Fermentation and the Future of Europe's Protein System

A report by Systemiq for The Protein Project

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Executive summary

Our EU protein system is under serious pressure. Mounting environmental stresses, including greenhouse-gas emissions, land degradation and water scarcity, coincide with socio-economic concerns about farmer incomes, rural vitality and the affordability of healthy diets.

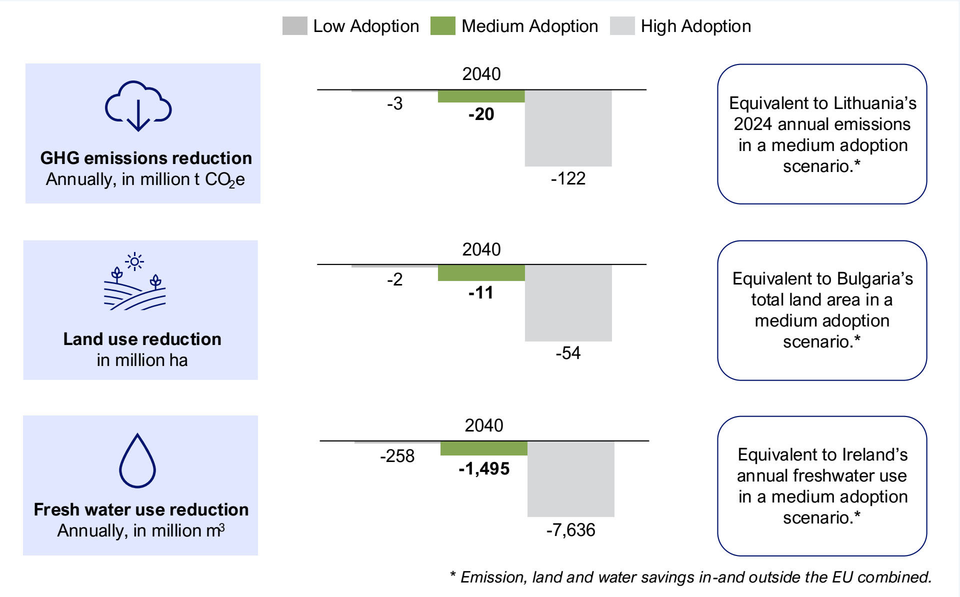
Fermentation technologies are increasingly cited as a lever to make the EU protein system more resilient. They are among humanity's oldest agri-food technologies and today encompass three main types: classical fermentation (e.g. bread, cheese, yoghurt, tempeh), biomass fermentation (producing microbial biomass as a source of protein for food or feed) and precision fermentation (using microorganisms to produce specific ingredients such as proteins, fats or vitamins).

This report by Systemiq for The Protein Project investigates their potential. It quantitatively assesses whether a growing fermentation sector could improve environmental outcomes by 2040 (through reduced GHG emissions, land use and water use) and qualitatively assembles case studies showing how farmers and consumers interact with fermentation in practice.

Environmental outcomes: emissions, land and water savings

In a medium adoption scenario, assuming a modest substitution of 3% of animal protein equivalent with fermented products, the EU could substantially reduce its global environmental footprint. By 2040, the uptake of biomass and precision fermentation in ***food applications*** would:

- Cut annual greenhouse-gas emissions by **20 million tonnes CO_2e**, equivalent to Lithuania's annual emissions in 2024 – of which at least 40% within the EU.
- Free up **11 million hectares** of land, equivalent to the size of Bulgaria – of which at least 35% within the EU.
- Reduce annual freshwater use by **1,5 billion m³**, equivalent to Ireland's total yearly freshwater use.– of which at least 33% within the EU.



2040 Annual environmental impact potential of fermented alternative proteins - emissions reduction (Million tonnes CO_2e emissions), land use savings (Million Ha) and water savings (Million m^3) - under a low, medium, and high adoption scenario of fermented proteins.

Fermentation also shows promising potential in ***feed***. At ingredient level, fermented products such as silage, microbial protein and precision-fermented whey or omega-3 can significantly reduce land and water use and, in some cases, emissions compared with grass hay, soy protein, fishmeal and animal-derived whey. Their overall contribution depends on energy source and feedstock choices and is likely to increase as power systems decarbonise and more circular feedstocks become available.

Socio-economic outcomes for farmers and consumers

Environmental benefits alone are not sufficient. For fermentation to support a just transition of the protein system, it must also create opportunities for farmers and consumers.

The case studies in this report show that, rather than viewing fermentation narrowly as competing with traditional agriculture, it can be seen to complement and diversify ***farmer business models*** through three main pathways:

- **New markets for crops and side streams**. Fermentation can provide additional outlets for sugar- and starch-rich crops and for agricultural co-products such as beet pulp and molasses, helping arable farmers smooth income, valorise residues and reduce exposure to shrinking markets in feed and fuel.
- **Higher value feed ingredients**. Precision-fermented additives, including omega-3 from microalgae and other functional nutrients, can improve feed quality for livestock and aquaculture, while reducing reliance on finite marine resources and help farmers lower their environmental footprint.
- **On-farm and local fermentation.** Classical fermentation of vegetables, legumes and dairy can help farmers turn surplus production into higher value products, extend shelf life, reduce waste and underpin diversified business models, especially when linked to local or direct-to-consumer channels.

For ***consumers***, fermentation helps to expand existing protein choices. Products such as tempeh, mycoprotein, animal-free dairy ingredients and algae-derived omega-3 allow health-oriented consumers to diversify their protein intake with foods that can be high in protein and fibre and lower in saturated fat. For others, their appeal may lie in their benefits for the environment and animal welfare or their convenience. Fermentation-derived ingredients are also increasingly used in hybrid foods, improving the taste, texture or nutritional quality of both plant-based and animal-based products.

Conclusion and policy recommendations

Taken together, the findings suggest ***that fermentation for food and feed is an essential building block of the European Union's protein future.*** If developed responsibly, it can lower environmental pressures, create complementary opportunities for farmers and rural communities and offer consumers additional healthy and convenient options.

