer projects with larger scope or complexity**
Standardizing procedures and methods	Consortium for standardization of protein characterization methods	Develop standardized protocols and lexicon for training expert sensory panels to assess nuanced attributes in innovative protein foods Publish open-access, reproducible models	Network of international labs collaborate on developing, validating, and maintaining standards for the industry
Controlling variability	Infrastructure collaborations between universities and companies	Invest in infrastructure and equipment necessary to build data to predict and control variability Cross-geographic data generation	Predictive modeling to anticipate and control for variability
Relating structure-function of plant- and fermentation- based ingredients and their sensory evaluation	Cross-geography data generation in protein function Provide necessary equipment to build relevant datasets	Human-computer interface to accelerate next-generation product development	Open-access database with structure-function relationships that relate ingredients to final product including cross-geography

Recommendations (cont.)			
Opportunity	**Short-term: Shorter projects with quick results**	**Medium-term: Projects that take more time but can start now**	**Long-term: Longer projects with larger scope or complexity**
Levering neural networks, AI, ML for next generation protein development	ML to understand basic structure-function relations in ingredients Identify pipeline of post-doc and student researchers to grow data sets Convenings to develop common language between food scientists and ML researchers	Physical informed neural network development for protein structures	Center of Excellence and data consortium for research, database, and modeling Open-access models that can consider complex food matrices
Developing high-throughput analytics techniques to expedite R&D	Development of high-throughput analytics Mouth-on-a-chip for multimodal attribute assessment	High-throughput methods are validated against more traditional analytics and standardized	Commercially-viable high-throughput analytics tools are affordable and accessible for R&D labs
Optimizing commercially-relevant TEA and LCAs	Best practices for LCA and TEA focused on cross-study comparison and results standardization	Open-access environmental impact and technoeconomic databases	Process improvement models for technoeconomics and sustainability fed by real-world data and comparative process modeling frameworks

Infrastructure recommendations

Investments in research infrastructure can accelerate the development of plant-based and fermentation-enabled protein ingredients, improving sourcing, optimization, and functionality.

- Data and computing infrastructure has a notable potential to catalyze R&D. A robust data infrastructure is essential ML and AI to advance ingredient optimization.

Standardized repositories and libraries are needed, especially for data on ingredients, protein extraction methods, and metabolic pathways. In addition, ML models and other modeling methods should be applied to ingredient functionality, metabolic modeling, and protein extraction design and optimization.

- Open access databases, methods, and best practices also have the potential to improve TEA and LCA of ingredients, which will be important for their translation to practice.

- Significant potential exists to catalyze ingredient sourcing, development, and optimization through simulators for digestibility, bioavailability, and sensory experience. Current methods to address these areas are costly and slow research and development.

Partnership recommendations

Strategic research catalysts provide the backbone for accelerating progress across all protein ingredient innovations, with each opportunity requiring distinct disciplinary expertise and partnerships.

- Standardizing procedures and methods will depend on food science, protein chemistry, and sensory science to harmonize protocols, supported by ingredient companies, large CPGs, and organizations already active in standardization.

- Controlling variability will draw on bioinformatics, process engineering, and agronomy to predict ingredient performance across geographies, with universities, industrial automation partners, and governments investing in infrastructure.

- Relating structure-function of ingredients to sensory evaluation requires food science, molecular biology, and data science to generate cross-geography datasets and develop open-access databases; ingredient companies and research innovation engines will ensure tools are adopted.

- Leveraging neural networks, AI, and ML will involve computer science, bioinformatics, and food science, with AI companies, governments, and large CPGs building physics-informed models and Centers of Excellence.

- Developing high-throughput analytics calls for process engineering, industrial automation, and sensory science to design and validate new methods, supported by governments and equipment manufacturers to ensure accessibility to labs globally.

- Optimizing TEAs and LCAs relies on economics, process engineering and modelling, and sustainability science to create open-access comparative databases and process improvement models, with governments and CPGs supplying critical data.

By combining academic expertise with industry and government support, these catalysts will ensure that protein innovation is reproducible, efficient, and commercially relevant.

Cross-sector calls to action

Several cross-sector calls to action emerged as essential considerations for the success of the above identified research areas and opportunities. These themes, summarized in Table 9 below, represent the foundational elements that can accelerate progress across the value chain. They are not isolated priorities, but interconnected enablers that influence ingredient innovation and market adoption. By embedding these principles into project design and funding strategies, researchers, industry stakeholders, and funders can maximize impact, reduce barriers, and ensure that advancements in innovative protein ingredients achieve both commercial viability and broad societal benefit.

