

Study on biomass and precision fermentation

Final Report

Written by Cogea and Stichting Wageningen Research

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List of abbreviations

Acronym	Name
B2B	Business-to-Business
BF	Biomass Fermentation
CA(s)	Competent Authority(ies) and Enforcement Authority(ies) of EU Member States
CAGR	Compound Annual Growth Rate
CAP	Common Agricultural Policy
CAPEX	CAPital EXpenditure
CF	Cell Factory (genetically-engineered production strain)
CO ₂	Carbon Dioxide
DG AGRI	Directorate-General for Agriculture and Rural Development
DSP	Downstream Processing
EC	European Commission
EP	European Parliament
EFSA	European Food Safety Authority
EU	European Union
F&B	Food & Beverage
FWC	Framework Service Contract
GHG	GreenHouse Gas
GM	Genetically Modified
GMMs	Genetically Modified Microorganisms
GRAS	Generally Recognised As Safe
GWP	Global Warming Potential
HOB	Hydrogen-Oxidising Bacteria
ISG	Interservice Group for the study
kWh	kiloWatt-Hour
LCA	Life-Cycle Assessment
LCB	Lignocellulosic Biomass
MP	Microbial Protein
MPSP	Minimum Product Selling Price
MS(s)	Member State(s)
NFR	Novel Food Regulation
NTM	Non-Tariff Measure
OPEX	OPerational EXpenditure
P2P	Power-To-Protein
PAFF	Standing Committee on Plants, Animals, Food and Feed
PF	Precision Fermentation
SCP	Single-Cell Protein (microbial biomass used as protein source)
SPS	Sanitary and Phytosanitary (measures)

Acronym	Name
SQ(s)	Study Question(s)
TBD	To Be Determined
TEA	Techno-Economic Analysis
TF	Traditional Fermentation
ToR	Terms of Reference
TRL	Technology Readiness Levels
TRY	Titer, Rate, Yield (fermentation key performance metrics)
CMO	Common Market Organisation
UTP	Unfair Trading Practices
NRP Plan	National and Regional Partnership Plan
LEADER	Liaison Entre Actions de Développement de l'Économie Rurale
AKIS	Agricultural Knowledge and Innovation Systems
EIP-AGRI	European Innovation Partnership for Agricultural Productivity and Sustainability
PO	Producer Organisation

1 Introduction

This Report presents the final results of the study on biomass and precision fermentation commissioned by the European Commission, Directorate-General for Agriculture and Rural Development.

Objective of the study

The study examines how the development and scaling-up of biomass and precision fermentation for the production of proteins for food and feed may affect the EU farming sector and rural areas in the medium and long term. Particular attention is given to the implications for conventional agricultural markets and production systems, the competitiveness and economic sustainability of EU farmers, the EU's dependence on imported proteins, and the policy conditions under which potential benefits for agriculture may be realised.

The report is situated in a context in which fermentation-based protein production has attracted growing policy, industrial and scientific interest, but remains at a relatively early stage of commercial development in Europe. A limited number of microbial protein products are currently authorised on the EU market, market uptake remains modest compared with conventional proteins, and robust quantitative evidence on future market development is still scarce. For this reason, the study does not seek to predict a single trajectory for the sector. Instead, it combines evidence on the current state of play with a forward-looking assessment of how different development pathways may affect farming sectors, agricultural markets and rural economies.

The focus of the study is on microbial proteins for food and feed derived from biomass fermentation and precision fermentation. These are referred to throughout the report as fermentation-derived proteins or microbial proteins. Other fermentation-based applications, such as enzymes used for fermentation, fall outside the scope of the analysis. Cell-based food or feed also falls outside the scope, as it is produced by animal cell culture rather than fermentation. The study is not primarily concerned with fermentation technologies as such, but with their possible interaction with conventional agriculture: where they may create new opportunities, where they may introduce adjustment pressure, and under what conditions they may complement, compete with, or partially substitute existing agricultural production and value chains.

Methodologically, the study combines three main components. First, it draws on a structured review of academic and grey literature, complemented by a regulatory mapping and a database of relevant EU firms. Second, it incorporates targeted stakeholder evidence, including interviews and foresight workshops bringing together representatives of farming, industry, and research. Third, it uses a scenario-based foresight approach to explore how different combinations of competitiveness, policy support and market acceptance may shape medium- and

long-term outcomes. This combined approach is necessary because the evidence base remains uneven: while some aspects of the current technological and regulatory landscape are relatively well documented, the future implications for agriculture and rural areas are characterised by uncertainty and depend heavily on how value chains evolve in practice.

The Final Report is structured around six study questions. It first reviews the current state of play of biomass and precision fermentation for protein applications in food and feed. It then examines the possible implications for the competitiveness and economic sustainability of EU farming sectors and farm sizes. The report subsequently assesses the medium- and long-term implications for agricultural markets, the potential opportunities for farmers and the rural economy, the possible challenges associated with scaling-up these technologies, and the role that policy and support mechanisms may play in shaping outcomes for the EU farming sector. Throughout the analysis, the report adopts a balanced perspective. Fermentation-derived proteins are neither treated as an inevitable substitute for conventional agriculture nor as a marginal technological niche. Rather, the report assesses the circumstances under which these technologies may generate positive, negative or mixed effects for agriculture, and the extent to which those effects are likely to differ between sectors, territories and time horizons.

Taken together, the study aims to support an evidence-based policy discussion on the place of biomass and precision fermentation in the future EU protein economy. Its central concern is not only how these technologies will develop, but how their development can be aligned with the interests of EU farmers, the resilience of agricultural production systems, and the vitality of rural areas.

2 Methodology and limitations of the study

2.1 Literature review

The literature review followed a systematic approach to identify and analyse evidence on microbial proteins produced via precision fermentation and biomass fermentation, including yeast proteins and mycoproteins. This process builds directly on the methodology outlined in the Inception Report (Chapter 5.1), using structured searches refined through team iteration to ensure transparency and replicability. Key adaptations include harmonised search strings for Scopus, with documented results and screening steps.

The search execution targeted peer-reviewed literature in Scopus using standardised blocks for technologies (e.g. “precision fermentation” OR “biomass fermentation” OR “single cell protein” OR “mycoprotein”) combined with economic indicators like cost structures, regulatory constraints and competitiveness. Restrictions matched the inception plan: English language, 2015-2025 publication years, and Scopus categories (Food Science, Biotechnology, Nutrition). Iterative refinements reduced initial hits (e.g. 165 to 4 for competitiveness) by adding thematic keywords such as “techno-economic”, “EFSA” or “life cycle”. Abstracts were scanned and chosen when relevant.

The primary database used for this study includes Scopus, supplemented by EU-Lex for regulatory documents. Grey literature searches used similar keyword structures on sites of organisations like EFSA, FAO, OECD, JRC and WUR, with snowballing from reference lists of key papers. In addition to papers selected through databases, several key papers on fermentation were selected by experts from Wageningen Food and Biobased Research.

Titles and abstracts were screened in EndNote for duplicates and relevance, applying coding per subject to extract the most relevant data. These coded subjects include: Production Efficiency, LCA, feedstock use, cost structure, consumers, competitiveness, aquaculture, alternative meat, regulatory and trade barriers. Through this systematic process, 87 sources were considered relevant and were included in the literature analysis.

After the literature review, attached in the annex, several data gaps remained. These are addressed through interviews with stakeholders. We executed six interviews with representatives from industry and academia. The results of these interviews further benefit the data collected through the literature review.

The first two questions of the report will present the findings based on the literature research.

2.2 Foresight

The foresight component was used primarily to address the forward-looking study questions, namely SQ3, SQ4, SQ5 and SQ6. It provided the main analytical basis for assessing how biomass and precision fermentation proteins may affect agricultural markets in the medium and long term (SQ3), what opportunities they may create for EU farmers and rural economies (SQ4), what challenges they may pose (SQ5), and what types of policy responses may be needed to maximise benefits and mitigate risks (SQ6). The foresight workstream was not intended to replace the evidence base developed for the earlier study questions on the current state of play, costs, competitiveness and existing market conditions. Rather, it built on that evidence and used it to explore plausible future pathways and their implications for agriculture and rural areas.

The foresight component provided the forward-looking analytical framework through which the medium- and long-term implications of biomass and precision fermentation for EU agriculture and rural areas were explored. In this study, foresight was not used to predict a single future, produce quantitative forecasts, or rank the probability of alternative outcomes. Its purpose was to construct and test a set of contrasting development pathways against which potential market, farm-level, rural-economy and policy implications could be assessed.

This distinction is important for interpreting the findings. The scenarios should be read as exploratory tools rather than predictions. They were designed to make explicit the assumptions, uncertainties and chains of consequences that could shape the future interaction between fermentation-derived proteins, agricultural markets and rural value chains. The inclusion of a highly favourable pathway, as well as more restrictive or weakly embedded pathways, is therefore a methodological feature of the exercise. Such scenarios allow the analysis to stress-test hypotheses, explore alternative consequences and identify the conditions under which positive or negative impacts for farmers might arise.

The foresight workstream was organised as a sequential, evidence-informed and participatory process. The systematic literature review and scoping interviews informed the analytical preparation of the workstream by identifying the main technological, market, regulatory and agricultural issues relevant to biomass and precision fermentation. This evidence base then fed into the foresight process, which consisted of three linked workshops held in March 2026. The first workshop focused on scenario building and narrative construction; the second applied the scenarios to opportunities and challenges for farmers and rural areas; and the third translated the preceding findings into policy implications, enabling conditions, safeguards and framework considerations.

A preliminary clarification on the scope is necessary. The formal focus of the study is biomass and precision fermentation in relation to food and feed proteins and their implications for EU agriculture. However, the foresight discussions

sometimes went beyond fermentation-derived proteins in a narrow sense and touched on the wider fermentation-based bioeconomy, including feed additives, amino acids, enzymes, biofertilisers, biopesticides, side-stream valorisation, biomass hubs, biorefineries and links with biogas or other rural industrial systems. This broader discussion was retained where it was necessary to understand the potential implications for farmers and rural areas. The rationale is that fermentation-derived protein value chains do not develop in isolation: they may share feedstocks, infrastructure, skills, ownership models, processing assets and regulatory issues with wider fermentation-based applications. References to this broader bioeconomy should therefore be understood as contextual and analytical extensions of the protein-focused study, not as a full assessment of the entire bioeconomy.

Methodologically, the foresight process followed a 2x2 uncertainty-matrix approach. In the first workshop, participants identified drivers influencing the development of fermentation technologies and their interaction with agricultural markets. These drivers included regulation and governance, technological and industrial capacity, economic competitiveness, market adoption, consumer and farmer acceptance, input availability, energy costs, sustainability pressures and global protein trade stability. From this wider set of drivers, two critical uncertainties were selected to structure the scenario framework. The first concerned EU value-chain competitiveness and acceptance relative to conventional agriculture. The second concerned the extent to which the regulatory and policy environment enables or constrains the development, scaling and market uptake of fermentation technologies.

The combination of these two uncertainties generated four scenario narratives. Each scenario explored how biomass and precision fermentation could evolve by 2030 and 2050 under different combinations of competitiveness, acceptance – both for farmers and consumers, regulatory support and policy incentives. Participants developed the narratives in breakout groups and assessed potential implications for traditional agricultural sectors through a structured market impact scorecard. The scorecards were qualitative and directional. They were used to identify plausible mechanisms, affected sectors and relative magnitudes of change, rather than to generate modelled estimates of market impact.

The second workshop used the scenario logic to examine opportunity pathways and challenge landscapes for EU farmers and rural areas. It did not systematically reopen or re-apply all four scenarios at the same level of detail. Instead, it used the scenario framework as a structured backdrop, with particular attention to the most favourable pathway, to explore what would need to happen for biomass and precision fermentation to generate meaningful benefits for farmers and rural territories. This “best-case” pathway was used as an analytical device rather than as a prediction: it helped participants identify the potential opportunity mechanisms, but also the practical barriers, distributional risks and institutional conditions that would have to be addressed for those opportunities to materialise. Where relevant, the discussion then contrasted these mechanisms with more

restrictive pathways, in which scale-up, farmer participation or territorial embedding remain weaker. This step was particularly important for SQ4 and SQ5, because the implications for farmers often arise not only through direct substitution of conventional proteins, but also through more indirect mechanisms such as feedstock demand, input markets, contracts, cooperative structures, processing location, infrastructure needs, territorial disparities and local value capture.

The third workshop built on this opportunity-and-challenge analysis to examine policy implications. It did not constitute a full policy evaluation of each scenario. Rather, it focused on the enabling conditions, safeguards and policy responses that would be needed to move closer to the more favourable pathway, while also mitigating the risks identified under less favourable or weakly embedded developments. In this sense, the policy discussion was deliberately conditional: it asked what would be required for microbial protein value chains, and related fermentation-based bioeconomy activities, to generate benefits for farmers and rural economies rather than develop mainly as externally controlled or weakly agriculturally embedded value chains. This workshop provided the main foresight input for SQ6. Its findings should therefore be understood as qualitative, scenario-informed policy reflections based on structured stakeholder discussion. They are not a full policy evaluation, nor do they represent a statistically representative consultation of all relevant agricultural and fermentation-related actors.

Several limitations should be kept in mind when interpreting the foresight evidence. First, the workshops were designed for analytical depth and technically informed discussion, not for numerical representativeness. Farmers' organisations, cooperatives and other traditional agricultural stakeholders were invited to participate, and agricultural perspectives were present in the foresight process. However, actual participation from traditional agricultural stakeholders remained limited compared with participation from actors already active in, or closely connected to, biomass fermentation, precision fermentation, biotechnology, food and feed innovation, research and policy. This imbalance is important because several of the issues explored in SQ4, SQ5 and SQ6 – including farmer participation, cooperative models, shared infrastructure, value-chain integration, advisory support and policy needs – depend heavily on the practical realities, constraints and strategic preferences of farmers themselves. The lower level of participation may reflect a combination of factors, including the technical and still emerging nature of the topic, uncertainty about its relevance for different farm types, or lower prior engagement with fermentation-related value chains. As a result, the workshops could not fully capture the diversity of the EU farming sector in terms of farm size, sector, region, production model, organisational capacity or degree of exposure to fermentation-related developments. The foresight findings are therefore strongest as a means of identifying possible directions of change, tensions, enabling conditions and risk mechanisms. They should be interpreted more cautiously when assessing how widely these views are shared across the farming sector, or how realistic different integration pathways would be for the majority of farms.

Second, the evidence base is qualitative. The scenarios do not provide forecasts, quantified projections or probability-weighted estimates. Their value lies in exploring plausible pathways and identifying the conditions that could make particular outcomes more or less likely. Further, **Scenario 2** and **Scenario 3** are deliberately “extreme”. They explore pathways that, albeit unlikely, may be useful to identify specific chains of consequences – to be noted that what is unlikely today might unexpectedly become likely tomorrow. Very few people would have considered a global pandemic likely in 2010. This is why it is important to also explore unlikely scenarios in foresight. Consequently, the market effects, farm-level implications and policy needs derived from the scenarios should be read as structured qualitative findings rather than as predictive estimates.

Third, there was a scope-alignment challenge across the foresight process. The initial scenario framework was centred on fermentation-derived proteins and their implications for agricultural markets. In the later opportunity, challenge and policy workshops, participants often broadened the discussion to the wider fermentation-based bioeconomy, because many potential farmer and rural-economy effects relate to feedstocks, side-streams, inputs, infrastructure and industrial organisation rather than to final protein products alone. This creates some asymmetry between the narrower protein focus of the scenario framework and the broader value-chain discussion in SQ4, SQ5 and SQ6. The report therefore uses the broader material selectively and only where it helps explain the conditions under which fermentation-derived protein value chains could affect farmers, rural territories or agricultural markets.

Fourth, the policy findings are particularly dependent on workshop input. This is appropriate given the purpose of foresight, but it means that SQ6 should be read as a scenario-informed discussion of possible policy needs, not as a definitive policy prescription. Where the analysis refers to support for infrastructure, cooperatives, advisory systems, local value capture or broader bioeconomy linkages, these should be interpreted as governance considerations arising from the foresight exercise and not as evidence that such outcomes will occur automatically.

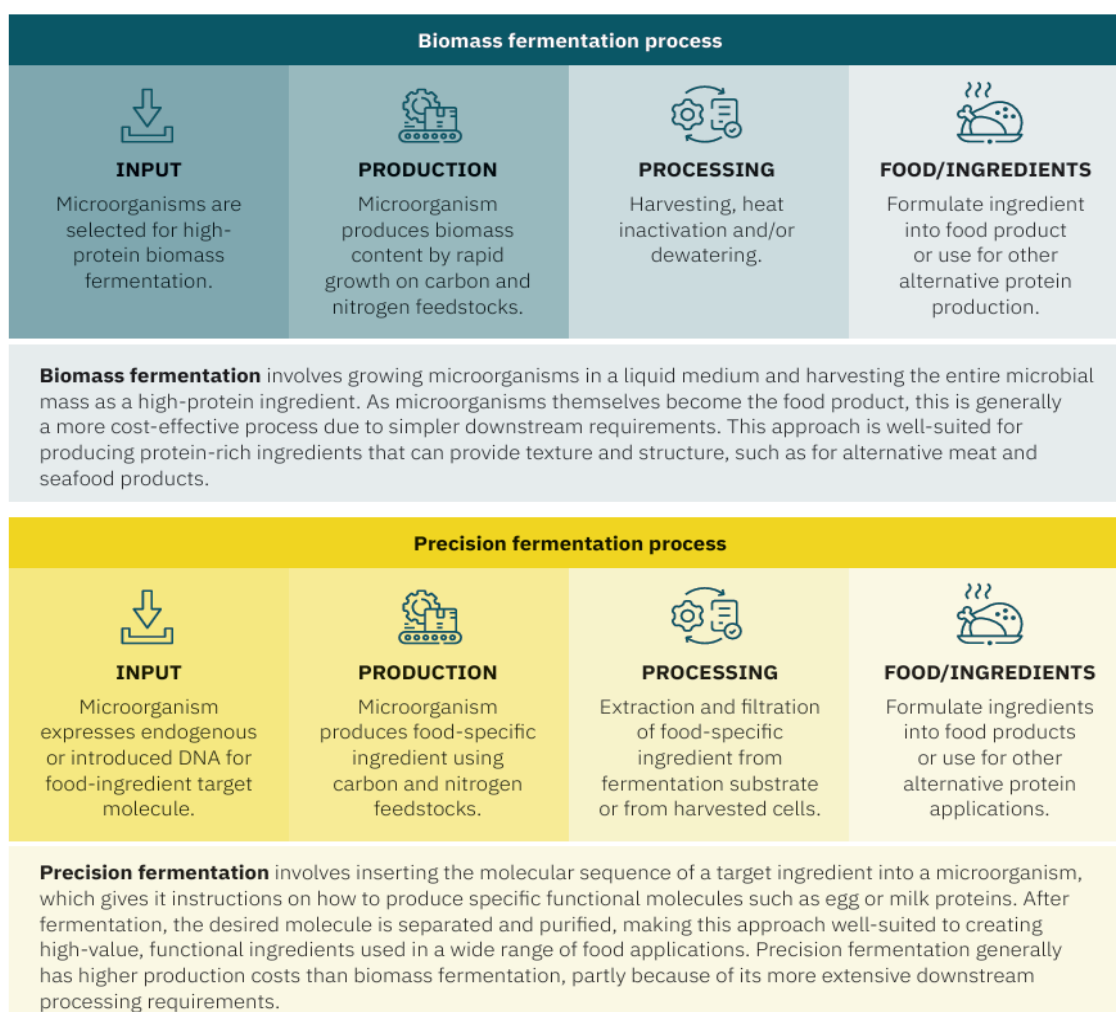
Overall, the foresight component should be understood as a structured qualitative method for linking uncertainty, scenario development and policy reflection. Its contribution is to clarify how different combinations of competitiveness, acceptance, regulation, policy support and value-chain organisation could shape the implications of biomass and precision fermentation for EU agricultural markets, farmers and rural areas. Its findings are therefore most useful for identifying plausible mechanisms, conditional opportunities, potential risks and enabling policy questions, rather than for predicting the future size or timing of market impacts.

3 Study questions

3.1 SQ1 - What is the current state of play regarding the development of the technologies and use of biomass and precision fermentation proteins for food and feed applications?

The answer to this question provides a comprehensive overview of the current state of play of biomass and precision fermentation technologies for microbial proteins in food and feed applications, with a specific focus on their technological maturity (Technology Readiness Levels- TRL) ⁽¹⁾, value chains, production resources, commercial deployment and sustainability performance. The analysis draws on the systematic literature review (Annex I – Literature review) and is further substantiated by six scoping interviews conducted with EU-based industry practitioners, investors and sector experts between January and February 2026. The following graphic provides a visual overview of the fermentation platforms discussed.

(¹) Technology readiness level (TRL) scale uses the parameter that evaluates the maturity of a technology according to a series of indicators that go from 1 (the basic principles are documented) to 9 (the technology is released, and industrial production is started". The TRL scale is currently the point of reference for determining the development or maturity of a research and its readiness for the market uptake and potential investments. More information can be found here: [TRL | EURAXESS](#)

Figure 1 Overview of biomass and precision fermentation processes (GFI, 2025)

State of play

The development of fermentation-based protein production has accelerated markedly over the past decade, driven by pressures on conventional agricultural systems, concerns over environmental sustainability, and advances in industrial biotechnology (Knychala et al., 2024; Ye et al., 2024). Within this broader landscape, biomass fermentation and precision fermentation represent two distinct but complementary technological paradigms. While both rely on the use of microorganisms, they differ fundamentally in their objectives, process configurations, maturity levels, and market positioning.

The literature reviewed provides a detailed picture of a sector characterised by the coexistence of both long-established and emerging production pathways. While some approaches, such as mycoprotein-based products, have a substantial commercial history, others remain in earlier stages of development. As a result, the sector remains uneven in terms of technological readiness, economic competitiveness, and regulatory integration, particularly for food applications. Across platforms, the evidence drawn from literature indicates that fermentation-enabled proteins can deliver very high land and water efficiency

relative to conventional animal-derived proteins. At the same time, the realised sustainability performance and economic competitiveness of these pathways depend strongly on a set of underlying conditions:

- First, energy demand for cooling, aeration, mixing and harvesting or drying, together with the carbon intensity of the energy mix, plays a central role in determining the climate footprint of fermentation facilities.
- Second, feedstock choice and its opportunity cost, specifically whether production relies on waste and side-streams, CO₂, other gas-based feedstocks, or on refined sugars, influences both environmental impacts and exposure to feedstock price volatility.
- Third, the intensity and cost of downstream processing, which are particularly high for purified precision-fermentation proteins, affect overall production costs and thus the range of viable market applications.
- Fourth, the pace and predictability of market authorisation, especially under the EU novel food framework, influence how quickly and in which segments microbial proteins can enter the European food markets.

This leads to a clear pattern: volume growth is most advanced where (a) the product is whole biomass (lower purification needs) and/or (b) feed applications provide a clearer near-term market pull than human food authorisations.

These structural drivers, identified from literature, are confirmed by interview evidence.

- Technical experts from the microbial protein sector emphasised that many companies systematically underestimate the true cost and complexity of scaling fermentation facilities: while early-stage R&D often focuses on proof of concept, the transition to commercial scale exposes weaknesses in process robustness that are not visible at the pilot stage.
- Representatives of a biomass fermentation company at pilot-to-demonstration scale noted that predictive process models lose their validity above approximately 2–3 m³, a threshold at which multiple parameters become unreliable.

This asks for stepwise scale-up strategies that can involve volume increases of up to a factor of thirty per step, with equivalent implications for capital expenditure. This observation is consistent with the broader techno-economic literature on bioprocess scale-up risk (Dickson & Mansouri, 2025; Risner et al., 2023) and shows why achieving cost parity with conventional proteins constitutes a structural rather than merely technical challenge.

A precision fermentation company operating at demonstration scale further illustrated this dynamic: despite having validated production runs at commercially relevant volumes and experiencing strong market demand, the current production

cost exceeds the market price, meaning each unit sold incurs a loss. In this context, scaling up is not primarily a technical challenge but a financial optimisation problem; increasing volumes under current cost conditions amplifies losses rather than reducing them. The company assessed its TRL at 6–7 (prototype tested in relevant environment and approved prototype), using economic viability as the criterion for TRL 9, and further noted that the TRL classification is also strategically maintained at a lower level to retain access to public subsidy instruments during the scale-up phase.

Animal feed first

Animal feed currently appears to be the most immediate commercial outlet for microbial proteins (GFI, 2026), whereas food applications remain more constrained; however, aggregate data on market volumes remain limited. Within feed, aquaculture is a clear entry segment identified, because single-cell proteins can provide favourable amino-acid profiles and high digestibility, and have shown promising performance at relevant inclusion levels in aquafeeds (Buttle et al., 2024). Nutritional quality alone, however, does not explain why feed applications are favoured, as many microbial proteins also exhibit strong profiles for human food. Rather, the near-term advantage of feed markets reflects differences in regulatory pathways and market access conditions; in the EU, novel foods for human consumption require pre-market authorisation under the Novel Food Regulation, whereas non-GMO feed materials are generally placed on the market under Regulation (EC) No 767/2009, subject mainly to registration or notification requirements, with separate regimes applying to feed additives and GM feed. As a result, it is not a question about ‘faster approval’ but of structurally different evidentiary requirements, timelines and uncertainty profiles, which together make feed applications a more accessible route to market for many fermentation-derived proteins in the current EU context.(Ahmad et al., 2022) ⁽²⁾.

Interview evidence further explains this situation in two ways. First, technical experts noted that early scaling successes in biomass fermentation have largely been achieved in fish feed and pet food precisely because regulatory barriers are lower (GFI, 2026). Second, an independent cross-sector expert highlighted that biomass fermentation targeting niche, high-functional-value applications, rather than bulk commodity protein, represents the most credible near-term investment thesis in the EU context, as bulk feed substitution of e.g. soymeal remains economically unviable at current production cost levels. However, it may become more viable in the longer term as costs decline and strategic considerations gain importance. This perspective reinforces the differentiated market-entry logic described in the literature and aligns with evidence on the persistent cost gap between microbial protein and conventional feed ingredients (Pesante et al., 2024; Sobhi et al., 2023). However, this gap may narrow over time with

(²) Muhammad Ijaz Ahmad, Shahzad Farooq, Yasmin Alhamoud, Chunbao Li, Hui Zhang, A review on mycoprotein: History, nutritional composition, production methods, and health benefits, Trends in Food Science & Technology, Volume 121,2022,Pages 14-29, ISSN 0924-2244, <https://doi.org/10.1016/j.tifs.2022.01.027>.

technological progress and scaling, and in light of regulatory developments such as the forthcoming application of the EU Regulation on Deforestation-free Products.

Consumer responses

Evidence from literature further suggests that consumer responses to precision-fermentation products are heterogeneous and depend on product type, framing, cultural reality, regional traditions, trust, perceived naturalness and perceived benefits, rather than indicating a uniform acceptance barrier. Some products are indeed positioned toward vegan or animal-free market segments, but this does not by itself imply broad market uptake (Banovic & Grunert, 2023). In this regard, a public investment institution active in the protein transition noted during the interview a meaningful shift in industry framing: whereas early-stage discourse was largely structured around sustainability and animal welfare, the sector is increasingly positioned in terms of food security, strategic economic opportunity, and ingredient supply chain resilience. This reframing reflects a broader recognition, which is supported by both practitioners and investors.

Stakeholder interviews, together with recent literature on consumer acceptance, indicate that market adoption in practice is largely shaped by price and sensory performance, while explicitly normative or ideological considerations tend to play a more indirect role. In this framing, industry and investor narratives increasingly present precision and biomass fermentation as tools for improving functional and sensory quality, rather than as standalone sustainability solutions, even though sustainability arguments remain part of the wider discourse (Banovic & Grunert, 2023; Systemiq, 2025).

Taken together

The above identified factors suggest a differentiated near-term pattern. Biomass-fermentation pathways appear most immediately relevant in feed ingredients and in some whole-biomass applications, while precision fermentation is more often directed toward higher-value food ingredients where specific functionality can justify higher processing costs and regulatory effort (Buttle et al., 2024).

1.1.1.1 Overview of fermentation processes for generating microbial proteins

The literature reviewed establishes a taxonomy that situates biomass fermentation and precision fermentation in relation to traditional fermentation. In the following section, the core processes of both traditional fermentation, biomass fermentation and precision fermentation are briefly reviewed. Traditional fermentation serves as the technological and economic benchmark for biomass and precision fermentation.

However, as this overview illustrates, the taxonomy is primarily intended for conceptual clarification, since specific organisms and techniques often exhibit overlapping characteristics.

Traditional fermentation

Traditional fermentation uses microbial metabolism to transform existing food or feed substrates, which may be of plant, animal, marine or fungal origin. In this study, it serves as a technological and economic baseline because it has been practised for centuries in households, farms, and more recently, industrial contexts. Traditional fermentation is primarily used to preserve products or to modify their sensory, nutritional or functional properties. Incremental innovation in traditional fermentation has largely focused on microbial selection and process control, with valorisation of agro-industrial by-products emerging only more recently in specific applications. Traditional fermentation represents the oldest and most culturally embedded fermentation pathway, with documented use spanning more than 10 000 years across global food systems. Historical accounts and scientific reviews show that this has been a foundational technology for food preservation, safety, nutrition, and flavour development across civilisations for ages. Fermented foods such as beer, wine, cheese, yoghurt, kimchi, sauerkraut, sourdough, and kefir form part of longstanding dietary traditions and continue to deliver measurable benefits to food quality, shelf life, and human health.

Traditional fermentation remains the technological and economic benchmark for biomass and precision fermentation. It relies primarily on naturally occurring or intentionally propagated single strains or microbial consortia, including lactic acid bacteria, yeasts, and filamentous fungi. These microorganisms transform raw materials through enzymatic and metabolic activity, producing organic acids, ethanol, peptides, vitamins, and bioactive compounds that enhance digestibility, reduce antinutritional factors, inhibit pathogens, and improve sensory attributes. Modern analyses emphasise that fermented foods can increase nutrient bioavailability and are associated with reduced incidence of noncommunicable diseases when incorporated into diverse diets (Diez-Ozaeta & Astiazaran, 2022).

Industrialisation of these fermentation processes, such as beer, yoghurt and wine production, has introduced standardised starter cultures, controlled fermentation environments, and optimised microbial communities, bridging the gap between artisanal heritage and modern process control. Nevertheless, traditional fermentation remains distinct from biomass and precision fermentation: its primary goal is transforming food matrices, not producing purified proteins or isolated microbial biomass.

From a technological readiness perspective, traditional fermentation systems represent fully mature (TRL 9) global industries with decades or centuries of operational experience. Large-scale dairy fermentation, brewing, winemaking, and vegetable fermentation have well-established supply chains, regulatory frameworks, and consumer familiarity. The stability and maturity of these systems have enabled continual innovation in starter-culture development, process optimisation, and product diversification among others.

Biomass fermentation

Whereas in traditional fermentation microorganisms transform raw materials through enzymatic and metabolic activity, biomass fermentation is explicitly oriented towards the production of new microbial proteins in the form of single-cell protein (SCP). Here, the microbial cell itself constitutes the final product, either used whole or after being subjected to limited downstream processing.

Among novel fermentation-based protein pathways, biomass fermentation is the most technologically mature and commercially established. The literature documents several decades of industrial experience, with filamentous fungal, yeast, and bacterial platforms having progressed from experimental concepts to large-scale production systems. Mycoprotein products, particularly those derived from the filamentous fungus *Fusarium venenatum*, represent the most advanced biomass fermentation platform. The most known product Quorn, based on *Fusarium venenatum* biomass, has been safely on the market since 1985 – well before today's EU novel-food framework providing a clear regulatory precedent that now enables other producers to enter the market following the recent expiry of key patents in the 2010s and early 2020s.

Biomass fermentation is based on continuous aerobic fermentation. It enables high biomass yields with protein contents exceeding 40% of dry weight and complete essential amino acid profiles (Souza Filho *et al.*, 2019; Ye *et al.*, 2024). Techno-economic modelling indicates that, under large-scale continuous production and optimised feedstock use, mycoprotein could reach price parity with beef protein in minced and processed applications, rather than across all beef product formats, and only under the specific assumptions used in the model (Sturme, Hugenholtz; and Bruins, 2022).

Life-cycle assessments show substantially lower land use, water use, and greenhouse gas emissions compared to conventional livestock protein (Souza Filho *et al.*, 2019; Fernández-López *et al.*, 2024). However, energy demand for aeration, agitation, cooling, and downstream dewatering remains a dominant operational and environmental cost driver (Dickson & Mansouri, 2025; Fernández-López *et al.*, 2024).

These cost dynamics are reinforced by operational experience from companies at the pilot-to-demonstration stage. A fungal biomass fermentation company operating its own demo plant noted that utility costs, particularly energy for temperature control, constitute a significant cost component. While in their case feedstock costs are comparatively lower owing to flexibility across sugar sources, including agro-industrial side-streams such as potato processing liquors. The same company confirmed that full sterility is not required for their process, which materially reduces capital expenditure compared to precision fermentation configurations, consistent with cost modelling in the literature (Dickson & Mansouri, 2025). Decontamination at demonstration scale nonetheless remains technically demanding, and the transition to continuous fermentation, which is necessary for optimal process economics, constitutes a key remaining

engineering challenge, consistent with the scaling risk literature (Risner et al., 2023; Hossain et al., 2024). Feedstock quality variability across suppliers was also identified as a persistent operational constraint, introducing process uncertainty that becomes more significant as production volumes increase.

Furthermore, interviewees representing biomass fermentation companies consistently positioned their products not as commodity protein sources competing on price, but as mid-to-high-value, functional whole-food ingredients targeting bakery, hybrid dairy, and nutritional applications. This market positioning reflects a deliberate strategy to enter segments where natural, minimally processed ingredients command a premium, and where functional properties such as texture, protein composition and fibre content differentiate the product from plant-based alternatives. This strategic logic is consistent with findings in the literature on competitive positioning of microbial proteins (Banovic & Grunert, 2023; Reinhardt & Monaco, 2025).

An established example product of biomass fermentation is Quorn™, produced from *Fusarium venenatum* grown in bioreactors in the UK, which produce approximately 67 000 t/y, supporting a global mycoprotein market valued at USD 805 million (EUR 692 million) in 2025, with industry projects to reach USD 1.46 billion (EUR 1.25 billion) by 2034. The process is TRL 9, competing directly with chicken and ground beef in processed segments (Precedence, 2025). Newer European platforms, such as ABUNDA® - which also uses *Fusarium veneratum*, illustrate a parallel trajectory in business-to-business markets. With a reported EU production capacity of 60 000 tonnes per year, ABUNDA® is positioned as an ingredient competing with soy and pea protein concentrates and is currently assessed at TRL 7-8, with rapid scale-up underway.

Yeast-based single cell proteins occupy an intermediate position between mycoproteins and more experimental bacterial systems. The literature highlights the robustness, substrate flexibility, and regulatory familiarity of yeasts such as *Saccharomyces cerevisiae* and *Candida utilis*. In this study, the focus is on yeast biomass produced and marketed as microbial protein, which is distinct from the long-standing use of yeasts in traditional food fermentations such as bread (CO₂), beer or wine (ethanol). Yeast SCP is already used at scale in feed applications, where its ability to grow on low-cost substrates, including molasses and spent industrial liquors, has enabled the development of large and established markets, particularly in aquaculture. By contrast, its direct use in human food applications as a protein-rich ingredient remains more limited, reflecting the challenges in mimicking textural and sensory properties of animal-derived products ⁽³⁾.

A representative industrial-liquor route is PEKILO®, originally developed in Finland in the 1970s, it converts sulphite liquor from paper mills into approximately 55% single-cell protein. In Finland, Enifer is constructing a 3 000

⁽³⁾ D'Almeida, A.P.; de Albuquerque, T.L. Is It Possible to Produce Meat Without Animals? The Potential of Microorganisms as Protein Sources. *Fermentation* 2025, 11, 24. <https://doi.org/10.3390/fermentation11010024>

t/y commercial facility, moving the platform from pilot scale (TRL 6) toward early commercial deployment (TRL 8) (Enifer, 2025).

Yeast protein isolates such as AngeoPro™, produced by Angel Yeast (China) compete with whey and soy isolates on both price and functionality and are embedded in a global yeast-based protein market valued at approximately USD 11.9 billion (EUR 10.2 billion) in 2025 (FNB, 2025). These systems are fully commercial (TRL 9). By contrast, Engevita®, produced by Lallemand (Canada), is better characterised as a yeast-derived ingredient platform based on spent brewer's yeast, used mainly as a feed additive and flavour ingredient with gut-health and functional benefits and is likewise considered a mature, established platform (Grigore, Mircea & Pogurschi, 2025).

Yeast SCP is typically positioned as an ingredient rather than a centre-of-plate protein, reflecting both sensory limitations with respect to the strong flavour of yeast extract and lack of textural functionality.

Methane-based bacterial SCP represents one of the most resource-efficient biomass fermentation routes and is also among the most mature non-sugar-based platforms (Dickson & Mansouri, 2025). By converting methane – typically sourced from natural gas, industrial off-gases or biogas – into microbial biomass, these systems can achieve very high protein yields per unit of land and water, which underpins their positioning as alternatives to fishmeal in aquafeeds. Available feeding trials report nutritional profiles and performance outcomes that are broadly comparable to fishmeal, supporting their use as partial substitutes in aquaculture diets (Woolley et al., 2023). Commercial deployment is already underway. FeedKind®, for example, operates a 20 000 tonne per year plant in China, producing a fishmeal-replacement protein, with amino acid profiles closely matching conventional fishmeal. These installations are typically assessed at TRL 7-8 (García Martínez *et al.*, 2022). Similarly, UniProtein®, a Danish company which recently entered into a Joint Venture with a Saudi Industrial Investment Group, produces a bacterial SCP with protein contents exceeding 70% and is commercially available as a fishmeal and soy alternative. This segment forms part of a rapidly expanding global market projected to reach approximately USD 3.1 billion (EUR 2.66 billion) by 2026, with annual growth rates exceeding 25%, and with around 70% of volumes directed to aquaculture feed (MRA, 2025).