Fermentation is already recognised in the European Commission's latest communication on the Bioeconomy Strategy as part of the wider bio-based and biomanufacturing toolbox[19]. To translate this recognition into tangible impact, ***three policy priorities*** stand out:

- **Clear, science-based regulation for food and feed.** Ensure proportionate, predictable approval pathways for fermentation-derived ingredients, and provide support to applicants throughout the process.
- **Targeted finance for scale-up and innovation.** Use public and blended finance to de-risk investment in fermentation infrastructure and open-access research and innovation, and to support farmers and cooperatives that wish to supply feedstocks or engage in on-farm processing.
- **Integration into core agricultural and food policies.** Embed fermentation within the Common Agricultural Policy, the Competitiveness Fund and EU research programmes to ensure fermentation contributes to farm incomes, rural development and healthier, more sustainable diets.

With the right policy framework in place, fermentation can become a flagship of the European bioeconomy and a strategic tool to strengthen the resilience, competitiveness and sustainability of Europe’s protein system, in ways that benefit farmers, rural areas and consumers alike.

1. Introduction

Fermentation is one of humanity's oldest and most versatile forms of biotechnology. Archaeological and historical evidence shows that humans have used microbial fermentation for over 10,000 years to transform and preserve food. Examples include yoghurt produced from milk stored in animal-skin bags in North Africa around 10,000 BCE; and fruit, honey, and rice fermented into alcoholic beverages in Neolithic China around 7,000 BCE[1,2] (Figure 1).

Early uses of fermentation were largely for food preservation and safety: fermentation extended shelf life by inhibiting spoilage, whilst in some cases also improving digestibility. Following Louis Pasteur's discovery in the 1850s that yeast and bacteria drive fermentation (Figure 1), the process became foundational not only to food and beverage production, but also to pharmaceuticals, biofuels and detergents[1,3].

Today, fermentation is again at the forefront of innovation. While classical fermentation continues to be used to produce established foods like cheese, yoghurt, bread, wine, soy sauce and kimchi (Figure 3), modern biotechnology has expanded fermentation into two new areas: biomass fermentation and precision fermentation[4,5]. These technologies are further explained in Section 1.1 below.

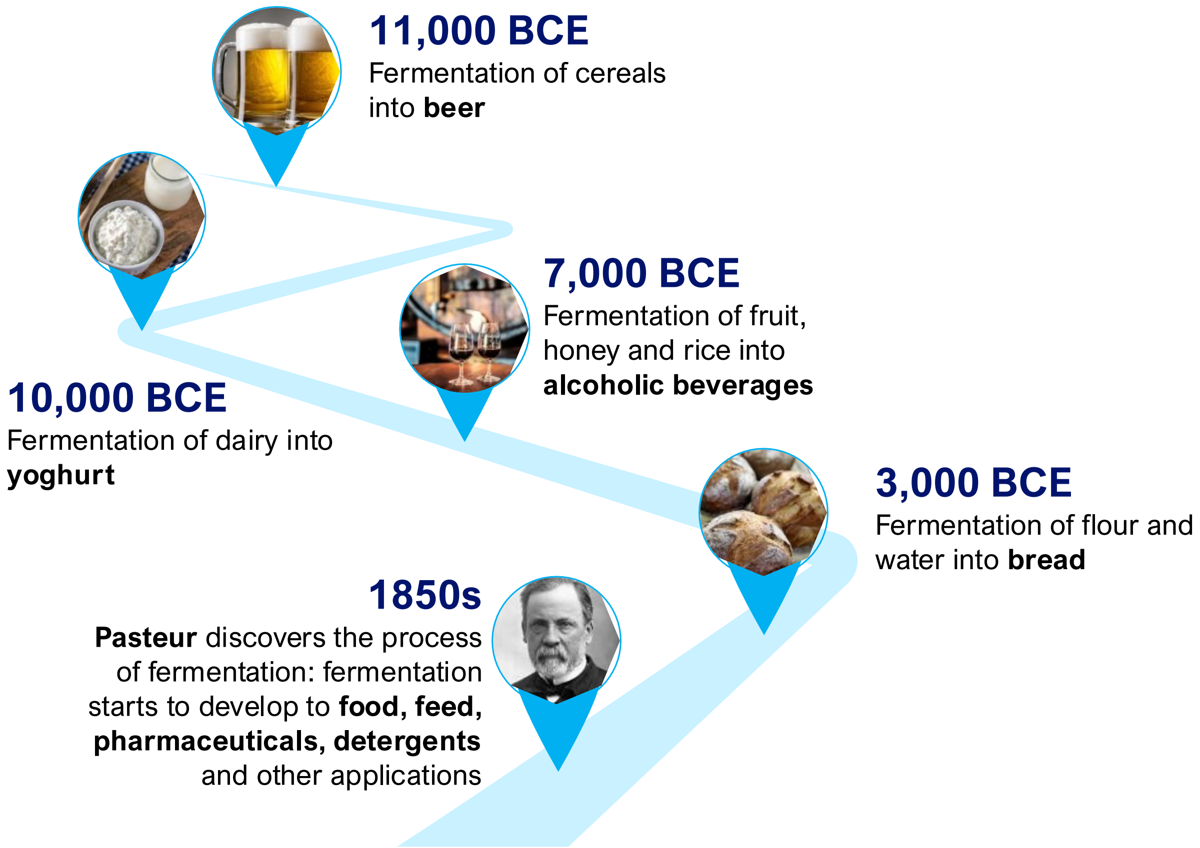


Figure 1 *Fermentation is a technology that dates back thousands of years.*

1.1 What is fermentation?

Fermentation is defined as a process in which micro-organisms such as bacteria, fungi, yeasts, and micro-algae are used to preserve and/or transform raw materials into e.g., food, feed, chemicals, pharmaceuticals, fuel, or biomass[6].

Fundamentally, all fermentation processes are based on micro-organisms cultivated in a carbon-rich solid, liquid, or gaseous medium, where their metabolic activity generates specific products.

While definitions of different fermentation "types" vary widely across literature and among industry stakeholders, this report uses a simplified categorisation based on three terms: **classical**, **biomass** and **precision** fermentation. For consistency, these three types are assumed to be defined by the primary target product of the fermentation process only, as outlined in Figure 2 below.