Examples of these actions can be leveraged and replicated to ensure global success of innovative proteins. For instance, MISTA, a U.S.-based innovation platform, and the Government of Catalonia have democratized access to information and physical resources for pre-industrial manufacturing of plant-based and fermentation-enabled proteins. Well-structured public-private partnerships like Novo Nordisk Foundation's Plant2Food collaboration platform will help bring industry and academic innovators together to commercialize promising foundational research. Furthermore, food safety and regulatory efforts like UN FAO's Food Safety Foresight Technical Meeting and Report will be critical in proactively engaging with regulatory agencies and streamlining novel food product safety and approval.

Table 9. Summary of cross-sector calls to action that enable innovative protein research opportunities

Theme	Insights
Optimize products with the consumer in mind	Taste and cost are the powerful drivers for consumer demand and essential to drive market adoption of innovative foods. Achieving price parity ensures products are accessible to a broad range of consumers and competitive in mainstream markets. Innovations in ingredient sourcing, enrichment, and formulation techniques can help deliver on both taste and cost, enabling high-quality sensory performance while reducing production costs.
Improve open-access data and infrastructure availability	Shared datasets, standardized methods, and open-source tools allow researchers, startups, and established companies to build on each other's work rather than duplicating efforts, speeding progress across the sector. Access to shared infrastructure, such as pilot-scale plant protein fractionation and texturization facilities, fermentation labs, and sensory evaluation centers, can lower barriers for smaller players and encourage broader participation in R&D.

Theme (cont.)	Insights (cont.)
Build public-private partnerships	Public-private collaborations leverage the complementary strengths of academic researchers, government agencies, and industry stakeholders by combining cutting-edge science with market knowledge, regulatory expertise, and commercialization pathways. Public sector involvement can de-risk early-stage research, provide infrastructure, and ensure broad societal benefits, while private partners bring investment, supply chain capabilities, and routes to markets. By aligning incentives and sharing resources, these partnerships can tackle complex challenges more efficiently.
Leverage existing systems	By tapping into established agricultural supply chains, processing infrastructure, distribution networks, and regulatory frameworks, the industry can reduce costs, shorten development timelines, and increase market reach. Existing research facilities, quality assurance protocols, and logistics systems can be adapted to handle novel ingredients, allowing innovators to focus resources on product differentiation rather than scale-up from scratch. Partnerships with organizations already operating in these spaces—such as growers' cooperatives, contract manufacturers, and distribution hubs—can further streamline efforts.
Support systems-level agriculture	Systems-level agriculture looks beyond individual crops or technologies to optimize the entire agricultural ecosystem, from soil health and water use to crop rotations and integrated supply chains. By aligning on practices that improve biodiversity, reduce inputs, and enhance climate resilience, systems-level strategies can provide a stable, sustainable supply of diverse raw materials for ingredient production. Collaborations among farmers, researchers, cooperatives, and policymakers ensure that these agricultural improvements are economically viable and relevant to food markets.
Ensure food safety and regulatory compliance	Rigorous safety testing, traceability systems, and hazard analysis protocols help identify and mitigate potential risks throughout protein ingredient supply chains. Compliance with local and international regulatory standards ensures that novel ingredients and processes meet all legal requirements. Engaging proactively with regulatory agencies can streamline approval timelines, reduce uncertainty, and foster a collaborative approach to bringing innovative protein foods to market.

Conclusion

More than 80 subject matter experts from around the world, representing varying technical expertise across industries, shaped the research funding opportunities and recommendations in this report—a testament to the power and influence of a strong scientific ecosystem that continues to expand and evolve, and that has a significant stake in creating a more resilient food system.

The research areas and opportunities that these experts identified—specifically around optimizing plant-based and fermentation-derived protein ingredients—serve as a blueprint for research institutions around the world who work on innovative food and agricultural solutions. Institutions and companies who prioritize these research needs and critical gaps in knowledge and capacities can significantly advance the field of protein innovation and diversification.

Collectively, such institutions and companies can multiply their impact even further when they act as a collaborative, interconnected ecosystem. The cross-sector calls to action that emerged from the FFAR-GFI call-for-ideas survey and in-person workshop, if adopted widely, can accelerate progress on plant-based and fermentation-enabled protein ingredients to hasten broad consumer adoption of in-demand foods. Such adoption can then deliver broad social and environmental benefits, from new livelihood-improving opportunities for farmers and farming communities to healthier lands and waters.