Methane-based SCP is treated here as a specific subset of bacterial SCP, distinct from other gas-fermentation routes such as CO₂/H₂-based systems (e.g. Solar Foods' Solein®), which are also emerging but are discussed separately in the broader mapping of biomass-fermentation platforms. In most current methane-SCP configurations, primary agricultural producers do not act as direct feedstock suppliers, as the methane stream is derived from natural gas or from centrally upgraded biogas rather than from farm-level manure or slurry; farmer involvement therefore arises mainly on the demand side, through potential changes in feed markets, rather than through participation in the upstream supply of substrates.

Precision fermentation

Precision fermentation occupies a more specialised niche, using microorganisms, which are generally genetically modified, as cellular factories to synthesise specific, purified molecules that can replicate or substitute animal- or plant-derived ingredients. These conceptual distinctions from traditional and biomass fermentation are important, as they underpin differences in performance metrics, cost structures, environmental profiles, and regulatory treatment.

Precision fermentation is technologically distinct from biomass fermentation and occupies a different position within the protein landscape. Whereas biomass fermentation focuses on generating high yields of whole microbial biomass as a protein source, precision fermentation leverages microbial hosts as production platforms for specific, high-value functional molecules. The literature emphasises that, despite its recent prominence in food system debates, precision fermentation is built upon decades of established industrial biotechnology (TRL 9 in pharma, and enzyme and other markets such as vitamins and amino acids). Moreover, the successful commercialisation of fermentation-derived chymosin enzymes in the cheese industry is repeatedly cited as proof of concept for large-scale, food-grade recombinant protein production. In contemporary food and feed contexts, precision fermentation is primarily deployed to produce high-value, functionally specific proteins rather than bulk protein sources, which are currently concentrated in a handful of commercial pillars (Mark Sturme, 2025; Knychala *et al.*, 2024).

Practitioner experience from a precision fermentation company operating at demonstration scale aligns with the literature's characterisation of the current stage of development. The largest validated production runs reported by interviewed companies fall in the range of tens to a few hundred cubic metres of reactor volume, a scale consistent with TRL 6–7 as defined in the academic literature (García Martínez *et al.*, 2022). The main technical uncertainties at this stage have shifted from fundamental feasibility toward scale behaviour and process robustness: recovery rates, purity-yield trade-offs, stability across consecutive runs, and the downstream implications of different separation strategies. The interviewee described this phase as 'learning by doing', with parallel scale-up and process development creating a configuration in which regulatory approval trajectories and investment planning must proceed under conditions of technical uncertainty. This feature of precision fermentation scale-up is not fully captured in literature-based TRL assessments (LEVER, 2022).

The most recent applications include animal-free dairy proteins (such as whey and casein), egg proteins (notably ovalbumin), and flavour-active compounds such as heme proteins. These products are already present in commercial food formulations, particularly in dairy alternatives and plant-based meat analogues:

- β -lactoglobulin and casein. Produced via fungal or yeast (e.g. *Trichoderma reesei*) fermentation and used in ice cream, cheese analogues, and other dairy alternatives. These ingredients are already used in consumer

products in countries such as the United States, Singapore, Israel and Canada, but have not yet obtained novel-food authorisation in the EU and continue to face regulatory hurdles there, including prolonged and sometimes unsuccessful validation of novel-food dossiers (e.g. for β -lactoglobulin applications by Perfect Day and Remilk) (Mark Sturme, 2025; FDA, 2022; LLP, 2019; Vartianen, 2026)). Typical TRL levels for food applications range from 6 to 8, depending on the regulatory and market context in each region.

- Collagen and elastin are specific high value collagen products produced by fermentation. They are already commercial in medical applications, cosmetics and advanced materials. These ingredients are produced by genetically engineered micro-organisms and when used in food, would be treated as novel foods requiring EU pre-market authorisation, whereas the current non-food applications are regulated under cosmetics or medical-device frameworks rather than the NFL. It provides consistent, pathogen-free collagen for scaffolds and high-value applications. TRL levels range from 8 to 9 in non-food and early-stage TRL levels in food uses (de Moura Campos *et al.*, 2025).
- Heme proteins (e.g. leghemoglobin, myoglobin) are central to recreating meat-like flavour and “bleeding” in plant-based analogues to meat and are already in commercial products (Knychala *et al.*, 2024). An example is the Impossible Food soy leghemoglobin which is regulated under both Regulation (EC) No 1829/2003 on genetically modified food and feed and (EC) No 1333/2008 on food additives and has received favourable EFSA safety opinions under both these regulatory tracks.

From a technological standpoint, the literature identifies precision fermentation as facing intrinsic yield limitations. The production of heterologous proteins imposes a metabolic burden on host organisms and has inherently lower yields (kg protein/kg sugar) as compared to biomass fermentation. This, in turn, drives up feedstock consumption and downstream processing costs. Consequently, precision fermentation is structurally disadvantaged in competing with either biomass fermentation or conventional agriculture for the provision of bulk dietary protein. Instead, its current and foreseeable role lies in enabling functional substitution rather than volume replacement. Precision-fermented proteins can replicate the techno-functional properties of specific animal-derived ingredients with high fidelity, thereby addressing specific performance gaps in other food products. This explains the strong interest from major food companies and investors, despite challenges around cost reduction.

From a market positioning perspective, interviewed precision fermentation actors target high-value functional niches, including speciality dairy proteins, infant nutrition ingredients, and medical or sports nutrition applications. One interviewee illustrated this clearly with reference to a highly functional dairy protein for which conventional production requires very large volumes of raw milk, creating structural scarcity and high price levels that precision fermentation can address

by creating a new, scalable supply source. In such cases, the relevant competitive benchmark is not bulk whey protein but the functional performance and availability of a scarce speciality ingredient. This niche framing substantially alters the economics of precision fermentation relative to how they are typically presented in bulk cost comparisons (Knychala et al., 2024; Reinhardt & Monaco, 2025).

Taken together

The literature portrays traditional, biomass and precision fermentation as a continuum of fermentation-based protein pathways, anchored in long-standing food processing practices but differentiated by their objectives, process configurations and market roles. Traditional fermentation provides the historical and technological reference, transforming existing food matrices, while biomass fermentation produces single-cell microbial biomass as a bulk protein ingredient and precision fermentation generates purified, functionally specific proteins for niche, high-value applications.

1.1.1.2 Focus on main differences between food and feed

Across both biomass fermentation and precision fermentation, the underlying biological and production platforms used for food and feed applications are largely similar, even though they are not fully identical in every case. In many cases, the same or closely related microorganisms, bioreactor systems, metabolic pathways, and downstream processing steps are used, with differences arising mainly from product specifications, purity requirements and end-use considerations (Ye *et al.*, 2024; Pereira *et al.*, 2025; Dickson & Mansouri, 2025). From a technical standpoint, it is therefore more appropriate to speak of broadly shared fermentation platforms for food and feed, rather than of two fundamentally different technological systems. The main points of divergence typically emerge downstream of the production process, shaped by regulatory regimes, market economics, functional requirements, and socio-cultural acceptance.

Regulation represents the most immediate and structurally binding point of separation:

- In the European Union, fermentation-derived proteins intended for human consumption may fall under different regulatory frameworks depending on their specific characteristics. These include the Novel Food Regulation (Regulation (EU) 2015/2283) or, where genetically modified products are involved, Regulation (EC) No 1829/2003 on genetically modified food and feed. These procedures require extensive data on safety, toxicology, nutritional profile and exposure, and can be time-consuming and costly to navigate, particularly when requirements are uncertain at the outset for novel production systems. The proposed Food and Feed Safety Simplification Omnibus clarifies the regulatory status of various fermentation products produced with genetically modified microorganisms

and aims to reduce uncertainty in their classification within the EU-legal system. At the same time, the stringency of these assessments reflects the need to ensure a high level of consumer protection, and recent opinions show that not all applications are considered safe (Reinhardt & Monaco, 2025; (Ranchordás, 2021) ⁽⁴⁾). Evidence from interviews further elaborates this picture: across interviewed industry actors, regulatory unpredictability, rather than the strictness of safety requirements, is identified as the primary operational constraint on EU market entry. The 'stop-the-clock' procedure, whereby the review is suspended pending additional information requests, can extend authorisation timelines beyond initial estimates, with trajectories of five years or more even for applications based on well-characterised organisms. With some attributing these delays to shortcomings in dossier quality, while others view them as a consequence of procedural ambiguity and limited opportunities for interaction to obtain timely clarification. These extensions of timelines can increase administrative costs and uncertainty for applicants and investors. In particular for early-stage companies, which must simultaneously adapt their production processes and maintain an active regulatory dossier, this unpredictability directly undermines investor confidence.

- Several interviewees reported that, as a consequence, the preferred near-term strategy of start-ups and other companies is to pursue initial market authorisation outside the EU, notably via the Generally Recognized as Safe (GRAS) procedures in the United States, where legal procedures for market authorisation are estimated by industry actors at under one year for comparable applications.
- At the same time, these GRAS regulations are evolving, with recent US announcements signalling a tightening of the GRAS system. In the United States, the Department of Health and Human Services has instructed FDA to explore rulemaking to eliminate the option for companies to self-affirm GRAS status without FDA review, with a proposed rule on GRAS expected in 2026; this could lengthen approval timelines or increase evidentiary requirements for some ingredients while also strengthening formal oversight.
- In the EU, the proposed Food and Feed Safety Simplification Omnibus and the so-called Biotech Act I aim, among other objectives, to clarify the regulatory status of specific fermentation-derived products produced with genetically modified micro-organisms and to reduce the duration and frequency of stop-the-clock periods by improving dossier quality and transparency of data requirements.

⁽⁴⁾For example, recent EFSA opinions on certain precision-fermented or otherwise microbial-derived ingredients have identified unresolved safety concerns, including limited toxicological data and uncertainties regarding allergenicity, which shows that not all novel food applications are considered safe (Reinhardt & Monaco, 2025).

- Together, these developments may either reinforce or partly narrow the gap between EU-based innovation and EU market deployment, depending on how they are implemented in practice (Systemiq, 2025; Annex II).

By contrast, feed ingredients follow a distinct regulatory pathway with comparatively lower evidentiary requirements and faster approval timelines (See annex II). As a result, many fermentation technology developers initially target feed markets even when their long-term strategic ambition is food (Sharif *et al.*, 2021; Buttle *et al.*, 2024; Grigore *et al.*, 2025). Economic dynamics further reinforce this divergence.

Functional requirements also differ markedly between the feed and food markets. In animal nutrition, protein ingredients must be nutritionally adequate, digestible, and stable, but sensory attributes are less relevant. For human food, however, proteins must also deliver acceptable taste, texture, and functional performance in food formulations, such as emulsification, foaming, or gelation (Knychala *et al.*, 2024;). Specific functional demands for food ingredients may require precision fermentation, which enables the targeted production and purification of specific proteins with well-defined functionalities suited to high-value food applications. By comparison, biomass fermentation is inherently better aligned with higher-volume applications across both feed and food value chains, given their lower production costs, prioritizing nutritional value and production efficiency over refined functional performance (Knychala *et al.*, 2024; Pereira *et al.*, 2025).

The same fermentation process must compete against very different price benchmarks depending on its end use. In feed markets, microbial protein substitutes soymeal and fishmeal, where higher price points are tolerated in exchange for performance, reliability, and sustainability benefits (Buttle *et al.*, 2024; MRA, 2025). In food markets, by contrast, fermentation-derived proteins must compete with established animal and plant proteins, which are produced at enormous scale and benefit from mature, optimised supply chains (Risner *et al.*, 2023; Dickson & Mansouri, 2025). This price sensitivity for companies operating in food markets is particularly constraining for many biomass fermentation configurations, which, despite strong sustainability credentials, can remain cost-intensive due to high energy use and capital requirements, although the extent of these costs varies across organisms, feedstocks, scales and energy systems (Fernández-López *et al.*, 2024; Dickson & Mansouri, 2025). These cost dynamics are further magnified by a structural investment gap that shapes the pace of deployment across both feed and food markets. Interview evidence points to two persistent financing constraints in the EU: (i) at the early development stage, where long time-to-market horizons deter private venture capital; and (ii) at the scale-up stage, where the capital requirements for commercial fermentation infrastructure exceed the risk appetite of conventional investors (Andersson, 2024).

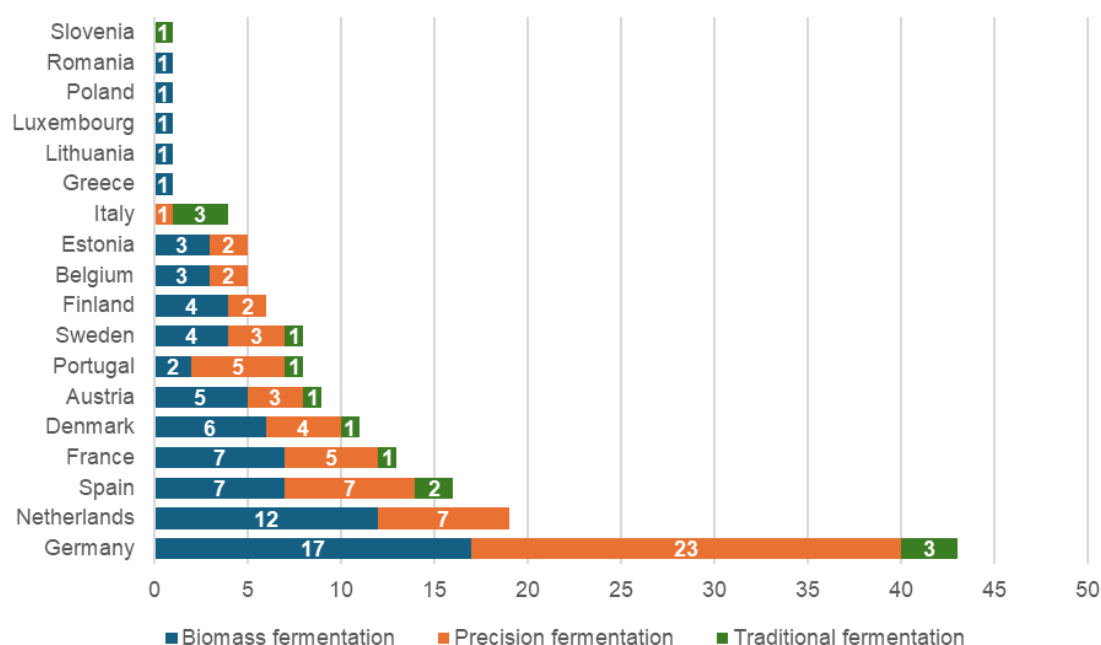
The combined effect of regulatory uncertainty and limited scale-up financing means that the cost reduction trajectories projected in the techno-economic

literature are conditional not only on process innovation but also on institutional and financial conditions that are currently not fully in place in the EU (Khatami et al., 2026; Dickson & Mansouri, 2025).

Geographical distribution of companies deploying biomass and/or precision fermentation

Across the EU-27, companies deploying biomass and/or precision fermentation for proteins are strongly geographically concentrated. Of the 122 EU-headquartered companies identified in the Good Food Institute Europe database, almost 40% are located in just two Member States, Germany (25%) and the Netherlands (14%), while the top five countries (Germany, the Netherlands, Spain, France and Denmark) together account for around two-thirds of all EU activity. Around 79% of EU companies were founded after 2010, with a particularly strong acceleration in the 2020s, which alone accounts for more than half. Earlier cohorts are limited and largely consist of legacy industrial biotechnology or ingredient companies, while the recent growth is driven by specialised start-ups targeting new protein value chains. Geographically, the new wave of company formation has remained concentrated in core innovation hubs – especially Germany and the Netherlands – but the 2020s also show a widening of activity into additional Member States, notably Spain and France ⁽⁵⁾.

Figure 2 Distribution of EU companies that deploy biomass, precision and traditional fermentation for proteins by Member State



N.B: Companies indicating more than one fermentation platform were counted under each relevant category.

Source: Authors' own elaboration based on [Good Food Institute Europe, European microbial protein company database](#).

⁽⁵⁾ Available literature does not enable to get insight into the production volumes or turnover of these companies.

The dataset also shows a general orientation – nearly 80% of companies – towards a B2B business model, indicating that fermentation proteins in the EU are primarily positioned as ingredients within food and, in particular, feed value chains, rather than as consumer-facing products. The vast majority of companies with a B2C business model were founded after 2014.

When looking at third countries, the global distribution outside the EU is highly concentrated, with a small number of countries accounting for a large share of activity. The United States clearly dominates the landscape, hosting around 38% of all non-EU companies included in the [Good Food Institute US companies database](#), followed by the United Kingdom (around 10%). A second tier of innovation hubs includes Israel, Singapore, China, Brazil and Canada, each with a comparable number of companies, and a further group comprising Australia, India and Switzerland ⁽⁶⁾. Although there is no direct evidence from the literature review, this geographical distribution might be due to the presence of large venture capital markets, advanced biotech infrastructures, and, in some cases, innovation-friendly regulatory environments. From an EU perspective, these locations represent the most likely sources of external competition, strategic partnerships and investment pull.

⁽⁶⁾ The figures presented provide an indicative overview of the global landscape beyond the EU. However, they are drawn from the Good Food Institute US companies database and are therefore likely to be partial. In particular, the dataset may not fully capture the global universe of companies active in biomass and precision fermentation, especially in regions where coverage is more limited.

3.2 SQ2 - For different farming sectors and different sizes of farms, what are the potential implications of biomass and precision fermentation technologies on their competitiveness and economic sustainability on domestic and international markets?

One of the major challenges in the microbial protein value chain is the high cost of production. Microbial proteins often have higher production costs compared to conventional animal proteins. This cost disparity is partly due to a lack of established infrastructure and limited economies of scale, both of which benefit traditional animal protein production. In this chapter, we present the main cost differences that exist between biomass and precision fermentation techniques and conventional agriculture, and analyse how these differences may affect the competitiveness and economic sustainability of various farming sectors and farm sizes in domestic and international markets.

3.2.1 SQ2.1 - What are the main cost components of the biomass and precision fermentation industries compared with conventional protein production (animals & plant-based)?

While conventional protein production systems are largely shaped by biological growth processes and agricultural input costs, fermentation-based systems operate as industrial bioprocesses (EPRS, 2024; Sinke et al., 2022; Grigore et al., 2025). Therefore the cost structure of biomass fermentation and precision fermentation industries differs fundamentally from that of conventional animal and plant-based protein production (EPRS, 2024; Grigore *et al.*, 2025).

This chapter distinguishes between biomass fermentation and precision fermentation, and compares their cost structures with those of conventional protein production from animal and plant sources. Although these three systems differ in their production technologies and outputs, their cost structures can be analysed using comparable economic categories.

Production costs can be distinguished between fixed costs, primarily related to capital investment in infrastructure and equipment, and variable operating costs, including feed or feedstock inputs, energy consumption, labour, and downstream processing requirements (Sinke et al., 2022; Li et al., 2025). Analysing these components allows for a comparison of the main cost drivers across biomass fermentation, precision fermentation, and conventional agricultural protein production systems.

3.2.1.1 Fixed production costs (capital investment)

Biomass fermentation

Biomass fermentation systems are characterised by substantial capital requirements for industrial-scale fermentation infrastructure. Core investments include large stainless-steel bioreactors, aeration and agitation systems, sterilisation infrastructure, and equipment for biomass recovery such as centrifuges, filtration units, and dryers. Techno-economic assessments indicate that bioreactors represent the dominant capital component, and may account for up to two-thirds of total equipment costs in some large-scale mycoprotein production facilities (Risner et al., 2023).

The capital intensity of biomass fermentation is driven primarily by bioreactor volume requirements and the need to maintain sterile and tightly controlled operating conditions. However, because the final product typically consists of whole microbial biomass, downstream processing infrastructure remains comparatively limited relative to other bioprocessing applications.

Precision fermentation

Precision fermentation generally exhibits higher capital requirements than biomass fermentation due to additional purification and separation stages required to isolate the target protein (LEVER, 2022; Voutilainen, et al., 2021). Beyond fermentation vessels, facilities require sophisticated downstream processing infrastructure such as ultrafiltration systems, chromatography columns, and concentration units. (Voutilainen et al., 2021; Pereira et al., 2025; Sturme et al., 2025). These intensive purification steps are necessary to achieve the functional and regulatory specifications associated with purified recombinant proteins such as bioidentical dairy proteins (casein, whey), egg white proteins (ovalbumin), and flavouring agents like heme-proteins, which are all used in food products that replace animal-derived foods (Knychala, 2024; Sturme et al., 2025). An example of a high regulatory specification is the use of commercialised dairy proteins like beta-lactoglobulin, which must reach a purity of $\geq 90\%$ to meet food-grade standards (Sturme et al., 2025). This requires a few purification steps in general, as initially the broth containing the produced protein will contain a range of additional compounds that will have to be separated from the protein product.

Consequently, the capital intensity of precision fermentation is driven not only by fermentation capacity but also by the degree of protein purity required by the final application and thus the additional units of operation required for purification. This can increase production costs by 30% to 78% for high-purity grades (Meliawati et al., 2022; Pereira et al., 2025). While depreciation of capital assets in various fermentation platforms typically accounts for 10% to 20% of total production costs, some models for microbial protein suggest capital-related charges can reach as high as 39% to 46% (Voutilainen, et al., 2021),

Conventional agriculture

In conventional agriculture, capital costs are lower per unit of protein produced because production systems rely on long-established infrastructure. Livestock production involves, amongst others, land, barns, feeding systems, milking equipment, and manure management infrastructure, while crop-based protein production depends, amongst others, on land, agricultural machinery, storage facilities, and irrigation systems.

However, capital requirements in conventional agriculture vary substantially across sectors, regions, and production systems. Establishing a new farm from scratch can require high upfront investments, particularly in intensive livestock systems. Within the EU farming sector, large regional variations can be observed: high-income, high-cost, and high-investment farming is concentrated in north-western Member States (Denmark, Netherlands, Germany, France), while lower-cost, more labour-intensive farming systems are generally found in Eastern Europe, for example. Processing operations for conventional proteins, such as milling, fractionation, extrusion, and drying, have long industrial histories and are active on large scales and therefore generally involve lower specific capital costs per unit of protein output compared with fermentation-based systems at current scales.

By comparison, alternative protein production systems currently require substantial upfront capital investments in dedicated industrial facilities. For example, a microbial protein production plant with a capacity of 10 kton per year is estimated to require approximately EUR 41 million in CAPEX.

3.2.1.2 Variable production costs

Feed and feedstock inputs

Biomass fermentation

In biomass fermentation systems that produce single-cell protein, microorganisms are supplied with carbon and nitrogen substrates in the fermentation medium. Typical carbon sources include refined sugars such as glucose or sucrose as well as lower-cost alternatives derived from side streams, including molasses, glycerol from biodiesel production, and corn steep liquor from starch processing (Li et al., 2025; Grigore et al., 2025).

Across techno-economic analyses, feedstock costs represent one of the largest cost components, typically accounting for approximately 45 to 75% of total production costs depending on substrate prices, microbial yield, and process efficiency (Li et al., 2025; Zhang et al., 2024). The use of refined sugars offers predictable fermentation performance but increases operational expenditure (Li et al., 2025). Consequently, many production models seek to incorporate lower-cost side streams as carbon substrates. Substituting refined glucose with industrial by-products such as molasses or corn steep liquor has been shown to

reduce raw material costs by 23 to 42%, while simultaneously enabling the valorisation of industrial residues (Li et al., 2025).

Using side streams

At the same time, the technological implications of such substitution of current substrate, refined sugars, with industrial side streams are more complex than cost comparisons alone suggest. Side streams are inherently heterogeneous, with composition varying across batches and supply chains. This variability can affect fermentation performance by altering nutrient availability, osmotic conditions, and the presence of inhibitory compounds, thereby introducing fluctuations in growth rates, yields, and product quality (Grigore et al., 2025; OECD, 2023). In practice, this may require more advanced monitoring systems and adaptive process control strategies to maintain consistent output.

Food and feed safety considerations also become more salient. Side streams frequently carry a higher microbial load or contaminants (e.g. heavy metals, pesticide residues, or mycotoxins, depending on origin), which increases the risk of contamination during fermentation and may necessitate more stringent sterilisation or purification steps (EFSA, 2021). These additional processing requirements can raise both capital and operating costs, partially offsetting the economic gains from cheaper substrates. Furthermore, the often dilute nature of these feedstocks can increase downstream processing and energy requirements, particularly in large-scale continuous systems.

Regulatory uncertainty represents an additional constraint. The classification and approval of side streams for use in feed or food fermentation processes are not always harmonised across jurisdictions, particularly when inputs originate from waste or by-product streams. This can create ambiguity regarding compliance with EU feed and food safety legislation, increasing due diligence costs and perceived investment risk (OECD, 2023; EFSA, 2021).

Overall, while the substitution of refined sugars with side-streams offers clear cost-reduction potential and aligns with sustainability targets, it introduces trade-offs in terms of process stability, safety assurance, and regulatory clarity. These factors suggest that optimal feedstock strategies are likely to be context-specific, often involving a balance between cost efficiency and operational robustness rather than a full substitution of refined inputs.

Precision fermentation

Precision fermentation feedstocks typically represent 30 to 45% of production costs in precision fermentation processes (GFI, 2025). Precision fermentation systems rely on similar carbon sources as in biomass fermentation systems but often require more complex fermentation media in order to support recombinant protein expression (Pereira et al., 2025; Sturme et al., 2025). In addition to carbon and nitrogen substrates, these fermentation media typically contain micronutrients, buffering agents, and other supplements necessary to maintain microbial growth and protein synthesis (AT Kearney, 2019; Pereira et al., 2025).

While carbon feedstocks remain a major cost component, an important economic constraint in precision fermentation arises from carbon utilisation efficiency (Skinner et al., 2025; Risner et al., 2023). A substantial share of supplied sugars is converted into microbial biomass rather than the target protein product, with over 90% of supplied carbon potentially ending up as residual biomass (Bekker, 2025). In some regulatory contexts, such as the EU, this residual biomass cannot always be valorised as animal feed limiting opportunities to recover value from fermentation by-products and increasing the effective cost of production (Bekker, 2025).

Alternative feedstocks

Emerging fermentation platforms explore the use of gaseous substrates such as carbon dioxide (CO₂), methane (CH₄), or hydrogen (H₂) as carbon or energy sources (Sobhi et al., 2023; García Martínez et al., 2022). These systems rely on specialised microorganisms capable of converting gaseous substrates into microbial biomass via autotrophic or methanotrophic metabolic pathways (Sobhi et al., 2023; Dickson & Mansouri, 2025). Potential cost advantages are partly offset by the technical complexity of gas fermentation systems, which require specialised infrastructure for gas handling, mass transfer, and process control (Sobhi et al., 2023; Dickson & Mansouri, 2025).

Conventional livestock production

The input stage for conventional livestock protein primarily involves feed crops such as wheat, maize, and soy, which rely on low-cost agricultural inputs and mature commodity supply chains (EPRS, 2024; AT Kearney, 2019). While the EU is self-sufficient in roughage, it faces a major feed protein deficit, producing only 24% of the high-protein oilseed meals required by its livestock sector. This has led to a heavy reliance on imports from the United States, Brazil, and Argentina. For example, in the 2023–2024 marketing year, the EU consumed approximately 25.8 million tonnes of soybean meal, while domestic production accounted for only 4 % of this demand (EC, 2024). Soybean meal FOB prices typically ranged between approximately EUR 350 to EUR 700 per tonne in European markets over the past five years (EC, 2026)

Feed production also embodies upstream inputs, including fertilisers, pesticides, fuel, and labour, which contribute indirectly to the cost structure of livestock-derived proteins.

Plant-based protein production

Plant protein production relies on similar agricultural inputs, including fertilisers, pesticides, seeds, and machinery operations. However, converting crops, such as legumes, directly into edible protein typically involves fewer conversion losses than animal production systems. Feed-to-animal protein conversion efficiencies vary substantially across livestock species, ranging from approximately 40% for

milk and eggs to below 10% for beef production (EPRS, 2024; AT Kearney, 2019). Processing stages may include milling, wet fractionation, protein isolation, and drying (Voutilainen et al, 2021; Sturme et al., 2022). These technologies are well established and benefit from mature industrial supply chains, contributing to comparatively stable cost structures.

Energy

Energy consumption represents a major operational cost component in fermentation-based protein production. Maintaining optimal fermentation conditions requires continuous aeration, agitation, temperature control, and sterilisation of equipment and media (van Peteghem et al., 2022; LEVER, 2022; Bekker, 2025)

Electricity consumption in industrial fermentation processes varies based on the organism and substrate used; for example, the production of 1 kg of mycoprotein (Quorn™) is estimated to require 10 kWh (van Peteghem et al., 2022). Other microbial protein models indicate total energy demands ranging from 2.4 kWh per kg for certain feed-grade applications to as high as 53 kWh per kg for food-grade products requiring extensive downstream processing (van Peteghem et al., 2022).

A substantial share of energy demand stems from cooling requirements rather than from operating the systems themselves (Dickson & Mansouri, 2025; Sturme et al., 2022). Microbial growth is highly exothermic, meaning it generates significant heat, and models for large-scale bioreactors suggest that approximately 70 to 75% of in-facility energy use is dedicated to removing this heat through active heat exchangers. This is necessary to maintain stable fermentation temperatures, typically around 28–30°C for fungi (Dickson & Mansouri, 2025; Sturme et al., 2022; Khatami et al., 2025).

Conventional livestock production and plant-based protein production

In comparison, direct on-farm energy consumption in livestock production is relatively modest (EPRS, 2024). However, a substantial share of energy use occurs indirectly through fertiliser manufacturing, feed production (e.g., diesel for tractors and natural gas for the production of nitrogen fertilisers), and transport (EPRS, 2024; Dickson & Mansouri, 2025). Plant-based protein production generally requires lower total energy inputs due to more efficient biological conversion; for instance, the energy input for growing wheat can be up to 30 times less than that required for rearing dairy cows (EPRS, 2024; AT Kearney, 2019; Humpenöder, et al., 2022). A study by Strzelecka et al. (2025) indicates that energy costs can constitute up to 30% of total production expenses in EU agriculture, with the average EU farm spending approximately EUR 162.51 per hectare of land per year on energy.

Labour, maintenance, and operational services

Fermentation facilities require specialised labour capable of managing complex bioprocess operations, maintaining sterile conditions, and monitoring process parameters. Operational expenditures therefore include skilled labour, process control systems, quality assurance, and regulatory compliance procedures (Hossain et al., 2024). Maintenance costs are also significant due to the technical complexity and continuous operation of fermentation equipment. Annual maintenance for these high-tech facilities is typically estimated at 1.5% to 3.0% of the total capital investment (Dickson & Mansouri, 2025; Voutilainen, 2021; Risner et al., 2023). In some single-cell protein models, total operating costs – including labour and maintenance – can account for a significant portion of the minimum product selling price, though these costs are often secondary to raw material feedstock expenses (Dickson & Mansouri, 2025; Pesante et al., 2024; Voutilainen, 2021).

Labour requirements in conventional agriculture vary widely depending on the production system and degree of mechanisation. While highly mechanised arable crop systems generally have relatively low labour costs per unit of protein produced, some farming systems remain labour intensive during specific seasonal operations, such as planting and harvesting. Nevertheless, overall labour demands in large-scale crop production are typically lower than the continuous operational labour requirements associated with industrial bioreactor-based protein production systems.

Downstream processing and product recovery

Downstream processing constitutes one of the main cost differentiators between fermentation-based proteins and conventional protein production. In biomass fermentation systems, downstream processing typically involves harvesting microbial biomass through centrifugation or filtration followed by thermal treatment and drying. For food applications, microbial biomass often requires RNA reduction to lower nucleic acid content to acceptable levels (Lonchamp, 2022). This heat treatment step can result in losses of approximately 30% of total solids, increasing the cost of the final product.

As highlighted in the text before, precision fermentation involves more complex downstream processing because the target protein must be separated and purified from the fermentation broth and microbial host cells. This often requires multiple purification stages such as ultrafiltration, precipitation, or chromatography. As a result, downstream processing can account for 20 to 30% of total production costs in biomass fermentation (Ye et al., 2024) and up to 60% in precision fermentation systems producing highly purified proteins (Khatami et al., 2026; LEVER, 2022).

In contrast, processing stages in conventional protein supply chains are generally less complex. Meat processing largely involves physical separation and preservation, while plant-based protein processing relies on established

extraction and fractionation technologies with relatively predictable cost structures.

Overall comparison of biomass fermentation and precision fermentation and traditional agriculture

Taken together, fermentation-derived proteins shift the economics of protein production from land- and feed-based agricultural systems toward capital- and technology-intensive industrial production processes.

In conventional animal and plant protein systems, costs are primarily driven by agricultural inputs such as feed, fertilisers, land, and labour. In contrast, biomass and precision fermentation systems are characterised by cost structures dominated by capital investment in fermentation infrastructure, feedstock inputs, industrial energy demand, and downstream processing requirements.

Recent techno-economic assessments indicate that biomass fermentation proteins are approaching cost competitiveness with some conventional animal proteins, with reported production costs generally converging around 3.5-5.2 EUR/kg, compared with market prices of approximately 5.1-12.8 EUR/kg for beef and pork products (GFI, 2025).

Precision fermentation generally exhibits higher production costs than biomass fermentation due to more complex media requirements (typically 5–10 times higher), and extensive downstream purification requirements. Precision fermentation-derived food proteins currently exhibit a much wider cost range, from approximately 9-9.5 EUR/kg for highly optimised large-scale systems to well above 850 EUR/kg for high-purity specialty proteins produced at limited scale, with some experimental cases exceeding 8 500 EUR/kg under low-yield conditions (GFI, 2025; Voutilainen et al., 2021) ⁽⁷⁾.

These findings highlight a clear divergence in technological and economic maturity between fermentation pathways. Biomass fermentation is increasingly positioned as a near-commercially competitive protein platform, whereas precision fermentation remains economically constrained by feedstock utilisation efficiency, capital-intensive downstream processing, and limited industrial-scale deployment. Achieving broader cost competitiveness for precision fermentation will therefore depend on substantial improvements in process efficiency, reductions in feedstock and purification costs, scaling of fermentation infrastructure, and innovation in downstream processing technologies.

(7) Based on ECB reference exchange rates for 5 May 2026. [European Central Bank \(ECB\) reference exchange rates for 5 may 2026 | xrates.eu](https://www.ecb.europa.eu/press/pr/2026/050526_en.htm)

Table 1 – Protein source and indicative cost range

Protein source	Indicative cost range	Key cost characteristics
Conventional animal proteins	~ 5.1-12.8 EUR/kg	Feed, land, labour, and energy costs
Plant proteins	Generally lower and relatively stable	Mature supply chains and established processing technologies
Biomass fermentation proteins	~ 3.5-5.2 EUR/kg	High yields on sugar, lower downstream processing requirements and improving scale efficiencies
Precision fermentation proteins	~ 9-9.5 EUR/kg to > 850 EUR/kg	High purification costs, lower yields on sugar, specialised infrastructure

Source: GFI, 2025

3.2.2 SQ2.2 - To what extent may EU farmers compete with domestic and external producers of fermentation proteins both on the EU market and the international market, considering the differences of tariffs, non-tariff measures (e.g. SPS), etc., that would be applicable?

The ability of EU farmers to compete with domestic and international producers of fermentation-derived proteins depends on a combination of cost structures, technological maturity, and the EU's regulatory and trade framework, including differences in tariffs, non-tariff measures such as SPS standards, and sustainability regulations.

On the one hand, conventional EU agriculture benefits from established supply chains, policy support under the CAP, and economies of scale across farming systems. On the other hand, it is highly dependent on imported protein feed, specifically soy. In this context, protein dependency is not only a cost issue but also a question of strategic autonomy.

Fermentation-based proteins – encompassing biomass, and precision fermentation – offer a strategic opportunity to enhance food system resilience and reduce this import dependency by providing efficient production alternatives with significantly lower requirements for land and water (Systemiq, 2025). However, these technologies currently face a "chicken and egg" investment problem, where high capital requirements for industrial-scale infrastructure and energy-intensive processes hinder the achievement of price parity with traditional animal proteins (Andersson, 2024).

From a regulatory perspective, the EU maintains comparatively stringent approval processes under the Novel Food and, where relevant, Genetically Modified Organism frameworks. While these ensure a high level of consumer safety and trust, they can lengthen time-to-market relative to jurisdictions such as the USA or Singapore, affecting the speed at which EU-based producers can innovate and compete globally. At the same time, these standards function as a form of non-tariff measure that also applies to imports, thereby shaping the competitive landscape on the EU market.

For fermentation-derived proteins, tariff protection on the EU market is generally moderate, meaning that competitiveness is more strongly influenced by non-tariff measures, notably SPS, food-safety and novel-food requirements. These requirements are not specific to imports: products placed on the EU market, whether imported or produced domestically, must comply with the same EU safety and regulatory standards, although imported products must additionally demonstrate compliance at the point of market entry. This creates a level playing field in regulatory terms, but not necessarily in cost terms. For fermentation-derived proteins, the available evidence does not support a claim that producers in third countries systematically face lower overall production costs, since major cost drivers are often capital expenditure, feedstock inputs, energy use, and downstream processing rather than labour alone. That said, some third-country producers may still benefit from more favourable electricity prices, lower labour costs, faster or more predictable approval pathways, or stronger scale-up support, which can improve their competitive position relative to EU-based firms even when the final product must meet the same EU regulatory requirements.