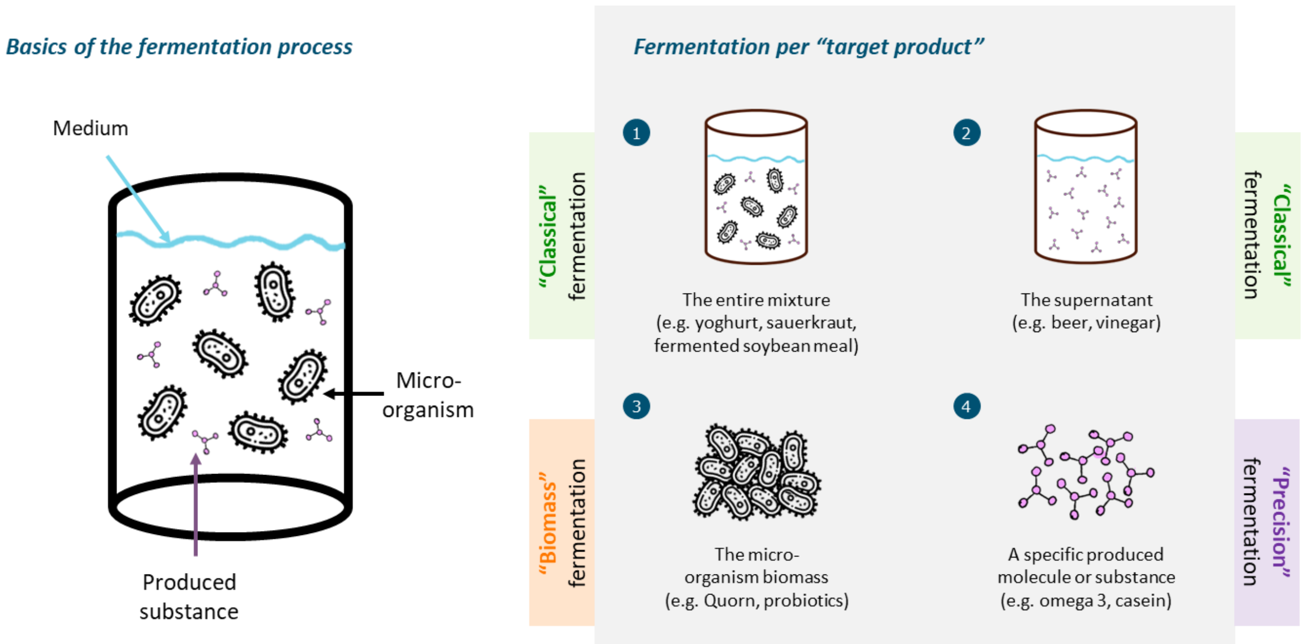


***Figure 2** Illustration of the fermentation process, for "classical," "biomass" and "precision" fermentation[7].*

1.1.1 Classical fermentation

Classical fermentation uses microorganisms such as lactic acid bacteria, yeasts, and molds to enhance taste, texture, and nutritional value of raw ingredients, while also producing bioactive components like vitamins and probiotics. It is used across all major food groups, including dairy, fruits, vegetables, cereals, herbs, legumes, meat and fish[2] (Figure 3).

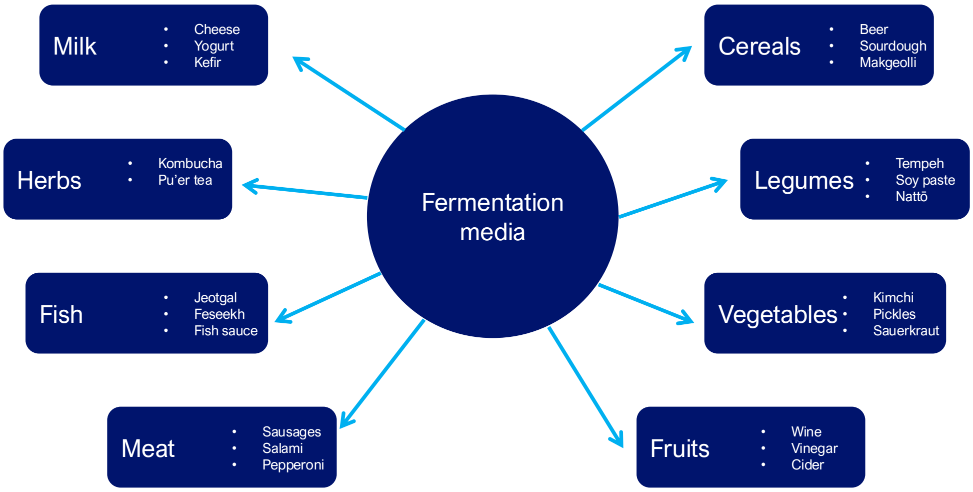


***Figure 3** Examples of traditional fermentation across different food groups.*[2]

1.1.2 Biomass fermentation

Biomass fermentation grows microorganisms as the main product for consumption. Fast-growing species such as fungi, yeast, or bacteria are cultivated in a nutrient-rich medium and the resulting microbial biomass – usually rich in protein, fibre, and other nutrients – is harvested, processed, and used either as a standalone food or as an ingredient. A well-known example is mycoprotein, developed in the 1980s by Quorn, which grows filamentous fungi biomass via fermentation, further used as a protein-rich food product or ingredient[8]. More recent but similar methods also produce microalgal and bacterial biomass for both human and animal nutrition[9].

1.1.3 Precision fermentation

Precision fermentation uses microorganisms to produce specific substances such as proteins, fatty-acids, or vitamins. Common examples include casein and whey (naturally found in milk), ovalbumin (naturally found in eggs), omega-3 fatty acids (naturally found in oil-rich seafood), and vitamin B2 (also known as riboflavin). These fermentation-derived ingredients fulfill the same functions as their animal-derived or synthetically produced equivalents[10].

Together, these three categories of fermentation form a continuum of innovation: classical fermentation at the foundation of global food culture, biomass fermentation representing a promising additional source of protein-rich nutritious food and feed, and precision fermentation supplying specialised functional ingredients. All three contribute to a more resilient, circular, and sustainable future of food.