It's both sobering and energizing to realize how much remains to be discovered—we've really just begun to scratch the surface of the science of plant-based and fermentation-enabled protein innovation. Greater investments in research and adoption of an ecosystem-mindset across the multi-sector research community, as laid out in this summary report, can unlock the full potential of such innovations to safely and sustainably feed a growing world.

Notes on limitations of this report:

This report is provided for informational purposes only. It reflects input from numerous experts and identifies areas of potential scientific research, infrastructure development, and policy engagement. It is far from comprehensive, and some of the research areas and opportunities identified are more developed and described than others. The inclusion or omission of any organization, company, or product in this report does not imply endorsement, approval, or disapproval by FFAR or GFI. The recommendations presented here are intended to support the advancement of open-access, publicly beneficial research and collaboration across the food system.

While focusing on plant-based and fermentation-enabled technologies allowed for focus and depth, this report and the input that shaped it only begins to explore the broader, rapidly evolving research landscape for protein innovation writ large.

While physical and biological science research dominates in this report, additional research can speed the path to commercialization, including social science that can help unlock greater public and private investment and address key consumer adoption challenges and opportunities.

Appendices

Appendix A: Call-for-ideas survey summary

FFAR and GFI launched a call-for-ideas survey to the public May–June 2025, designed for protein research and development leaders to help identify key challenges and opportunities in plant-based and fermentation-enabled protein ingredients. The survey was then used to outline significant research areas and opportunities, which were in turn used to format an in-person, invite-only workshop (Appendix B). The survey had a total of 63 responses with varying technical expertise (Figures A1a–d). These responses were then used to define four research areas with accompanying 22 research objectives (Figure A2).

Figure A1. (a) Demographic distribution of FFAR-GFI call-for-ideas survey respondents' primary areas of expertise

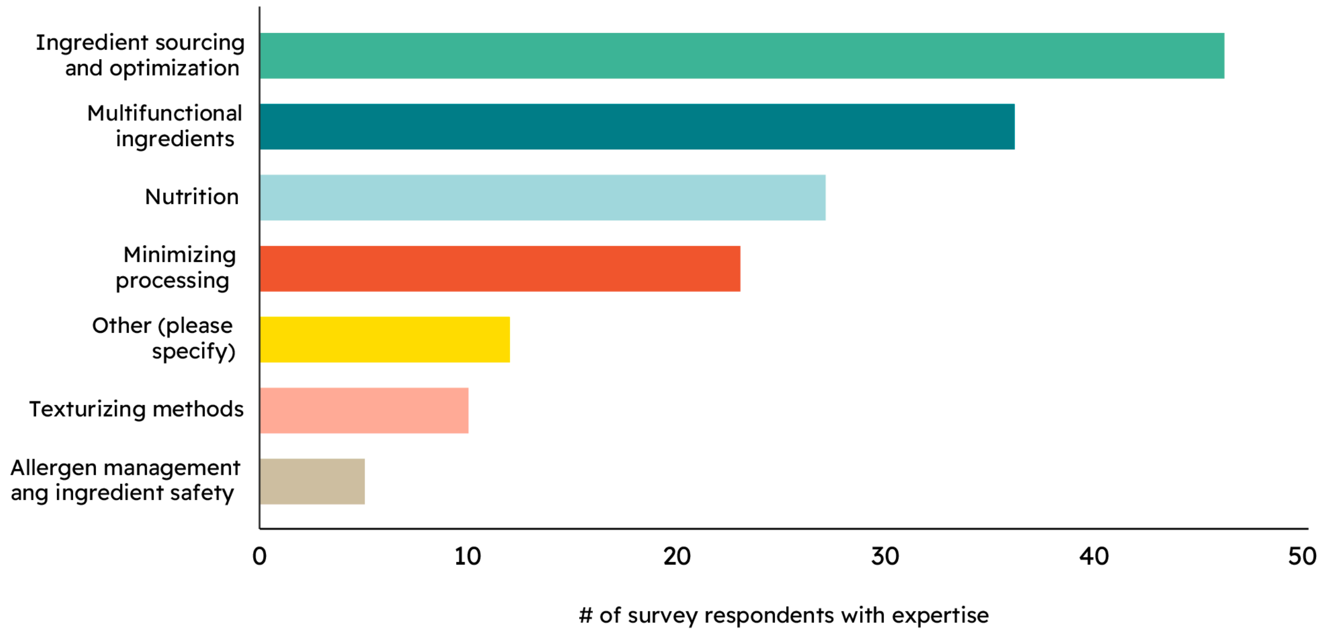

Figure A1. (b) Demographic distribution of FFAR-GFI call-for-ideas survey respondents' region/country