The emergence of fermentation-derived proteins need not be understood solely in terms of direct competition with EU farmers, as these products currently operate mainly at the ingredient level within food and feed value chains rather than as direct substitutes for farm-level outputs. At the same time, their development may create opportunities for farmers to participate in emerging value chains, including by supplying conventional feedstocks and co-products such as sugar beet, cereals, maize, potatoes, and molasses, particularly where fermentation activities are linked to existing processing infrastructure. The extent to which such opportunities would strengthen farmers' competitiveness or economic sustainability would depend on how value is distributed along the chain, since part of the economic benefit may accrue primarily to processors and downstream agri-food industries rather than to primary producers.

For this reason, potential benefits for farmers may be greater when participation occurs through contracts, cooperatives, or other arrangements that enable a stronger degree of local value capture. By contrast, direct on-farm processing appears less likely to be a widespread model under current conditions, given the capital intensity, technical requirements, and regulatory complexity associated with fermentation-based production. More generally, fermentation technologies may contribute to a partial reconfiguration of existing agricultural production systems and value chains, rather than simply displacing them.

Competition in bulk feed markets

The extent of competition is highly market-segment specific. In the animal feed or bulk feed market, microbial proteins continue to struggle to match the low prices of conventional feed ingredients such as soybean meal, which has historically traded around 0.40 EUR/kg (Sobhi *et al.*, 2023). By contrast, microbial biomass produced via biomass fermentation using natural gas and electricity is estimated to cost between 2.6 EUR/kg and 4.3 EUR/kg. These large cost differentials mean that, even in the absence of tariff protection, fermentation

proteins are currently unable to partially substitute conventional feed proteins at scale.

However, the competitive outlook changes where fermentation is integrated with existing agricultural or waste-based infrastructure, such as anaerobic digestion plants that valorise agro-waste (Pesante *et al.*, 2024). Initial assessments of such integrated biorefineries suggest break-even prices of around 1 300 EUR/tonne of microbial protein, which translates to 1 750 EUR/tonne of crude protein. While these costs remain above the benchmarks for soymeal – which averages approximately 385 EUR/ tonne of product, or 960 EUR/tonne of crude protein – they are already competitive with higher-value feed ingredients such as fishmeal, priced at approximately 1 570 EUR/tonne of product, or 2 315 EUR/tonne of crude protein (Pesante *et al.*, 2024). In these niches, fermentation proteins may begin to compete with third country producers' higher-value feed ingredients for exporting to the EU, albeit on a limited scale.

Competition in human food markets, including high-value protein ingredients

Most fermentation-based products, particularly precision-fermented proteins, are currently used as ingredients within processed foods rather than as end products, and therefore do not compete directly with farm-level production (Reinhardt & Monaco, 2025; Food Fermentation Europe, 2025). Certain fermentation-derived products, notably mycoprotein used in products such as Quorn, have reached economic parity with some animal-based proteins on a price-per-protein basis (Risner *et al.*, 2023). Quorn products are economically competitive with beef on a price-per-protein basis, with production costs estimated at 25.1 EUR/kg of protein compared to 25.5 EUR/kg for beef (ibid). While beef remains cheaper on a caloric basis due to its higher energy density, the high protein digestibility of mycoprotein makes it a robust competitor in niche markets (ibid).

Precision-fermented dairy proteins are currently not authorised for food use in the EU and therefore do not compete in EU dairy markets. Precision fermented dairy products mainly target high-value functional niches, such as lactoferrin for infant formula, where scarcity and high prices of conventional counterparts create viable entry points without directly challenging mainstream EU dairy production (Knychala *et al.*, 2024).

Tariff exposure and the EU feed protein deficit

Trade policy plays a critical role in shaping competitive conditions, particularly in the feed sector. Despite benefiting from long-standing financial safety nets under the Common Agricultural Policy (CAP), EU farmers face a structural vulnerability stemming from a historical “tariff chink” in the protein feed market (Swinnen, 2008). During the Dillon Round of the 1960s, the EU bound tariffs on imported oilseeds and oilmeals at zero or very low levels. This legacy has allowed cheap foreign soy to dominate the EU feed market, effectively imposing a price

ceiling that constrains both domestic protein crop production and emerging microbial feed alternatives.

A related mechanism is the EU's system of tariff-rate quotas (TRQs), which allows limited volumes of certain conventional agricultural products, such as dairy and beef, to be imported at reduced or zero tariffs before higher duties apply. TRQs are intended to balance market protection with access to imports, but they currently do not apply to microbial proteins. The relevance of this distinction for fermentation-derived proteins depends first on the *erga omnes* tariffs applicable to imported microbial proteins – and/or products based on them – and, where relevant, on the tariff treatment available under preferential trade agreements. However, a key point is that the EU does not apply one single tariff to fermentation-derived proteins – or their derived products – as a category. Instead, the applicable *erga omnes* tariff depends on the final customs classification of the imported product, and therefore on the product's form and composition, for example whether it is imported as a purified fermentation-derived protein ingredient, as a microbial biomass ingredient, or as a processed food or feed preparation. In practice, the relevant benchmark is the ordinary Common Customs Tariff line for the specific product. For countries which do not currently benefit from an EU preferential trade agreement in force, such as China, fermentation-derived proteins therefore face the EU's ordinary "most-favoured nation" *erga omnes* tariff for the relevant tariff line, together with any applicable trade-defence measure. By contrast, for partners that do have EU agreements in force, such as the UK, Canada, Singapore and South Korea, preferential treatment may reduce duties or eliminate them altogether where the imported product satisfies the applicable rules of origin. The bottom line is that the current system does not make it possible to discriminate whether a product or a specific protein was obtained through biomass and precision fermentation. The Harmonised System (HS) codes currently in force are too broad to allow for such a discrimination. It follows that an overall assessment of the (potential) tariff barriers faced by fermentation-derived proteins and products is not possible overall, whereas it can only be carried out case by case. By way of an example, the table below outlines the logic behind this reasoning:

Table 2 – Preferential tariff treatment for representative fermentation-derived protein products

Product archetype	Product assumption used for tariff lookup	HS code used	MFN / <i>erga omnes</i> tariff	Representative preferential treatment
Purified precision-fermentation protein ingredient	Isolated, purified protein substance; not an enzyme, gelatin, albumin or formulated food/feed preparation	3504 00 90 00 "Other protein substances and their derivatives, not elsewhere specified"	6.4%	EU-UK TCA: 0% where UK origin is met. EU-Japan EPA: 0% where Japan origin is met, as this line is not separately scheduled for reduction/exclusion
Inactive yeast biomass / yeast-derived high-protein ingredient	Dried, non-viable yeast biomass, e.g. <i>Yarrowia</i> or <i>Saccharomyces</i> biomass, imported in bulk	2102 20 19 00 "Inactive yeasts, other"	12.8%	EU-UK TCA: 0% where UK origin is met. EU-Japan EPA: 0% where Japan origin is met, as this line is not separately

Product archetype	Product assumption used for tariff lookup	HS code used	MFN / erga omnes tariff	Representative preferential treatment
				scheduled for reduction/exclusion.
Dead microbial biomass other than yeast	Dried, non-viable bacterial, fungal or algal single-cell biomass, not otherwise formulated	2102 20 90 00 "Other dead single-cell micro-organisms"	12.8%	EU-UK TCA: 0% where UK origin is met. EU-Japan EPA: 0% where Japan origin is met, as this line is not separately scheduled for reduction/exclusion.
Formulated microbial-protein food preparation	Mycoprotein or microbial-protein preparation for human food, not elsewhere specified, possibly mixed with other food ingredients	2106 90 98 00 "Food preparations not elsewhere specified, other"	12.8%	EU-UK TCA: 0% where UK origin is met. EU-Japan EPA: preferential duty remains positive: 4.5% + 0.500 EA after staged reduction.
Microbial-protein feed preparation	Formulated animal-feed product containing microbial protein, without starch/milk components triggering other sublines	2309 90 96 90 "Preparations of a kind used in animal feeding, other"	12%	EU-UK TCA: 0% where UK origin is met. EU-Japan EPA: 0% where Japan origin is met.

At the same time, market access is shaped not only by tariffs but also by non-tariff measures, particularly EU food and feed safety requirements. Market access is therefore shaped first by customs classification and origin, and second by non-tariff measures, including EU food and feed legislation, and other safety requirements.

The absence of TRQ volume ceilings means that imports of fermentation-derived proteins are not constrained by the same quota architecture that applies to some conventional agricultural products. However, this does not itself imply a competitive advantage over dairy or livestock products. A TRQ is only one element of market access. In some cases, conventional agricultural products may enter the EU at reduced or zero in-quota tariffs, while fermentation-derived proteins may face a positive MFN tariff under their own CN/TARIC classification. Conversely, fermentation-derived proteins may not face an out-of-quota tariff escalation, but this only matters if import volumes would otherwise exceed a quota and if the product is commercially substitutable for the conventional product concerned. Further, fermentation-derived proteins are generally not imported under the same tariff headings as e.g. milk, meat or eggs, against which they often compete mainly as ingredients in food and feed applications. Their competitive position therefore cannot be assessed by comparing the presence or absence of TRQs alone. It must be assessed on a product-by-product basis, taking into account the applicable erga omnes duty, any preferential tariff treatment available under EU trade agreements, rules of origin, trade-defence measures, food/feed safety requirements and the cost structure of the imported product.

This is particularly important because biomass and precision fermentation currently operate primarily at the ingredient level and, in the context of this subsection, are more relevant to competition with imported feed proteins than to direct competition with final animal-based food products. Some degree of indirect

or functional competition with dairy and livestock products cannot be excluded, but that question can be assessed separately from the feed-market dynamics discussed here. At present, the EU has 44 preferential trade agreements with 76 countries and regions around the world (European Commission, 2025). These agreements provide partner countries with preferential access to the EU market, including zero or significantly reduced tariffs on many goods, thereby facilitating international trade and reducing customs duties for businesses.

Against this background, the central vulnerability in this subsection is the EU's persistent dependence on imported protein feed. This is reflected in the EU's persistent feed protein deficit, with the EU producing only around 24% of the high-protein oilseed meals required by its livestock sector (EPRS, 2024). This deficit represents a clear strategic opportunity for fermentation-derived proteins to enhance EU self-sufficiency. Table 1 illustrates the EU's self-sufficiency levels in 2023/2024 for several protein crops used for feed.

Table 3 – EU self-sufficiency in protein crops for feed

Product	Protein content (%)	Feed use 2023/2024(Mil ton)	Feed use with EU origin (M ton)	EU self-sufficiency
Soybean meal	45.5%	25.8	1.1	4%
Rapeseed meal	33%	13.9	10	72%
Common wheat	11%	45.8	37.8	83%
Barley	10%	31.5	31.5	100%
Maize	8%	58.9	43.2	73%
Fodder legumes	7.2%	73	73	100%
Silage maize	2.9%	237	237	100%

Source: [\(Comission, 2024\)](#)

Non-tariff measures (SPS) and regulatory barriers

Non-tariff measures, particularly Sanitary and Phytosanitary (SPS) standards and food safety regulations, act as the standard conditions applied by all countries, both EU Member States and third countries, to ensure that products placed on their markets comply with their respective safety frameworks (Reinhardt & Monaco, 2025). The EU Novel Food Regulation applies to all products placed on the EU market and represents a challenge due to its complexity and duration (ibid). Although the legal target for authorisation is 17 months, approval processes generally take longer – 2.6 years on average, with some applications extending to six years (CEPS, 2025). A major factor contributing to these delays is the variable quality of dossiers submitted by applicants, which often fail to meet the required scientific standards. In addition, since 2018, the EU Novel Food Regulation has established the duration of commercial exploitation under an exclusivity regime for authorised novel foods to a maximum of five years. After that, novel food authorisations become 'generic'. Whereas, in high-tech fermentation, imports from countries such as the United States, Singapore, or Israel, regulatory frameworks are generally more agile, and governments actively

support the development and export of microbial proteins (Reinhardt & Monaco, 2025; Food Fermentation Europe, 2025). In any event, the existence of a relevant novel food authorisation is a pre-requisite for international producers to secure access to the EU market. Table 4 presents the microbial protein products approved as novel foods by EFSA since the introduction of the Novel Food Regulation in 1997 to date.

Table 4 - Microbial protein products approved by the EU to date as novel foods.
CIR: Commission Implementing Regulation

#	Authorised as novel food
CIR 2024/2044	Yarrowia lipolytica biomass amendment
CIR 2023/938	Yarrowia lipolytica biomass amendment
CIR 2020/1822	Chromium-containing yeast (<i>Yarrowia lipolytica</i>) biomass
CIR 2020/1993	Selenium-containing yeast (<i>Yarrowia lipolytica</i>) biomass
CIR 2020/1820	Dried algae (<i>Euglena gracilis</i>)
CIR 2019/760	Yarrowia lipolytica yeast biomass

In addition, there are a number of microbial-derived novel food applications undergoing risk assessment by EFSA ⁽⁸⁾.

Table 5 - Biomass fermentation-based novel food applications (pending at EU level)

Year	Product / substance	Microorganism	Applicant	Remarks	Geography
2024	Dried biomass powder	<i>Xanthobacter</i> sp. SoF1	Solar Foods Oy	CO ₂ and hydrogen-based process	Finland
2024	Iron-containing yeast biomass	Yeast (unspecified strain)	Danstar Ferment AG	Mineral-enriched microbial biomass	Switzerland
2024	Dry biomass	<i>Paecilomyces variotii</i>	EniferBio Oy		Finland
2024	Microbial hydrolysate	<i>Vibrio natriegens</i>	MicroHarvest GmbH	Biomass-derived hydrolysate	Germany
2022	Dried algal biomass	<i>Chlamydomonas reinhardtii</i>	Triton Algae Innovations Ltd.	Whole algal biomass	USA
2021	Fungal protein	<i>Fusarium</i> strain flavolapis	Nature's Fynd	Mycoprotein-type product	USA

⁽⁸⁾ The list of products submitted within the meaning of Article 10(1) of Regulation (EU) 2015/2283 is available at: [Summary of applications and notifications - Food Safety](#). All biomass applications that aim to be marketed as probiotic, postbiotic or as a supplement are not included in the list as these are deemed not relevant to the scope of this study.

Year	Product / substance	Microorganism	Applicant	Remarks	Geography
2020	UV-treated baker's yeast	<i>Saccharomyces cerevisiae</i>	Lallemand	Increased vitamin D2	Canada
2020	Extension of use: yeast biomass	<i>Yarrowia lipolytica</i>	Skotan S.A.	Yeast biomass	Poland
2020	Whole-cell, heat-killed bacterium	<i>Mycolicibacterium aurum</i> DSM 33539 (non-GMM)	Aurum Switzerland AG	Non-viable bacterial biomass	Switzerland
2020	Fermotein™	<i>Rhizomucor pusillus</i>	The Protein Brewery B.V.	Recently received a positive EFSA opinion	The Netherlands
2019	Dried biomass	<i>Galdieria sulphuraria</i>	Fermentalg	Algal biomass	France
2018	Yeast biomass	<i>Yarrowia lipolytica</i>	Skotan S.A.	Yeast biomass	Poland

Table 6 - Precision fermentation-based novel food applications (pending at EU level)

Year	Product / substance	Production organism	Applicant	Remarks	Geography
2023	β-lactoglobulin (r-βLG)	<i>Komagataella phaffii</i>	Remilk	Precision-fermented dairy protein	Israel

The overview shows a growing pipeline of fermentation-derived novel foods at the EU level, with a strong emphasis on fungal, algal, and yeast biomass, which have clear potential relevance for protein diversification.

Conversely, in the case of feed, the EU market presents fewer regulatory barriers as opposed to human food. This is because, pursuant to EU legislation, new feed materials are not subject to pre-market authorisation, unless they are classified as GM feed (See Annex II).

Long-term outlook competition versus complementarity

Looking ahead, the relationship between EU farmers and producers of fermentation-derived proteins may increasingly evolve towards complementarity and circular synergy (Pesante *et al.*, 2024; EPRS, 2024; Food Fermentation Europe, 2025). Fermentation technologies offer opportunities to valorise agricultural by-products - such as wheat straw, molasses, or whey – into high-value protein ingredients, creating additional revenue streams for farmers. Retrofitting existing agricultural or industrial facilities, including breweries or paper mills, for microbial protein production could reduce capital costs by more than 40%, accelerating deployment while maintaining linkages with the agricultural sector (García Martínez, 2022).

3.2.3 SQ2.3 - What could be the implications for farm incomes for the different relevant EU farming sectors and farm sizes?

The integration of biomass and precision fermentation into the European food system presents both opportunities and challenges to conventional farming. On the one hand, it may create new revenue streams for crop producers, on the other hand, some products may compete with those from traditional livestock sectors, generating competitive pressure. The economic implications, however, depend on the specific farming sector and the scale of operations, as outlined below.

3.2.3.1 Sector-specific implications for income

Arable and sugar farmers

Arable farmers, especially those producing sugar- and starch-rich crops like sugar beet, wheat, corn, and potatoes, are positioned to see a positive impact on their earnings (Systemiq, 2025). As fermentation scales, it creates a new, stable, and year-round outlet for these primary crops and their co-products (such as molasses and straw), helping farmers diversify away from volatile or shrinking markets in animal feed and potentially strengthening their position in remaining food applications where demand is stable or growing

Legume and pulse producers

The shift toward fermentation-based and hybrid protein products is expected to increase demand for European legumes such as field peas, fava beans, and lentils, because these products are used as ingredients for new (hybrid) protein products. For many farmers, these nitrogen-fixing crops could become more attractive because the expansion of hybrid protein products creates new market outlets for locally grown pulses, which can be processed into high-value ingredients that meet rising demand for protein diversity and nutritional functionality. Whether EU-grown legumes will compete effectively with imports depends not on fermentation perse, but on whether regional processing capacity, short supply chains, sustainability certification and consumer or industrial preference for traceable, lower-carbon ingredients create sufficient differentiation to offset potential price advantages of imported protein concentrates. This improved business case, could support diversifying crop rotations and reduce reliance on expensive synthetic fertilisers (Systemiq, 2025, 2026).

Dairy and livestock producers

Fermentation is increasingly leveraged to produce high-value feed additives – including probiotics, specialised enzymes like phytase, and microalgae-derived omega-3 fatty acids – which are designed to enhance animal health and improve feed conversion ratios (Systemiq, 2025; Bullvine, 2025). By streamlining the digestive processes of livestock and aquaculture, these precision-engineered

nutrients allow farmers to reduce their environmental footprints while lowering overall production costs (Systemiq, 2025).

More recently, precision fermentation has also been applied to the production of specific dairy proteins, such as casein and whey proteins. However, this does not equate to direct one-to-one competition with conventional milk production, as these processes typically produce isolated functional proteins rather than complete dairy products. Potential competitive effects are therefore more likely to be concentrated in specific downstream applications – particularly high-value ingredient markets such as sports nutrition, medical supplements, and infant formula – rather than in the broader commodity milk market (Bullvine, 2025). At present, the extent of any market displacement remains uncertain and is expected to be partial and segment-specific rather than systemic. More information about how the market may develop in the future is available under SQ 3.

Meanwhile, large agricultural cooperatives are adapting their business models to this “new protein economy”. A clear illustration is FrieslandCampina, which in 2023 initiated its “Expedition 2030” strategy to remake the company into a more competitive, innovative, and sustainable industry player (FrieslandCampina, 2023). This repositioning extends beyond internal restructuring: through the so-called FCI Side Stream Challenge, developed jointly with ICOS Capital, FrieslandCampina is actively mobilising external innovation to transform nutrient-rich dairy by-products into high-value food products, feed, and pharmaceutical ingredients. While these transformations aim to ensure the long-term valorisation of their members’ milk, they involve significant one-off restructuring costs, which for FrieslandCampina reached EUR 136 million in 2023 alone (9). Consequently, the sector faces a delicate balancing act between investing in future resilience and maintaining the current income levels necessary for farmers to stay operational during the transition.

Implications by farm size

Given the early and still path-dependent stage of biomass and precision fermentation deployment in Europe, the organisation of future value chains remains uncertain, and several distinct integration models may coexist rather than a single dominant pattern emerging. Large EU farms distinguish themselves through significantly higher equity turnover compared to smaller holdings, achieving much greater production volumes per euro invested through specialisation and enhanced technology (Kryszak et al., 2021). This efficiency makes them better suited to supply to fermentation facilities, that require a stable, year-round feedstock supply of crops like sugar beet or cereals (Systemiq, 2025). By producing at industrial scale, these farms can smooth seasonal income fluctuations and provide a reliable outlet to shrinking traditional markets in

(9) These drastic financial requirements contributed to a net loss of EUR 149 million for the cooperative, resulting in a situation where member dairy farmers received no supplementary cash payments for that year (FrieslandCampina, 2023)

biofuels and animal feed while in principle also creating an additional revenue stream from better valorisation of residues and by-products that are currently sold into lower-value uses or remain underutilised.

However, the high capital intensity of fermentation infrastructure and the need for long-term supply contracts suggest that large farms, agribusinesses, and cooperatives are more likely to act as primary integrators or anchor suppliers in the emerging “new protein economy” (Systemiq, 2025; 2026). In practice, this may involve different business cases: (i) supplying part of the main harvest as a dedicated fermentation feedstock, (ii) channeling co-products or side streams from on-farm or cooperative processing (e.g. sugar beet processing, starch plants, or dairy side streams), and (iii) valorising crop residues where sufficient standardisation, preprocessing and logistics can be achieved. This configuration creates a risk that value creation becomes concentrated upstream and downstream industrial processing hubs, potentially limiting direct participation opportunities for smaller farmers beyond feedstock provision or cooperative membership. Moreover, compared to smaller farms, large holdings tend to provide more stable operating conditions and more predictable output volumes. In addition, they make more effective use of external production factors – such as hired labour and rented land – to enhance efficiency, reinforcing their potential role as key players for a competitive EU “new protein economy”.

At the same time, small and medium-sized farms (SMEs) are not excluded from this transition, but are more likely to engage through alternative, collective, or niche-oriented business models. One key pathway is participation in cooperative structures or producer organisations, which can aggregate supply, reduce transaction costs, and improve bargaining power vis-à-vis fermentation companies. In this model, SMEs may contribute feedstock either by (i) contracting a share of their main crop (e.g. cereals, sugar beet, or legumes), by (ii) delivering side streams from on-farm primary processing (such as cleaning, drying or initial fractionation), or by (iii) supplying standardised residues collected and pre-processed at cooperative level while sharing in value creation through collective ownership or contractual arrangements.

A second opportunity lies in crop diversification toward higher-value or functionally differentiated inputs, particularly legumes and specialty crops used in hybrid or plant-fermentation products. For smaller farms, these crops can fit well within diversified rotations and agroecological systems, offering agronomic benefits (e.g. nitrogen fixation) while targeting emerging ingredient markets rather than bulk commodity supply. In such cases, only part of the harvest may be directed toward fermentation or hybrid applications, with the remainder continuing to serve conventional food, feed or local processing outlets. However, these opportunities depend on the development of reliable local processing capacity and stable offtake agreements for differentiated ingredients, which are currently still limited in many regions.

Third, SMEs may benefit from the valorisation of on-farm or regional side streams and residues, either by supplying them as fermentation feedstocks into

centralized plants or by engaging in small-scale, decentralised biorefinery models where feasible. While technological and regulatory barriers remain significant, especially regarding the standardisation, quality control and legal status of waste- and by-product-derived inputs, such approaches could allow smaller farms to capture additional value from residues that are currently underutilized, provided that aggregation, preprocessing and risk-sharing arrangements are carefully organised.

Despite these opportunities, several structural challenges remain more binding for smaller farms. These include limited access to capital for upgrading production systems, higher relative transaction costs in establishing and monitoring supply contracts, and greater exposure to market uncertainty in emerging value chains. In addition, the technical requirements for consistent feedstock quality and volume may favour more standardised, large-scale production systems and well-organised cooperatives, potentially disadvantaging more heterogeneous small-farm outputs unless intermediaries or collective structures effectively pool and stabilize supply.

3.3 SQ3 - How and to what extent will the development of biomass and precision fermentation proteins affect agricultural markets in the medium and long term?

Given the novelty of many microbial proteins, and the limited availability of robust quantitative evidence on their medium- and long-term implications for EU agriculture, this question was addressed through the study's foresight component. The purpose of the foresight exercise was not to predict a single future, but to explore a set of plausible development pathways and assess how different combinations of competitiveness, market uptake and policy support could shape agricultural market outcomes over time through a scenario framework.

The scenario framework is built around two critical uncertainties, as visible in Figure 3. The first uncertainty concerns the extent to which the EU becomes a competitive and accepted location for the development, production and market uptake of biomass and precision fermentation proteins. This includes production costs, industrial capability, consumer and farmers acceptance, the maturity of supply chains, and the ability of EU firms to compete with producers in other global regions. The second uncertainty concerns the extent to which the regulatory and policy framework actively supports the sector through approvals, scale-up support, public investment, and broader alignment with agricultural and food policy. Taken together, these uncertainties generate four distinct futures for the evolution of EU biomass and precision fermentation protein markets. These futures are translated into four scenarios. These scenarios show that the future of biomass and precision fermentation proteins in the EU depends not only on technical feasibility, but on a broader combination of industrial competitiveness, policy support, regulatory design, market acceptance and cost implications. They also show that the key question is not whether microbial proteins will exist, but how far they move beyond specialist applications and whether the EU captures their value domestically as well as the availability of infrastructure in the EU. Table 7 offers a summarised description and comparison across the four scenarios.

Scenario 1

In **Scenario 1**, the EU creates a formally supportive environment, but this support does not translate into a competitive protein industry. Regulation is relatively open and innovation-friendly on paper, yet the industry remains weakly scaled, costly and poorly embedded in domestic value chains. Consumer demand also remains limited, with microbial proteins struggling to gain broad legitimacy in food markets. The result is a protein market in which microbial proteins originating from biomass and precision fermentation are present, but largely confined to specialist and higher-value niches.

In this scenario, the central problem is that policy support is not sufficient to overcome structural weaknesses. Production costs remain too high, domestic value chains remain fragmented, and market incentives are not strong enough to

drive widespread uptake. This creates a risk that the EU opens its market without building the industrial base needed to compete effectively. In protein market terms, this means that microbial proteins may enter a limited number of premium ingredient markets, but without generating broad market transformation. Over time, the more serious consequence is that imported microbial proteins may well gain ground in selected segments – because consumer acceptance is low in the scenario – of the EU market, if the sector develops outside the EU, while domestic producers remain uncompetitive. The scenario therefore describes a protein market that changes at the margins, but without securing either broad uptake or strong domestic value creation.

Scenario 2

Scenario 2 represents the most conservative market pathway. Here, both regulatory support and competitiveness remain weak. Approvals are slow, public support for scale-up is limited, and the wider innovation environment does not enable the EU to become a strong location for protein fermentation. Market uptake remains low, acceptance is limited, and conventional protein products continue to dominate the internal market with little visible change in the medium term.

The defining feature of **Scenario 2** is not immediate substitution, but prolonged hesitation. Microbial proteins do not disappear globally, but Europe does not become a significant place to develop, produce or capture value from them. This leaves the EU on a path of delayed structural disadvantage. By 2030, the market for conventional proteins looks broadly similar to today, with little change in dairy, beef, pigmeat, poultry or eggs. By 2050, however, the strategic consequences become more apparent. If other global regions build scale and lower costs more quickly, the EU may end up importing microbial proteins or related protein ingredients produced elsewhere – provided these products comply with the relevant EU authorisation requirements – while preserving a largely conventional domestic system through adaptation and support. The agricultural impact would not necessarily be large-scale direct displacement of EU farm production. Rather, the risk is that domestic agriculture and rural economies fail to capture the associated value: there would be less demand for EU feedstocks, fewer opportunities for farmer-linked processing or rural industrial activity, and more selective competitive pressure in authorised ingredient or feed-input markets. In this sense, Europe could preserve a largely conventional domestic agricultural system in volume terms, while becoming more dependent on imported innovation and externally produced protein-related inputs. The key implication is therefore not rapid market disruption, but the possibility that Europe remains a follower rather than a shaper in the future protein economy.

Scenario 3

Scenario 3 is the most transformative scenario for protein markets. In this pathway, strong policy support and strong competitiveness for microbial proteins reinforce one another. Regulatory processes become faster and more

predictable, scale-up support is available, investment accelerates, and microbial proteins begin to move from pilot and niche applications into more established market segments. Public support also helps create bridges with agriculture, allowing farmers, co-operatives and rural industries to participate in emerging value chains rather than being displaced by them, although some minor displacement may take place.

This scenario envisages a gradual but meaningful expansion of microbial proteins across the protein economy. By 2030, the market is still in an early growth phase: microbial proteins enter shelves through niche and premium applications, and microbial proteins still account for only a small share of overall categories. However, this early foothold is significant because it is linked to continued cost reductions, technological improvements and wider social acceptance. From there, the market accelerates. By 2050, microbial proteins are no longer confined to specialist uses, but will begin to penetrate specific segments of the meat, dairy and egg protein markets. Importantly, the scenario does not describe this simply as replacement. It presents a market in which microbial proteins complement plant proteins, create hybrid product categories, and integrate with remaining agricultural value chains through feedstocks, residues, co-products and local processing. In this sense, This is not just a scenario of higher uptake; it is a scenario of broader restructuring of protein markets, including conventional ones, and would also allow the EU to become competitive at a global level, exporting microbial proteins.

Scenario 4

Scenario 4 describes a protein market in which the underlying technology improves, but the wider policy and regulatory conditions do not allow that progress to be translated into broad-based deployment. Competitiveness improves to some extent, firms optimise processes, and some products become commercially credible, yet the absence of stronger incentives, clearer regulatory pathways and coordinated public support prevents the sector from reaching scale. The result is a persistent niche market and, ultimately, a lost opportunity for the EU, for all participants in the microbial proteins value chain.

In this scenario, microbial proteins do enter the market, but mostly in those segments where they can create value despite limited scale. This means that the effects are concentrated in specific dairy and egg protein ingredients, in food manufacturing applications, and in niche higher-value uses. The technology proves relevant, but not transformative. Because regulatory bottlenecks continue to slow approvals and deter large-scale investment, the market never fully expands. By the time the EU might become more supportive, other regions will have already built a substantial lead. Europe therefore risks becoming a place where technologies are only proven and de-risked, while the commercial-scale production of microbial proteins takes place elsewhere. In market terms, this means that the EU internal protein market may gradually see an increase in the uptake of such products without having established a strong domestic production base.

Figure 3 – 2x2 foresight matrix, uncertainty axes and the four scenarios



Table 7 – Foresight scenarios, comparison and characteristics

Dimension	Scenario 1	Scenario 2	Scenario 3	Scenario 4
<i>Position in the 2x2 matrix</i>	<i>Supportive policy environment, but weak industry development</i>	<i>Weak policy support and weak competitiveness</i>	<i>Strong policy support and strong competitiveness</i>	<i>Technology improves, but policy support remains weak</i>
Regulatory and policy context	Formally supportive and innovation-friendly, but not enough to drive scale	Slow approvals and limited public support	Faster, more predictable regulation with scale-up support and investment	Regulatory bottlenecks and limited public coordination persist
EU industrial competitiveness	Low: production remains costly and weakly embedded in EU value chains	Low: EU does not become a strong production location	High: EU develops competitive domestic value chains and export potential	Moderate: firms improve processes, but scale remains limited
Market uptake	Limited to specialist and high-value niches	Very low uptake	Gradual but meaningful expansion from niche to established segments	Uptake increases in selected niches, especially ingredients
Consumer and market acceptance	Limited acceptance and weak legitimacy in food markets	Low acceptance and little visible market change	Wider social acceptance supports growth	Some commercial credibility, but not broad acceptance
Effects on conventional proteins	Marginal change; limited disruption	Little to no change by 2030	Meaningful restructuring by 2050, including partial substitution, hybrid products and complementarity	Limited effects, concentrated in specific dairy and egg protein ingredients
Role of agriculture and rural value chains	Weak domestic embedding; limited value creation for EU agriculture	Conventional system largely preserved, but EU may fall behind globally	Farmers, co-operatives and rural industries may participate through feedstocks, residues, co-products and local processing	EU risks proving technologies without capturing commercial-scale value
EU position globally	EU may open its market without building a competitive industry	EU becomes a follower rather than a shaper	EU becomes globally competitive and may export microbial proteins	Other regions build the lead while EU deployment remains limited
Main risk	Policy support fails to overcome structural weaknesses	Delayed structural disadvantage and dependence on external innovation	Some displacement of conventional sectors, though partly mitigated by integration	Lost opportunity due to weak regulatory and policy conditions
Overall market outcome	Marginal change with limited domestic value creation	Conservative continuity in the medium term, with long-term strategic risk	Broad restructuring of EU protein markets by 2050	Persistent niche development without full transformation

3.3.1 SQ3.1 - How and to what extent will the development of fermentation technologies affect the internal market for conventional protein products (animal & plant-based)?

Summary of the main findings

Analysis of across the four scenarios showed that the expected effect of biomass and precision fermentation proteins on the internal market for conventional protein products is expected to remain limited in the medium term and to become more differentiated only in the longer term. The central pattern is that microbial proteins is unlikely to affect the market through broad displacement of conventional animal and plant proteins. Instead, the most plausible effects arise in specific protein ingredients and processed applications, particularly where proteins are valued for their functional, nutritional or compositional properties rather than for their identity as conventional agricultural products. This means that the first points of interaction are most likely to concern specialised dairy proteins, egg proteins – used as ingredients, and certain plant-protein-based formulations. On the other hand, replacement of bulk meat proteins and the feed protein market, remains more constrained by cost competitiveness and low-margin market conditions, which limit the scale of uptake of microbial proteins, especially in the medium term.

A second general finding is that the internal market dynamics depends fundamentally on the interaction between competitiveness, regulatory support, market acceptance, and the extent to which production capacity is actually built within the EU. Where regulatory support and the market acceptance and competitiveness conditions are weak – namely Scenario 1 and Scenario 2, microbial proteins remain confined to narrow specialist markets and do not materially alter the structure of conventional protein markets. Where these conditions align more positively, microbial proteins move beyond narrow niches and begin to affect conventional protein markets more visibly, mainly through ingredient substitution, product reformulation and hybrid products combining microbial and plant-based proteins.

A third important point is that the effect on the internal market is unlikely to take the form of a simple replacement dynamic. Even in the most favourable scenario, the expected change is better understood as a selective restructuring of protein markets. Some protein products will likely not be replaced at all due to e.g. their structural and sensory complexity; some conventional protein ingredients may face substitution pressure; some conventional sectors adapt by integrating microbial proteins into their innovation strategies; and some plant protein markets benefit from complementarity rather than competition. The effect is therefore uneven across products, uses and value chains.

Taken together, the four scenarios support three main conclusions on the internal market for conventional proteins:

- First, the effect of biomass and precision fermentation proteins remains limited by 2030 in all scenarios. Even under the most favourable trajectory, microbial proteins still represent only a small share of protein categories at that horizon. Under less favourable conditions, the impact across the main conventional protein markets remains negligible or highly niche.
- Second, the protein markets most likely to be affected first are specialised dairy proteins, egg proteins and other high-value protein ingredients used in processed foods, as their functionality can be replicated, whereas many whole food products, such as milk and eggs, cannot be directly substituted. By contrast, meat proteins and feed proteins remain consistently less exposed across the scenarios. Plant proteins used in human food applications, especially in plant-based and hybrid products, are more likely to interact with microbial proteins through complementarity than through direct competition, for example where microbial proteins improve the nutritional profile, functionality, taste or texture of plant-based formulations.
- Third, the scenarios diverge materially by 2050. Under **Scenario 3**, microbial proteins could achieve meaningful – in value – but still partial penetration of selected meat, dairy, as well as egg and other protein markets, primarily through partial substitution in high-value and functional ingredient applications. Under **Scenario 1**, **Scenario 2**, and **Scenario 4**, the more plausible outcome is narrower market change concentrated in specialist protein applications, combined with an increasing risk that the EU protein market is shaped by imported microbial proteins rather than strong domestic production.

Findings per scenario

Scenario 1

Under **Scenario 1**, biomass and precision fermentation proteins remain concentrated in narrow, high-value protein niches. By 2030, their effect on the internal market for conventional proteins would be very limited. Fermentation-derived proteins would compete mainly in high-value uses such as specific milk proteins and other premium protein applications, while the overall structure of conventional protein markets would remain largely unchanged.

This scenario implies that low competitiveness and weak farmers and consumer acceptance prevent microbial proteins from moving beyond small market segments. Conventional animal and plant proteins, therefore, continue to dominate both food and feed markets. The main reason is not the absence of regulatory openness, but the inability of the sector to achieve sufficient cost competitiveness and demand to enter mainstream protein markets. Microbial proteins may be technically present in the market, but they do not reach the scale required to alter market shares in a meaningful way.

The effect on meat proteins would remain particularly weak. Beef and other meat products would continue to be insulated by consumer preferences, limited market acceptance of fermentation-derived alternatives, and the continued dominance of conventional products in volume terms. The effect on feed proteins would also remain limited, as price-sensitive feed markets do not offer an attractive entry point for relatively expensive microbial proteins. As a result, protein market change remains confined primarily to specialist food and feed ingredients.

By 2050, some broadening of the internal market effect becomes possible, but the scenario still does not point to major restructuring of conventional protein markets. The most plausible development is that selective pressure increases in a small number of higher-value protein ingredients, especially in dairy-related applications, while mainstream protein markets remain largely conventional. Imported microbial proteins could nevertheless have an impact by increasing competitive pressure in these selected segments and by raising the EU market's exposure to external suppliers. The more serious long-term risk is not large-scale domestic substitution, but the possibility that parts of the EU protein market become increasingly exposed to imported microbial proteins, while domestic production remains too expensive and too weakly embedded in EU value chains to compete effectively. Under this scenario, the internal market changes only marginally in sectoral composition, but it becomes more vulnerable strategically. The overall conclusion for **Scenario 1** is therefore that microbial proteins would have a limited and highly selective effect on the internal market for conventional proteins. Their presence would be visible mainly in niche protein ingredients and premium protein applications, while conventional protein volumes remain broadly intact.