1.2 Addressing challenges of the EU food system with fermentation

1.2.1 Rising demand meets environmental limits

Global food demand is expected to increase by around 45 percent between 2010 and 2050, driven by population growth, urbanisation, and rising incomes[11], with protein consumption expected to follow the same trend[12]. Today's protein production systems are stretching to meet that demand while respecting our planetary boundaries. Since the 1960s, the share of animal-based proteins in the European protein mix has significantly increased and animal-based proteins now constitute the majority of the protein intake[13], driving greenhouse-gas emissions, deforestation and excessive water use[14,15]. Marine ecosystems are also under pressure: in addition to seafood and fish catch for direct human consumption, 18 million tonnes of wild fish are reduced into fishmeal and fish oil annually for aquaculture and poultry feed[16].

With protein demand on the rise, food and feed technologies, such as fermentation, are frequently cited as promising tools to help reduce the pressure on the environment by providing opportunities for circular agricultural flows and the efficient production of nutrients for food and feed. This in turn could also strengthen the resilience of the food system, as around two thirds of high-protein feed used in the EU is imported and exposed to the volatility of the global market[17,18].

Section 2 of this report aims to test the environmental hypothesis above and models the resource efficiency and environmental potential of modern biomass and precision technologies, particularly focusing on impacts on greenhouse gas emissions, land – and freshwater use.

1.2.2 A broader strategic opportunity across the EU food system

Fermentation builds directly on the European Union's industrial and agricultural strengths. The EU is the world leader in biotechnology and agri-food, from brewing and dairy processes to enzyme and bioethanol production. These sectors secure the technical expertise, feedstock availability, and infrastructure to scale fermentation rapidly. The EU Bioeconomy Strategy highlights fermentation as an enabler for expanding bio-based value chains, strengthening biomanufacturing capacity and converting biomass into higher-value products[19], while contributing to the objectives of the EU's Green Deal.

At the same time, fermentation could help to diversify protein production by providing consumers with access to a wider range of conscious foods, while being complementary to existing agricultural value chains. Understanding and steering farmer and consumer dynamics is essential to ensure fermentation technologies contribute to a just food system: Sections 3 and 4 compile a qualitative overview of case studies assessing the interplay between fermentation-derived food and feed, and these two important stakeholder groups.

2. Environmental analysis

This section assesses the effect of a growing fermentation sector on three environmental parameters: (1) greenhouse gas (GHG) emissions, (2) land use and (3) freshwater use. Impacts are modelled across different fermentation technologies and for both food and feed applications, presented in Sections 2.1 and 2.2 respectively.

2.1 Environmental impact of food proteins

This section focuses on the environmental impacts of a growing adoption of *biomass and precision fermentation in food applications*. These are the most rapidly emerging fermentation technologies for food, and the growing availability of product-level environmental data enables a shift from isolated case studies to an integrated projection of their potential impacts.

Systemiq developed three growth scenarios for these technologies – low, medium, and high adoption[a], drawing on data from an analysis of FAOSTAT consumption data for key food groups[20]. The medium-adoption scenario, in which EU production of fermentation-based proteins increases from 40 tonnes in 2025 to 3.6 million tonnes in 2040, serves as the basis for the environmental modelling presented in this report, corresponding to a combined 3% substitution of EU consumption of animal protein equivalent by volume.

To quantify impacts on GHG emissions, land use and freshwater use, the analysis compiles and synthesizes LCA studies and academic publications across relevant product categories and applications. Inputs have been adjusted where necessary to ensure methodological consistency. The environmental impact estimates presented below exclude potential additional gains associated with demand growth for plant-based products via hybrid applications in which fermentation-derived ingredients improve convenience, texture or taste. (e.g. casein in plant-based cheeses, see Section 3.2.3).

2.1.1 GHG emissions

Fermentation-derived protein products are in most cases associated with a low carbon footprint, with average per-unit emissions approximately 59% lower than animal-based equivalents[15,21-26]. When applying per-unit emissions reduction per protein category on a medium adoption scenario, the increased share of biomass and precision fermented proteins results in an estimated **20 million tonnes of CO_2e emissions** avoided annually by 2040 (Figure 4). Of this total, at least 8 million tonnes of CO_2e (40%) is expected to be saved within EU borders, with the remainder depending on import and export dynamics. This result excludes additional emission savings due to nature restoration and rewilding (see Section 2.1.2).

[a] These scenarios are referred to as “business as usual,” “moderate policy support” and “high ambition” in the forthcoming publication “Seizing the economic opportunity of alternative proteins in Europe", written by Systemiq with the support of the Good Food Institute Europe[74]. The “moderate policy support” pathway is described as follows: “consumer appetite grows steadily as products improve in taste and reduce in price. Regulatory processes become more predictable and inefficiencies are reduced, while targeted public R&D investment maintains the EU’s position as a global innovation hub. Pilot infrastructure expands in leading countries, attracting more private capital.”

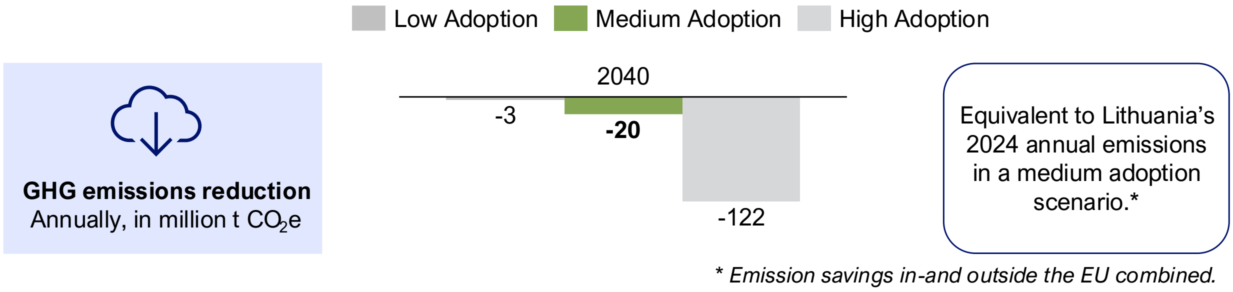


***Figure 4** 2040 Annual emissions reduction potential of fermented alternative proteins, Million tonnes CO_2e emissions, under a low, medium, and high adoption scenario of fermented proteins.*