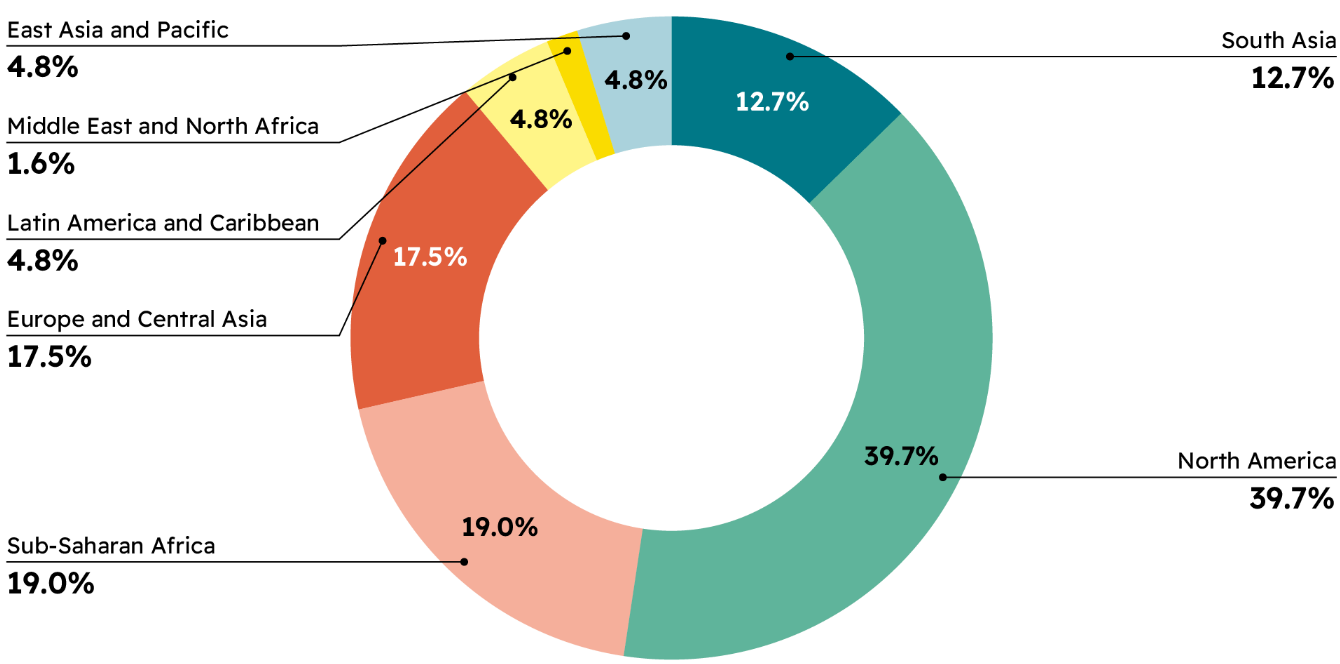

Figure A1. (c) Demographic distribution of FFAR-GFI call-for-ideas survey respondents' primary role