Scenario 2

Under **Scenario 2**, the internal market for conventional protein products remains closest to the status quo in the medium term. By 2030, biomass and precision fermentation proteins would have little or no material effect across the main conventional protein categories. Dairy, beef, pigmeat, poultry and eggs would all remain overwhelmingly dominated by conventional proteins, with microbial proteins present only at a marginal scale. In this scenario, the internal market effect is not merely limited; it is close to negligible over the medium term.

The defining feature of **Scenario 2** is not early substitution, but the persistence of a highly conventional protein market in which regulatory incentives, investment conditions and market uptake remain too weak to support meaningful domestic scaling. Conventional animal and plant proteins, therefore, continue to structure the internal market, and microbial proteins remain peripheral. This applies across the main protein sectors, including both food and feed. Also, the biomass and precision fermentation industry may leave the EU altogether, if not only for hyper-specific and luxurious niche markets.

The more significant implications emerge by 2050. Even then, however, the expected effect is not a strong domestic market transition driven by EU-based

fermentation production. Instead, the main concern is that the internal market for conventional proteins becomes exposed to delayed structural disadvantage. If other regions succeed in scaling microbial proteins more rapidly and at lower cost, the EU may eventually face competitive pressure from imported proteins or imported protein ingredients without having developed a domestic production base of its own. In that case, the internal market would still experience pressure, but through external competition and imported innovation rather than through an internal EU-market transformation.

This longer-term risk in **Scenario 2** is more relevant for some protein markets than for others. Dairy proteins could face growing pressure in selected ingredient markets if imported fermentation-derived alternatives become cheaper and more widely available. Pigmeat and poultry proteins may also become indirectly vulnerable because of their closer linkage to imported feed proteins and broader cost competitiveness. Beef proteins remain comparatively less exposed, both because of lower direct substitutability and because the market remains more insulated from the ingredient-driven forms of substitution that dominate elsewhere. Egg proteins are likely to remain only weakly affected in the medium term, although industrial ingredient uses could eventually become more exposed if microbial proteins become globally established.

The key point is that under **Scenario 2**, the internal market for conventional proteins remains stable in the medium term but potentially more fragile in the long term. The scenario does not produce a visible restructuring of protein markets by 2030, and even by 2050, the change is less one of broad domestic substitution than of strategic exposure to imported protein innovation, followed by a risk of long-term competitive erosion in selected protein segments, particularly if imported microbial proteins reach scale globally while the EU remains hesitant and fragmented.

Scenario 3

Under **Scenario 3**, biomass and precision fermentation proteins are expected to exert the most substantial effects on the internal market for conventional proteins. However, even in this scenario, the medium-term impact remains moderate rather than transformative. By 2030, the share of the protein market partially substituted by microbial proteins remains limited. Conventional proteins, therefore, remain dominant across the main product categories, although the increasing popularity of plant-based alternatives contributes to a broader opening of the market to microbial protein sources.

The initial market effects are expected to be concentrated in those segments where proteins are valued for their specific functional or compositional properties. In this respect, dairy proteins represent one of the clearest entry points, particularly in relation to individual dairy proteins and higher-value ingredients. Microbial proteins may also strengthen plant-based formulations by improving their nutritional profile, functionality or sensory performance. Accordingly, early market uptake is not confined to isolated niche products, but begins to affect

selected segments of the internal market through ingredient substitution, reformulation and hybrid applications.

By 2050, the impact on the internal market more pronounced under this best-outcome pathway. Instead of remaining confined to niche applications, microbial proteins could become an established component of selected meat, dairy, egg and other protein markets. The strongest effects would still be expected in high-value and functional ingredient applications, hybrid products and reformulated foods, where microbial proteins can provide specific properties that are difficult to obtain from conventional or plant-based ingredients alone. This would imply a meaningful restructuring of parts of the internal protein market, but not a wholesale replacement of conventional proteins.

The increase between 2030 and 2050 is driven by a combination of factors. A key element is the growing recognition within the farming sector that biomass and precision fermentation may create opportunities for traditional agriculture rather than competing with parts of it. This progressively facilitates the development of synergies between conventional farming, feedstock supply and fermentation-based value chains. In parallel, expected technological breakthroughs in process efficiency and scale-up are likely to support broader commercial uptake. An important caveat that was repeatedly highlighted by foresight participants is that, for all of this to happen, it would be necessary to look at and address biomass and precision fermentation in their entirety, as opposed to only focusing on protein production. As both biomass and precision fermentation can develop applications that span a wide range of sectors besides food, participants – especially those from the precision fermentation sector – repeatedly pointed out that, for the sector to scale up as required, one should foster the development of a robust and comprehensive value chain.

Rising demand for proteins is also expected to strengthen the overall market case for diversified protein sources. In addition, policy developments, including more stringent emission-reduction targets, are likely to reinforce incentives for the uptake of microbial proteins. Pressure on arable land may further favour production systems capable of delivering proteins with lower land-use requirements.

Even under this favourable trajectory, the expected market effect should not be interpreted as a wholesale replacement of conventional proteins. The dominant pattern is one of market re-composition rather than simple substitution. Microbial proteins are expected to complement plant-based proteins in hybrid products, enter reformulated food applications, and compete in selected ingredient markets where conventional animal proteins have traditionally held strong positions. As a result, market change is likely to occur through a combination of partial substitution, new product development and reorganisation of value chains.

Scenario 3, also has the strongest implications for the relationship between microbial proteins and conventional agriculture. Certain crop sectors may become more relevant as suppliers of feedstocks, including co-products,

residues, and side-streams. This creates the possibility for parts of conventional agriculture, particularly those linked to processing and feedstock supply, to participate in the emerging protein economy. The effect on the internal market should therefore not be understood solely in terms of market loss for conventional proteins, but also in terms of increasing integration between agricultural and microbial protein value chains. At the same time, this scenario remains subject to a number of significant risks. Rising energy costs, driven, for example, by geopolitical tensions or wider structural increases in electricity demand, could weaken the cost competitiveness of fermentation-based production. High capital expenditure requirements and long return periods on investment may also slow industrial deployment. Trade conflicts and tariff-related disruptions could constrain supply chains and increase costs further. In addition, the spread of misinformation or fake news could undermine consumer confidence and slow market uptake, even in a context of improving technology and supportive policy.

Scenario 4

Under **Scenario 4**, the internal market effect remains more limited than under **Scenario 3**, but more differentiated than under the two low-competitiveness scenarios. In this scenario, technological capability improves, and some microbial proteins become commercially credible, but weak regulatory and policy support prevents broad market deployment. As a result, the internal market effect is real, but concentrated in a relatively narrow set of protein applications.

The strongest market interaction arises in protein ingredient markets, especially where microbial proteins can reproduce or complement specific functional properties. This is particularly relevant for dairy proteins and egg proteins, because these proteins often play highly valued functional roles in food manufacturing. Under this scenario, dairy-related fermentation products remain a small share of the overall market by 2030, but they begin to diversify the market for specific milk components and specialised dairy proteins. Similarly, fermentation-derived egg proteins have the potential to substitute for conventional egg-derived proteins in industrial uses where binding, emulsification or foaming matter more than the identity of the original agricultural product.

This means that the internal market effect is concentrated in processed food and ingredient applications. The likely pressure on conventional proteins is therefore stronger in the downstream industrial use of eggs and dairy proteins than in conventional raw milk or shell eggs as such. This distinction is central. It implies that microbial proteins would alter particular protein markets without necessarily causing broad disruption across the associated primary sectors.

By contrast, the effect on beef proteins remains very limited. Microbial proteins are not treated as a major substitute for beef because of the continued importance of product texture, sensory characteristics and consumer expectations. Likewise, the effect on feed proteins remains constrained by strong price competition. Microbial proteins may continue to play a role in some

specialised feed additives, but they do not fundamentally alter mainstream feed protein markets under this scenario.

The interaction with plant proteins is also more complementary than competitive. Microbial proteins can be combined with plant proteins in hybrid products or used to improve the nutritional or functional profile of plant-based foods. This means that the internal market effect is not one of uniform competition between microbial and conventional plant proteins. Instead, some plant-protein-based markets may be reinforced through complementarity, especially where hybrid formulations become commercially relevant.

By 2050, the internal market effect becomes somewhat broader, particularly in industrial food applications using dairy and egg proteins, but the scenario never reaches the threshold of wider systemic change. Microbial proteins remain too niche and too weakly supported to transform mainstream protein markets. The overall market structure, therefore, remains conventional in aggregate terms, albeit with growing specialist competition in selected protein segments and an increasing strategic risk that the EU consumes microbial proteins without establishing a strong domestic base for their production.

The overall conclusion is therefore that under **Scenario 4**, microbial proteins would have a focused but incomplete effect on the internal market. The strongest impacts would occur in functional protein ingredients, especially in dairy- and egg-related applications, while conventional meat and feed protein markets would remain largely stable.

3.3.2 SQ3.2 - Which specific sectors (e.g. dairy, meat, eggs, crops) are likely to be the most (positively and negatively) impacted?

The foresight workshops' evidence points to a differentiated pattern of sectoral impacts. The primary sectors most likely to be affected are those in which proteins are used as functional ingredients in food manufacturing, those that might benefit from better feed formulation obtained through precision fermentation, and those able to benefit from new demand for fermentation feedstocks. Across the discussions, the clearest negative exposure concerns egg ingredients and parts of the dairy protein and ingredient market, while the clearest positive effects concern sugar-, starch- and other carbohydrate-rich crop sectors, which could reap additional benefits from the development of a strong fermentation industry, mainly by supplying feedstock. Pigmeat and poultry emerge as largely unaffected in terms of competition, although workshops also identified specific opportunities for these sectors through more tailored feed composition. Beef appears less directly exposed to microbial protein substitution, although it remains relevant within the broader shift towards hybrid protein products.

The egg sector is one of the most clearly exposed sectors. The main reason is that egg proteins are widely used in food manufacturing for their technological

properties, especially foaming, emulsification and binding. These functions can be replicated more readily than the sensory or structural characteristics of many other animal products. The likely effect is therefore concentrated first in ingredient and processing markets, particularly in bakery, food manufacturing and processed foods. In the medium term, the impact remains limited by cost and scale, but by 2050 eggs are consistently identified as one of the most plausible areas for wider substitution by microbial proteins. This holds true for egg-derived ingredients, whereas table/shell eggs will most certainly be unaffected, as fermentation – be it biomass or precision – cannot replace whole products. The workshop evidence therefore suggests that egg-derived ingredients are among the most directly exposed protein segments.

The dairy sector is also expected to be significantly affected, although in a scenario-dependent and more mixed way. The strongest area of impact concerns specialised dairy proteins, functional ingredients and individual milk components. In the more constrained scenarios, fermentation competes first in niche ingredients and higher-value dairy proteins, with limited implications for broader market volumes and therefore limited direct effects on raw milk demand, milk prices or dairy herd size. In the more favourable scenario, however, the implications for dairy farmers become more material. If fermentation-derived dairy proteins scale beyond niche applications and substitute conventional dairy proteins in a wider range of food and nutrition markets, this could reduce demand for specific milk components and create knock-on pressure on raw milk demand, farmgate prices, production volumes and herd size. Such effects could reinforce existing structural pressures already contributing to exits from the dairy sector. At the same time, parts of the dairy processing sector may be among the better-placed actors to adapt, because processors already have relevant capabilities in protein processing, biotechnology and ingredient innovation. Cooperative structures may also help connect farmers to downstream processing and value creation. The overall implication is therefore twofold: dairy is exposed to competitive pressure in some ingredient markets, but also has stronger adaptation potential than many other sectors if microbial protein value chains remain embedded in Europe.

Within the meat sector, the workshop evidence points to an important internal differentiation. Pigmeat and poultry are more exposed than beef, especially over the longer term. Their vulnerability is not primarily framed as direct replacement in consumer markets, but as a consequence of their dependence on imported feed proteins and their sensitivity to feed-cost shifts. In the more conservative scenarios, this creates limited effects by 2030 but stronger vulnerability by 2050, particularly if competing regions adopt fermentation-based inputs more quickly and lower production costs more effectively. At the same time, the later workshops introduced an important nuance: fermentation-derived inputs may also offer benefits for pig and poultry feed formulation, especially through amino acids, vitamins, enzymes and other ingredients that help tailor feed composition more precisely. The pig and poultry sectors already make extensive use of amino acids, vitamins, enzymes and other specialised feed additives. The potential additional benefit is therefore not that fermentation would introduce these inputs

into feed systems for the first time, but that further development of fermentation capacity could improve the availability, affordability, specificity or security of supply of such technical feed inputs. It was repeatedly underlined that pigs and poultry (especially young animals) usually need more tightly formulated feeds than beef cattle do. The main reason is digestive biology: pigs and poultry are monogastric, so diet formulation has to hit a fairly precise balance of digestible amino acids, energy, minerals, and vitamins. Authoritative nutrition references for both pigs and poultry emphasise that formulation is driven by specific essential amino acids such as lysine, methionine, threonine, and tryptophan, not just crude protein ⁽¹⁰⁾. Implementation of additives/ microbial proteins could reduce overfeeding, lower nitrogen losses and improve feed efficiency. The evidence therefore suggests that pigmeat and poultry are both structurally vulnerable and potential beneficiaries, depending on whether fermentation develops mainly as an external competitiveness challenge or as a complementary feed innovation within EU production systems.

Beef should be treated more cautiously. The workshop discussions do not support the view that microbial proteins are currently a major direct substitute for beef within the time horizon considered. Participants repeatedly emphasised the difficulty of replicating beef's texture, structure and sensory profile. At the same time, beef remains commercially relevant within the wider shift towards microbial proteins because hybrid protein products as an alternative to beef are seen as an important market trend. However, workshop participants also noted that these hybrid products are, at present, driven mainly by plant-based proteins, rather than by microbial proteins. Theoretically, a massive uptake of plant-based analogues to meat might end up having an indirect positive impact on the precision fermentation sector, and create competitive pressure on conventional beef demand in the affected product segments. In addition, beef may be affected indirectly through the dairy channel: if fermentation-derived dairy ingredients reduce demand for conventional dairy proteins, this could affect dairy herd size and therefore the supply of cull cows and dairy-bred calves entering beef value chains. The implication is that beef is not unaffected, but it is less directly exposed through fermentation itself than eggs or dairy ingredients. Its relevance lies more in the broader market evolution of alternative and hybrid proteins than in direct fermentation-based substitution.

The strongest positive impacts are expected in crop and feedstock sectors, especially those supplying sugar beet, cereals, maize, potatoes, lower-grade grains, and potentially also some secondary biomass streams ⁽¹¹⁾. These sectors

⁽¹⁰⁾ <https://www.merckvetmanual.com/management-and-nutrition/nutrition-pigs/nutritional-requirements-of-pigs>

⁽¹¹⁾ Secondary biomass streams refers here to non-primary material flows from agriculture and agri-food processing. These include residues left after harvesting or processing, such as straw or stalks; co-products with established economic value, such as beet pulp, molasses or bran; by-products generated incidentally during processing, such as whey, spent grain or

recur across the workshops as the clearest pathway through which farmers could participate in fermentation-based value chains. In the more favourable scenario, the opportunities are substantial: fermentation plants create demand for beet juice, molasses, starch, beet pulp, straw and corn stalks, and, generally speaking, all lignocellulosic biomass. The second and third workshops made clear, however, that these opportunities depend on practical conditions such as feedstock quality, pre-processing infrastructure, biomass hubs, logistics, cooperative organisation and long-term contracts capable of giving farmers more stable revenues. This means that crop sectors are the most clearly positive case, but only where fermentation production and value capture remain located in Europe. Under more restrictive scenarios, the main risk is not direct loss, but foregone opportunity, if the same feedstock markets develop mainly outside the EU.

A separate point concerns feed proteins and feed markets more broadly. The workshop evidence does not suggest that the bulk feed protein market will be transformed quickly, since feed remains highly price-sensitive and conventional feed ingredients such as soybean meal are difficult to compete with on cost. However, this should not be interpreted as meaning that feed is unimportant. The more precise conclusion is that fermentation-derived products are more likely to matter first in feed additives and feed formulation, rather than as bulk substitutes. This is particularly relevant for pig and poultry systems, where more tailored amino-acid composition and other functional feed ingredients could create concrete advantages. Feed is therefore not one of the most clearly negatively affected sectors, but it is an important area of complementary impact.

fruit pomace; and broader side-streams, meaning any secondary material flow separated from the main production stream that could potentially be valorised as a fermentation feedstock.

Table 8 – Summary of market impact scorecards for traditional agriculture sectors

Sector	Likely impact	Main direction	Main mechanism of impact	When most relevant	Scenario difference
Egg ingredients	One of the most exposed sectors	Negative	Microbial proteins can replicate foaming, emulsifying and binding functions used in bakery and processed foods; strongest effect is in ingredient/B2B markets rather than table eggs	Limited by 2030; stronger by 2050	More pronounced in Scenario 3 and Scenario 4 ; weaker in restrictive scenarios in the medium term
Dairy proteins and ingredients	One of the most affected sectors, but in a mixed way	Mixed: negative pressure + adaptation opportunity	Competition in specialised proteins and functional ingredients; potential to produce specific milk components via fermentation; existing dairy processing capacity may support adaptation, however dairy farms likely to be affected	Ingredient pressure starts earlier; stronger restructuring by 2050	In restrictive scenarios, effect remains niche or import-driven; in Scenario 3 , dairy can also adapt and integrate
Pigmeat	Structurally vulnerable in the longer term	Mixed, but mainly negative in conservative scenarios	Strong feed dependence and sensitivity to imported proteins and feed-cost shifts; at the same time, pig feed can benefit from more tailored amino acid composition and other fermentation-derived inputs	Mainly by 2050	More negative in Scenario 2 ; more mixed in Scenario 3 if feed innovation is adopted domestically
Poultry	Structurally vulnerable in the longer term	Mixed, but mainly negative in conservative scenarios	Similar to pigmeat: high sensitivity to feed costs and imported feed proteins; also scope for fermentation-derived enzymes, amino acids and additives to improve feed composition	Mainly by 2050	More negative in Scenario 2 ; more mixed if domestic feed applications scale
Beef	Less directly exposed than eggs and dairy ingredients	Limited direct negative effect	Microbial proteins are not seen as a major direct substitute for beef; however, beef remains relevant through dairy, hybrid burger – and potentially other meat products – trends, even if these are currently driven mainly by plant proteins	Mostly long term, and indirect	Beef stays less exposed across scenarios; relevance increases only through broader hybrid/microbial protein trends

Sector	Likely impact	Main direction	Main mechanism of impact	When most relevant	Scenario difference
Sugar beet	One of the clearest positive opportunities	Positive	New demand as a sugar feedstock for fermentation; possible contracts, cooperative models, biorefinery logic, regional processing	Can emerge before 2030; stronger by 2050	Strongest in Scenario 3 ; weaker or missed opportunity in restrictive scenarios
Cereals / starch crops	Clear positive opportunity	Positive	Demand for glucose, starch and other carbohydrate-rich feedstocks; possible long-term contracts and diversification of farm income	Mostly medium to long term	Strongest where fermentation plants are in the EU; weaker where value chains relocate abroad
Maize / potatoes / lower-grade grains	Positive opportunity, but conditional	Positive	Potential feedstocks for fermentation, especially if crop demand increases beyond refined sugar supply; may create more stable outlets if linked to contracts	More relevant with scale-up	Much stronger in Scenario 3 ; uncertain in restrictive scenarios
Residues and side-streams	Positive but highly conditional	Mixed-positive	Straw, beet pulp, corn stalks and other side-streams may become feedstocks, but only if pre-processing, purity and logistics are solved	Mainly long term	Strongest in Scenario 3 ; weaker or missed opportunity in restrictive scenarios
Feed proteins (bulk market)	Limited structural change	Limited / mixed	Bulk feed remains highly price-sensitive; microbial proteins are not expected to replace soybean meal widely in the short term, but may partially substitute in the long term	Mostly limited throughout period	Across scenarios, bulk change remains constrained; however, targeted feed applications matter

3.3.3 SQ3.3 - To what extent may these innovations help to reduce the EU's dependence on imported proteins?

Summary of the main findings

The evidence suggests that biomass and precision fermentation are unlikely to materially reduce the European Union's dependence on imported proteins in the medium term. In the longer term, any reduction would likely remain partial, limited in scope, and conditional. At most, they may contribute to a modest reduction in dependency in selected segments, provided that a demanding set of conditions is met simultaneously. The key condition is that microbial proteins and related inputs are produced within the EU, rely to a meaningful extent on EU-based feedstocks, and substitute for imported proteins or imported protein-related inputs in applications where they are technically and economically viable. If these conditions are not met, fermentation is unlikely to reduce external dependency. On the contrary, it may simply alter its form, replacing imported conventional proteins with imported fermentation-derived products, imported feedstocks, or imported fermentation-related inputs.

Differences between the scenarios

Even under the most favourable pathway, the likely effect remains modest. The evidence associated with **Scenario 3** points to some easing of dependence on imported proteins such as soy and fishmeal. However, it does not suggest a major structural shift. The likely contribution is better understood as one of incremental diversification and resilience gains rather than large-scale substitution. Moreover, the potential effect is highly uneven across product categories. In bulk feed proteins, fermentation-derived products are not expected to compete widely with commodity imports such as soymeal because of cost constraints and market structure. Nevertheless, even limited substitution in selected applications may contribute to resilience where it reduces reliance on a narrow set of imported protein sources. In this area, biomass and precision fermentation technologies are more likely to remain confined to specialised or higher-value applications. This substantially limits their ability to change the overall import balance. A somewhat more credible contribution exists in relation to feed additives and targeted feed inputs, especially amino acids, vitamins, enzymes and similar components already used in livestock nutrition. Here, microbial proteins may reduce reliance on certain imported strategic inputs, particularly in pig and poultry systems. However, this remains a narrower and more indirect effect than a significant reduction in dependence on imported protein crops or bulk feed ingredients.

A further limitation on the possible impact of biomass and precision fermentation regarding EU's dependence on imported protein is that the location of upstream feedstock sourcing remains uncertain. Several contributions stressed that, unless policy or market conditions actively favour European feedstocks and short value

chains, fermentation-based production in Europe could still rely on imported sugars or other imported biomass inputs. In such a case, the net effect on strategic autonomy would be weak. The issue is therefore not only whether fermentation plants are located in the EU, but whether the wider value chain is genuinely rooted in European agriculture.

Under the more restrictive pathways, the outlook for a positive effect on strategic autonomy is weaker still. In **Scenario 2**, and to a lesser extent in **Scenario 1**, the evidence points not to lower dependency, but to the risk of new forms of dependency. This risk should not be understood primarily as the large-scale replacement of bulk feed imports such as soymeal by imported microbial proteins. Rather, it concerns those fermentation-derived products that are more likely to become internationally traded and cost-competitive first, including higher-value protein ingredients and targeted feed inputs such as amino acids, vitamins, enzymes and specialised proteins used in livestock nutrition or food manufacturing. In these segments, producers in other regions may achieve cost reductions earlier if they benefit from lower energy costs, cheaper standardised feedstocks, larger fermentation capacity, faster industrial scale-up or more predictable regulatory pathways. Similar cost reductions could in principle occur within the EU, but under these scenarios domestic production remains constrained by high capital and operating costs, regulatory uncertainty, slow scale-up and weak integration with EU feedstock and processing chains. In these pathways, fermentation therefore does not strengthen protein autonomy in any meaningful sense. Instead, it risks shifting dependency from imported conventional protein crops and bulk feed ingredients towards imported fermentation-derived ingredients, strategic feed inputs or production technologies.

On balance, the most defensible conclusion is therefore a cautious one. Biomass and precision fermentation may offer a limited supplementary contribution to reducing EU dependence on imported proteins, particularly in some specialised food ingredients and feed-related inputs, but not even the most optimistic stakeholders believe they will deliver a major reduction in overall import dependence within the time horizon considered. Their main relevance lies more in diversification and resilience than in any substantial replacement of imported protein sources: they may broaden the range of protein and feed-input options available to the EU, reduce exposure to concentrated dependencies in selected segments such as fishmeal alternatives, amino acids, vitamins and enzymes, and improve flexibility in feed and ingredient formulation. However, these effects remain selective and conditional on production being located in Europe and linked, at least partly, to EU-based feedstocks and value chains.

3.4 SQ4 - What potential opportunities could biomass and precision fermentation offer to EU farmers and rural economy in the medium and long terms?

The evidence suggests that biomass and precision fermentation could create a broad but highly conditional set of opportunities for EU farmers and rural economies over the medium and long term. However, there is considerable uncertainty regarding whether, where and to what extent these opportunities will materialise in practice. They should therefore be understood as potential opportunity pathways rather than expected or automatic outcomes. These opportunities do not arise simply from the existence of a new technology. They depend on whether fermentation develops in ways that are embedded in European agriculture, linked to rural territories, and organised through value chains that allow farmers and rural actors to capture part of the value created. In this respect, the opportunity set extends beyond new demand for feedstocks. It also includes more stable market outlets, diversification of farm business models, stronger local value capture, access to new farm inputs, participation in innovation systems, and wider rural industrial development.

The opportunity set is also highly differentiated in time. By 2030, the most plausible gains are relatively narrow and concentrated in feedstock supply, selected uses of fermentation-derived products on-farm, and more structured market relationships such as contracts and cooperative supply arrangements. By 2050, the range of opportunities could broaden to include residues and side-stream valorisation, biomass hubs and pre-processing systems, cooperative or farmer-linked processing assets, circular territorial models, and stronger links between farming, energy and local industry. However, these longer-term opportunities remain conditional on technological progress, infrastructure, industrial scale-up and supportive governance. This includes alignment with the EU Bioeconomy Strategy, which already provides a broader policy framework for circular biomass use, bio-based value chains, sustainable use of biological resources and rural bioeconomy development, even though it is not specific to microbial proteins.

A further cross-cutting finding is that opportunities are unlikely to be distributed evenly. Regions with large arable farms and existing sugar, starch or processing industries are much better placed to benefit directly than less-favoured areas, mountain regions or more diversified small-scale farming systems. Similarly, some opportunities depend on farmers being involved not only as suppliers or users, but also as participants in advisory systems, pilot projects, demonstration activities, regional innovation networks and, in some cases, cooperative ownership structures. The workshops, therefore, point not only to market opportunities, but also to the importance of early farmer involvement in shaping how those opportunities materialise. Stakeholders from both traditional farming and biomass and precision fermentation agreed that it is pivotal to find

mechanisms to empower farmers within the value chain, otherwise any transformation would fail to yield the expected benefits to farmers.

At the same time, the same developments that may generate opportunities can also create exclusion risks, territorial imbalances or limited value capture for farmers if production scales elsewhere, relies on imported feedstocks, or remains detached from local processing and governance. For this reason, SQ4 should be read together with SQ5. SQ4 identifies where and how benefits could arise; SQ5 addresses the corresponding challenges and conditions that may prevent those benefits from being broadly realised. The analytical task is therefore not to present fermentation as inherently beneficial, but to assess under what conditions it may generate net gains for farmers and rural areas.

Against this background, the analysis of SQ4 is structured around three dimensions:

- first, the ways in which farmers could participate directly in emerging value chains;
- second, the wider benefits that may arise for farm competitiveness beyond direct participation; and
- third, the extent to which biomass and precision fermentation could support wider rural economic development.

3.4.1 SQ4.1 - In what ways could farmers participate in the value chain, through the supply of feedstocks (e.g. sugars, cereals, whether locally produced or imported) or the use of fermentation-derived products (e.g. for animal feed)?

By 2030, the most credible participation route is through the supply of feedstocks for microbial protein production. The clearest candidates are sugar beet, cereals, wheat, maize, potatoes, starch crops and, in some cases, lower-grade grains. Across the workshops, these crops recur consistently because they already fit existing European production systems and because fermentation processes still depend heavily on relatively standardised sugar- and starch-based inputs. In the medium term, the opportunity is therefore less about a radical change in farming systems than about the emergence of an additional outlet for existing crop production, especially where farmers are already linked to sugar, starch or ethanol processing chains. A second medium-term opportunity lies in the commercial structure through which these feedstocks for microbial protein production are supplied. The most plausible route is not spot-market sales, but contract farming, long-term supply agreements and/or cooperative supply models. These arrangements matter because they can stabilise demand and make fermentation a more credible outlet than current annual commodity markets alone. In practical terms, the contractual and cooperative supply arrangements

used in sugar beet and starch processing appear to be the closest template for medium-term farmer participation. This is especially relevant because the workshop evidence repeatedly linked farmers' participation to income stability and risk-sharing, not just to the existence of new demand.

Also, by 2030, farmers may participate in value chains of microbial proteins as users of fermentation-derived products on-farm, although this route is likely to be narrower than feedstock supply. The clearest applications concern animal feed additives and feed-improving inputs, especially amino acids, vitamins, enzymes and similar fermentation-derived ingredients. These are not expected to transform the bulk feed market quickly, but they can already support more tailored feed composition, particularly in monogastric systems. The practical opportunity here is therefore to improve feed efficiency and input quality rather than to replace conventional feed systems outright. Bio-fertilisers and other biobased inputs were also identified as relevant, although less concretely than feed-related uses.

By 2050, the opportunity set broadens beyond the supply of conventional crops. If scale-up occurs within Europe, farmers could participate through the valorisation of residues, by-products and side-streams, including beet pulp, molasses, straw and corn stalks. This does not mean that only crop-based side-streams are relevant. Indeed, other agri-food processing streams may also be used or become relevant as fermentation feedstocks, including dairy co-products such as whey or dairy permeates, as well as fibre-rich or lignocellulosic streams from food and agricultural processing. This is important because it changes farmers' participation from the sale of primary crops alone to a wider form of biomass provision. It also creates scope for new revenue streams from materials that are currently low-value, wasted or used in lower-value applications. However, this opportunity remains conditional on advances in sorting, pre-processing and fractionation, since current fermentation systems still require relatively standardised inputs.

The longer-term opportunity also includes feedstock diversification. Beyond the core sugar and starch crops, the evidence points to oats, peas, tubers and other carbohydrate-rich crops becoming more relevant if industrial demand expands. In that case, farmers would not simply add one new buyer; they could reposition part of their crop mix towards fermentation-linked outlets. The optimistic pathway goes further and envisages farms rotating or reallocating land in response to this demand, including livestock farms producing fermentation feedstocks alongside existing activities.

A further long-term opportunity is deeper participation in value creation, especially through cooperatives, farmer-owned assets and regional processing systems. This was not framed as the most immediate route for most farms, but it was clearly presented as one of the most valuable routes where it can be achieved.

The example of a French cooperative acquiring a lysine plant ⁽¹²⁾ illustrates that farmer-linked ownership of fermentation-related processing is not purely hypothetical. More broadly, the evidence points to the possibility of cooperative fermentation units, biomass hubs, pre-processing centres and regional biorefineries, which would allow farmers to capture more than the raw-material margin and retain part of the value added locally.

This is also where scenario differences matter most. In the more favourable pathway, especially **Scenario 3**, these deeper forms of participation become materially more plausible because public support, shared infrastructure and early farmer engagement help build integrated value chains. By 2030, that could already mean feedstock supply combined with co-financed hubs or cooperative arrangements; by 2050, it extends to a more structural role for farmers as co-owners, regional processors or participants in circular biorefinery systems. In the more restrictive pathways, by contrast, feedstock supply remains the dominant opportunity, while deeper participation stays niche or unrealised because scale-up and investment take place elsewhere.

A related long-term opportunity is the development of more circular territorial systems. Where fermentation is embedded in rural areas and linked to regional feedstocks, it can support local processing, logistics, energy production and ancillary services. The evidence explicitly links this to biogas, biomass hubs and cooperative biorefinery models, where farmers do not just supply biomass but become part of a wider local system that aggregates, upgrades and channels agricultural resources into higher-value uses. This does not apply equally across Europe: the benefits are expected to be much stronger in regions with large competitive arable farms and existing sugar or starch industries than in less-favoured areas or highly diversified small-scale systems.

One further nuance is important. These opportunities depend not only on technology, but on where the value chain is located. Several contributions stressed that, unless policy or market conditions favour European feedstocks and short value chains, new fermentation chains may rely on imported sugar or sugar cane rather than EU biomass. In that case, the technology may still develop, but farmer participation in the EU would be much weaker. The opportunity is therefore not simply “fermentation growth”, but “fermentation growth anchored in European agriculture”.

A further – and more ambitious – opportunity lies in earlier and stronger farmer involvement in innovation systems, including pilots, advisory structures, demonstration activities and regional platforms. This matters because participation is not limited to supplying feedstocks or using products on-farm; it may also involve shaping how value chains develop and how benefits are distributed. In addition, some rural actors may participate through hosting and

⁽¹²⁾ <https://www.aquafeed.com/regions/europe/avril-group-takes-over-metex-noovistagoo-relaunching-lysine-production-in-europe/>

service functions, including biomass aggregation, pre-processing, storage, logistics and links with local energy systems. These participation routes remain more conditional than feedstock supply, but become more relevant in the longer term, where fermentation develops as a territorially embedded value chain.

3.4.2 SQ4.2 - In what ways could farmers obtain other potential benefits beyond participating in the value chain, and how might these benefits strengthen their overall competitiveness?

Beyond direct participation as feedstock suppliers or users of fermentation-derived products, the evidence points to a broader set of potential benefits that could strengthen farmers' competitiveness at the farm level and within rural production systems. These benefits are less about a single new outlet and more about improving income stability, bargaining position, input efficiency, diversification capacity, and the ability to capture value locally. Their importance increases over time: by 2030, the most plausible gains are those linked to more predictable outlets and selected input improvements; by 2050, the benefit set broadens towards more structural improvements in farm resilience and local value creation, especially where fermentation develops as a European and regionally embedded value chain.

A first potential benefit concerns risk-sharing and income stabilisation. Long-term supply relationships with fermentation plants could reduce exposure to annual commodity volatility and provide more predictable outlets for crops. This does not automatically imply higher prices, and participants were clear that contracts do not in and of themselves guarantee favourable remuneration. Their main value lies in reducing uncertainty, spreading risks between farmers and processors, and allowing production decisions to be made against a more stable planning horizon. As in other agricultural value chains, including dairy, long-term supply relationships can still leave farmers exposed to price volatility, buyer power, input-cost changes and unfavourable contract terms. Any stabilising effect would therefore depend less on fermentation as a technology than on the way supply relationships are organised. This is a conditional benefit rather than an inherent feature of fermentation-derived value chains. Where such arrangements are combined with cooperative ownership or strong producer organisations, they may also improve farmers' bargaining position. In competitiveness terms, this could strengthen farm resilience by smoothing income fluctuations and making crop planning less dependent on short-term market swings.

However, cooperation, producer organisations and cooperative ownership should therefore be understood as enabling responses, not as benefits in themselves. They may improve farmers' bargaining position and allow them to negotiate better contractual terms, but this is more likely to benefit farmers acting collectively than individual farmers negotiating alone. For individual farmers without access to such arrangements, the competitiveness benefit is likely to be limited.

A second benefit lies in diversification of the farm business model. Fermentation-related demand could create additional outlets not only for primary crops, but also for by-products, residues and lower-value streams that currently generate limited returns. In the more favourable long-term pathway, this moves farming towards a broader portfolio of revenue sources linked to food, feed, biomaterials, inputs and circular bioeconomy uses. Such diversification matters for competitiveness because it reduces reliance on a single market and can make farms more adaptable to shifts in demand. The benefit is strongest where residues, side-streams and crop co-products can be valorised rather than discarded or sold into lower-value channels. The challenge is that farms may be encouraged to see residues as a new revenue source before the technical and commercial conditions for that market are sufficiently mature.

A third benefit concerns better access to improved farm inputs, especially in livestock systems. Fermentation-derived feed additives and related inputs may help improve feed formulation, feed efficiency and, in some cases, environmental performance. While this does not amount to a wholesale transformation of feed systems in the medium term, it does create a route through which farmers may strengthen competitiveness by improving productivity or resource efficiency. Similar arguments were also made for bio-fertilisers and other biobased inputs, although these were discussed less concretely than feed-related applications. Where such products become affordable and available, they may reduce reliance on selected imported or externally controlled technical feed inputs, and marginally strengthen farm autonomy.

A fourth benefit relates to recognition and possible remuneration for sustainability performance. Participants linked fermentation-based value chains to broader decarbonisation pressures moving down the supply chain from processors and consumer brands to primary producers. In principle, this could create leverage for farmers to be recognised and possibly rewarded for supplying lower-carbon feedstocks or for participating in more circular production systems. In competitiveness terms, this could improve farmers' market position where low-carbon or traceable feedstocks become commercially relevant. However, the evidence is cautious here: participants stressed that translating sustainability effort into actual price premiums remains difficult in basic commodity chains, and additional certification or reporting requirements may raise costs if not matched by clear economic returns.

A fifth benefit lies in stronger local value capture, especially where farmers participate through cooperatives, regional biorefineries, pre-processing hubs or local industrial ecosystems rather than supplying raw materials alone. This does not only matter for rural economies in aggregate; it can also strengthen individual farmers' competitiveness if more of the processing margin remains in the territory and if farmers gain access to collective bargaining or ownership structures. The evidence suggests that this is one of the most significant longer-term opportunities, because it shifts the farm's position from commodity supplier towards a more integrated role in regional value creation. This benefit is strongest where fermentation facilities are located near agricultural hubs and use regional

feedstocks, and weaker where production is concentrated in ports or external industrial centres.