2.1.2 Land use

Most fermentation-based proteins are associated with lower land use compared to animal-based equivalents, on average needing 93% less land per kg of product[15,21-26]. In a 'medium adoption' scenario for biomass and precision-fermented proteins, an estimated **11 million hectares of land** would be saved by 2040 (Figure 5). Of this total, at least 4 million hectares (35%) of land is expected to be saved within EU borders, with the remainder depending on import and export dynamics. Restoring or rewilding this land could unlock substantial additional carbon savings. Accounting for land use restoration potential across regions, up to 9 million additional tonnes of CO_2e could be saved per year by 2040, of which at least 4 million tonnes within the EU. Beyond carbon sequestration, rewilding would also deliver wider ecosystem and societal benefits, including enhanced biodiversity, improved soil and water quality, and greater resilience to climate and environmental shocks.

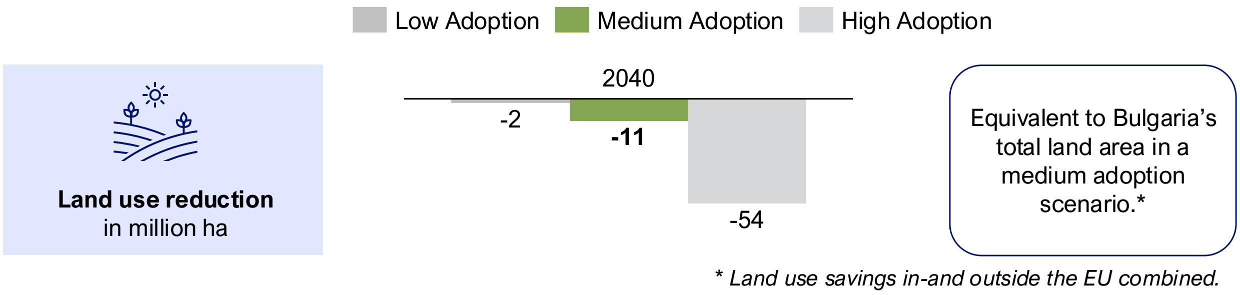


***Figure 5** 2040 Annual land-use reduction potential of fermented alternative proteins, Million Ha land use, under a low, medium, and high adoption scenario of fermented proteins.*

2.1.3 Water use

Fermentation-based proteins are associated with improved water efficiency, requiring around 74% less water per kilogram of product than animal-based equivalents[15,21-26]. Applied to the medium adoption scenario in the EU, this translates into an estimated **1,5 billion m³ of water saved annually** by 2040 (Figure 6). Of this total, at least 490 million m³ (33%) of water is expected to be saved within EU borders, with the remainder depending on import and export dynamics.

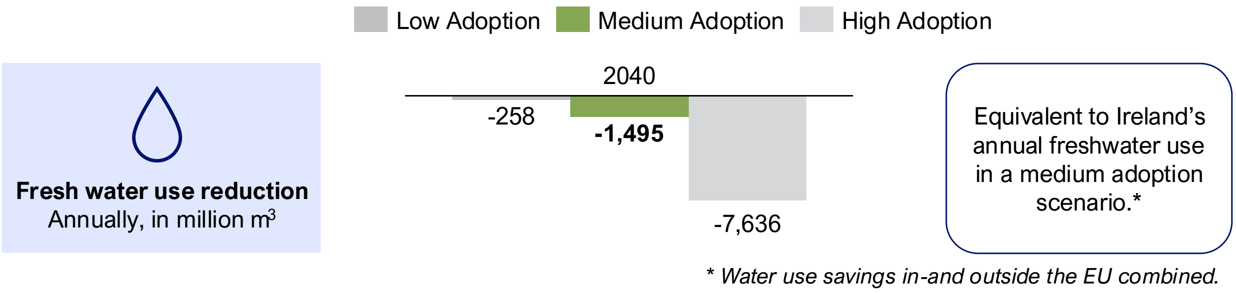


***Figure 6** 2040 Annual water use reduction potential of fermented alternative proteins, Million m³ of water, under a low, medium, and high adoption scenario of fermented proteins.*

2.2 Environmental impact of animal feed proteins

Beyond food applications, the analysis also considers whether applying fermentation technologies to feed could unlock comparable benefits. Three potential pathways were investigated:

A. Replacing grass hay (conventional) with silage (fermented)
B. Replacing bulk protein from soy and fish meal (conventional) with microbial biomass (fermented)
C. Replacing conventional with precision fermented whey protein