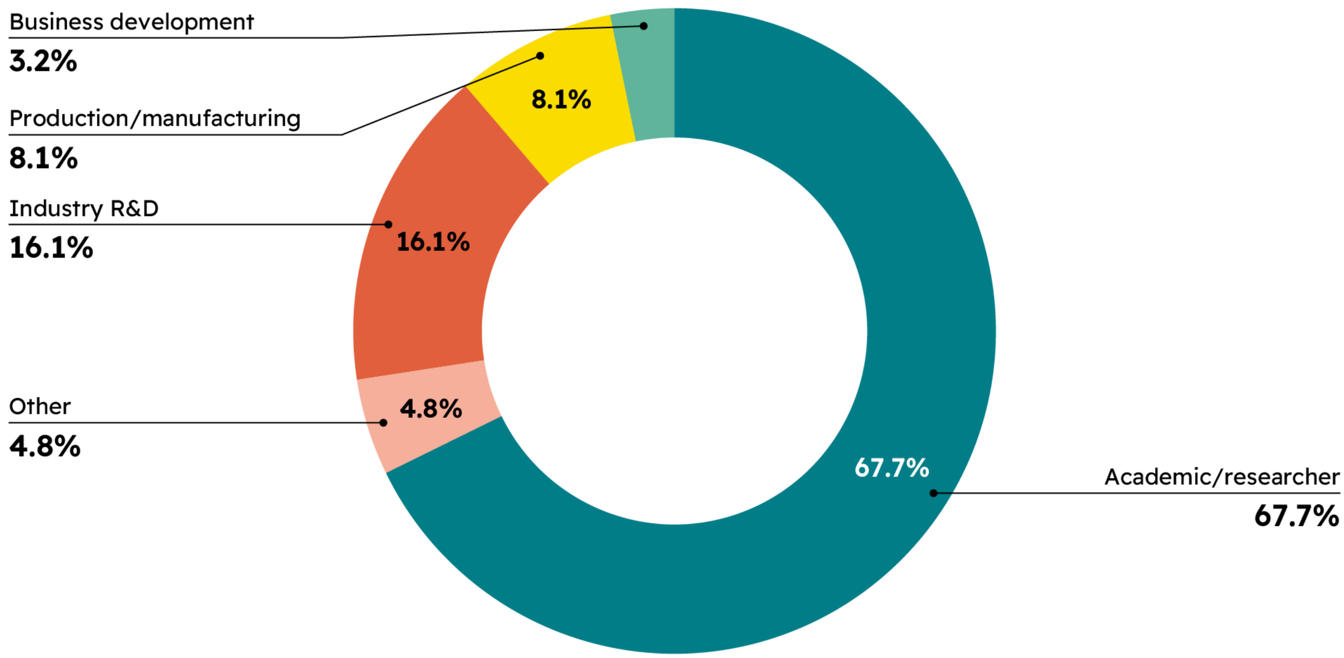

Figure A1. (d) Responses from FFAR-GFI call-for-ideas survey when asked which disciplines should be involved in addressing ingredient optimization challenges

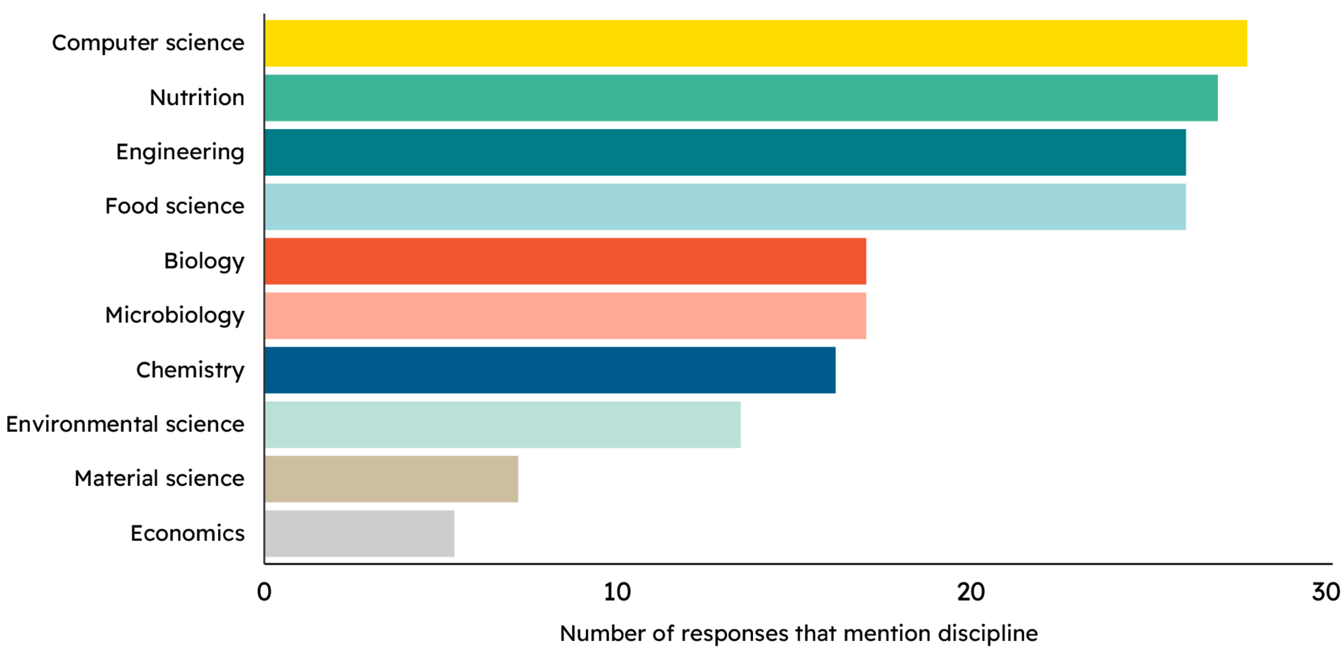

Figure A2. The greatest research needs in ingredient optimization as identified in FFAR-GFI call-for-ideas survey responses.