A sixth benefit concerns skills, knowledge and innovation capacity. Farmers may benefit not only from selling into new value chains, but also from earlier involvement in pilot projects, advisory systems, demonstration activities, living labs and regional innovation platforms. In the medium term, this can improve awareness of new markets and production possibilities; in the longer term, it may help farms adjust cropping choices, diversify strategies, and engage with higher-value business models. However, farmers' ability to engage with these systems is uneven. Participation requires time, technical support, trusted advisory capacity and, in many cases, compensation for the effort involved. Living labs and similar initiatives often depend on highly motivated farmers and that the benefits may be long term rather than immediate. This means that such opportunities are more likely to be accessible to farms already connected to cooperatives, producer organisations, advisory services or innovation networks, while smaller or more resource-constrained farms may face higher barriers. This benefit is especially relevant under more favourable pathways where fermentation is developed with farmers rather than around them. Its competitiveness effect lies in reducing informational barriers and helping farms adapt earlier but only where participation mechanisms are designed around the practical realities of farming. The scale of these benefits differs across future pathways. In a more favourable development trajectory, especially **Scenario 3**, the more ambitious benefits could become cumulative: more stable outlets, better value capture, stronger local processing, new input options and greater involvement in innovation may reinforce one another. By contrast, in more restrictive trajectories, the same benefits may remain partial or fail to materialise. Contracts may exist without strong bargaining power, sustainability requirements may increase without corresponding remuneration, and local value creation may remain weak if production scales elsewhere or relies on imported feedstocks. The evidence therefore suggests that the competitiveness gains are plausible, but highly dependent on whether fermentation develops as a European, regionally embedded and farmer-linked system, rather than as a market largely served from outside the EU.

Beyond direct economic gains, an important competitiveness benefit may lie in earlier access to knowledge, innovation networks and advisory support, which can help farmers adjust production choices and engage with new markets sooner than they otherwise would. In parallel, some participants linked the opportunity set to a broader resilience gain, namely the possibility of reducing exposure to imported proteins and other strategic inputs, although this benefit remains conditional on fermentation developing as a European value chain rather than as a European market supplied from elsewhere.

These benefits should, however, be distinguished by likelihood. The most likely benefits by 2030 are relatively modest and incremental: additional outlets where contractual arrangements are favourable, selected improvements in feed formulation or input efficiency, and earlier awareness of emerging markets for

those farms already connected to advisory or innovation systems. A second group of benefits is more conditional: diversification through residues, by-products and side-streams, sustainability-related remuneration, and stronger local value capture depend on market development, infrastructure, contractual design and farmer organisation. A third group is more aspirational and mainly associated with the more favourable long-term pathway: cumulative gains from cooperative ownership, regional biorefineries, farmer-linked processing assets and a more structurally embedded rural bioeconomy.

3.4.3 SQ4.3 - In what ways could these technologies provide benefits to the rural economy?

The main rural-economy benefit would arise where biomass and precision fermentation are not confined to isolated plants, but develop as regional production systems linked to local feedstocks, pre-processing, energy and services. In that case, the benefit goes beyond demand for crops and extends to industrial activity, logistics, local maintenance, energy generation, and processing-related employment. Fermentation plants were repeatedly framed as potential anchor industries for rural areas, able to attract or sustain ancillary activities such as transport, storage, local technical services and energy supply. This effect was discussed particularly in connection with biorefineries and cooperative ownership models, where value is retained not only in farming but also in regional processing and service provision.

By 2030, the most plausible benefits are likely to remain concentrated in rural areas that already possess the right combination of feedstock availability, industrial infrastructure and processing capacity. This includes territories with established sugar, starch or cereal industries, where fermentation could be layered onto existing rural-industrial systems rather than requiring an entirely new territorial base. In such contexts, the main gains would be relatively practical: additional throughput for existing infrastructure, more local transport and logistics, some growth in technical and operational employment, and stronger use of local biomass streams. The evidence also points to possible early benefits through shared infrastructure near major crop regions, including crop hubs and pre-processing systems that connect farms more directly to local industrial demand.

By 2050, the opportunity becomes broader if the sector scales within Europe. Under more favourable conditions, rural areas could benefit from the emergence of cooperative biorefineries, biomass hubs, regional pre-processing systems and local energy linkages, including the use of residues for biogas or biomass-based electricity. Several contributions explicitly linked fermentation to a more circular rural economy, where residues and by-products are valorised, energy is produced locally, and multiple activities – agriculture, processing, energy and logistics – reinforce one another. In this longer-term view, the rural-economy benefit lies not only in extra jobs, but in denser local economic linkages and more diversified rural industrial structures.

A particularly concrete benefit discussed in the more favourable pathway is the possibility of year-round processing of crop by-products, especially in areas specialised in sugar beet and starch crops. In that context, beet juice, molasses, starch and associated co-products or residues can support not only farm incomes but also local processing continuity, which in turn sustains jobs and service activity in the surrounding rural area. The scenario material goes as far as linking this to higher rural incomes and significant employment creation in food technology, processing and agri-innovation, although this should still be read as contingent on successful scale-up and not as a baseline expectation.

The workshop material also points to a more specific territorial mechanism: the rural-economy benefit is strongest where processing is located close to feedstocks. This is not only a question of local sourcing, but of cost and industrial geography. Participants explicitly discussed the advantage of siting production near sugar mills or crop-growing areas in order to reduce feedstock transport costs and strengthen local economic spillovers. In that logic, rural benefits increase where fermentation plants are physically integrated into agricultural production territories, rather than being located mainly near ports or external industrial centres.

However, the evidence is equally clear that these benefits are unlikely to be evenly distributed. The rural areas best placed to benefit are those with large, competitive arable farms and existing sugar or starch industries, including some parts of Central and Eastern Europe. By contrast, less-favoured areas, mountain regions and territories dominated by small-scale, diversified farming are much less likely to gain directly from feedstock-based fermentation value chains. In such places, direct benefits may be weak or absent unless broader redistributive or CAP-type support is provided. This means that fermentation could strengthen some rural economies while doing little for others, and may even reinforce existing territorial disparities if value chains concentrate only in already competitive regions.

There is also a more qualitative rural-economy benefit linked to skills and labour demand. One contribution explicitly associated fermentation-linked industrial development with increased demand for higher-educated workers as well as operators, suggesting that, where rural industrialisation occurs, it can widen the local employment base rather than create only a narrow set of specialist jobs. This matters for the rural economy because it implies benefits not only for farms, but for the broader local labour market and service economy.

At the same time, these benefits remain conditional. If fermentation production and R&D continue to move outside Europe, or if European plants are located mainly near ports and rely on imported feedstocks, then rural areas in the EU may see little benefit beyond commodity crop supply. In that case, there would be limited local employment, limited processing value added, and weak territorial spillovers. Even where production initially develops in the EU, these benefits may not be durable if parts of the value chain subsequently relocate to third countries with lower production costs, cheaper energy, larger-scale fermentation capacity

or more favourable regulatory and investment conditions. The same applies if feedstock value chains remain too narrow, niche markets remain too small, or capital costs prevent local biorefinery models from becoming viable.

3.5 SQ5 - What challenges could the development and scaling-up of biomass and precision fermentation technologies pose to EU farmers and the rural economy in the medium and long terms?

The foresight evidence suggests that the main challenges for EU farmers and rural economies do not stem simply from the existence of new protein technologies, but from the conditions under which these technologies scale, who captures the value created, and how evenly the benefits and costs are distributed across sectors and territories. In that sense, the challenge question is best understood as the counterpart to SQ4. Many of the developments that may create opportunities for farmers under favourable conditions can also generate pressure, exclusion or new forms of dependency under less favourable ones. A new outlet for crops may become a weak bargaining position vis-à-vis a small number of industrial buyers; new local processing may create territorial value where it is regionally embedded, but very little where production is concentrated elsewhere or supplied through imported inputs; new feed and farm inputs may improve efficiency, but can also increase dependence on external technologies if domestic production and ownership remain limited.

A central conclusion of the workshops is therefore that the relevant analytical question is not whether biomass and precision fermentation are “good” or “bad” for traditional farming, but under what circumstances they generate net gains, adjustment pressure, or a mixture of both. This is particularly important because the effects are unlikely to be uniform. Some sectors may face direct pressure in selected ingredient markets; others may be affected more indirectly through feed dependence, changes in cost structures or altered value-chain geography. Some rural regions may benefit from new processing, infrastructure and local industrial activity; others may see little direct gain because they are not well positioned to supply the relevant feedstocks or host the associated investments. Even in a hypothetical best case scenario where biomass and precision fermentation scale up in the EU and create win-win synergies with traditional farming systems, thus producing overall net societal benefits, there will be uneven impacts at the individual level. The challenge profile is therefore inherently differentiated by sector, region, farm type and time horizon.

The time horizon is especially important. In the medium term, the challenge is less one of immediate shifts than of uncertainty, weak bargaining power, uneven preparedness and limited farmer influence over value-chain formation. By 2030, most risks are likely to concern whether new demand remains too small, too unstable or too narrowly captured to benefit a broad farm base; whether farmers are drawn into new supply arrangements without retaining adequate value; and whether the early industrial geography of the sector bypasses large parts of rural Europe. In the longer term, the challenge becomes more structural. If biomass and precision fermentation scale successfully but in ways weakly connected to European agriculture, some farming sectors may come under stronger

adjustment pressure, some territories may remain marginal to the new value chains, and Europe may risk becoming a market for these products without retaining enough production, know-how or strategic control.

Another important finding is that the workshops point not only to potential future competition, but also to systemic and distributional challenges. These include the possibility of concentration of value downstream; asymmetries in bargaining power between farmers and processors; the risk that rural development benefits are confined to already competitive arable regions; the persistence of dependence on imported proteins, imported feedstocks or imported technological inputs; and the danger that farmers are incorporated into the new value chains only as commodity suppliers, without meaningful participation in ownership, governance or innovation. In other words, the challenge is not only whether farmers may lose market share in some sectors, but whether they may remain structurally peripheral to the higher-value parts of the emerging bioeconomy.

The workshops also underline that several of the most frequently cited opportunities are conditional rather than automatic. Residues and side-streams may create new value, but only if pre-processing, purity and logistics constraints are overcome. Fermentation-derived feed inputs may strengthen livestock competitiveness, but only if they are accessible, affordable and not themselves a source of external dependency. Regional biorefineries may support rural jobs and services, but only if processing is geographically embedded and linked to local feedstocks. This conditionality is critical to the challenge analysis because it means that the mere emergence of a fermentation sector does not guarantee broad-based benefits for farmers or rural areas.

Taken together, the challenge landscape can therefore be read as a question of integration on whose terms. The technologies may be integrated into European agriculture in ways that support diversification, resilience and local value capture. Equally, they may be integrated in ways that leave some farmers exposed to possible competition, greater dependence on external actors, and territorially uneven outcomes. SQ5 should therefore be read as an assessment of the main constraints, tensions and risk factors that could prevent the opportunities identified under SQ4 from being broadly realised. The purpose is not to invert the opportunity analysis into a uniformly negative reading, but to identify the mechanisms through which potential benefits may remain partial, fragile or concentrated unless actively addressed.

This introductory framing then leads naturally into three more specific analytical dimensions: the implications for the rural economy, the differentiated effects across farming sectors, and the practical and structural questions surrounding the integration of these technologies into farms and farming systems.

3.5.1 SQ5.1 - How might the rural economy be affected?

The rural-economy effects are likely to be mixed, territorially uneven, and highly dependent on where processing, ownership and feedstock sourcing are located. This is the central point that emerges when the challenge discussion is read against the opportunity discussion. The same development that may support rural jobs, logistics and local processing under favourable conditions may, under less favourable conditions, create only a thin upstream link to farming, with most value captured elsewhere. The question is therefore not simply whether fermentation reaches rural areas, but how deep that integration is and on whose terms it occurs.

A first challenge is the risk of thin local value capture. In the more optimistic reading, fermentation plants can function as anchor activities for rural areas, stimulating transport, storage, pre-processing, technical services and local industrial demand. The challenge, however, is that this outcome is not automatic. If plants are highly capital-intensive, highly automated, externally owned, or supplied through imported feedstocks, rural areas may capture only a limited part of the value created. In that case, the rural economy is connected to fermentation mainly through crop supply and some logistics, while the more profitable functions – formulation, processing, intellectual property, branding and strategic control – remain concentrated elsewhere. The result would not be rural decline in an immediate sense, but a form of partial integration in which rural territories participate without controlling or retaining much of the value.

A second challenge concerns territorial concentration and regional divergence. The opportunities identified under SQ4 are strongest in rural areas with large arable farms, established sugar and starch industries, good logistics and an existing industrial base. That is precisely what makes the rural challenge sharper: the same conditions imply that other rural areas are much less likely to benefit. Livestock-dominated areas, mountain regions, less-favoured areas, and territories structured around smaller and more diversified farming systems may remain peripheral to the main crop-based fermentation value chains. Dairy-processing regions may have different opportunities where side-streams such as whey, dairy permeates or other nutrient-rich co-products can be used as fermentation inputs. However, these opportunities depend on the presence of processing facilities, sufficient and consistent volumes, and technical feasibility. The likely result is not a uniform rural transformation, but a geography of selective inclusion. Some rural economies may attract plants, hubs and service activity, while others see very little beyond indirect market effects. In that sense, fermentation could reinforce existing territorial disparities if the associated value chains develop mainly in already competitive regions.

A third challenge lies in the quality and resilience of rural employment effects. The opportunity narrative often assumes that new processing and local industry will support jobs. The workshop material points in that direction, but it also suggests several caveats.

Fermentation plants may create skilled and semi-skilled jobs, but they may not generate broad-based rural employment if facilities are technologically sophisticated and labour-light unless appropriate training is provided. The more realistic employment gains may lie in ancillary activities – transport, maintenance, biomass aggregation, quality control, pre-processing and local services – rather than in very large numbers of direct plant jobs. This matters analytically because it changes the rural development profile of the technology. Rural benefits may be real, but more modest, more indirect, and more dependent on local ecosystems than some initial narratives suggest.

A fourth challenge concerns infrastructure burdens and entry barriers. The opportunity side highlights biomass hubs, pre-processing centres, shared infrastructure and local energy integration. These same elements can also function as constraints. Rural territories need roads, storage, water access, energy, technical services, aggregation systems and quality-control capacity if they are to participate meaningfully. Regions that lack these assets may be bypassed entirely. Even where such infrastructure is developed, it may favour larger producers or already well-organised territories. In other words, the existence of a new bio-based industry may create infrastructure-led opportunities, but it may also widen the gap between rural regions that can mobilise these assets and those that cannot.

A fifth challenge is that the expected rural-economy benefits from residues, by-products and side-streams may remain more limited than often assumed. One of the most attractive opportunity narratives is that fermentation can create value from underused biomass streams and thereby support more circular local economies. The challenge is that this depends on overcoming significant technical and organisational constraints: sorting, fractionation, contamination control, pre-processing, logistics and contractual coordination. If these constraints remain unresolved, rural actors may invest time and organisational effort in building supply systems that do not ultimately generate reliable revenue. This could produce disappointment and stranded expectations rather than a genuine circular-economy gain.

A sixth challenge is the possibility of new dependency structures in rural economies. Under the opportunity framing, long-term contracts and stable demand are potentially beneficial because they reduce exposure to annual commodity volatility. Under the challenge framing, the same contractual structures may create dependence on a small number of buyers, especially if fermentation develops through concentrated industrial actors with strong bargaining power. In that case, farmers and rural suppliers may gain more predictable outlets but lose strategic autonomy over pricing and cropping choices. The rural-economy issue is therefore not only one of whether there is demand, but whether local actors have sufficient bargaining power, organisational strength and ownership presence to avoid becoming mere input providers in a possible new form of concentrated value chain.

A seventh challenge concerns the location of strategic control and industrial learning. Rural development benefits are much stronger where production, technical know-how and scaling remain in Europe and, ideally, close to agricultural territories. If Europe instead becomes mainly a market for products or technologies developed elsewhere, the rural economy may see relatively little benefit beyond limited upstream activity. This is particularly important because the workshops repeatedly highlighted the risk that fermentation may scale first and more competitively outside Europe. Under that outcome, the challenge for rural economies is not only missed income, but missed upgrading: they would remain suppliers of raw materials while higher-value activities and learning curves develop abroad.

An eighth challenge is that resource competition may itself become a rural-economy issue. Where fermentation plants expand, they may create new demand for sugars, starches, biomass, water and energy. Under favourable conditions, this can support crop demand and local industrial activity. Under less favourable conditions, it may intensify competition for land use, energy, water or biomass streams, particularly in already pressured production areas. The foresight exercise touched on this primarily as land-use and feedstock competition, including possible competition between crops destined for feed and crops destined for biomass and precision fermentation. This is not a universal effect, but it is a relevant rural challenge because it means that the benefits of industrial demand may come alongside new tensions over resource allocation and infrastructure capacity. Moreover, this should be treated as a very conditional risk rather than a baseline expectation, and its scale would depend on feedstock type, local market conditions, contract design, and on whether fermentation relies.

The overall rural-economy conclusion is therefore more complex than either a positive spillover story or a partial displacement story. Biomass and precision fermentation could support rural economies where production is tied to regional feedstocks, local processing, cooperative or territorial governance, and a broad ecosystem of services and infrastructure. Equally, they could leave rural areas only weakly connected to the higher-value parts of the chain, with benefits concentrated in a few crop regions and limited spillovers elsewhere. The strongest challenge is not simply that some rural activities may lose out, but that the rural economy may be incorporated into fermentation value chains in a narrow and uneven way, with value capture, skills, and strategic control remaining concentrated outside the territories that supply the biomass.

This is also where the comparison with SQ4 is most important. The opportunity case rests on fermentation becoming a territorially embedded rural-industrial system. The challenge case is the mirror image: fermentation scales, but as a more externally controlled, unevenly distributed and weakly embedded system. The practical policy implication, which belongs more fully to SQ6, is that rural benefits are likely to depend far less on the technology itself than on where plants are sited, how feedstocks are sourced, how contracts are structured, who owns

the assets, and whether local infrastructure and services are developed in ways that allow rural territories to capture more than a commodity margin.

3.5.2 SQ5.2 - How might different farming sectors be affected?

The foresight evidence suggests that the sectoral effects of biomass and precision fermentation are unlikely to follow a simple “winners versus losers” pattern. Different farming sectors may be affected through different mechanisms, on different time horizons, and with very different degrees of directness. In some sectors, the main challenge is potential substitution in specific downstream applications. In others, the greater risk lies in indirect effects through feed costs, bargaining power, changes in demand for agricultural raw materials, or the geography of value creation. This is important analytically because the same sector may face both opportunities and vulnerabilities at the same time. What matters is not only whether a sector produces protein, but whether it is exposed to competition in ingredient markets, dependent on imported inputs, able to reposition itself within new value chains, or structurally peripheral to them.

A first broad distinction concerns the difference between sectors whose proteins are already used in highly functional and processed applications and sectors whose value is more strongly tied to whole products, sensory characteristics or existing production structures. The workshop evidence consistently points to stronger adjustment pressure in the former category, particularly parts of the egg and dairy economies, than in the latter, where beef remains the clearest case. A second distinction concerns the difference between sectors exposed mainly through product-market competition and those exposed through input dependence and competitiveness, which is particularly relevant for pigmeat and poultry. A third distinction concerns the crop sector, where the same development may create new demand and new dependence simultaneously.

The egg sector appears to be one of the most directly exposed. The workshops repeatedly identified egg proteins as particularly vulnerable because they perform well-defined technological functions in food manufacturing, especially in bakery, prepared foods and other industrial formulations. This creates a route through which microbial proteins can enter the market but will not substitute eggs across all uses. The challenge, therefore, is not best described as a sudden collapse in egg farming, but as a gradual erosion of selected downstream markets where the functional role of egg proteins can be replicated under industrial conditions. This is precisely why eggs were also identified as one of the clearer opportunity areas for microbial proteins in the opportunity discussion: what makes egg proteins commercially valuable in processing also makes them technologically contestable. The challenge is therefore unusually direct. At the same time, the workshops do not imply that all egg markets are equally exposed. Consumer-facing shell egg markets and some higher-value segments may remain more resilient than ingredient channels. The analytical challenge for the sector is thus

one of internal differentiation: the more important industrial and ingredient uses become, the stronger the competitive pressure may be.

The dairy sector faces a similarly complex challenge, but one that is more mixed and perhaps more structurally significant. The strongest pressure is expected where dairy proteins and components are already highly processed, differentiated and traded for specific nutritional or functional properties. This makes some parts of the dairy value chain particularly relevant to precision fermentation, especially where individual proteins or functional components can be replicated, reformulated or supplied into ingredient markets. However, the impact should not be assessed only from the perspective of downstream processors. If fermentation-derived dairy proteins substitute conventional milk components in significant volumes, this could reduce demand for raw milk or specific milk fractions, with possible knock-on effects on milk prices, production volumes and dairy herd size. Under higher-scale scenarios, such as **Scenario 3**, this could reinforce existing structural pressures already leading some dairy farmers to exit the sector. At the same time, parts of the dairy processing sector may be better placed than other sectors to adapt, because they already have strong processing capacity, ingredients expertise – such as the experience in turning raw agricultural outputs into higher-value ingredients, and, in some Member States, cooperative organisation. These adaptation benefits are likely to be strongest where farmers are linked to cooperatives or processors that can integrate fermentation-related activities and transmit value back to primary producers through member returns, stable supply relationships or investment opportunities. For individual dairy farmers outside such structures, the benefits are less clear and the main effect may be exposure to weaker demand or price pressure. This is what makes the dairy case analytically important: it is both an exposure point and an adaptation case. Under favourable conditions, dairy may adjust by moving further upstream into innovation, processing and value-added applications. Under less favourable conditions, it may lose selected parts of the downstream market while retaining a weaker position in the emerging value chain. The challenge for dairy is therefore not only possible substitution, but whether the sector can reposition quickly enough to retain value where technological change is strongest.

Within the meat sector, the workshops point to a much clearer differentiation between pigmeat and poultry on the one hand, and beef on the other.

Pigmeat and poultry do not appear to be the main targets of direct fermentation-based substitution in consumer markets, at least not in the medium term. Their challenge is instead more structural. Their exposure is mainly linked to feed systems, input costs and narrow margins, and strategic dependence on externally sourced feed ingredients and additives. This point should be treated carefully, because the EU pig and poultry sectors already import a significant share of their feed and feed-additive needs.. Fermentation-derived inputs would therefore not necessarily create a new type of vulnerability. Rather, they could either reinforce existing dependency patterns or help reduce them, depending on where

production capacity is located and whether EU producers can access these inputs at competitive prices and under predictable regulatory conditions. If amino acids, vitamins, enzymes or specialised feed ingredients are produced mainly outside Europe, EU livestock producers may continue to depend on imported technical feed inputs, with limited improvement in supply-chain autonomy. The workshops were clear that this risk becomes more significant over the longer term, especially by 2050. Conversely, if such inputs become more available, affordable or better tailored within Europe, they could support feed efficiency and nutrient management, particularly in monogastric systems. This is why the sectoral picture is not one-dimensional. Pigmeat and poultry are structurally exposed because of feed-cost sensitivity and reliance on external inputs, but they may also benefit from fermentation-enabled feed produced in the EU. The relevant question is not whether fermentation will directly displace pork or poultry consumption, but whether it changes the cost, availability and strategic control of the feed inputs on which these sectors already depend.

The beef sector is affected differently. The workshop material did not support the view that microbial proteins are likely to become a major direct substitute for beef within the time horizon considered. Participants repeatedly stressed the difficulty of replicating beef's structure, texture and sensory profile, and they saw current hybrid or alternative beef products as being driven mainly by plant-based proteins rather than microbial ones. This does not mean beef is unaffected. First, it remains commercially relevant within the broader shift towards alternative and hybrid protein products, and it may face some indirect pressure through changing consumption patterns, climate narratives, or the reformulation of processed foods, specifically through the replacement of beef with non-animal alternatives. Second, beef may also be affected through the dairy channel. If fermentation-derived dairy proteins reduce demand for conventional milk proteins or other milk components, this could directly affect dairy production and dairy herd size. Since cull dairy cows and dairy-bred calves form part of the beef meat supply, such changes could have knock-on effects for beef availability, prices or sector structure. The implication is therefore not that beef is insulated, but that its exposure differs by channel. Suckler beef and beef meat markets are less directly exposed to fermentation-based substitution than eggs or dairy ingredients, while dairy-origin beef may be affected more directly through any contraction or restructuring of the dairy herd. In analytical terms, beef is better understood as facing indirect and cross-sectoral pressure rather than immediate direct technological substitution of beef meat itself.. That relative insulation is important, because it shows that fermentation does not challenge all animal sectors in the same way. The arable crop sector is perhaps the most ambiguous case, because the same developments that create opportunities may also generate sector-specific challenges. Sugar beet, cereals, maize, potatoes and other carbohydrate-rich crops were repeatedly highlighted as the most plausible feedstocks for fermentation. That creates a potential opportunity for new demand, but also introduces several risks. One is dependence on narrow industrial demand. If fermentation becomes a meaningful outlet for certain crop types,

farmers may find themselves more tied to a limited number of buyers, contracts and quality specifications. Another is rotational and strategic dependence: increased demand for specific carbohydrate crops may encourage further concentration of cropping systems in already specialised regions, reinforcing agronomic simplification or exposing farms to more concentrated market risk. A third is uneven benefit distribution within arable farming itself. Large-scale competitive arable producers in sugar- and starch-rich regions are far better placed to benefit than more diversified or less competitive crop farms elsewhere. A fourth is that the expected value from residues and side-streams may fail to materialise if pre-processing, logistics, and standardisation remain difficult. For crop sectors, then, the challenge is not simply whether demand rises, but whether new demand creates dependence without sufficient bargaining power or diversification benefits.

The position of mixed farms and livestock-linked arable systems deserves separate consideration. In the more favourable opportunity narrative, these farms may benefit from supplying feedstocks and using fermentation-derived inputs, while also participating in regional circular models through residues, biogas or local processing linkages. The challenge, however, is that these more integrated benefits require coordination, infrastructure and territorial organisation. Without those conditions, mixed farms may see only fragmented benefits and may face the same asymmetries of market power as more specialised farms. This is particularly important because integrated farming systems are often the ones most frequently invoked in circular-bioeconomy narratives, yet in practice, they may also bear some of the highest coordination costs.

Another important theme is that sectoral exposure is likely to intensify over time. By 2030, most sectors are more likely to face uncertainty, experimentation and selective pressures than full-scale restructuring. The challenge is then largely one of preparedness – whether sectors have the organisational, processing and strategic capacity to respond early. By 2050, the issue becomes more structural. If fermentation has scaled and integrated into food, feed and ingredient systems by then, sectors that failed to reposition – or that were never well placed to do so – may experience more durable loss of market position, higher dependency on external inputs, or greater exposure to concentrated downstream power.

It is also important to retain conflicting viewpoints from the workshops. Not all participants treated sectoral effects as uniformly threatening. Some argued that established sectors, especially dairy, could use their existing capabilities to move into the higher-value parts of the new economy. Others stressed that even exposed sectors might retain strength if consumers continue to value origin, familiarity, product identity or established quality regimes. The challenge analysis should therefore not assume that technological possibility automatically translates into market displacement. Equally, however, the workshops did not support a complacent reading in which existing sectors remain unaffected. The consistent message was that selected parts of current agricultural sectors are

likely to come under pressure first, and that the sectors best able to manage this pressure will be those capable of controlling more of the downstream value chain.

3.5.3 SQ5.3 - How could these technologies be integrated into farms?

The challenge of “integration into farms” is more complex than the phrase may initially suggest. The workshop material does not support a simple picture in which farms either adopt fermentation technologies or remain untouched by them. Rather, it points to several distinct modes of integration, each with very different implications for farm organisation, risk, autonomy and value capture. At one end, integration may be relatively light-touch: farms use fermentation-derived inputs such as amino acids, enzymes, probiotics, other feed additives, biopesticides or biofertilisers, while continuing to operate broadly as they do today. At the other end, integration may imply bigger changes in cropping choices, residue handling, contractual dependence, infrastructure, or even participation in shared processing or cooperative ownership structures. The main challenge is that these different modes of integration are often conflated, even though their economic and institutional requirements are fundamentally different.

A further distinction is needed between pathways that are realistic for a relatively broad group of farms and pathways that are likely to remain sector-specific, region-specific or aspirational. For most farms, especially in the medium term, integration is likely to be indirect and relatively limited: farms may use fermentation-derived or fermentation-enabled inputs, sell existing crops into new outlets, or enter contractual arrangements with processors. More demanding forms of integration, such as residue-based supply systems, nutrient circularity, biomass hubs, cooperative fermentation units or direct participation in processing assets, are unlikely to be realistic for the majority of individual farms. They depend on farm size, specialisation, proximity to processing infrastructure, access to cooperatives or producer organisations, technical capacity and the availability of reliable markets. The section, therefore, treats these routes not as equally likely outcomes, but as a spectrum ranging from relatively plausible forms of commercial linkage to more ambitious forms of structural integration.

A first and comparatively realistic route is integration through farm inputs. In the medium term, this is the most plausible way in which biomass and precision fermentation enter farms directly. This should not be understood as the introduction of amino acids, vitamins or enzymes into pig and poultry feed for the first time: these sectors already make extensive use of such inputs, many of which are produced through fermentation and supplied through existing feed and premix markets. The relevant question is instead whether further development of fermentation capacity changes the cost, availability, tailoring or strategic control of these inputs. For livestock farms, particularly pig and poultry systems, better access to specific amino acids, vitamins, enzymes and related feed components could support more precise feed formulation, but the gains would be incremental

rather than transformative. More generally, fermentation-derived products may enter farm management through probiotics, biofertilisers, biopesticides and other biobased inputs. This route matters because it does not require farms to host fermentation facilities or radically alter their business model. However, it is not without challenge. The central issue is whether these inputs improve farm competitiveness enough to justify their cost, and whether farmers remain users of externally controlled proprietary products rather than participants in a value chain they influence. In other words, this form of integration may strengthen efficiency, but it may also deepen technological dependence if the relevant products are produced and controlled elsewhere.

A second route is integration through cropping and feedstock decisions. Arable farms may integrate with fermentation value chains not by installing fermentation equipment, such as bioreactors, or onsite processing, but by adjusting rotations, crop choice and marketing channels to supply sugar beet, cereals, wheat, maize, potatoes, starch crops or downgraded grains under more structured arrangements. From the opportunity perspective, this creates new outlets; from the challenge perspective, it can lock farms more tightly into a narrow set of buyers, quality requirements and contract structures. Many farmers are already linked to a limited number of buyers, quality requirements and contractual arrangements, particularly in sectors such as sugar beet, starch crops or other processing-oriented supply chains. The specific challenge with fermentation is therefore not that these dynamics are entirely new, but that they could become more pronounced where processors require standardised feedstocks, reliable year-round supply, tighter quality specifications or long-term contractual coordination. Integration in this form is not technologically spectacular, but it can be economically significant. It may alter how land is allocated, how crops are valued, and how farms balance flexibility against revenue security. The main challenge is therefore not whether farms *can* integrate in this way, but whether they do so with sufficient bargaining power and sufficient room to diversify, rather than becoming more dependent on a small number of industrial customers.

A third route is integration through residues, by-products and biomass management. This is one of the most attractive long-term visions: farms supply not only primary crops but also straw, beet pulp, molasses, corn stalks, downgraded food products, lignocellulosic biomass and other side-streams, potentially turning currently under-used materials into additional income. In principle, this could link farms more closely to circular bioeconomy models and increase the value extracted from existing production systems. However, the workshops consistently stressed that this is a much more demanding form of integration than it first appears. Current fermentation systems still rely heavily on purified and standardised inputs. Residues and side-streams are often heterogeneous, contaminated or costly to collect and pre-treat. Integration on this basis, therefore, depends on sorting, preprocessing, standardisation and logistics. The challenge is that farms may be encouraged to see residues as a new revenue source before the technical and commercial conditions for that

market are sufficiently mature. This creates a risk of overestimating near-term feasibility.

A fourth route is integration through nutrient and circular resource flows, including discussion around nitrogen and manure. This is one of the more exploratory areas in the material. The idea is that farm-level nutrient streams, especially from livestock systems, might in future be linked to fermentation processes, thereby supporting more circular nutrient use. This is conceptually attractive because it would connect fermentation to existing farm environmental challenges rather than treating it solely as an external industrial activity. However, the workshops treated this route cautiously. Technical feasibility, economic viability, purification requirements and regulatory treatment remain uncertain. In analytical terms, this is less a current integration pathway than a possible long-term direction. The challenge is precisely that such ideas can easily be used rhetorically to imply strong farm-level integration, even though the underlying conditions remain unresolved.

A fifth route is integration through shared infrastructure and collective organisation. This includes biomass hubs, pre-processing centres, cooperative fermentation units, links with biogas, agro-industrial clusters and regional biorefinery models. The basic organisational logic is not entirely new. Cooperatives and producer organisations already aggregate supply, coordinate quality requirements, structure contracts and, in some cases, invest in storage or processing assets. The potential novelty lies in extending these existing models into fermentation-linked systems that require dispersed agricultural feedstocks to be aggregated, standardised, pre-processed and connected to industrial fermentation plants.

In these cases, farms are integrated not individually, but through territorial systems that aggregate biomass, standardise feedstocks and create local industrial synergies. This is one of the most significant routes in strategic terms because it is where farms begin to move beyond simple supplier status and become part of broader value-creating systems. Yet this is also the route with the strongest barriers. Shared infrastructure requires capital, coordination, governance, logistics, technical capability and reliable throughput. It is much easier to imagine than to implement. These barriers are not necessarily prohibitive, especially where strong cooperatives, producer organisations or existing processors are already present, but they are likely to be substantial for individual farmers or weakly organised territories. The challenge is not simply financial, but that fermentation-linked cooperation may require a higher level of technical, organisational and financial coordination than many existing supply arrangements. The key questions are who leads, who invests, how risk is allocated, and whether farmers participate as genuine partners rather than merely feedstock sources.

A sixth and more ambitious route is direct participation in processing or ownership. Some workshop contributions suggested that farmers, particularly

through cooperatives, might become investors or co-owners in fermentation-related assets. The example of a French cooperative taking over a lysine plant was important because it showed that farmer-linked ownership is not purely theoretical. Nevertheless, the workshops did not imply that this would become a widespread model quickly. The challenges are substantial: high capital expenditure, technological complexity, long return periods, regulatory compliance, market volatility and the need for specialised management. For most farms, and certainly for most individual farms, direct ownership of fermentation capacity is unlikely to be a realistic medium-term pathway. The more plausible route is collective ownership, but even that depends on strong institutions and favourable economic conditions. The challenge here is therefore one of the scalability of the ownership model itself.

This leads to a crucial analytical distinction between integration into farms and integration around farms. In the medium term, most integration is likely to happen *around* farms rather than *inside* them: through contract structures, local processing hubs, cooperative arrangements and input markets. Direct on-farm integration remains much more limited. This matters because it changes the policy and competitiveness implications. If farms are mainly users and suppliers rather than operators, then the key challenge is not technological adoption in the classic sense, but the terms on which farms are connected to external systems.

The time horizon reinforces this conclusion. By 2030, the most credible forms of integration are the lighter-touch ones: supply of sugar- and starch-based feedstocks, use of fermentation-derived feed additives and selected farm inputs, and some early involvement in structured supply relationships. Deeper integration – residues at scale, nutrient circularity, biomass hubs, cooperative pre-processing, farmer-linked processing assets – remains more contingent and localised. By 2050, wider integration becomes more plausible, but only where fermentation has scaled within Europe, where rural infrastructure exists, and where value chains have been designed to include farmers rather than simply source from them. Without these conditions, the long-term result may still be a relatively shallow form of integration, in which farms adjust to fermentation-driven markets without actually moving into the higher-value parts of the chain.

There is also a strong farm-structure dimension to the challenge. Large arable farms in regions with sugar, starch and processing industries are much better placed to integrate through feedstock supply and biomass systems. Livestock farms may integrate more through feed formulation and input use. Mixed farms may be best positioned for circular models linking crops, residues, manure and energy. Small farms, less-favoured areas and regions with weak industrial infrastructure are much less likely to integrate in meaningful ways. This is important because it means “integration into farms” is not a universal pathway. This means that the deeper integration pathways described above should not be read as representative of the farming sector as a whole. They are more plausible for organised groups of farms, cooperatives, producer organisations or regions with existing agro-industrial infrastructure than for individual farms acting alone.

It is selective, and likely to privilege farms that already have scale, organisation or proximity to relevant infrastructure.

The conflicting viewpoints in the workshops are instructive. One view treated integration as a way to re-embed biotechnology in agriculture: farms provide biomass, recover value from side-streams, use better inputs, and in some cases participate in local processing. Under this reading, fermentation becomes part of a more circular and diversified farm economy. The other view was more sceptical: farms would remain upstream suppliers and downstream users, while the core industrial and intellectual value would sit elsewhere. Under that reading, “integration” risks becoming a misleading term, because it describes commercial linkage without genuine co-ownership of value creation. Both views are plausible, and the difference between them depends less on the technical properties of fermentation than on governance, territorial anchoring, infrastructure and bargaining power.

Overall, the challenge is not whether these technologies can be integrated into farms in some technical sense. They can. The more important question is what kind of integration emerges. For the majority of farms, the most realistic medium-term outcome is likely to be light or indirect integration through input use, supply contracts or participation in existing cooperative and processing structures. A thin form of integration would leave farms supplying feedstocks, buying specialised inputs, and adjusting production around an externally shaped market. A deeper form of integration would allow farms, cooperatives and rural territories to participate in processing, infrastructure, circular systems and local value capture. However, this deeper form is unlikely to be a baseline outcome for most farms; it is more likely to remain conditional on scale, organisation, infrastructure, capital access and territorial anchoring. The foresight evidence suggests that the former is the more likely medium-term outcome, while the latter remains a longer-term possibility rather than a baseline expectation. The core challenge is therefore to avoid a situation in which integration takes place mainly as dependency without strategic influence.

3.6 SQ6 - How can policy and support mechanisms help farmers benefit from biomass and precision fermentation while addressing potential challenges?