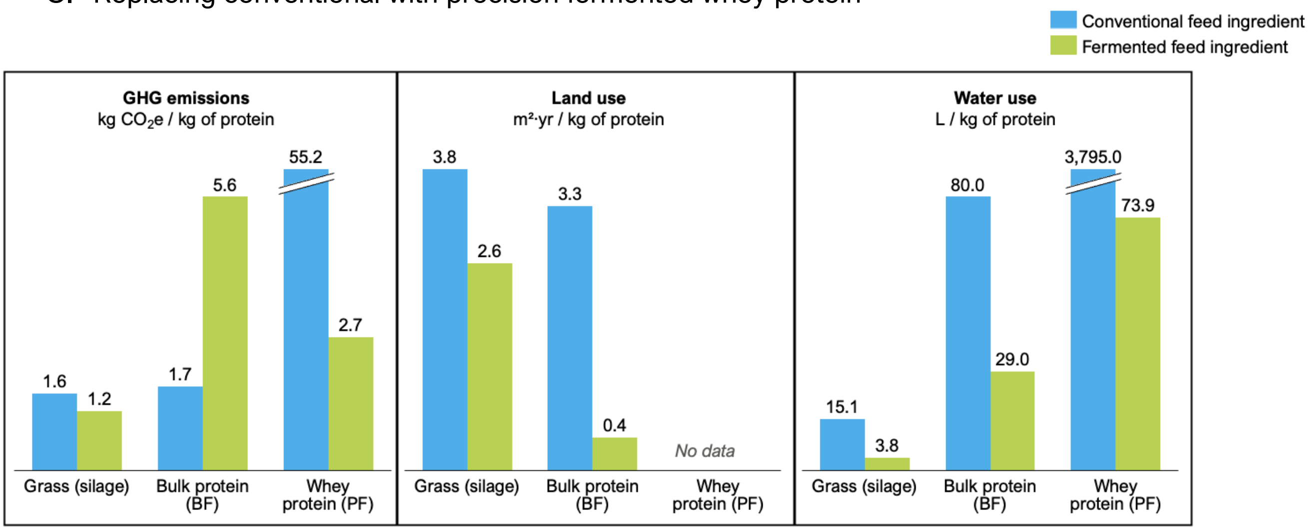


***Figure 7** Comparison of per unit impacts of conventional and fermented feed ingredients. "Grass (silage)" compares grass hay (conventional) with silage (fermented); "Bulk protein (BF)" compares the average impacts of soy protein and fish meal (conventional) with average impacts of Hydrogen Oxidizing Bacteria Microbial Protein and Methanotrophic Single Cell Protein (fermented);" Whey protein (PF)" compares impacts of conventional and precision fermented whey protein. "BF" and "PF" refer to biomass fermentation and precision fermentation, respectively.*

A. Silage fermentation is a long-established method for conserving fresh forage. It stabilises the feed product and ensures it can be safely fed to cattle, sheep, and other ruminants throughout the year. In addition, fermentation increases the protein concentration compared to fresh forage, making it a more protein-efficient feed product per kilogram[27]. A drawback of using silage as feed is that it can boost methane formation of ruminants, inflating total emissions. This effect is however not shown in Figure 7, which only covers production-stage emissions. With regards to land and water use, silage has a lower environmental footprint than grass hay (30% and 75% reduction respectively).

B. Biomass fermented microbial protein is today mainly used to replace soy- and fish-protein in aquaculture, but is also suitable for pigs, ruminants, poultry and pets[28]. While biomass fermented feed could result in land and water use savings, their average per unit emissions are higher than their conventional soy or fish equivalents (Figure 7). The emission-intensity of this technology could further decrease with decarbonisation of the grid, the use of more circular feedstocks, and increased performance of the fermentation process as it matures. [21,22]

C. Whey protein is commonly used in the nutrition of various animals: piglet feed, milk substitute for calves, goat kids and lambs, and in pet food[29,30]. Precision-fermented whey protein showed the strongest potential environmental impact reduction amongst the three types of fermented feed analysed in this report, having much lower emissions than animal whey protein[23]. The impact on land use was not evaluated due to a lack of data (Figure 7). It is important to note that the impacts described above were evaluated in the context of the related examples and should not be transposed transposable to precision-fermented products in general.

2.3 General considerations on environmental impact of fermented proteins

Overall, the analysis indicates that in both food and feed applications, fermentation technologies show positive environmental potential on key indicators of GHG emissions, land use and freshwater use, compared with their plant- or animal-based counterparts. Although the assessment for feed was limited to per-kilogram environmental footprints, fermentation still showed potential to help reduce the environmental footprint of our food system. In addition, expanding fermentation in both food and feed applications simultaneously is likely to be both desirable and complementary: feed markets can provide early routes to market with less stringent requirements, enabling innovators to scale and refine their technologies for food grade while already delivering modest environmental gains and supplying nutritious inputs to livestock and aquaculture farmers.

3. Socio-economic considerations

Beyond the environmental potential of fermentation technologies for food and feed, their wider socio-economic implications also need to be considered. Food technologies such as fermentation should contribute to a more just food system across the supply chain, from farmers to consumers. This section therefore provides a qualitative overview of case studies examining how fermentation-derived food and feed products could positively interact with these two stakeholder groups.

3.1 Fermentation as part of the agricultural value chain

Agriculture and technologies such as fermentation are often portrayed as competitors for the same protein markets. This section adds nuance to that debate by examining how fermentation technologies and arable or animal agriculture already intersect in complementary ways. Figure 8 lays out the interconnectedness between agricultural and fermentation value chains and highlight seven main opportunity areas for farmers. Three of these opportunities will be futher explored through deep dives and selected case studies in Sections 3.1.1 to 3.1.3:

- Arable farmers supplying fermentation feedstock by cultivating raw materials or revalorising agricultural co-products
- Fermentation supplying high quality ingredients to protein-rich feed for livestock farmers
- Farmers undertaking on-farm fermentation to further valorise their agricultural outputs.

These cases show how fermentation can create new demand for crops, support efficient, low-impact protein production across food systems, and strengthen farmer business cases.