Ingredient sourcing optimization	• Upcycle sidestreams into food ingredients • Develop regional crops • Breed crops for improved quality and yield • Tailor cell lines for fermentation and plant cell culture
Low cost, mild processing protein enrichment innovation	• Upcycle sidestreams into fermentation feedstock • Streamline downstream processing of fermentation products • Tailor bioreactors for food development • Reduce off-flavors, antinutrients, and other undesirable compounds in plant protein ingredients • Scale low-energy plant protein extraction • Create value-add, small-scale processing technologies
Multifunctional, palatable, nutritious ingredients	• Create nutritious formulations • Leverage hybrid ingredients for complementary functions • Design desirable flavors and colors • Engineer proteins for optimal function and taste • Texturize plant proteins using low-energy, reproducible methods • Incorporate fat and nutrients into texturized food matrices
Strategic research catalysts	• Standardize procedures and methods • Control variability • Relate structure-function of plant- and fermentation-enabled ingredients and their sensory evaluation • Leverage neural networks, artificial intelligence, and machine learning for next generation protein development • Develop high-throughput analytics techniques to expedite R&D • Optimize commercially-relevant technoeconomic analyses and life cycle assessments

Appendix B: Workshop summary

Building on insights from our call-for-ideas survey, FFAR and GFI convened 31 international experts (excluding FFAR and GFI staff) in protein ingredient development across academia and industry to discuss state-of-the-art, key challenges, research opportunities, and research infrastructure needs for plant-based and fermentation-enabled proteins. Additionally, experts pinpointed funding and actionable strategies and identified key stakeholders needed to address these challenges and advance solutions. Discussion groups were divided amongst four key topics:

- Ingredient sourcing optimization
- Low-cost, mild processing innovations
- Multifunctional, palatable, and nutritious ingredients
- Catalysts for improved ingredient development

The input from these discussions is summarized in this report and includes anonymized and collective insight from group discussions and therefore does not represent the opinions or strategic priorities of individuals, companies, or organizations names. The workshop took place on July 17, 2025, and the majority of attendees were from North America and academia. Additionally, there was notable presence from industry innovators, Europe, South Asia, and Brazil as well.

Table A1. International experts that contributed to the FFAR-GFI plant-based and fermentation-enabled protein ingredient optimization workshop

First	Last	Institution
Rajni	Aneja	Cornell University
Akshay	Arora	Ingredion
Sanah	Baig	Plant Based Foods Institute
Frédéric	Baudouin	IMPROVE
Janelle	Carlin	Pulse Canada
Kushal	Chandak	PURIS
Dimitris	Charalampopoulos	University of Reading, UK
Anto	Charles	University of Nebraska-Lincoln
Da	Chen	Purdue University
Ana Paula	Dionisio	Embrapa Tropical Agroindustry - Fortaleza - Ceara - Brazil
Max	Elder	Food System Innovations
Samira	Feyzi	University of Arkansas System Division of Agriculture
Girish	Ganjyal	Washington State University

First	Last	Institution
Audrey	Girard	University of Wisconsin-Madison
Lutz	Grossmann	University of Massachusetts Amherst
Ling	Li	ADM
Mark	Luecke	Houdek
Chris	Mallett	FFAR Board Member
Rosemary	Peter	Griffith Foods
Ewa	Pietrysiak	USA Pulses
David	Potts	Givaudan
Stacy	Pyett	Wageningen University & Research
Mahfuzur	Rahman	University of Arkansas
Ana Carla	Sato	University of Campinas
Rohan	Shirwaiker	North Carolina State University
Paula	Speranza	ProVerde
Johan	Ubbink	University of Minnesota
Jon	Wiese	Kraft Heinz
Jing	Zhao	San Diego State University
Weibiao	Zhou	National University of Singapore
Leon	Zhou	Roquette