The foresight evidence suggests that the policy question is not whether biomass and precision fermentation should simply be promoted or restrained. The more relevant issue is how these technologies are governed, where value creation takes place, and on what terms farmers and rural areas are connected to the emerging value chains. This follows directly from the preceding analysis. The workshops did not point to a single, automatic outcome. Rather, they showed that the same developments can generate opportunities under some conditions and challenges under others. New demand for crops may support farm incomes, but may also create dependence on a limited number of industrial buyers; new processing activity may strengthen rural economies where it is territorially embedded, but may generate little local value where ownership, know-how or feedstocks remain external; new feed and farm inputs may improve efficiency, but may also deepen reliance on externally controlled technologies if domestic production capacity is weak.

For this reason, policy enters the analysis as a shaping force rather than a secondary adjustment tool. It affects whether fermentation develops as a European value chain linked to farming and rural territories, or as a European market supplied mainly from elsewhere. It also influences whether farmers participate only as upstream suppliers and downstream users, or whether they are able to capture part of the value through contracts, cooperatives, infrastructure, regional processing, advisory systems and innovation networks. In this sense, policy is not only about supporting technological deployment. It is about determining the distribution of benefits and risks across sectors, farm types and regions.

A second lesson from the workshops is that policy needs are likely to differ between the medium term and the long term. In the medium term, the main task is to reduce uncertainty, improve regulatory clarity, de-risk early participation, and strengthen the conditions under which farmers and rural actors can engage with emerging value chains. In the longer term, the challenge becomes more structural: how to prevent concentration of value downstream, how to avoid reinforcing territorial disparities, how to support adjustment in more exposed sectors, and how to ensure that Europe does not remain dependent on imported products, feedstocks or strategic inputs even where fermentation technologies are adopted.

SQ6 should therefore be read as the practical counterpart to SQ4 and SQ5. If SQ4 identifies the possible benefits, and SQ5 the risks and constraints that may prevent those benefits from being broadly realised, SQ6 asks what kinds of policy environment, support measures and governance arrangements would be required to steer development towards more favourable outcomes for farmers

and rural economies. The core issue is not whether intervention is needed in the abstract, but which combinations of regulatory clarity, investment support, contractual safeguards, territorial measures and strategic policy coordination are most likely to turn conditional opportunities into durable benefits while limiting the most significant adjustment pressures. On that basis, the most actionable EU response could be a three-part package: first, organise bargaining power through producer organisations and written contracts; second, use CAP investment/cooperation tools only for territorially anchored infrastructure and pilots; third, create a joint regulatory pathway for fermentation feedstocks, side-streams and product authorisations before scale-up ⁽¹³⁾. Most of this can already be done under the current CAP, the Common Market Organisation, the UTP (Unfair Trading Practices), novel food, feed additive and waste frameworks, and then carried forward - if adopted - through the Commission's 16 July 2025 CAP post-2027 package, especially the new NRP Plan architecture and the proposed CAP investment, LEADER, AKIS and EIP-AGRI provisions.

Proposal 1: collective contracting and bargaining power

Instrument: the CMO Regulation could be used to make recognised producer organisations and cooperatives the default contracting vehicle for fermentation feedstocks: Arts 152-154 already provide the recognition/statute route for producer organisations; Art 171 allows recognised POs to negotiate contracts for certain arable crops directly relevant to fermentation pathways, including wheat, barley, maize, rapeseed, soya beans, field beans and peas; and Art 168 allows Member States to require written contracts and even establish mediation where agreement fails.

Implementation: the Commission could publish voluntary model clauses for fermentation-feedstock contracts, Member States could recognise or scale up feedstock POs/coops and, where justified, activate Art 168 written-contract rules, while national authorities enforce abusive practices under the UTP Directive.

Conditionality: any publicly supported fermentation-supply arrangement could be made eligible only if the contract is negotiated through a recognised PO/co-op or contains, at minimum, a transparent price formula, quantity and quality specifications, delivery schedule, payment deadline, termination clause and dispute-resolution/value-sharing clause.

Proposal 2: territorially anchored investment and local value capture

Instrument: under the current CAP, Regulation (EU) 2021/2115 already allows Member States to support investments (Art 73), cooperation/EIP-AGRI and producer organisations (Art 77), knowledge exchange and advisory services (Art 78), and to set selection criteria targeting those interventions (Art 79), including

⁽¹³⁾ Of note, these are re-elaborations of workshop findings into concrete EU policy entry points, not verbatim workshop outputs.

through financial instruments (Art 80); after 2027, if adopted, COM(2025) 560 would carry this logic forward through Art 13 on investments, Art 18 on LEADER, and Arts 19–20 on innovation, AKIS and farm advisory systems.

Implementation: Member States could amend current CAP Strategic Plans now – and later design NRP Plans – to prioritise biomass hubs, side-stream aggregation, drying/storage, local pre-processing and farmer-facing pilot chains linked to existing sugar, starch, ethanol or biogas assets, using CAP managing authorities, LEADER groups and EIP-AGRI operational groups as delivery channels.

Conditionality: eligibility could be restricted to projects in which farmers or cooperatives have a governance or supply role – such as equity, a board seat, or a multiannual PO contract – and where a defined minimum share of feedstock or side-stream value is sourced and pre-processed regionally; that rule can be embedded in current Art 79 selection criteria and, post-2027, in NRP Plan design.

Proposal 3: Regulatory and side-stream certainty before scale-up

Instrument: the EU does not need a wholly separate fermentation regime to start mitigating farmer risk; it can use the existing legal architecture more coherently, especially the Novel Food Regulation (Arts 4, 10-13), the Feed Additives Regulation (Arts 5, 7, 8), and the Waste Framework Directive (Arts 5–6 on by-products and end-of-waste), with Regulation (EC) No 1829/2003 applying where GM food/feed rules are triggered.

Implementation: the Commission, EFSA and Member States could issue a joint fermentation guidance package clarifying which route applies to fermentation-derived foods, feeds and inputs, when a residue or side-stream can qualify as a by-product or end-of-waste, and what dossier content is expected; EFSA could strengthen applicant guidance under Art 7(6) of the Feed Additives Regulation, while the Commission can use the implementing-act powers in Art 13 of the Novel Food Regulation to refine administrative and scientific requirements.

Conditionality: publicly supported pilots could be eligible only if the applicant demonstrates ex ante whether each side-stream is a by-product or has end-of-waste status, and commits to publish a verified mass-balance and techno-economic feasibility report linked to at least one farmer or cooperative supply or use case.

3.6.1 SQ6.1 - To what extent will changes in the policy environment be needed to help achieve potential positive impacts on farmers?

The workshop evidence suggests that some degree of policy change will be necessary if the potential positive impacts on farmers are to be realised in a meaningful and broad-based way. The need for change does not arise because

no relevant policies currently exist. It arises because the existing environment is not yet sufficiently coherent, predictable or farmer-oriented to ensure that biomass and precision fermentation develop in ways that are effectively connected to agricultural production, farmer participation and rural value creation. In other words, the key issue is less the absolute absence of policy than the mismatch between current policy settings and the kind of outcomes that would be needed for farmers to benefit.

A central conclusion of the policy workshop was that, left largely to market forces and fragmented regulation, the most likely outcome is not necessarily one that maximises value for farmers. The sector may still grow, but it may do so through value chains that are externally owned, geographically concentrated, weakly linked to European feedstocks, or oriented mainly towards downstream industrial and consumer markets rather than towards farming and rural development. Under that kind of trajectory, farmers might participate as raw-material suppliers or users of some new inputs, but would capture only a limited share of the benefits. This is why policy change matters: it is needed not only to enable the technology, but to shape the distribution of value, risk and participation.

The extent of policy change required varies by time horizon. In the medium term, the workshops pointed primarily to the need for a more enabling environment. By 2030, the main bottlenecks are uncertainty, fragmented rules, slow approvals, weak coordination between agricultural and industrial policy, and insufficient support for the early formation of farmer-linked value chains. At this stage, the challenge is not yet one of large-scale sectoral restructuring, but of whether farmers and rural actors can enter the new value chains early enough, with sufficient clarity and support, to avoid being confined to marginal roles. This suggests that policy change in the medium term needs to focus primarily on clarity, de-risking and coordination, possibly building on already existing synergies from farmers that have already entered the biomass and precision fermentation value chains.

By the longer term, the issue becomes more structural. If fermentation scales successfully but without stronger alignment with agricultural and rural objectives, the risk is that Europe develops a market without developing a sufficiently embedded production base. In that case, the technologies may be present, but the positive effects for farmers remain weak because processing, ownership, intellectual property, specialised inputs and strategic control are concentrated elsewhere. From that perspective, longer-term policy change is needed not simply to “support innovation”, but to prevent a situation in which Europe accelerates technological uptake without improving the position of farmers within the value chain. The policy question is therefore not only whether change is needed, but whether it is needed early enough to influence the structure of the sector before market power, geography and ownership patterns are fixed.

A first area where policy change appears necessary is regulatory clarity and predictability. This is one of the strongest and most consistent themes in the

workshop material. Participants repeatedly linked positive impacts for farmers to a policy environment in which investors, processors, cooperatives and farmers can understand the rules, approval timelines and market conditions with enough certainty to make long-term decisions. Without this, the main effect is delay. Delay in turn matters because it weakens domestic scale-up, discourages infrastructure investment, and makes it more difficult for farmers to engage through contracts, feedstock planning, cooperative structures or local processing initiatives. In that sense, regulatory uncertainty is not only an industrial problem; it directly affects the likelihood that farmers see real opportunities rather than speculative promises.

A second area concerns policy coherence across domains. The workshops consistently treated fermentation as a cross-cutting issue sitting between agriculture, food and feed regulation, industrial strategy, regional development, climate policy and energy. This matters because positive farmer impacts depend on how these domains interact. If support is designed only through an innovation or industrial lens, the sector may scale without strong links to agricultural feedstocks or rural areas. If it is addressed only through agricultural policy, the wider conditions for industrial development may remain too weak. The implication is that the current policy environment is not merely incomplete; it is insufficiently integrated. Changes are therefore needed to align policy instruments that are currently dispersed across different institutions and objectives.

A third area is the governance of feedstock and value-chain anchoring. The workshops made clear that many of the hoped-for benefits for farmers depend on fermentation being linked to European agriculture rather than relying on imported sugars, other imported biomass or externally controlled supply chains. This suggests that, if positive impacts on farmers are taken seriously as an objective, policy change may be needed to make European feedstocks, short value chains and local sourcing commercially credible rather than simply desirable in principle. Otherwise, there is a risk that the sector develops in Europe while bypassing the agricultural base that is meant to benefit from it. Here, the need for change is not necessarily a need for protectionism in a narrow sense, but for a policy environment that rewards local integration and territorial value creation rather than treating feedstock origin as irrelevant.

A fourth area concerns farmer inclusion in early-stage value-chain formation. The workshops repeatedly suggested that positive impacts are much more likely if farmers are involved early through contracts, cooperatives, demonstrations, advisory systems, pilot projects and regional innovation networks. This implies that existing policy settings are too weak if they allow the sector to consolidate first and invite farmers in only later, once governance structures and value distribution are already set. The lesson here is important: policy change may be needed not only to support technology, but to support farmer participation in shaping the technology's institutional and territorial embedding. Without that, farmers risk becoming peripheral actors in a value chain built largely by others.

A fifth area concerns territorial and regional differentiation. The workshops made clear that opportunities will not emerge evenly across rural Europe. Regions with strong arable production, sugar and starch industries, infrastructure and industrial know-how are much better placed to benefit. This means that, if the objective is to achieve positive impacts on farmers more broadly rather than only in a few already competitive areas, some policy change is likely to be needed to avoid a strongly uneven outcome. This does not mean all regions can benefit in the same way, but it does suggest that a purely horizontal or neutral policy environment would probably reinforce concentration rather than broaden participation. The implication is that positive impacts on farmers may require territorially differentiated policy responses, not only general enabling measures.

A sixth issue is the extent to which policy change is needed to support fairer value capture. One of the strongest challenge themes in the earlier workshops was that new outlets do not automatically translate into strong farmer benefits if bargaining power remains weak or if value is concentrated downstream. The policy workshop did not resolve this tension, but it made clear that positive impacts on farmers depend on more than technical access to a market. They depend on contracts, organisational forms, cooperative capacity, risk-sharing arrangements, and, in some cases, ownership structures that give farmers more than a commodity margin. This suggests that, if current policy settings do little to support collective organisation, local processing or farmer-linked infrastructure, then they are unlikely to be sufficient for achieving the more ambitious positive outcomes discussed in SQ4.

At the same time, the workshop material does not support an equally strong conclusion that a complete policy overhaul is required in every respect. There are also more cautious viewpoints. Some participants implied that existing policy frameworks could already support part of the transition if used more strategically, and that what is missing is not always a new instrument but a more coherent use of existing ones – as explained in SQ6.3. Others warned against overdesigning a policy environment too early, especially in a field where technologies, business models and feedstock pathways are still evolving. From that perspective, excessive intervention could harden assumptions prematurely, favour particular pathways too soon, or create unnecessary regulatory burden. This is an important counterpoint. It suggests that the need for policy change should not be interpreted as a need for wholesale institutional redesign across the board. In several areas, the real issue may be better coordination, clearer guidance and more targeted use of existing tools rather than entirely new structures.

This tension between the adaptation of existing policies and the creation of new mechanisms is one of the most important analytical conclusions of the workshop material. The evidence supports the view that meaningful policy change is needed, but not necessarily in the form of an entirely separate parallel system. In some areas, clearer implementation of current frameworks may be enough to improve predictability and participation. In others – especially where local value capture, farmer organisation, territorial infrastructure or feedstock anchoring are

concerned – more explicit intervention may be needed because these outcomes might be comparatively more difficult to achieve, by simply adapting all existing relevant policies.

Another important distinction concerns the difference between enabling positive impacts and guaranteeing them. Even a well-designed policy environment cannot ensure that all sectors, regions or farm types benefit equally. Some asymmetries are structural. However, the workshops strongly suggest that the absence of policy change would make positive impacts much less likely, more geographically concentrated and more weakly captured by farmers. The role of policy is therefore not to remove all risk or all unevenness, but to improve the probability that positive effects become real rather than remaining contingent or narrowly distributed.

Overall, the most defensible conclusion is that moderate to substantial changes in the policy environment are likely to be needed, depending on the level of ambition attached to the positive outcomes. If the objective is limited – for example, simply allowing the sector to emerge while letting farmers participate where markets create openings – then more modest adjustments may be sufficient. If, however, the objective is to ensure that biomass and precision fermentation deliver meaningful benefits for farmers, strengthen rural value creation, reduce dependence on imported inputs, and avoid excessive concentration of benefits, then more substantial change is required. In that case, regulatory clarity, cross-policy coordination, territorial targeting, support for farmer organisations, and stronger anchoring of feedstocks and value chains in Europe all become central. The workshop evidence therefore points to a clear conclusion: positive impacts on farmers are possible, but they are unlikely to emerge at scale under the current policy environment without significant adaptation.

3.6.2 SQ6.2 - What types of measures or support mechanisms could help mitigate potential negative impacts on farmers?

Building on the three instrument-based policy options identified in the introduction for this study question, this section explains the broader categories of support mechanisms emerging from the foresight workshops. These should not be read as separate recommendations of equal priority. Rather, they identify the types of risks that the three main policy routes need to address.

The workshop evidence suggests that the most relevant support mechanisms are not those that simply accelerate the deployment of biomass and precision fermentation in general, but those that shape the terms on which farmers and rural actors are connected to the resulting value chains. This distinction is important. Many of the negative impacts identified under SQ5 do not arise because the technology exists, but because farmers may enter the emerging system from a structurally weak position: as fragmented suppliers facing concentrated buyers, as users of externally controlled inputs, or as actors located

in regions that lack the infrastructure and bargaining power needed to retain value locally. Measures that help mitigate these risks therefore need to address not only technological uptake, but also market organisation, territorial anchoring, adjustment capacity and value capture. Table 9 summarises the mitigation functions identified in the foresight workshops and shows how they relate to the broader policy response. The table should be read as a structured mapping of support needs, not as a list of ten standalone policy proposals.

A first set of measures concerns contracts, bargaining power and collective organisation. One of the clearest risks identified in the challenge analysis is that new outlets for feedstocks may become new forms of dependency if they are controlled by a small number of processors or if farmers enter long-term supply arrangements without adequate leverage. In that context, support for producer organisations, cooperatives, model contracts, mediation mechanisms and fairer risk-sharing arrangements would be central. The aim would not be to eliminate contractual relationships – indeed, the opportunity analysis suggests that long-term contracts could be beneficial – but to ensure that contractual integration does not translate into one-sided dependence. This is especially important for arable producers who may face pressure to reorient part of their production towards fermentation-linked crops while remaining price takers in the relationship. The workshops imply that without some support for collective organisation, the value created by more stable demand could be offset by weak farmer bargaining power.

A second set of measures concerns territorial infrastructure and local value-chain development. Many of the negative rural effects identified in SQ5.1 stem from the possibility that fermentation scales in ways that are territorially thin: some biomass is sourced locally, but most processing, know-how and value remain elsewhere. To mitigate that outcome, support would need to go beyond generic innovation funding and include de-risking instruments for biomass hubs, pre-processing facilities, local logistics, storage, regional biorefineries and links to existing rural-industrial assets such as sugar, starch or biogas systems. The objective would be to reduce the risk that farmers remain only raw-material suppliers while higher-value stages are captured elsewhere. The workshop logic is clear on this point: where local infrastructure is absent, rural participation remains narrow; where it exists, more of the margin can potentially remain in the territory. This also means that support cannot be purely horizontal. Some rural areas are simply better placed than others to host such systems, and without territorial targeting, the result is likely to be a reinforcement of existing regional inequalities.

A third set of measures concerns targeted support for more exposed sectors. The workshops did not support a generalised fear that all of agriculture would be displaced. They did, however, identify selected pressure points: egg ingredients, specialised dairy proteins and functional dairy ingredients, and, more indirectly, pigmeat and poultry through feed dependence and competitiveness. This implies that mitigation measures cannot consist only of supporting the new value chains;

they also need to help more exposed sectors adapt, reposition or move up the value chain. In practice, this could mean support for product innovation, processing upgrades, diversification, cooperative investment and targeted advisory services in those sectors most likely to experience downstream pressure. It could also mean transitional support for sectors facing more indirect competitiveness risks, especially where producers are structurally dependent on imported feed proteins or narrow margins. The key point is that mitigation should not be confined to helping farmers “join the new economy”; it should also help exposed sectors manage the adjustment pressures generated by it.

A fourth set of measures concerns advisory systems, demonstration and knowledge transfer. This may appear secondary compared with finance or regulation, but the workshop discussions suggest otherwise. Many of the risks identified in SQ5 – unrealistic expectations around residues, weak understanding of feed applications, uncertainty around costs, and the possibility that farmers are invited into value chains too late or on unfavourable terms – are compounded by limited access to trusted knowledge. Advisory services, demonstration farms, living labs, pilots and farmer-facing innovation platforms can therefore play a mitigation role by reducing information asymmetries. This is especially important where the technologies are easily over-simplified in public debate. Farmers need to understand not only what the opportunities are, but also where technical, commercial or organisational constraints remain unresolved. In this respect, advisory and demonstration support is not simply a dissemination tool; it is a way to reduce the risk of badly informed integration.

A fifth set of measures concerns input-side resilience, especially for livestock systems. The workshop evidence suggests that pig and poultry systems may face a double-sided future: they could benefit from fermentation-derived amino acids, vitamins, enzymes and other feed-related inputs, but they could also become more exposed if these inputs remain imported or controlled by external actors. Support mechanisms that help rebuild or retain domestic capacity in these strategic input categories – or at least reduce the vulnerability associated with depending on them – could therefore mitigate some of the longer-term competitiveness risks for monogastric systems. The point here is not that fermentation will replace imported soymeal at scale in the short term. It is that selected feed inputs may become increasingly important to competitiveness, and that dependence on imported strategic inputs may simply change form unless policy pays attention to where these products are made and how they are accessed.

A sixth group of measures concerns residues, side-streams and circularity, but this is an area where the workshops were more cautious and where support would need to be designed carefully. It is easy to frame side-stream valorisation as an unambiguous opportunity. The challenge analysis showed that this would be misleading. Residues and side-streams only become meaningful farm opportunities if quality, standardisation, sorting, preprocessing and logistics are solved. Support in this area would therefore need to focus less on generic

encouragement and more on technical feasibility, pilot infrastructure, aggregation systems and proof of economic viability. Otherwise, there is a risk that farmers and local actors are encouraged to reorganise biomass flows around markets that remain immature. In policy terms, the implication is that circularity should be supported, but not romanticised. Measures need to reduce technical uncertainty before asking farms to reorganise around it.

A seventh set of measures concerns income stabilisation and risk buffering. One of the more subtle negative impacts identified in the workshops is that fermentation may introduce new forms of market and contractual uncertainty even where it creates nominal opportunity. Support mechanisms such as revenue-stabilisation tools, crop insurance adaptations, public guarantee schemes or risk-sharing finance for cooperative ventures could therefore play an important role, especially in the early phases of market formation. This is particularly relevant where farmers are asked to shift production patterns, supply more specialised feedstocks, or participate in cooperative processing structures that carry unfamiliar commercial risk. The rationale is not to insulate farmers fully from market signals, but to avoid a situation in which the risks of transition sit disproportionately on primary producers while downstream actors capture the potential upside.

An eighth set of measures concerns regional targeting and cohesion-oriented support. The challenge analysis showed that fermentation is likely to favour some rural regions much more than others, especially large arable regions with existing sugar and starch industries. If this is left entirely to market geography, the result could be a widening gap between regions that are well positioned to participate and those that are not. The workshops therefore imply a need for support mechanisms that recognise different starting points. In some regions, the relevant measure may be co-financing for biomass hubs or local pre-processing. In others, it may be support for advisory capacity, rural diversification or alternative adjustment pathways because direct integration into fermentation value chains is unlikely to be substantial. This is analytically important: mitigation cannot mean forcing all territories into the same model. It means recognising that the negative impacts of exclusion and concentration may need to be addressed differently from place to place.

A ninth set of measures concerns conditionality around local value capture. The workshop evidence repeatedly raised the risk that new plants in Europe may still rely on imported sugars, imported feedstocks or externally controlled processing chains. One way of mitigating negative impacts on farmers would be to attach stronger conditions to public support, investment incentives or demonstration funding so that these favour, where feasible, European feedstocks, farmer-linked supply arrangements, local pre-processing, cooperative participation, or stronger local anchoring of value chains. This is a sensitive area, because participants also recognised that excessive conditionality could reduce competitiveness or deter investment. That tension is real. Nonetheless, the workshops suggest that without some form of conditionality or strategic steering, the policy goal of

benefitting farmers could easily be displaced by a narrower industrial logic. The policy challenge is therefore to design incentives that encourage local value retention without making viable investment impossible.

A tenth set of measures concerns workforce, skills and institutional capacity. Rural economies will not capture value from fermentation if they lack operators, technicians, advisers, cooperative managers, quality-control staff and local innovation brokers. Skill support may therefore be less visible than contracts or infrastructure, but it is central to mitigation because it affects whether rural areas can participate meaningfully or remain dependent on external expertise. This also applies to public administration and advisory institutions, which need enough capacity to help farmers interpret contracts, understand new input markets, and assess participation options realistically. Where such capacity is absent, rural actors may be structurally disadvantaged even if formal opportunities exist.

At the same time, the workshop evidence also points to the need for restraint in some areas. Not every risk should trigger a heavy new support layer, and not every support mechanism will necessarily mitigate the intended problem. Some participants were cautious about over-subsidising immature pathways, warning that poorly targeted public support could lock in inefficient models, favour large incumbent actors, or create expectations that markets cannot sustain. Others noted that support can itself become a source of unevenness if it is mainly captured by the most organised actors, leaving smaller farms or weaker regions behind. Overall, the answer to SQ6.2 is not simply “more support”. The foresight evidence points to selective, conditional and instrument-based mitigation. In practical terms, the most actionable measures are: using CAP-type investment, cooperation and advisory tools to support farmer-linked pilots and infrastructure; strengthening contracts, collective organisation and value-sharing safeguards in emerging feedstock chains; and using risk-management or transition-support tools where farmers or sectors face disproportionate adjustment costs. The other support needs identified in the workshops – advisory systems, skills, regional targeting, input resilience and side-stream feasibility – should be treated as design conditions for these measures, rather than as a separate layer of generic support.

Table 9 – Policy mechanisms to mitigate potential negative impacts on farmers

Area of support	Negative impact addressed	Possible support mechanisms	Main target	Key caveat
Contracts, bargaining power and collective organisation	Farmers may enter fermentation value chains from a weak position, especially as fragmented feedstock suppliers facing concentrated buyers.	Support for producer organisations, cooperatives, model contracts, mediation mechanisms and fairer risk-sharing arrangements.	Especially relevant for arable producers supplying fermentation-linked crops.	Long-term contracts can stabilise demand, but may also create one-sided dependence if farmers lack bargaining power.
Territorial infrastructure and local value-chain development	Fermentation may scale in a territorially thin way, with biomass sourced locally but processing, know-how and value captured elsewhere.	De-risking instruments for biomass hubs, pre-processing facilities, local logistics, storage, regional biorefineries and links to sugar, starch or biogas systems.	Rural areas with potential feedstock supply and existing rural-industrial assets.	Support cannot be purely horizontal, because some territories are much better placed than others.
Targeted support for exposed sectors	Some sectors may face adjustment pressure from downstream substitution or competitiveness effects.	Support for product innovation, processing upgrades, diversification, cooperative investment, targeted advisory services and, where needed, transitional support.	Egg ingredients, specialised dairy proteins, functional dairy ingredients, and indirectly pigmeat and poultry.	Mitigation should not only help farmers join new value chains; it should also help exposed sectors adapt to pressure from them.
Advisory systems, demonstration and knowledge transfer	Farmers may enter value chains with unrealistic expectations, limited information or weak understanding of technical and commercial constraints.	Advisory services, demonstration farms, living labs, pilots and farmer-facing innovation platforms.	Farmers considering feedstock supply, side-stream valorisation, use of fermentation-derived inputs or cooperative participation.	Advisory support must be trusted and practical; otherwise it risks becoming generic dissemination rather than useful risk mitigation.

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Area of support	Negative impact addressed	Possible support mechanisms	Main target	Key caveat
Input-side resilience for livestock systems	Pig and poultry systems may become more dependent on externally controlled or imported feed-related inputs.	Support to retain, rebuild or secure access to domestic or European capacity for amino acids, vitamins, enzymes and other strategic feed inputs.	Mainly monogastric systems, especially pig and poultry production.	This is not about replacing soymeal at scale, but about reducing vulnerability in selected technical feed inputs.
Residues, side-streams and circularity	Side-stream valorisation may be over-promised if technical, logistical and economic barriers remain unresolved.	Support for technical feasibility studies, pilot infrastructure, aggregation systems, sorting, preprocessing, standardisation and proof of economic viability.	Farms and rural actors seeking to valorise residues, by-products and side-streams.	Circularity should be supported but not romanticised; farms should not be encouraged to reorganise biomass flows around immature markets.
Income stabilisation and risk buffering	Fermentation may introduce new contractual and market risks, especially where farmers shift production or invest in unfamiliar value chains.	Revenue-stabilisation tools, adapted crop insurance, public guarantees and risk-sharing finance for cooperative ventures.	Farmers supplying specialised feedstocks or participating in cooperative processing structures.	The aim is not to insulate farmers from market signals, but to avoid transition risks falling disproportionately on primary producers.
Regional targeting and cohesion-oriented support	Benefits may concentrate in already well-positioned arable regions, reinforcing territorial disparities.	Region-specific support such as co-financing for biomass hubs, local pre-processing, advisory capacity, rural diversification or alternative adjustment pathways.	Regions with different starting points, including those unlikely to integrate directly into fermentation value chains.	Mitigation should not force all territories into the same model; exclusion and concentration need place-specific responses.
Conditionality around local value capture	Public support may enable fermentation growth without ensuring benefits for EU farmers or rural areas.	Conditions attached to public support, investment incentives or demonstration funding, favouring European feedstocks, farmer-linked supply, local pre-processing, cooperative participation or local anchoring.	Publicly supported fermentation projects and pilot value chains.	Excessive conditionality could reduce competitiveness or deter investment, so conditions must be carefully calibrated.

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Area of support	Negative impact addressed	Possible support mechanisms	Main target	Key caveat
Workforce, skills and institutional capacity	Rural areas may lack the skills and institutional capacity needed to capture value from fermentation.	Training for operators, technicians, advisers, cooperative managers, quality-control staff and local innovation brokers; capacity-building for advisory and public institutions.	Rural labour markets, cooperatives, advisory bodies and public administrations.	Skills support is less visible than infrastructure, but central to whether rural areas participate meaningfully or remain dependent on external expertise.

3.6.3 SQ6.3 - Is there any need to create a policy framework for the production of proteins from biomass and precision fermentation?

The workshop evidence points to a fairly clear conclusion: there is a need for a more coherent policy framework, but that need should not be understood too narrowly as a simple question of whether to create a single, entirely separate legal regime from scratch. The more substantive issue is whether the current policy environment is capable of governing the production of proteins from biomass and precision fermentation in a way that is predictable for investors, understandable for farmers, consistent across policy domains, and aligned with broader agricultural, food and rural objectives. On that criterion, the evidence suggests that the present framework is only partially adequate.

The case for some form of policy framework arises from the fact that biomass and precision fermentation technologies sit at the intersection of multiple policy domains that are currently only loosely connected. Production from biomass and precision fermentation touches food and feed law, industrial policy, agricultural policy, regional development, sustainability governance, energy systems, environmental permitting, feedstock sourcing, and, in some cases, waste and by-product regulation. The challenge identified in the workshops is not only that this creates complexity. It is that fragmentation can produce outcomes that are internally coherent from the perspective of one domain, but inconsistent with the stated objective of ensuring benefits for farmers and rural areas. A technology may be legally admissible and industrially supported, for example, while still being weakly linked to European feedstocks, weakly embedded in rural territories, or poorly aligned with the needs of farming systems.

In that sense, the question is not simply whether a “policy framework” is needed in the abstract. The real question is whether there is a sufficient policy architecture to coordinate the roles of different actors across the value chain and to avoid a situation in which production of microbial proteins develops under a patchwork of rules that may allow market growth, but do little to shape where production happens, what inputs it uses, whether farmers participate meaningfully, or how value is distributed. Such a framework would not replace market dynamics or determine outcomes by policy design alone. Costs, demand, investment decisions, consumer acceptance and international competitiveness will remain central to whether and how the sector scales. However, policy can shape the conditions under which these market dynamics unfold, including by improving regulatory clarity, reducing coordination failures, supporting farmer participation and ensuring that public support is aligned with agricultural and rural objectives. The workshops strongly suggest that such shaping matters. Without it, positive impacts for farmers and rural areas remain contingent and may easily be displaced by a more narrowly production-oriented approach, focused on

scaling output and reducing costs without necessarily addressing farmer participation, territorial embedding or fair value capture.

A first argument in favour of a clearer framework is regulatory certainty. One of the most repeated themes in the policy discussions was that uncertainty around classifications, approvals, applicable rules and administrative pathways slows investment and weakens the case for building value chains in Europe. This matters directly for farmers because delayed or uncertain scale-up means delayed or uncertain feedstock demand, weaker incentives for cooperative participation, and reduced confidence in local processing or infrastructure investments. A framework is therefore needed, at minimum, to clarify the regulatory conditions under which production can occur. Without such clarity, the likely result is not regulatory neutrality but a bias towards jurisdictions that provide more predictable conditions.

A second argument is the need to clarify the treatment of feedstocks, side-streams and circular inputs. The workshops repeatedly highlighted residues, by-products and side-streams as a potential opportunity, but also pointed to uncertainty around their usability, purity requirements, preprocessing and regulatory treatment. This is an area where the absence of a coherent framework has practical consequences. If actors do not know under what conditions certain materials can be treated as feedstocks, by-products, or waste-derived inputs, then some of the most promising circular opportunities remain underdeveloped. Here, the argument for a policy framework is not only about controlling the technology; it is about giving legal and administrative form to pathways that are otherwise likely to remain experimentally attractive but commercially marginal.

A third argument concerns alignment with agricultural and territorial objectives. The workshop material is very clear that fermentation can generate very different outcomes depending on whether production is linked to European agriculture and rural territories or whether it develops largely as an externally sourced, downstream industrial activity. A policy framework matters here because it can determine whether the sector is treated only as an innovation domain or also as part of a broader strategy for agriculture, strategic autonomy, and rural value creation. In practical terms, this includes questions such as whether the framework recognises the relevance of local feedstocks, short value chains, regional processing, cooperative participation and territorial spillovers, or whether those issues remain outside its scope. If they remain outside, the framework may be formally complete from an industrial standpoint while still being insufficient from an agricultural one.

A fourth argument relates to public legitimacy and market confidence. The workshops repeatedly suggested that the future of microbial proteins depends not only on technical viability and price, but also on how the sector is socially and politically framed. A fragmented or ambiguous framework can reinforce perceptions of opacity, regulatory inconsistency or lack of strategic direction. A more coherent policy environment can help create legitimacy by clarifying the

principles under which these proteins are produced, assessed and integrated into European food and feed systems. This matters because public and stakeholder acceptance is itself part of the enabling environment.

At the same time, the workshop evidence does not support a simple or unqualified call for a wholly separate stand-alone framework in the strongest possible sense. There are several reasons for caution.

First, a fully separate regime could create excessive complexity. Biomass and precision fermentation are not isolated from existing agricultural and food systems; they interact with them. Building an entirely parallel legal structure risks duplicating rules, creating new borderline problems, and making coordination harder rather than easier. Some participants were implicitly sceptical of overly technology-specific regulation for this reason. They suggested that what is often missing is not an entirely new system, but better coordination and adaptation of existing rules.

Second, there is a risk of premature hard-coding. The technologies, feedstock pathways and business models are still evolving. If the EU were to create a highly detailed, self-contained framework too early, it could unintentionally lock in some pathways and marginalise others before technical and economic realities are clearer. This is particularly relevant for questions such as side-stream use, farm-level integration, or the balance between food, feed and non-food applications. The workshops did not ignore this danger. There was an underlying recognition that too rigid a framework can be as problematic as too fragmented a one.

Third, there is a risk that a new framework could become industrially legible but agriculturally thin. In other words, it might clarify production rules and facilitate investment, but still fail to address the concerns most relevant to farmers and rural areas. This is why the central issue is less whether the framework is “new” than whether it incorporates the right objectives and connections. A purely industrial framework for fermentation would not by itself solve the challenge of territorial embedding, local value capture or farmer participation.

This leads to a more nuanced conclusion. What the workshops appear to support most strongly is not necessarily a single brand-new legal instrument, but the construction of a coherent policy framework in functional terms. That could be achieved through a combination of clearer interpretation of existing rules, targeted amendments where real gaps exist, better coordination across policy domains, and dedicated guidance or support mechanisms where needed. In other words, the need is real, but the institutional form it should take remains open.

On this, an important temporal distinction also emerges from the workshops. In the medium term, the more pressing need is for clarification, coordination and targeted adaptation of existing frameworks. The sector is still at a stage where uncertainty itself is a major barrier. A large and entirely separate legal edifice may not yet be necessary to address the most immediate needs. In the longer term,

however, if the sector becomes commercially significant and begins to affect agricultural markets, feed systems and regional development more materially, the case for a more explicit and dedicated policy architecture becomes stronger. In that sense, the need for a framework is not static; it is likely to grow with the scale and strategic relevance of the sector.

There is also a distributional dimension to this question. If no clearer framework is developed, the likely outcome is not a neutral market order. It is more likely a system in which the most capable industrial actors navigate complexity successfully, while farmers, cooperatives, smaller firms and rural regions struggle to understand where they fit. From that perspective, the absence of a framework may itself favour concentration. A clearer framework therefore, has a role not only in enabling production, but in reducing asymmetries between actors with very different resources and regulatory capacities. Based on the workshop logic, such a framework should have at least five functions:

- First, it would need to provide clarity on classifications and approval pathways, so that firms, cooperatives and farmers can understand under what conditions production and market entry are possible.
- Second, it would need to clarify the treatment of feedstocks, side-streams and circular inputs, especially if one objective is to support more integrated and locally anchored value chains.
- Third, it would need to improve coordination between industrial, agricultural and rural policy objectives, so that support for the sector does not become detached from the interests of farming systems and rural territories.
- Fourth, it would need to create the conditions for farmer participation and fairer value capture, not only by enabling production, but by recognising the governance and organisational conditions under which farmers benefit.
- Fifth, it would need to support strategic anchoring in Europe, including attention to feedstock origin, production location and dependence on imported inputs, if one of the objectives is to improve resilience rather than simply create a new class of imported products.

Overall, the most defensible answer is therefore that there is a need for a policy framework for proteins from biomass and precision fermentation – in fact many participants advocated a broader framework for biomass and precision fermentation, implying that a focus on protein production would narrow down its scope to the detriment of industrial development – but the need is best understood as a need for coherence, coordination and targeted adaptation rather than necessarily for a wholly separate legal regime from the outset. The workshops support the view that current arrangements are too fragmented to

reliably deliver positive outcomes for farmers and rural areas. They also support caution against overdesigning a rigid, stand-alone regime too early. The preferable approach appears to be a progressive one: strengthen and align the existing policy environment where possible, create targeted additions where real gaps exist, and ensure that any future framework is designed not only to enable production, but to shape the sector in ways that are agriculturally, territorially and strategically meaningful.

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5 Annex 1 - Literature review

5.1 Introduction

This literature review is a part of the Study on biomass and precision fermentation, Interim Report.

5.1.1 Reading guide

The first section establishes a taxonomy defining three main processes: traditional fermentation modifies existing plant ingredients to improve flavour or nutrition; biomass fermentation produces Single-Cell Protein (SCP) where the microbial cells themselves are the final food product; and precision fermentation uses microbes as cellular factories to produce specific, high-value molecules.