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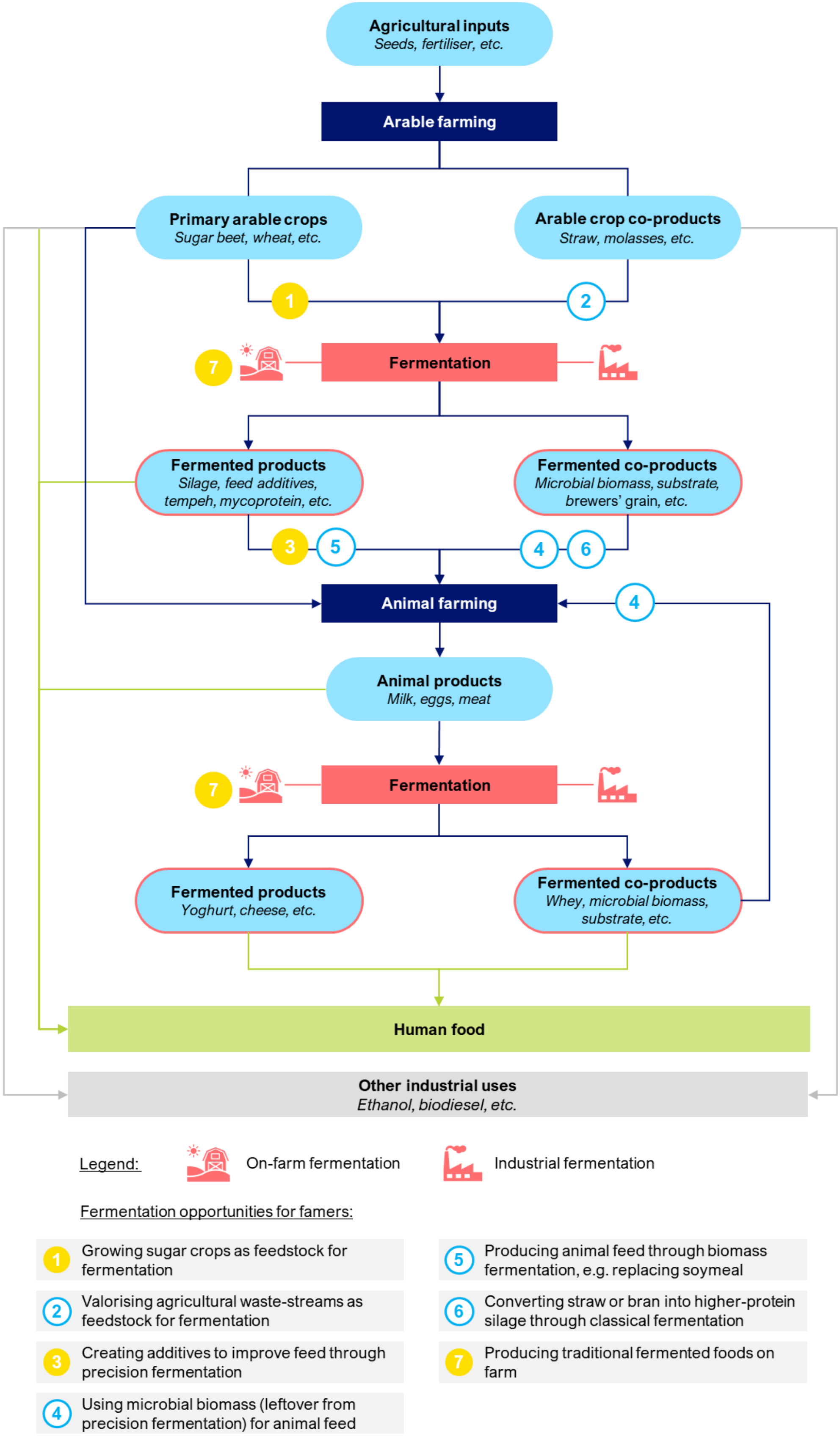

Figure 8 *Representation of how fermentation technologies and arable or animal agriculture intersect today, highlighting the areas of opportunity created by fermentation for farmers. Opportunities 1, 3 and 7 are the subject of further deep dives in this report.*

Deep dive 1: Growing sugar crops as feedstock for fermentation

Fermentation relies on carbon-rich inputs, typically supplied by sugar- and starch-rich crops such as sugar beet, wheat, corn, and potatoes. As biomass fermentation scales, it can create a new, stable outlet for these crops, helping European farmers diversify beyond markets that are projected to contract, including livestock feed, sugar and biofuels[31]. As fermentation facilities can use beet pulp and other by-products throughout the year rather than only at harvest (as is largely the case for sugar production), they can also smooth income seasonality.

At the same time, modern fermentation processes are increasingly compatible with second-generation feedstocks - non-edible residues and co-products such as lignocellulosic materials, beet pulp, and molasses. This gives arable farmers an additional route to monetise materials that currently have lower or fluctuating value, while reducing waste and improving the environmental profile of fermentation inputs. Although pre-processing costs remain a barrier, the broader implication is that fermentation can expand the set of viable crops and co-products that generate income, strengthening farm business models as food and energy markets evolve[32,33].

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1

Case Study | Fermentation as a Diversification Pathway for the Sugar Beet Sector

Context

The EU sugar beet sector continues to face pressure from low sugar prices, import competition, and factory closures, as explained by an expert at the European Association of Sugar Manufacturers (CEFS): "20 factories have been closed since 2017, including five in the past year." This leads to interest in new markets that could stabilise revenues. Today, sugar beet producers and processors already valorise side streams such as molasses and thick juice, primarily directed towards animal feed and ethanol sectors.

Opportunities

Food and feed fermentation could offer a growing outlet for sugar beet and its side streams, especially as demand for alternative proteins – such as those derived from fermentation – is expected to rise over the next decade while demand for animal feed and biofuels declines[31]. Biomass and precision fermentation in particular use sugar as their primary carbon source and could provide a stable year-round outlet for beet juice, syrups and side streams in contrast to the sugar industry, which must process fresh beet, usually immediately after harvest. An example of such a biomass fermentation company is planetary, which uses sugar industry leftovers to produce mycoprotein. As markets expand, fermentation could generate additional revenue streams for the sector and support diversification from traditional end uses such as ethanol and animal feed towards higher-value food products and fermented feed ingredients.

Challenges

An expert from Cosun Protein explained that scaling fermentation production requires significant upfront capital: "A 10,000-tonne biomass fermentation facility uses around 30,000 tonnes of sugar and would need approximately €50 million in upfront investment. There are few players in the EU who can finance a project of that scale." In addition, food-producing fermentation start-ups face challenges with European food safety approvals, and sugar and fermentation value chains are not yet sufficiently aligned.

Policy support

For fermentation to become a viable diversification pathway for sugar beet producers and processors, targeted policy support will be critical. Priorities include mobilising early-stage public–private investment instruments to de-risk the scale-up of biomass and precision fermentation facilities, and developing shared fermentation infrastructure in the EU, particularly near sugar production and processing hubs. Additional support is needed to help applicants navigate European Food Safety Authority approval processes and to pilot initiatives that more closely integrate sugar and fermentation value chains.

Photo: Wikimedia Commons

Deep dive 2: Creating additives to improve feed through precision fermentation

Precision fermentation is emerging as a promising technology for producing specialised feed additives that enhance the nutritional quality, efficiency, and sustainability of livestock and aquaculture feed. Feed additives produced by precision fermentation include probiotics, enzymes (such as phytase, which helps the digestive system break down grain), anti-mycotoxins (to counteract the toxins produced by molds on feed), vitamins and other nutrients (such as amino acid lysine).