Traditional fermentation represents the oldest and most culturally embedded fermentation pathway, with documented use spanning more than 10,000 years across global food systems. Historical accounts and scientific reviews show that this has been a foundational technology for food preservation, safety, nutrition, and flavour development across civilisations for ages. Fermented foods such as beer, wine, cheese, yogurt, kimchi, sauerkraut, sourdough, and kefir form part of longstanding dietary traditions and continue to deliver measurable benefits to food quality, shelf life, and human health.

Biomass fermentation (§ 6.2) focuses on the large-scale production of microbial biomass, notably mycoprotein from filamentous fungi like *Fusarium venenatum*, which offers a meat-like fibrous structure and high digestibility. Innovative bacterial SCP can also be produced from methane (sourced from natural gas or biogas) using methanotrophic bacteria in specialised U-loop reactors. Furthermore, the Power-to-Protein (P2P) pathway represents a breakthrough in resource independence, using captured CO₂ and hydrogen from water electrolysis to cultivate hydrogen-oxidising bacteria without requiring agricultural land.

Precision fermentation (§ 5.33) is reaching commercial maturity for advanced applications such as producing animal-free dairy proteins, egg white proteins, and heme-based flavouring agents used to replicate meat flavours.

Environmental analysis (§ 6.4) demonstrates that while these technologies, depending on their power source, can use 100 times less water and 1 000 times less land than conventional crops (such as soy), electricity consumption for cooling and aeration remains a significant environmental “hotspot”.

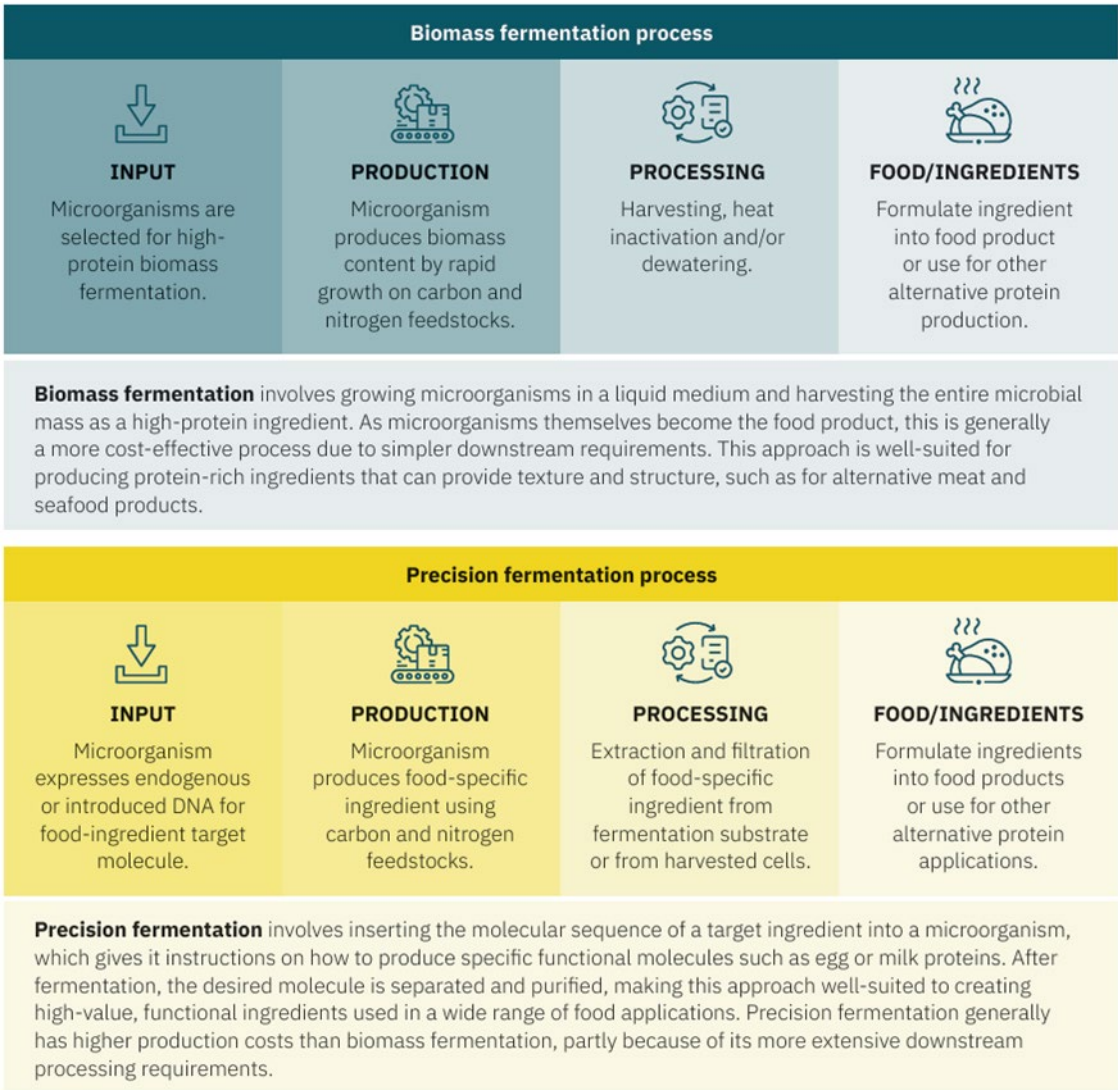
Operational challenges (§ 6.5.5) include managing the “metabolic burden” on microorganisms, where energy is diverted from growth to target molecule

synthesis, as well as the high costs associated with downstream processing and purification.

5.1.2 Fermentation definitions

This section introduces the key concepts and terminology used throughout the report. It clarifies the distinction between traditional fermentation, biomass fermentation, and precision fermentation and defines how the report uses terms such as single-cell protein and microbial protein. In this report, single-cell protein (SCP) refers specifically to products in which the microbial biomass itself is the main product, whereas microbial proteins is used more broadly to include both SCP and other protein ingredients derived from microbial fermentation.

Figure 1: Biomass and Precision Fermentation (GFI, 2025)



Establishing these definitions provides a common language for analysing technologies, costs, regulatory frameworks, and farm-level impacts in the subsequent sections.

Traditional fermentation (TF) is the oldest fermentation method, used for millennia by cultures worldwide to transform raw food materials rather than generate new protein biomass (Mark Sturme, 2025; Mirsalami & Mirsalami, 2025). The objective of traditional fermentation is to transform existing raw materials, such as carbohydrates or starches, by using metabolic pathways of micro-organisms such as bacteria, fungi or yeasts (Bekker, 2025).

Final products of fermentation include modified ingredients, where live microbial cells typically remain present. One can think of products such as cheese, yoghurt, tempeh or alcoholic beverages.

Biomass fermentation focuses on generating large volumes of microbial cells themselves for use as a bulk protein ingredient. Single-cell protein (SCP) refers to the resulting protein-rich biomass (Bekker, 2025; Fernández-López et al., 2024). “Single-cell protein is the biomass or protein extract from pure or mixed cultures of algae, yeasts, fungi or bacteria.” (Djuragic et al., 2021). Biomass fermentation aims to achieve efficient, large-scale production of microbial biomass. This is achieved by cultivating fast-growing organisms on various carbon sources, including agro-industrial residues (such as molasses and lignocellulose) or gases (such as methane or CO₂) in order to create protein-rich microbial products. The final product is the whole microbial cell mass, which can be used intact or minimally processed (heat-treated, nucleic acid reduction). One of the most well-known commercial examples is Quorn™, from the fungus *Fusarium venenatum* (Bekker, 2025; Risner et al., 2023).

Precision fermentation (PF) is a specific sub-category of fermentation that uses advanced biotechnology and innovations for the controlled cultivation of selected and/or modified microbial cells to produce specific substances. These fermentation-derived products can be a single molecule or multiple molecules purified from the fermentation broth or biomass” (FAO, 2025). PF’s main purpose is to produce a specific, functional molecule (such as a fat, vitamin or single protein). This requires genetically modified microorganisms, also referred to in literature as ‘cell factories’ (Mirsalami & Mirsalami, 2025). PF therefore relies on genetic modification techniques, including synthetic biology, to reprogram the host metabolic pathways (Mark Sturme, 2025). The final product is usually a highly purified, specific molecule that is bio-identical to those found in nature but produced without the original plant or animal source.

Having established how this report defines biomass, and precision fermentation, the next chapter situates these concepts within existing food systems.

5.2 Biomass fermentation

Single-cell protein (SCP), a protein-rich microbial biomass derived from yeasts, fungi, bacteria, or algae, has evolved over the past 50 years from a wartime necessity to a modern pillar of the global protein transition (Grigore et al., 2025; Ye et al., 2024). While early industrial attempts like Imperial Chemical Industries' Pruteen⁽¹⁴⁾ process failed due to the high cost of methanol feedstocks, successors like Quorn™ and the PEKILO® process demonstrate the technical and commercial feasibility of large-scale fungal and yeast fermentation (Risner et al., 2023; Ye et al., 2024). Current efforts focus mainly on improving affordability and sustainability by shifting from refined sugars to the valorisation of agro-industrial residues and lignocellulosic biomass to improve both cost and sustainability aspects (Ye et al., 2024; Zhang et al., 2024). Lignocellulosic biomass (LCB) represents the most abundant renewable raw material on Earth and is a primary byproduct of agricultural activities, produced in vast quantities globally. It is defined as a non-edible organic material that consists mainly of the structural components of plants, such as straw (wheat, rice, barley), corn stover, sugarcane bagasse, and cotton stalks. For instance, wheat straw alone accounts for approximately 865 million tonnes of production per annum (Voutilainen et al., 2021).

5.2.1 Mycoproteins

Quorn™ mycoprotein, produced since 1985 from the filamentous fungus *Fusarium venenatum*, represents the most established commercial example of biomass fermentation (Sobhi et al., 2023; Sturme; et al., 2022). Large-scale airlift external loop reactors (typically 155 m³ working volume) enable continuous aerobic fermentation, yielding a “complete protein” with all nine essential amino acids and digestibility comparable to milk and eggs (Risner et al., 2023; Sobhi et al., 2023).

Marlow Foods dominates the global mycoprotein market, valued at approximately USD 805 million (EUR 692 million) in 2025 and is projected to reach USD 1,46 billion (EUR1.25 billion) by 2034 (Precedence, 2025). Their UK facility produces up to 67 000 metric tons annually, supplying over 100 B2B and retail products, including KFC® vegan burgers ⁽¹⁵⁾ across Europe (Queen, 2025;

⁽¹⁴⁾ A single-cell protein production method that grew the bacterium *Methylophilus methylotrophus* on methanol to yield a high-protein feed powder for pigs and poultry.

⁽¹⁵⁾ [Veggie - KFC](#)

Marlow, 2025). Table provides an overview of the largest companies active in the mycoprotein market, next to Marlow Foods.

Table 10 - Leading mycoprotein producers

Company	Based in (HQ)	Main product	Direct market competition	Potential competitive advantage
Marlow Foods (Quorn™)	UK	Quorn™ mycoprotein	Analogues to meat products, soy-based protein	Long-term brand trust; low price due to massive scale.
Meati Foods	US	Mushroom Root™ steaks	Analogues to meat products	Fibre-rich “whole food” appeal; cleaner label than soy-isolates.
Enough	UK	ABUNDA® mycoprotein	Soy/pea protein concentrates (B2B)	Massive capacity (60k tonnes); low carbon footprint via Cargill partnership.
Enifer	FI	PEKILO® mycoprotein	Fishmeal (aquafeed), Soy in pet food	High digestibility; circular use of food-industry side streams.
Nature's Fynd	US	Fy™ Protein	Cream cheese, yoghurt, breakfast sausage	Extreme versatility (liquid to solid); non-GMO/neutral taste.

Source: Precedence, 2025

Quorn™ demonstrates that fungal biomass fermentation can already compete with chicken and ground beef on a price-per-protein basis, particularly in processed meat segments (Risner et al., 2023).

Yeast-based production

Yeast-based SCP bridges traditional fermentation and modern biomass platforms, with roots dating back to World War I. *Saccharomyces cerevisiae* grown on molasses supplemented both animal feed and direct human consumption, where it was typically incorporated as a nutritional additive in sausages, soups and bread to address acute meat and protein shortages (Djuragic et al., 2021; Ye et al., 2024).

A commercial milestone came in the 1970s-80s with Finland's PEKILO® process, which used filamentous fungus *Paecilomyces variotii* to convert paper industry spent sulphite liquors into 55% protein feed (Grigore et al., 2025; Voutilainen et al., 2021). Approved for human consumption in Finland by 1983, PEKILO® demonstrated yeast/fungal resilience on waste substrates (Zhang et al., 2024).

Modern production favours *Saccharomyces cerevisiae*, *Candida utilis* (Torula yeast), and *Kluyveromyces marxianus* for their substrate flexibility, rapid growth, and food-safety track record. Yeast biomass delivers 45–55% protein plus B-complex vitamins, positioning it between mycoprotein and commodity feeds (Grigore et al., 2025).

The global single protein product market size is valued at USD 11.9 billion (EUR 10.2 billion) in 2025 and expected to reach USD 28.2 billion (EUR 24.3 billion) by 2034, with the largest market in North-America with yeast dominating due to regulatory familiarity (FNB, 2025). Starting in 2026, the Finnish start-up Enifer aims to complete its first commercial-scale factory to begin production of mycoproteins with a capacity of 3000 metric tons ([Enifer - Ingredients for a sustainable food chain](#)). Table 11 shows the leading yeast SCP producers active in this market.

Table 11 - Leading commercial yeast-based protein and yeast-derived ingredient producers

Company	Based in (HQ)	Main product	Direct market competition	Potential competitive advantage
Angel Yeast	CH	AngeoPro™ isolates	Whey protein, Soy isolates	Cost-efficiency; high glutamic acid (natural umami flavour).
Lallemand	CA	Engevita® / feed yeast	Specialty animal feed additives	Established global supply chain; proven gut-health benefits.
Leiber GmbH	GE	Brewers' spent yeast	Fishmeal, standard soybean meal	100% Upcycled; very low price point compared to primary yeast.
Biospringer	FR	Yeast extracts	MSG, chemical flavour enhancers	Clean-label status; multi-functional (flavour + protein).

Source: FNB, 2025

5.2.2 Methane-based bacterial single-cell protein

Methane-based SCP represents the most resource-efficient biomass fermentation platform, converting gaseous carbon sources, particularly biogas from food waste, directly into protein (Dickson & Mansouri, 2025). Anaerobic digestion first transforms organic waste into biogas, which is then purified and fed to methanotrophic bacteria in aerobic fermenters, integrating waste management with high-value protein production. This technology is among the most commercially advanced, with Calysta's FeedKind® plant in China already operational at 20 000 metric tonnes/year capacity. Unibio's UniProtein®, produced via proprietary U-loop reactor technology (Buttle et al., 2024), is commercially available, while String Bio and Circe Biotechnology scale biogas-to-protein platforms (García Martínez et al., 2022).

The market for methane-based bacterial protein is valued at approximately USD 3.1 billion (2.66 billion) in 2026, with projected annual growth rates of over 25%. Aquafeed represents the vast majority (70%) of consumption due to high demand for sustainable alternatives to fishmeal because it has a remarkably similar amino acid profile to fishmeal (MRA, 2025). Table 10 provides an overview of the leading methane-based SCP producers in the world.

Table 12 - Methane-based SCP leaders

Company	Based in (HQ)	Main product	Direct market competition	Potential competitive advantage
Calysta	US	FeedKind®	Fishmeal, high-quality soybean meal	Traceability; zero-land use; stable pricing vs. volatile commodities.
Unibio	UK	UniProtein®	Fishmeal, Soy-based aquafeed	Extremely high protein density (>70%); highly efficient U-Loop reactor.
String Bio	IN	Protin / PRO-S	Poultry feed, aquaculture pellets	Uses biogas (waste methane); integrates waste management.

Source: MRA, 2025

5.2.3 Power-to-Protein (P2P)

Power-to-Protein (P2P) represents the newest biomass fermentation platform, using renewable electricity and captured CO₂ to produce microbial protein entirely independent of agriculture (Sobhi et al., 2023). The current state of P2P technology is defined as being in its infancy, requiring significant further research to enhance performance and achieve full commercial implementation. The literature identifies three primary technological pathways:

Table 13 - P2P technological pathways

Pathway	Process	Key microbes	Yield (t/MWh)	Example companies
Autotrophic	H ₂ + CO ₂ → biomass (direct)	<i>Cupriavidus necator</i> (HOB)	34	Solar Foods, Air Protein
Sequential	CO ₂ → acetate → yeast biomass	<i>Clostridium ljungdahlii</i> + yeast	88	Arkeon Bio
Indirect	CO ₂ → methanol/methane → fermentation	Heterotrophic microbes	Variable (max 118)	DeBranch, KnipBio, Farmless

Source: Buttle et al., 2024; Institute, 2025

Pathway comparison:

- Autotrophic = simplest but least efficient (H₂ gas handling is tricky)
- Sequential = highest yield but most complex (two bioreactors needed)
- Indirect = leverages existing chemical industry but adds conversion steps

Table 14 - P2P commercial leaders

Primary product	Key active companies	Direct market competition	Possible competitive advantage
Solein®, Air Meat™	Solar Foods (FI), Air Protein (US), NovoNutrients (US)	Egg powder, soy isolates, casein (Dairy)	100x land efficiency vs. dairy; decoupled from weather/climate; high micronutrient density (Iron/B12).
Farmless Protein, Arkeon Amino Acids	Farmless (NL), Arkeon Bio (AT)	Whey protein, amino acid supplements, soy meal	Higher energy efficiency (24.4 mg/kJ); uses established yeast fermentation infrastructure in step two.
Proton™ (via Methanol/Methane)	Deep Branch (UK/NL), KnipBio (US)	Fishmeal, high-quality soy (for aquaculture)	Leverages the existing global methanol economy; easier gas-liquid mass transfer than gas.

Source: solarfoods.com, novonutrients.com, farmless.com

In summary, the biomass-fermentation pathways discussed here, including fungal (e.g. Quorn™), yeast-based, methane-based and emerging Power-to-Protein configurations, illustrate the diversity of technological approaches to producing microbial protein. While Quorn™ is already positioned as a competitor to processed meat products and methane-based SCP targets fishmeal replacement in aquaculture, P2P routes remain at an earlier and more uncertain stage of development, with high potential but significant technical and economic risks. These platforms, together with other biomass-fermentation options not detailed here, will only translate into substantial market impact if they can achieve competitive economics and robust environmental performance, aspects which are examined in the subsequent chapters

5.3 Precision fermentation

Precision fermentation (PF) represents a specialised sub-category of fermentation that utilises biotechnological advances, such as metabolic engineering and synthetic biology, to program microorganisms as "cell factories" for the production of specific, high-value functional ingredients. Unlike traditional fermentation, which uses whole microbes to alter a food matrix, or biomass fermentation, where the cell itself is the product, precision fermentation focuses on the targeted synthesis of molecules such as proteins, fats, and vitamins that are often purified from the fermentation broth (Knychala et al., 2024; Sturme et al., 2025).

5.3.1 Commercial maturity

Precision fermentation builds on 40+ years of proven industrial biotechnology, despite recent food-sector attention. The underlying recombinant DNA technology matured in the late 1970s-1980s.

Table 15 - Precision fermentation milestones

Year	Product	Host microbe	Replacement for	Market impact
1982	Human insulin	<i>Escherichia coli</i>	Pig/cow pancreas	Pharma scale-up
1980s	Growth hormone, erythropoietin	Various	Animal extraction	Protein therapeutics
1990	Chymosin (rennet)	<i>Aspergillus niger</i>	Calf stomachs	>90% global cheese production; vegetarian standard

Source: (Knychala et al., 2024; Mark Sturme, 2025)

Chymosin is a vital part of cheese production and is used to bring about the extensive precipitation and curd formation in cheese-making. Traditionally sourced from the stomachs of calves, chymosin is now predominantly produced via precision fermentation using genetically engineered filamentous fungi like *Aspergillus niger*. This shift made cheese production more affordable and suitable for vegetarian consumption, establishing a precedent for the “animal-free” production of animal proteins in an industry that is currently expanding (Knychala et al., 2024; Mark Sturme, 2025).

5.3.2 Market acceleration

Precision fermentation is experiencing a period of rapid acceleration, with the global market valued at USD 1.6 billion (EUR 1.4 billion) in 2022 and projected to reach approximately USD 67.9 billion (EUR 58.4 billion) by 2032 (Knychala et al., 2024). In the Netherlands, the broader alternative protein market, of which precision fermentation forms one part, is expected to surge from EUR 346 million in 2022 to over EUR 10 billion by 2030 (Bekker, 2025). This momentum is fuelled by significant financial backing, with PF companies raising nearly USD 2 billion (EUR 1.7 billion) between 2013 and 2022, attracting interest from major food conglomerates like Nestlé, Unilever, and General Mills (Knychala et al., 2024).

The positive outlook for PF is centred on its potential to revolutionise food security and sustainability. The technology is projected to be up to 100 times more land-efficient and 10 times more water-efficient than traditional animal farming (Pereira et al., 2025). Unlike conventional livestock, PF allows for production in closed, controlled environments that are resilient to climate-related disruptions and disease (Knychala et al., 2024). Furthermore, production costs have seen a dramatic decline, falling from 1 million USD/kg (0.9 million EUR/kg) in 2000 to roughly 100 USD/kg (86 EUR/kg) per kilogram today, with forecasts suggesting parity with animal proteins below 10 USD/kg (8.6 EUR/kg) by 2030 (Hossain et al., 2025). Consumer openness is also a driver.

Conversely, several critical challenges could slow this acceleration. Transitioning from laboratory success to commercial-scale operations remains a formidable hurdle involving high initial capital requirements and technologically demanding

scaling processes (Bekker, 2025; de Moura Campos et al., 2025; Knychala et al., 2024). A major biological bottleneck is the “metabolic burden”, where microbial hosts divert energy away from synthesising target proteins toward primary growth, resulting in low yields of only 0.005-0.05 grams of protein per gram of sugar (de Moura Campos et al., 2025). Because the protein of interest represents only a small fraction of the fermented material, downstream processing (DSP) to isolate and purify the product becomes exponentially expensive and energy-intensive (Bekker, 2025).

Furthermore, regulatory frameworks are often described as slow and lacking the agility needed to keep pace with innovation, particularly in the EU under the Novel Food Regulation. A significant contributing factor is the low quality of many applications, which often delays evaluations and increases administrative burden; however, recent EU proposals under the Biotech Act and related food and feed simplification measures seek to improve this through earlier and more technical pre-submission support by EFSA, particularly for SMEs. Finally, there is a potential risk of market concentration; the high cost of development and the prevalence of patented technologies may favour larger firms, agribusinesses, and cooperatives. At present, however, the sector still includes many younger specialised companies and SMEs, so concentration should be framed as a risk rather than as an established outcome. Core applications

Precision fermentation applications span a broad range of product categories, including enzymes, lipids, vitamins and other specialised metabolites. In this report, we focus on three high-value examples that are particularly relevant to protein and protein-like functions in food systems: animal-specific proteins, structural proteins, and flavour/functional agents (Knychala et al., 2024; Sturme et al., 2025).

Table 16 - Precision fermentation product examples

Category	Key products	Companies	Livestock replacement	Market status
Animal Proteins	β-lactoglobulin (whey), caseins, ovalbumin (egg)	Perfect Day, Remilk, EVERY Company	Analogues to dairy products, analogues to egg white	Commercial
Structural	Collagen, elastin	Geltor, Modern Meadow	Cell-based scaffolds for food applications, cosmetics	Commercial (non-food)
Flavour/Functional	Heme (Impossible), myoglobin, thaumatin	Impossible Foods, Motif FoodWorks	Analogues to meat products, sweeteners	Commercial

Source: de Moura Campos et al., 2025; Knychala et al., 2024; Mark Sturme, 2025; Pereira et al., 2025)

Animal proteins deliver bio-identical functionality in that they are molecularly and structurally identical to their conventional counterparts, enabling them to perform the same biological, nutritional, and techno-functional roles. For example, Perfect Day’s *Trichoderma reesei*-produced β-lactoglobulin enables animal-free ice

cream; EVERY Company's ovalbumen replicates egg gelling/foaming; caseins replicate cheese melt/stretch.

Precision fermentation is instrumental in recreating the sensory experience of meat in plant-based alternatives. The most prominent example is soy leghemoglobin, produced by engineered *Komagataella phaffii* (*Pichia pastoris*), which gives the Impossible™ Burger its characteristic iron-rich flavour and bleeding appearance (Sturme et al., 2025; Knychala et al., 2024). Similarly, Motif FoodWorks uses PF to produce bovine myoglobin to enhance the authenticity of alternative meat products (Knychala et al., 2024).

5.4 Environmental analysis of biomass and precision fermentation

This section summarises the available evidence on the environmental performance of microbial proteins relative to conventional animal and plant proteins. It reviews techno-economic assessments and life-cycle analyses (LCA) for key biomass and precision fermentation routes, including bio-SCP, methane-based SCP, microalgae, and Power-to-Protein systems. The aim is to identify the main cost and sustainability drivers that condition future competitiveness on domestic and international markets.

5.4.1 SCP from waste streams

Techno-economic analytical studies show that large-scale SCP production can be economically competitive with traditional protein supplements like fishmeal when integrated into waste-management systems. A facility processing 25 000 kg/h of food waste is estimated to produce roughly 34.2 Mt of SCP per year with several valuable by-products (Dickson & Mansouri, 2025). Co-products, particularly high-purity nitrogen produced from onsite air separation, are an important source of revenue and help to offset production costs, while partial combustion of biogas can provide nearly all of the plant's energy demand for electricity and heat (Dickson & Mansouri, 2025).

From an environmental perspective, cradle-to-gate LCA results indicate that SCP has substantially lower global warming potential than both conventional livestock products and SCP made from fossil methane. By diverting food waste from landfill and replacing fishmeal or other resource-intensive proteins, SCP can simultaneously reduce greenhouse gas emissions from waste management and decrease pressure on marine and land resources.

Despite these advantages, several constraints remain. High nucleic acid contents in bacterial biomass (often 8–12%) require additional processing to reduce levels below about 2% for safe human consumption, and the construction of large-scale plants is capital-intensive. In addition, the use of waste-derived feedstocks and

live microbial cultures must comply with strict food- and feed-safety and novel-food regulations in major markets such as the EU and US.

5.4.2 Methane-based SCP

Methane-based SCP systems that use natural gas or biogas as a carbon source are among the most advanced microbial protein technologies (Dickson & Mansouri, 2025). LCA studies suggest that, when powered by low-carbon energy and operated with high resource efficiency, methane-based SCP can use around 100 times less water and 1 000 times less land per ton of protein than soybean cultivation (García Martínez et al., 2022). Under favourable conditions, the carbon intensity of SCP can fall to about 0.73 kg CO₂-eq/kg protein, which is lower than the average for soybean meal (around 0.85 kg CO₂-eq/kg protein) and far below fishmeal (about 2.72 kg CO₂-eq/kg protein) (Dickson & Mansouri, 2025). Modelling results show that using currently flared, vented, or re-injected “stranded” methane could cover a very large share of global protein requirements (García Martínez et al., 2022).

However, these environmental benefits depend critically on process design and regulation. Fugitive methane emissions from fermentation and gas handling can quickly erode or reverse climate advantages if not tightly controlled, and high capital costs for gas-fermentation infrastructure remain a barrier to rapid deployment (Specht, 2025). As with other microbial proteins for human these products must meet stringent safety and regulatory requirements, including nucleic-acid management and authorisations under the EU Novel Food Regulation (EU) 2015/2283. In the United States, safety assessment can be conducted through the Generally Recognised as Safe (GRAS) framework⁽¹⁶⁾, under which a substance may be marketed on the basis of general recognition of safety by qualified experts, but GRAS status is not itself a pre-market authorisation in the same sense as an EU Novel Food approval.

Power-to-Protein

P2P offers theoretical environmental benefits when powered by renewables. When SCP is produced using wind-driven water electrolysis and CO₂ captured from biogenic point sources (such as ethanol plants), reported carbon intensities can be as low as 0.73 kg CO₂-eq/kg protein (green energy, wind-driven), significantly below fishmeal and comparable to or lower than soymeal (Buttle et al., 2024; Van Peteghem et al., 2022). Because P2P production is almost land-free, using only a small fraction (around 0.4%) of the land required per ton of protein from soy, it can decouple protein supply from agricultural land availability and climatic variability (García Martínez et al., 2022). The process also generates water as a metabolic byproduct (for example, approximately 2.1 kg of water per kg of ethanol-derived biomass), which can be recycled into the

¹⁶ More information is available at: [Generally Recognized as Safe \(GRAS\) | FDA](#)

electrolysis stage, supporting a highly water-efficient system (Van Peteghem et al., 2022).

This combination of low land use, low direct emissions, and closed reactors makes P2P particularly relevant in resilience scenarios. Because production is independent of sunlight and occurs in controlled, enclosed environments, P2P has been proposed as a robust food supply option under catastrophic conditions, such as abrupt sunlight reduction. At present, however, high electricity demand and associated costs limit its economic competitiveness relative to other fermentation routes and conventional proteins (García Martínez et al., 2022).

5.4.3 Conclusions

Three consistent patterns emerge across fermentation platforms:

1. Resource decoupling: all routes achieve 100-1,000x land/water efficiency vs. agriculture; P2P and methane SCP minimise feedstock dependence entirely.
2. TRY optimisation: AI, omics, and strain engineering boost Titer-Rate-Yield (TRY), potentially enabling the use of heterogeneous waste streams with minimal quality loss.
3. Regulatory gating: environmental wins require proving mycotoxin/heavy metal/nucleic acid safety under Novel Food frameworks.

Table 17 - Sustainability synergy

Platform	Best-case GWP	Conventional benchmark	Key enabler	Key constraint
Trad. By-products	0.5-1.0*	Soy: 0.85	Waste diversion	Pre-treatment energy
SCP from waste	<0.85	Fishmeal: 2.72	Biogas CHP	Nucleic acids
Methane SCP	0.73	Soy: 0.85	Low-C energy	Fugitive CH ₄
P2P	0.73	Soy: 0.85	Renewables	Electricity cost

Taken together, these trends point to a gradual shift from linear “take-make-dispose” protein systems toward integrated biorefineries that valorise multiple outputs and minimise environmental externalities. How quickly these systems can scale, and in which regions, will be determined by their ability to combine environmental performance with robust economics and regulatory compliance, directly shaping the competitive landscape that EU farmers will face.

5.5 Operational challenges

This section examines the main technical and operational bottlenecks that currently constrain the scale-up and cost reduction of biomass and precision fermentation. It discusses challenges in downstream processing, scale-up risks, process stability on substrates, and safety and quality control requirements.

5.5.1 Protein production

Laboratory success does not guarantee industrial viability. While mycoprotein and precision proteins work at bench scale with TRL between 2 and 4, commercialisation faces three fundamental challenges: Key fermentation performance metrics like Titer, Rate, Yield (TRY) differ in trade-offs, metabolic burden and yield disparities between biomass and precision fermentation applications (Bekker, 2025). These are shown in the table below:

Table 18 - Overview of operational challenges

Challenge	Biomass fermentation	Precision fermentation	Impact
Titer	Relevant	Titer critical (g/L product)	Economic viability of DSP
Rate	Relevant	Relevant	Directly linked to volumetric productivity and therefore CAPEX
Yields (g product/g fermentable substrate)	0.3–0.6 g (dry cell mass/g sugar))	0.005–0.05 g (purified protein)	Substrate (sugar) and DSP costs explode
Metabolic Burden	Absent (native metabolism)	High (heterologous proteins)	Genetic instability, cell death

Source: (Bekker, 2025; Wibow, 2022)

The above mentioned challenges for industrial viability are interconnected and multiplicative. The TRY trade-offs imply that optimising growth rate often sacrifices final yield, while precision fermentation's lower yields (0.005-0.05 g purified protein vs. biomass's 0.3-.6 g dry cell mass) drive up sugar prices and are generally linked to lower titers, which make downstream purification exponentially more expensive. This yield disparity suggests that, under current and foreseeable technological conditions, precision fermentation is unlikely to achieve the same cost structure as biomass fermentation for bulk protein production. The operational reliability of precision fermentation is further challenged by the "metabolic burden" imposed on the microbial host. When a host is reprogrammed to produce non-native proteins, essential energy, cofactors, and precursors are diverted away from primary cellular growth. This diversion can trigger metabolic stress responses, leading to genetic instability, structural changes in the expression vector, or even cell death.

Biomass fermentation avoids these specific bottlenecks by utilising the entire microbial cell as the product, thereby eliminating the need to synthesise and purify high-value proteins present at low concentrations (Knychala et al., 2024; Werten et al., 2019).

5.5.2 Downstream processing

Downstream processing (DSP) involves the harvesting, separation, purification, and stabilisation of the final product. While biomass fermentation recovers whole biomass relatively easily, precision fermentation must extract dilute target proteins, driving costs to 20-30% of total production costs (Ye et al., 2024).

Another challenge for biomass fermentation is the bacterial/yeast SCP that contains 5–16% nucleic acids (Van Peteghem et al., 2022). RNA must drop below 2% for human consumption to avoid gout/kidney stone risks (Souza Filho et al., 2019). Heat shock treatment achieves this, but it also destroys up to 30% of the total protein biomass (Van Peteghem et al., 2022).

Achieving the necessary purity levels (often exceeding 99.5% for medical or specialised food applications) requires, in addition to the removal of RNA, the removal of host cell proteins, DNA, and endotoxins (Pereira et al., 2025). While secretory hosts like *Pichia pastoris* (*Komagataella phaffii*) can simplify this by exporting the protein into the supernatant, intracellular production requires costly cell disruption techniques.

5.5.3 Scaling risks

Scaling up from laboratory-scale experiments to industrial volumes (often exceeding 100 000 litres) involves substantial physical and financial risks. Building commercial-scale facilities requires massive initial investment. For example, a large-scale methane-based SCP facility is estimated to require a total capital investment of approximately USD 733 million (EUR 629 million) (Dickson & Mansouri, 2025). Fermentation is highly energy-intensive. A major climate and energy hotspot is needed for active cooling to maintain the bioreactors at optimal growth temperatures (e.g., 37°C), as microbial metabolism generates significant heat (Sinke et al., 2023). Cooling can account for an estimated 75% of in-facility energy demand. At large scales, ensuring uniform mixing and oxygen transfer becomes technically difficult. Larger bioreactors often suffer from oxygen depletion at the top of the bioreactor, which can drastically reduce yields. Furthermore, high agitation speeds required for mixing can introduce shear stress that damages or kills sensitive cells (Bekker et al., 2025).

5.5.4 Costs of microbial protein production

The largest cost drivers for both BF and PF are determined by factory capital expenditure (CAPEX), energy consumption, feedstock conversion efficiency and the level of product purity required (for downstream processing).

Table 19 - Examples of cost drivers for fermentation

Cost component	Details	Cost impact/significance
Capital investment (CAPEX)	These include costs related to bioreactor systems, RNA reduction equipment and purification equipment; depreciation is estimated at 15% costs	One paper provides the example of 66,7% capital costs related to the bioreactor (Risner et al., 2023)
Operational Energy/Utilities	Significant Kwh amounts (2-10 kWh/kg) are required for biochemical processes to be stable and optimised (Fernández-López et al., 2024)	Electricity is seen as a main operational 'hotspot' for various microbial production systems (Fernández-López et al., 2024). At EU industrial electricity prices (0.15 - 0.25 EUR/kWh), energy alone contributes 0.60-2.50/ EURkg to the cost of production (Bekker, 2025).
Feedstock (Raw materials)	Carbon sources (such as sugars, molasses, gases), nitrogen (ammonia/urea) and other minor nutrients. Feedstock costs account for 36% of SCP COP (Eastham et al., 2025; Specht, 2025)	One of the major operating costs accounts for a large portion of variable costs. Yet lower-cost waste feedstocks lower unit production costs (Li et al., 2025)
Downstream Processing (DSP)	Purification steps include: filtration and centrifugation (Bekker, 2025).	Depends on the purification process and complexity, biomass loss can occur (Lever, 2022; Risner et al., 2023)
Transportation (Logistics)	Shipping, dependent on transportation method (Skinner et al., 2025)	Often overlooked in theory, transportation still represents a significant cost factor.

6 Annex 2 - Regulatory context

Microbial proteins intended for human consumption and animal nutrition may result from different fermentation techniques, including conventional, biomass and precision fermentation. The 2030 Life Sciences Strategy, which the European Commission published in July 2025, and the Bioeconomy Strategy, published in November 2025, acknowledged the potential that biomass and precision fermentation harbour as advanced fermentation technologies for the production of sustainable products, ingredients and applications ⁽¹⁷⁾.

Overall, these techniques lack a specific legal definition under EU agri-food law and may be subject to different regulatory frameworks, considering:

1. the intended use of the final product/ingredient (e.g., food, feed, additive, processing aid, etc.); and
2. the reliance on source materials or production processes that ultimately result in **novel foods or genetically modified (GM) food and feed**.

In the following paragraphs, a brief overview of the EU regulatory frameworks applying to **food, feed and additives** that can be obtained through biomass and precision fermentation is provided. This overview is not meant to be exhaustive as other substances can be obtained through the processing technologies under examination (e.g., enzymes, flavourings).

Food derived from biomass and precision fermentation

If products (including ingredients) obtained through biomass or precision fermentation are intended for **human consumption**, the EU sectoral regulatory frameworks for **food** (e.g. on novel foods, food enzymes, food additives, flavourings, etc.) and/or **GM** food and feed may be relevant. While the novel food and the GM food and feed regulatory frameworks are mutually exclusive, this is not the case for the other sectoral food regulations. This means that, if a product or ingredient obtained through biomass or precision fermentation falls under EU GMO legislation, the EU novel foods legislation does not apply, but other relevant sectoral food legislation may still apply.

As regards food (including food ingredients) obtained using genetically modified microorganisms (GMMs), what determines whether the GMO regulatory framework applies is:

- a) whether **GMMs** are used in the fermentation process; and

⁽¹⁷⁾ Communication from the Commission, Choose Europe for life sciences A strategy to position the EU as the world's most attractive place for life sciences by 2030, COM/2025/525 final.

- b) whether GMMs or material derived from the GMM source material are present in the final product or ingredient.

If neither GMMs nor material derived from the GMM source material are present in the food, the GMO regulatory framework does not apply. This is the case in particular where the food is manufactured with the help of a GM processing aid (recital 16 of Regulation (EC) No 1829/2003). In that case, the EU regulatory framework for novel foods will apply, provided that the food complies with the definition of novel food. Conversely, if GMMs or material derived from the GMM source material are present in the final product or ingredient, EU legislation regulating GMOs will apply⁽¹⁸⁾. Due to the lack of clarity as to the legal status of food and feed produced using GMMs and containing unintentional minute amounts of DNA residues from the GMMs, the European Commission adopted on 16 December 2025 a legislative proposal under the so-called **Food and Feed Safety Simplification Omnibus**, amending, amongst others, the GM food and feed Regulation. The proposed amendment seeks to provide further legal clarity on the conditions under which food and feed obtained using GMMs would fall outside the EU GMO legislation⁽¹⁹⁾.

In the EU, **novel foods** are currently governed by Regulation (EU) 2015/2283⁽²⁰⁾. Applicable as of 1 January 2018, this regulatory framework requires that foods without a history of consumption in the EU before 15 May 1997 and falling under at least one of the 10 categories listed in the regulation must obtain a pre-market authorisation at EU level. Two of those novel food categories are primarily relevant for biomass and precision fermentation and namely:

- a) foods consisting of, isolated from or produced from microorganisms; and
- b) foods resulting from a production process not used for food production in the EU before 15 May 1997, which gives rise to significant changes in the composition or structure of a food, affecting its nutritional value, metabolism or level of undesirable substances.

⁽¹⁸⁾ Standing Committee on Plants, Animals, Food and Feed Section Genetically Modified Food and Feed 20 September 2021. Summary report. A.07 Food and feed resulting from fermentation with genetically modified microorganisms in contained used – Discussion.

⁽¹⁹⁾ Proposal for a Regulation of the European Parliament and of the Council amending Regulations (EC) No 999/2001, (EC) No 1829/2003, (EC) No 1831/2003, (EC) No 852/2004, (EC) No 853/2004, (EC) No 396/2005, (EC) No 1099/2009, (EC) No 1107/2009, (EU) No 528/2012, (EU) 2017/625 as regards the simplification and strengthening of food and feed safety requirements, COM (2025) 1030 final.

⁽²⁰⁾ Regulation (EU) 2015/2283 of the European Parliament and of the Council of 25 November 2015 on novel foods. OJ L 327, 11.12.2015, pp. 1–22.

In the EU, **GM foods** are currently regulated by Regulation (EC) No 1829/2003 ⁽²¹⁾. As mentioned above, if food or food ingredients obtained through biomass or precision fermentation contain **GMMs or material derived from the GMM** source material, they qualify as **GM foods**. As such, they require prior authorisation at EU level before being placed on the market, and products are subject to GM labelling and traceability requirements. Overall, the GMO authorisation procedure is more demanding and lengthier than that governing novel foods, besides being subject to specific labelling and traceability rules. In any case, whenever GMMs are used in advanced fermentation production processes under contained conditions, the provisions of Directive 2009/41/EC on the contained use of GMMs apply ⁽²²⁾.

Feed derived from biomass and precision fermentation

If products or ingredients obtained through biomass and precision fermentation are intended for **animal nutrition**, the EU regulatory frameworks for **feed materials** and **GM food and feed** are both relevant.

In the EU, **feed materials** are regulated by Regulation (EC) No 767/2009 ⁽²³⁾. Pursuant to EU law, feed materials are defined as *'products of vegetable or animal origin, whose principal purpose is to meet animals' nutritional needs, in their natural state, fresh or preserved, and products derived from the industrial processing thereof, and organic or inorganic substances, whether or not containing feed additives, which are intended for use in oral animal-feeding either directly as such, or after processing, or in the preparation of compound feed, or as carrier of premixtures'*. In addition, Regulation (EC) No 767/2009 defines **compound feed** as *'a mixture of at least two feed materials, whether or not containing feed additives, for oral animal-feeding in the form of complete or complementary feed'*.

In the EU, **feed materials** do not require prior authorisation to be placed on the market. A non-exhaustive list of the main feed materials is provided by Regulation (EU) No 68/2013 on the Catalogue of feed materials ⁽²⁴⁾. In addition, other legislative provisions relating to animal feed must be considered. This includes

⁽²¹⁾ Regulation (EC) No 1829/2003 of the European Parliament and of the Council of 22 September 2003 on genetically modified food and feed, OJ L 268, 18.10.2003, pp. 1–23.

⁽²²⁾ Directive 2009/41/EC of the European Parliament and of the Council of 6 May 2009 on the contained use of genetically modified micro-organisms, OJ L 125, 21.5.2009, pp. 75–97.

⁽²³⁾ Regulation (EC) No 767/2009 of the European Parliament and of the Council of 13 July 2009 on the placing on the market and use of feed, OJ L 229, 1.9.2009, pp. 1–28.

⁽²⁴⁾ Commission Regulation (EU) No 68/2013 of 16 January 2013 on the Catalogue of feed materials, OJ L 29, 30.1.2013, pp. 1–64.

Regulation (EC) No 183/2005, which lays down requirements for **feed hygiene** ⁽²⁵⁾.

Conversely, as GM foods, **GM feed products** are subject to Regulation (EC) No 1829/2003 and, as such, subject to a pre-market authorisation procedure at EU level. In addition, whenever GMMs are used in fermentation production processes under contained conditions, the provisions of Directive 2009/41/EC on the contained use of GMMs apply. In parallel, GM feed products are required to comply with the requirements set out by EU feed legislation referred to above.

Additives derived from biomass and precision fermentation

Although food and feed additives fall legally within the broader food and feed regulatory frameworks, they are addressed separately here because they represent a distinct route through which biomass and precision fermentation-derived products may enter the market. In these cases, the relevant question is not only whether the product is intended for food or feed use, but whether it performs a specific technological or nutritional function in another food or feed product. Where this is the case, the product may fall under the specific EU regimes for food additives, food enzymes, food flavourings or feed additives, in addition to any other applicable rules.

In the EU, **food additives**, together with food enzymes and food flavourings, are considered as **food improvement agents**. As such, they are subject to a common pre-market authorisation, which is currently regulated by Regulations (EC) No 1331/2008 and (EU) No 234/2011 ⁽²⁶⁾⁽²⁷⁾. The list of food additives authorised at EU level is currently provided by Regulation (EC) No 1333/2008 ⁽²⁸⁾, whose Annex II and III set out, respectively, the additives authorised and their conditions of use in food and food improvement agents. Some of the additives that are currently authorised at EU level result from precision fermentation (e.g., E960b). However, even in this case, if **GMMs or material derived from GMM source material** are present in the final product, the EU GM food/feed legal framework will apply in parallel with the regulation on food

⁽²⁵⁾ Regulation (EC) No 183/2005 of the European Parliament and of the Council of 12 January 2005 laying down requirements for feed hygiene, OJ L 35, 8.2.2005, pp. 1-22.

⁽²⁶⁾ Regulation (EC) No 1331/2008 of the European Parliament and of the Council of 16 December 2008 establishing a common authorisation procedure for food additives, food enzymes and food flavourings, OJ L 354, 31.12.2008, pp. 1–6.

⁽²⁷⁾ Commission Regulation (EU) No 234/2011 of 10 March 2011 implementing Regulation (EC) No 1331/2008 of the European Parliament and of the Council establishing a common authorisation procedure for food additives, food enzymes and food flavourings, OJ L 64, 11.3.2011, pp. 15-24.

⁽²⁸⁾ Regulation (EC) No 1333/2008 of the European Parliament and of the Council of 16 December 2008 on food additives, OJ L 354, 31.12.2008, pp. 16–33.

improvement agents and such products will require two pre-market authorisations.

As far as **feed additives** are concerned, in the EU these are currently regulated by Regulation (EC) No 1831/2003 ⁽²⁹⁾. This regulation requires a pre-market authorisation at EU level before a feed additive can be placed on the market. The list of authorised feed additives is provided in the European Union Register of Feed Additives ⁽³⁰⁾. The Register contains, among others, some additives obtained through fermentation processes (e.g., riboflavin (vitamin B2) produced with *Bacillus subtilis* CGMCC 7.449). In this respect, it is important to note that for feed additives containing, consisting of, or produced **from GMMs**, two authorisations are needed: one under EU GMO legislation and one under EU legislation governing feed additives. Conversely, for additives produced **with GMMs** (but not containing, consisting of, or produced from GMMs), only the standard authorisation procedure for feed additives applies.

⁽²⁹⁾ Regulation (EC) No 1831/2003 of the European Parliament and of the Council of 22 September 2003 on additives for use in animal nutrition OJ L 268, 18.10.2003, pp. 29–43.

⁽³⁰⁾ <https://ec.europa.eu/food/food-feed-portal/screen/feed-additives/search>.

7 Annex 3 - Table of EU fermentation-based alternative protein companies database (biomass, precision fermentation)

Table 20 - EU fermentation-based alternative protein companies database (biomass and precision fermentation)

Company	MS	Year	Fermentation approach	Type of product	Type of ingredient	Final product	Food	Feed	Ownership	Ownership details
21st.BIO	DK	2020	Precision fermentation	Oils and fats		Dairy-product analogue inputs (beta-lactoglobulin, alpha-lactalbumin, caseins); protein sweeteners; collagen; biomaterials; biopesticides		X	EU	
ÄIO	EE	2022	Precision fermentation	Ingredients, Eggs	Lipids, Oils	Oils; Yeasts	X		EU	
Algama	FR	2013	Biomass fermentation		Algae, Microalgae	Processed chlorella	X		EU; Non-EU	At least 55.54% EU
Allbiotech	ES	2024	Precision fermentation	Ingredients		Lab bioreactor; foodtech labs	X		EU	
Allmicroalgae	PT	2007	Plant-based, Cultivated, Precision fermentation	Ingredients	Microalgae, Chlorella, Blue-green algae (cyanobacteria), Algae	Microalgae (chlorella, spirulina, tetraselmis, nannochloropsis, scenedesmus. phaeodactylum tricornutum, chlorococcum amblystomatis)	X	X	EU	
Arbiom	FR	2016	Biomass fermentation	Equipment/Infrastructure	Yeast	Proteins	X	X	EU; Non-EU	At least 50.01% non-EU (US)
Arsenale Bioyards	IT	2023	Precision fermentation	Analogues to curded dairy products		Bioprocessing infrastructure (industrial fermentation capacity; bioreactors + process/automation platform)			EU; Non-EU	At least 97.08% EU
Bel Group	FR	1865	Precision fermentation, Plant-based	Equipment/Infrastructure	Casein	Analogues to curded dairy products (cheese-style; milk proteins, mainly caseins)	X		EU	

Study on biomass and precision fermentation

Company	MS	Year	Fermentation approach	Type of product	Type of ingredient	Final product	Food	Feed	Ownership	Ownership details
Bilfinger Life Science	AT	1880	Plant-based, Cultivated, Traditional fermentation, Biomass fermentation, Precision fermentation	Ground meat analogues/seafood analogues		Food/bioprocessing plant engineering & equipment (e.g., dosing/mixing systems; bioreactor/fermentation plants; CIP/SIP systems)	X		EU	
Biohifas	LT	2023	Biomass fermentation	Ingredients	Mycelium, Mycoprotein	Mycoprotein/mycelium-based analogues to meat products (patty-style formats); fungal protein via solid-state fermentation using side-stream substrates (e.g., bread crumbs)	X		No information available	
BioMush	FI	2021	Biomass fermentation	Equipment/Infrastructure	Fungi	Umami flavour ingredients (clean-label) from food-industry side streams via solid-state fungal fermentation; plus plug-and-play SSF bioreactor/tech solution for industrial clients	X		EU	
Bionet	ES	1999	Precision fermentation, Cultivated	Ingredients		Bioprocessing equipment & software (bioreactors/fermenters; TFF systems; process software) + bioprocess services (engineering, qualification, scale-up support)			EU	
BioProcesia	ES	2021	Biomass fermentation	Equipment/Infrastructure	Bacteria	Microbial (bacterial) protein ingredient (>70% protein) for animal feed/pet food, produced via fermentation of agro-food industry byproducts; optimised with digital-twin/AI methodology		X	No information available	
Biostream International	NL	2013	Cultivated, Biomass fermentation	Whole-cut meat/seafood analogues		Bioreactor/fermenter systems (bench to pilot/production), vessels (glass/stainless), control software, service & customisation; also photobioreactors for microalgae			No information available	
Bosque Foods	DE	2022	Precision fermentation, Biomass fermentation	Ingredients	Mycelium, Fungi	Mycelium-based whole-cut meat analogues (chicken- and pork-style formats) and seafood analogues (species not specified publicly)	X		Non-EU	100% US

Study on biomass and precision fermentation

Company	MS	Year	Fermentation approach	Type of product	Type of ingredient	Final product	Food	Feed	Ownership	Ownership details
BRAIN-Biocatalysts Life Science Solutions	DE	1993	Precision fermentation	Equipment/Infrastructure	Enzymes	Specialty enzymes (processing aids/biocatalysts) + tailored microbial strains/food cultures; contract enzyme discovery/engineering and scale-up production via fermentation	X	X	EU	
Bürkert Fluid Control Systems	DE	1946	Plant-based, Cultivated, Biomass fermentation, Precision fermentation	Ingredients		Fluid control systems for bioprocessing & food plants (hygienic/aseptic valves, flowmeters/sensors, valve islands and control systems for fermenters/bioreactors and CIP/WFI-like loops)			EU	
Calidris Bio	BE	2019	Biomass fermentation	Ingredients	Bacteria	Microbial protein ingredient (high-protein biomass) for petfood and human food; also positioned as substitute for fishmeal/soymeal in feed/aquaculture	X	X	No information available	
Cambrium	DE	2020	Precision fermentation	Oils and fats	Collagen	Collagen (novaColl™) – micro-molecular, 100% skin-identical vegan collagen active			EU; Non-EU	At least 87.65% EU
CarboCode	PT	2017	Precision fermentation	Equipment/Infrastructure	Lipids, Oils	Human-identical glycosphingolipids/gangliosides (e.g. GM3 ganglioside) for infant nutrition (human milk molecules)	X		EU; Non-EU	At least 64.28% EU
ChainReactor	PT	2024	Traditional fermentation, Biomass fermentation, Precision fermentation	Ingredients		3D-printed bioreactors with automation/ML; rapid manufacturing of scalable bioreactor systems			No information available	
Circe Biotech	AT	2019	Biomass fermentation	Ingredients	Microorganisms	Single cell protein (bacterial biomass) for food & feed; biodegradable biopolymers (PHA/PHB)	X	X	EU	
Cirkulär	SE	2019	Biomass fermentation	Oils and fats	Mycoprotein, Fungi	Mycomeal™ (fungal biomass: high-quality proteins + fibres + nutrients) produced from industrial sidestream feedstocks via proprietary fermentation	X	X	No information available	
Corbion	NL	1903	Plant-based, Biomass fermentation	Ingredients	Algae, Microalgae, Omega-3, EPA/DHA	Algae oils rich in omega-3 (DHA; some products positioned for DHA/EPA): algaPrime™ DHA (feed) + algaVia™ algae oils/DHA (human nutrition/nutraceutical)	X	X	EU; Non-EU	

Study on biomass and precision fermentation

Company	MS	Year	Fermentation approach	Type of product	Type of ingredient	Final product	Food	Feed	Ownership	Ownership details
Corden Biochem	DE	1863	Precision fermentation, Fermentation-derived	Equipment/Infrastructure		Contract manufacturing (CDMO) of fermentatively produced products: biomass/proteins/functional ingredients/natural flavours for food; feed additives/products	X	X	Non-EU	At least 99.91% non-EU (British Virgin Islands)
CULTZYME	ES	2022	Cultivated, Biomass fermentation, Precision fermentation	Services/Analytics		Bioreactors; bioprocess monitoring systems; cell culture media			No information available	
Cx Bio	LU	2022	Plant-based, Biomass fermentation	Ingredients		Techno-economic analysis models; fermentation TEA reports; fermented fats and oils company database			EU	
Darwin Bioprospecting Excellence	ES	2016	Biomass fermentation, Traditional fermentation	Services/Analytics	Yeast	Microbial strains library; food starter cultures; probiotic strains; microbial consortia; fermentation methods	X	X	EU	
Developeat	NL	2020	Cultivated, Plant-based, Precision fermentation	Services/Analytics		Product formulation prototypes; NPD management; production upscaling support			No information available	
Differential Bio	DE	2023	Biomass fermentation, Precision fermentation	Ingredients		Bioprocess optimisation models; AI-driven fermentation analytics; microbial growth simulation platform			EU; Non-EU	At least 88.52% EU
Duplaco	NL	2012	Biomass fermentation	Ingredients	Algae, Microalgae	Chlorella microalgae powder; chlorella tablets; microalgae concentrate paste	X	X	EU	
econutri	AT	2021	Biomass fermentation	Ingredients	CO2	Microbial protein; protein ingredients for human food; protein ingredients for pet food; protein ingredients for livestock feed	X	X	EU; Non-EU	At least 69.60% non-EU (US)
Edonia	FR	2023	Biomass fermentation	Ingredients	Microalgae	Edo-1 textured microalgae ingredient	X		EU	
Enifer	FI	2020	Biomass fermentation	Equipment/Infrastructure	Mycoprotein, Fungi	Pekilo® mycoprotein powder; Pekilo®Pet mycoprotein; Pekilo®Aqua mycoprotein	X	X	No information available	
Eppendorf	DE	1945	Precision fermentation, Biomass fermentation	Equipment/Infrastructure		Single-use bioreactors; parallel bioreactor systems; bioprocess controller			EU	

Study on biomass and precision fermentation

Company	MS	Year	Fermentation approach	Type of product	Type of ingredient	Final product	Food	Feed	Ownership	Ownership details
ERIDIA	AT	2022	Cultivated, Biomass fermentation, Precision fermentation	Whole-cut meat/seafood analogues		Bioprocessing plant engineering; process scale-up; project execution for fermentation and cellular agriculture			No information available	
Esencia Foods	DE	2022	Biomass fermentation	Ingredients	Mycoprotein, Fungi, Mycelium	Whole-cut seafood analogues; fish-style fillet analogues	X		EU	
Eternal	FI	2018	Biomass fermentation	Services/Analytics	Mycoprotein, Fungi	Mycofood™ mycoproteins	X		No information available	
EV Biotech	NL	2018	Precision fermentation	Ingredients, Oils and fats		Microbial strain development services; fermentation process development; strain optimisation services			EU	
Evonik Health Care	DE	2007	Precision fermentation, Biomass fermentation	Ingredients	Omega-3, EPA/DHA, Lipids, Oils	Omega-3 fatty acids; DHA; EPA; cell culture media components	X	X	EU; Non-EU	At least 49.23% EU
Farmless	NL	2022	Biomass fermentation	Equipment/Infrastructure	CO2	Microbial protein	X		EU	
Flottweg	DE	1943	Plant-based, Traditional fermentation, Biomass fermentation, Precision fermentation, Plant molecular farming	Ingredients, Oils and fats		Decanter centrifuges; separators; belt presses; separation systems			EU	
Fooditive Group	NL	2018	Precision fermentation	Equipment/Infrastructure	Casein, Proteins, Lipids, Oils	Precision-fermented casein; plant-based sweeteners; plant-based fats	X		EU	
Formical	NL	2025	Cultivated, Biomass fermentation, Precision fermentation	Analogues to curded dairy products		Modular fermentation units; fermentation infrastructure			No information available	
Formo	DE	2018	Precision fermentation	Ingredients, Analogues to fermented dairy products/other dairy-product analogues	Casein, Fungi	Animal-free analogues to curded dairy products (cheese-style); precision-fermented casein	X		EU	At least 74.06% EU
FourStrain Labs	ES	2024	Precision fermentation	Ingredients	Whey, Fungi	Precision-fermented whey protein; animal-free dairy-product analogue ingredients	X		No information available	

Study on biomass and precision fermentation

Company	MS	Year	Fermentation approach	Type of product	Type of ingredient	Final product	Food	Feed	Ownership	Ownership details
Fungu'it	FR	2022	Biomass fermentation	Other meat analogues/seafood analogues, Whole-cut meat/seafood analogues		Fermented aromatic ingredients; umami flavour ingredient; chocolate flavour ingredient	X		EU	
FUNKI	EE	2022	Plant-based, Biomass fermentation	Equipment/Infrastructure	Mycoprotein, Fungi, Mycelium	Mycelium-based meat analogues; whole-cut meat analogues	X		No information available	
GEA	DE	1881	Plant-based, Cultivated, Biomass fermentation, Precision fermentation, Traditional fermentation	Oils and fats, Ingredients		Industrial food processing systems; bioprocessing equipment; fermentation plants			EU; Non-EU	At least 53.11% EU
Green-On	SE	2020	Biomass fermentation	Equipment/Infrastructure	Lipids, Oils	Palm oil alternatives; coconut oil alternatives	X		No information available	
IKA	DE	1910	Plant-based, Cultivated, Biomass fermentation, Precision fermentation	Ingredients, Other meat analogues/seafood analogues		Laboratory bioreactors; cell culture equipment; lab fermentation systems			EU	
Infinite Roots	DE	2018	Biomass fermentation	Other meat analogues/seafood analogues	Mycoprotein, Fungi, Mycelium	Mycelium-based ingredients; mycelium meat analogues	X		No information available	
Innfoods	IT	2025	Biomass fermentation	Services/Analytics	Mycoprotein, Fungi, Mycelium	Mycoprotein-based seafood analogues	X		EU	
Innocent Meat	DE	2018	Cultivated, Precision fermentation	Ingredients, Other meat analogues/seafood analogues, Analogues to fermented dai...	Recombinant proteins	Cultured meat production systems; recombinant growth factors; cell media comp...			EU; Non-EU	At least 93.07% EU
Innomy	ES	2020	Biomass fermentation	Ingredients	Mycelium, Mycoprotein, Fungi	Mycelium-based proteins; meat analogue ingredients; dairy-product analogue in...	X		EU	

Study on biomass and precision fermentation

Company	MS	Year	Fermentation approach	Type of product	Type of ingredient	Final product	Food	Feed	Ownership	Ownership details
Ironi Biotech	SE	2020	Precision fermentation	Whole-cut meat/seafood analogues, Other meat analogues/seafood analogues	Recombinant proteins	Non-animal heme iron ingredient; bioavailable iron protein	X		EU	
Koralo	DE	2021	Biomass fermentation	Ingredients	Microalgae, Fungi, Omega-3, Mycelium	Whole-cut seafood analogues; omega-3-enriched analogue products	X		EU; Non-EU	At least 68.31% EU
Kynda Biotech	DE	2019	Biomass fermentation	Equipment/Infrastructure	Mycoprotein, Fungi, Mycelium	Mycoprotein ingredients for pet nutrition; mycelium-based proteins		X	EU; Non-EU	At least 74.78% EU
LAUDA	DE	1956	Precision fermentation, Cultivated	Services/Analytics		Temperature control systems; thermostats; circulators for bioprocessing and I...			EU; Non-EU	At least 91% EU
LenioBio	DE	2016	Cultivated, Precision fermentation	Ingredients, Services/Analytics		Cell-free protein expression platforms; scalable protein expression services; ...			EU; Non-EU	At least 71.1% non-EU (65.61% UK)
Levprot Bioscience	ES	2020	Precision fermentation	Equipment/Infrastructure	Recombinant proteins; functional proteins	Recombinant functional proteins; rBSA; brazzein; cell culture supplements; ne...	X		EU	
Lyras	DK	2017	Precision fermentation, Biomass fermentation, Plant molecular farming			Raslysation™ liquid processing systems; UV non-thermal pasteurisation equipme...			EU	
Maash	BE	2021	Biomass fermentation	Ingredients	Fungi, Mycoprotein	Locylia®, a high-quality textured protein that enhances the taste and texture...	X	X	EU	
Marsavet	DE	2025	Precision fermentation	Whole-cut meat/seafood analogues, Ingredients	Yeast, Sweet potato, Pea, Malt extract	MicroBell, a dry dog food with microbially produced protein; microbial protei...	X	X	EU	
Mati Foods	EE	2021	Biomass fermentation	Whole-cut meat analogues/Ground meat analogues/Seafood analogues	Fungi, Mycoprotein	Mati chicken (brand/product name), a chicken-style meat analogue; chicken-sty...	X		EU	

Study on biomass and precision fermentation

Company	MS	Year	Fermentation approach	Type of product	Type of ingredient	Final product	Food	Feed	Ownership	Ownership details
MATR Foods	DK	2021	Plant-based, Biomass fermentation	Oils and fats	Oat, Pea, Potato, Lupine, Beetroot, Fungi	MATR Patty (brand/product name), a fungi-fermented patty-style analogue desig...	X		EU	
Melt&Marble	SE	2021	Precision fermentation	Ingredients	Yeast, Bioactive lipids	MeatyMarble™ and DairyMarble™, specific fat ingredient lines aimed at mimicki...	X		EU	
MicroHarvest	DE	2021	Biomass fermentation	Ground meat analogues/Other meat analogues	Microorganisms	MP-X Care (rich in essential amino acids, a vegan product supporting modern p...	X	X	EU; Non-EU	At least 93.89% EU
Millow	SE	2022	Biomass fermentation	Ingredients, Equipment/Infrastructure	Mycelium	Mycelium mixed with oat protein that can be shaped into analogues to meat pro...	X		EU	
MOA Foodtech	ES	2020	Biomass fermentation	Ingredients, Equipment/Infrastructure	Yeast	MOA Box, a platform for starch-rich byproduct valorisation; MOA Yeast, a ferm...	X	X	EU	
Myco4Food	DK	2022	Biomass fermentation	Ingredients	Mycoprotein, Fungi, Microorganisms (edible fungal biomass)	Solid-state fermentation (SSF) systems to produce protein-rich food ingredien...			EU	
MycoVibes Biotech	PL	2024	Biomass fermentation	Ingredients	Mycoprotein, Mycelium	Nutrient-dense, allergen-free protein naturally rich in vitamin B12 and iron; ...	X		EU	
Naplasol	BE	2021	Biomass fermentation	Services/Analytics	Mycoprotein, Fungi	Products like Promyc S110, Promyc L100 and other mycoprotein ingredient codes...	X		EU	
NIZO	NL	2003	Plant-based, Precision fermentation	Services/Oils and fats		Services/analytics and equipment/infrastructure with capabilities ranging fro...			EU	
NoPalm Ingredients	NL	2012	Biomass fermentation	Ingredients	Lipids, Fats, Microbial oil	REVÓLEO™, an ingredient platform which includes soft and silk variants tailor...	X		EU	
Nosh.bio	DE	2022	Biomass fermentation, Blended	Enzymes/Microorganisms/Probiotics	Fungi	Koji Protein, a core fermentation-derived protein used by food manufacturers; ...	X	X	EU; Non-EU	At least 97.42% EU
Novonesis	DK	1874	Precision fermentation	Analogues to curded dairy products, Ingredients	Ingredients/Other	Advanced protein solutions; probiotics, microbes and enzymes; baked goods; No...	X	X	EU	
Nutropy	FR	2021	Precision fermentation	Ingredients	Yeast	Bioidentical milk proteins/caseins; fermentation-derived milk proteins; analo...	X	X	EU; Non-EU	At least 75.88% EU

Study on biomass and precision fermentation

Company	MS	Year	Fermentation approach	Type of product	Type of ingredient	Final product	Food	Feed	Ownership	Ownership details
ODS Protein	ES	2021	Plant-based, Biomass fermentation, Precision fermentation	Ingredients	Mycoprotein, Fungi	NAWA Protein, a fermented mycoprotein ingredient derived from filamentous fun...	X		EU	
Onego Bio	FI	2022	Precision fermentation	Ingredients	Corn, Egg protein	Bioalbumen®, a fermentation-derived ovalbumin identical to the main protein i...	X		EU; Non-EU	At least 99.9% EU
Onima	FR	2021	Biomass fermentation	Whole-cut meat analogues/Seafood analogues	Yeast protein	Yeast Super Flour”, a debittered, inactivated brewer’s yeast ingredient produ...	X		EU	
Pacifico Biolabs	DE	2022	Biomass fermentation	Ingredients	Mycelium, Fungi	Viando, a meat analogue that captures the taste and texture of traditional me...	X		EU; Non-EU	At least 95.69% EU
paleo	BE	2020	Precision fermentation	Ingredients, Services/Analytics	Yeast	Hme proteins (myoglobins), bio-identical to animal myoglobin, supplied as ing...	X		EU; Non-EU	
PFX Biotech	PT	2022	Precision fermentation	Ingredients	Proteins, Microbial proteins, Enzymes	Human milk proteins for use in advanced nutrition applications; animal-based ...	X		EU	
PhycoFerm	PT	2024	Plant-based, Biomass fermentation, Precision fermentation	Ingredients	Microalgae, Microorganisms, Bioactive compounds (proteins, lipids, antioxidants)	Protein-rich algal ingredient and functional microalgae powder; prebiotic mic...	X		EU	
Phycom	NL	2009	Biomass fermentation	Ingredients, Services/Analytics	Microalgae, Bioactive compounds, Lipids	Algae for food, nutraceuticals and animal feed; specific fermentation-derived...	X	X	EU	
Picea Biosolutions	DE	2022	Plant-based, Precision fermentation	Equipment/Infrastructure, Services/Analytics	Yeast, Fungi	Fermentation-derived protein ingredient; highly pure proteins or complex mixt...	X	X	EU	
Pierre Guerin	FR	1949	Precision fermentation, Plant-based, Biomass fermentation, Cultivated	Ingredients		Process infrastructure and industrial equipment for fermentation and other pr...			EU	

Study on biomass and precision fermentation

Company	MS	Year	Fermentation approach	Type of product	Type of ingredient	Final product	Food	Feed	Ownership	Ownership details
Poseidona	ES	2023	Biomass fermentation	Equipment/Infrastructure, Research project	Algae	Sustainable protein ingredients extracted from seaweed, for example algal pro...	X	X	EU	
Power to Protein	NL	2015	Biomass fermentation	Ingredients		Research/project platform focused on exploring a concept for producing microb...			EU	
ProteinDistillery	DE	2021	Biomass fermentation	Ingredients, Services/Analytics	Microorganisms, Microbial protein (yeast-based)	Prew: tein®, a clean-label yeast protein derived from upcycled spent brewer's ...	X	X	EU; Non-EU	At least 93.21% EU
Protevo	DE	2025	Precision fermentation, Plant-based	Equipment/Infrastructure, Services/Analytics	Enzymes, Functional protein molecules	Protein molecules (growth factors, enzymes, etc.) that are inputs for cultiva...	X		EU	
Qubicon	AT	2021	Cultivated, Biomass fermentation, Precision fermentation	Analogues to dairy drinks, Analogues to fermented dairy products/other dairy-p...		Qubicon Bioprocess Control Platform which is an automated fermentation monito...			EU	
Real Deal Milk	ES	2021	Precision fermentation	Ingredients	Yeast, Casein, Whey	Animal-free dairy-product analogues, including analogues to dairy drinks (mil...	X		EU	
Sartorius	DE	1870	Cultivated, Precision fermentation	Oils and fats, Ingredients		Bioreactors and fermenters; cell culture and filtration systems; fermentation...			EU; Non-EU	At least 83.27% EU
Smey	DE	2021	Precision fermentation	Ingredients	Oils and fats	Noyl silk™ (cultivated high-oleic oil); Noyl cocoa™ (cultivated cocoa butter ...	X		EU	
Solar Foods	FI	2017	Biomass fermentation, Cultivated	Ingredients, Equipment/Infrastructure	Microorganisms, Single-cell protein, Solar energy	Solein® microbial protein powder, a high-protein single-cell protein ingredient	X		EU; Non-EU	
Solmeya	EL	2019	Biomass fermentation	Ingredients	Microalgae, Microbial protein, Lipids (omega-3 DHA)	GRAS, carbon-negative ingredients; white algae biomass; protein for food; lip...	X		EU	
Sophie's BioNutrients	NL	2017	Biomass fermentation	Ingredients	Microbial protein, Fungi, Microorganisms	Microbial protein and nutrient-rich fermentation biomass from sustainable fee...	X		Non-EU	100% Singapore
Standing Ovation	FR	2020	Precision fermentation	Equipment/Infrastructure, Services/Analytics	Milk proteins, Casein, Whey	Fermentation-derived dairy-protein ingredients, such as casein and whey, for dairy-product analogue applications	X		EU	

Study on biomass and precision fermentation

Company	MS	Year	Fermentation approach	Type of product	Type of ingredient	Final product	Food	Feed	Ownership	Ownership details
Steinecker	DE	1876	Plant-based, Cultivated, Traditional fermentation, Biomass fermentation, Precision fermentation	Services/Analytics		Industrial brewing and fermentation equipment and other services like brewing systems, turnkey process lines; automation and control systems			EU	
Studio Fava	NL	2020	Plant-based, Cultivated, Precision fermentation, Biomass fermentation	Equipment/Infrastructure, Services/Analytics		Food product concepts and product formulation prototypes			EU	
Swan Neck Bio	DK	2023	Biomass fermentation, Precision fermentation	Other meat analogues/seafood analogues, Ground meat analogues/seafood analogues		Bioreactor systems and fermentation scale-up trials; services like microorganism robustness testing			EU; Non-EU	At least 65% EU
Tempty Foods	DK	2021	Biomass fermentation, Plant-based	Ingredients	Mushroom roots, Lentils, Quinoa, Carrots, Parsley, Oats, Mycoprotein	Meat analogues, including mycelium burger-style patty, square mycelium pieces and spicy Korean stick mycelium snack	X		EU	
Terra Wave	RO	2025	Biomass fermentation	Equipment/Infrastructure	Fungi, Mycoprotein	Protein-rich textures for meat analogue applications; textured and fermented fungal protein ingredient; mycoprotein biomass powder	X	X	EU	
Tetra Pak	SE	1951	Biomass fermentation, Cultivated, Plant-based, Precision fermentation, Traditional fermentation	Services/Analytics		Fermentation and processing equipment used by companies producing microbial proteins, dairy proteins and other alternative foods			EU	
TFTAK	EE	2004	Plant-based, Precision fermentation, Biomass fermentation	Equipment/Infrastructure, Services/Analytics		Services for developing future protein extraction technologies, analytical characterisation, fermentation optimisation and prototype formulation			EU	

Study on biomass and precision fermentation

Company	MS	Year	Fermentation approach	Type of product	Type of ingredient	Final product	Food	Feed	Ownership	Ownership details
The Cultivated B	DE	2021	Cultivated, Plant molecular farming, Precision fermentation	Ingredients		Technology using bioreactors (e.g., AUXO V systems), cell lines and media components designed for cellular agriculture and precision fermentation workflow; technology for serving various sectors, like food (e.g. cultivated meat), pharma (e.g. active ingredients), cosmetic and personal care (e.g. antioxidants)			EU	
The Protein Brewery	NL	2019	Biomass fermentation	Ingredients	Fungi, Mycoprotein	Fermotein®, a fungal fermentation ingredient produced from a proprietary microorganism and processed into a protein- and fibre-rich powder used by food manufacturers in applications such as snacks, dairy-product analogues and active nutrition products	X		EU; Non-EU	
Those Vegan Cowboys	BE	2020	Precision fermentation, Plant-based	Ingredients	Casein	Analogues to curded dairy products (cheese-style), using milk proteins; precision-fermented casein, casein powder and casein micelles for camembert- and mozzarella-style curded dairy-product analogues and beverages	X		EU	
UniBio	DK	2001	Biomass fermentation	Analogues to dairy drinks, Analogues to curded dairy products, Analogues to fermented dairy products/other dairy-product analogues	Essential amino acids, Microorganisms	Uniprotein® which is a high protein ingredient for agricultural feed, aquaculture feed and pet food	X	X	Non-EU	100% UK
Verley	FR	2021	Precision fermentation	Analogues to fermented dairy products/other dairy-product analogues, Ingredients	Whey, Beta-lactoglobulin (BLG)	FermWhey™ Native and FermWhey™ Native 100 which are pure whey proteins designed for superior nutrition; FermWhey™ Gel which provides natural gelling properties; FermWhey™ MicroStab which is an enhanced microparticulated whey protein	X		EU	
Vivici	NL	2022	Precision fermentation	Services/Analytics	Whey, Beta-lactoglobulin (BLG)	Vivitein™ functional protein ingredients portfolio which contains Vivitein™ BLG (a beta-lactoglobulin protein) and Vivitein™ LF	X		EU; Non-EU	

Study on biomass and precision fermentation

Company	MS	Year	Fermentation approach	Type of product	Type of ingredient	Final product	Food	Feed	Ownership	Ownership details
VTT	FI	1942	Plant-based, Cultivated, Precision fermentation	Oils and fats		Research and development services for meat alternatives; science-backed methods for developing technologies for fermentation process development and product prototyping			EU	
Zayt Bioscience	DE	2022	Precision fermentation	Services/Analytics	Lipids, Oils	Zayt Butter (brand/product name), a precision-fermented lipid and structured fat for food applications	X		EU	

Source: Good Food Institute Europe ([Alternative protein industry - GFI Europe](#)) for companies, MS, years founded, fermentation approach, type of product and type of ingredient. Each website has been scouted for the final product, food and feed columns. For ownership and ownership details, the source is [Orbis \(Bureau Van Dijk\)](#).

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