These feed additives are essential to animal husbandry, helping keep animals healthy and growing efficiently. Precision fermentation can help farmers to source these critical additives from more sustainable sources, hence reducing the externalities linked to their operations as well as their dependance on diminishing natural resources. Indeed, animal-based feed additives in particular can be costly to the environment[34]. Omega-3 fatty acids, for example, are used as feed additives to promote health and productivity in poultry, pigs and farmed fish[35-37]. Omega-3 is traditionally extracted from wild caught fish, contributing to the overfishing of oceans. By replacing these essential animal-based additives, precision fermentation can reduce pressure on marine and other animal-based ecosystems, while supporting farmers in reducing their environmental footprint[38] and reducing their dependency on finite resources. This is underscored by global fish-oil production remaining largely flat for decades despite growing demand from aquaculture and poultry[39,36].

Although the sector is in the early adoption phase, several precision-fermented feed ingredients are already approved for use by EFSA and used on a commercial scale in aquaculture, poultry, and pig feed (e.g., Algal DHA oil by Corbion, DSM-Firmenich Precision Feed Additives). Omega-3 produced by microalgae fermentation supplies roughly 10 percent of global omega-3 demand (for both direct human consumption and for animal feed), with significant room for growth as aquaculture and poultry sectors continue to expand while fish oil production is capped[36]. Fermentation-based additives have the potential to become significantly cheaper as scale increases and bioprocessing improves[40].

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3

Case Study | A Leading European Producer of Precision Feed Additives

Context

Precision fermentation is already used at global commercial scale to produce key feed additives for pig, poultry, ruminant and aquaculture systems. Some production processes use genetically modified microorganisms (e.g. phytase), while others rely on non-GMO strains (e.g. algal omega-3). In all cases, the microorganisms themselves are fully removed from the final product, meaning "no GMO material enters the food chain," explains an expert from a leading European feed producer.

Opportunities

The primary purpose of these additives is to provide the best nutrients for animals to stay healthy and reach their growth potential, which means supporting conventional livestock farmers whose productivity and margins depend on highly optimised animal diets. Precision fermentation makes it possible to produce additives with tailored and consistent nutrient profiles, enhancing digestibility, improving feed conversion ratios (the amount of feed required per unit of animal weight) and supporting overall animal resilience. Better feed conversion ratios help lower the environmental footprint of animal protein production, while replacing marine-derived ingredients with fermentation-based omega-3 reduces pressure on wild fish stocks.

Challenges

Despite its advantages, precision fermentation remains costly and technically demanding. Processes can be energy-intensive and require specialised infrastructure, further increasing capital needs. "Genetic optimisation is sometimes necessary to achieve viable production economics" explains the animal feed expert - but this can create regulatory complexity and increase development costs.

Policy support

To strengthen the role of precision fermentation in the feed sector, policy can help by ensuring clear and predictable regulatory pathways for fermentation-derived feed ingredients, including processes involving genetically modified micro-organisms, and by supporting scale-up and infrastructure investments. In parallel, funding open-access research and incentivising the sector to advance reactor performance, energy efficiency and compatibility with secondary feedstocks could further enhance the environmental savings enabled by these additives. To ensure benefits reach livestock farmers, policy can pilot measures that improve the affordability of these additives and reduce the risks of switching to new feed formulations.

Photo: Wikimedia Commons

Deep dive 3: Producing traditional fermented foods on farm

Lastly, fermentation – mostly in its "classical" form - can also create opportunities at farm level. Just as on-farm fermentation has long been used in the EU to convert primary animal products such as milk into higher-value products such as cheese and yoghurt, it can similarly transform surplus crops into value-added products such as sauerkraut, kimchi, tempeh, or miso. This can improve farm resilience and cash flow, enabling off-season sales through extended shelf-life, reducing food waste, and supporting diversification to healthy and plant-based products.

While fermentation can be initiated at low cost, commercially compliant operations typically require dedicated facilities, robust food safety protocols, and market development capacity. Evidence from Estonia, Serbia and the U.S. shows that on-farm fermentation can generate significantly higher margins than raw crop sales (i.e. 20-100% increases), particularly when paired with direct-to-consumer channels[41,42]. However, scaling remains constrained by regulatory and knowledge barriers, access to or investment in certified processing infrastructure and the high transaction costs associated with small batch volumes. At European level, CAP Rural Development Funds and value-added producer grants help address this barrier by supporting small-scale fermentation initiatives[43].

[continues on next page]

7

Case Study | Tempeh from Njordstorp Farm, Sweden

Context
Njordstorp Permakultur Gård is a self-sufficient organic farm that has applied permaculture principles since 2011. The farm produces a range of fermented foods, including an artisanal tempeh made from its own fava beans. Njordstorp also sells tempeh starter cultures and starter kits to encourage people to make tempeh at home.

Opportunities
Njordstorp promotes its tempeh as a "natural alternative to meat," based on Swedish-grown fava beans. They also emphasise that fermentation enriches tempeh with vitamin B12 and eases digestibility. By using locally grown legumes, Njordstorp's tempeh provides a way to add value to their farm-grown fava beans and to meet consumer demand for regional, plant-based protein products. The combination of on-farm legume cultivation, artisanal processing, and direct sales (online shop and farm shop) suggests an opportunity for higher value capture compared to the commodity market.

Challenges
Because Njordstorp's tempeh is not pasteurised, there is a risk that the culture becomes "activated" during transport, leading to the farm limiting shipments of their tempeh. Small batch sizes and handcrafted processing likely limit economies of scale and keep production labour-intensive, which can constrain margins and make it harder to compete with large, imported tempeh producers. Because Njordstorp uses Swedish-grown fava beans rather than global commodity soy, production is also tied to local harvest conditions and the availability of suitable legume varieties.

Policy support
Njordstorp's model illustrates how on-farm fermentation can create higher-value plant-based products, but also how scaling is constrained by infrastructure, logistics, and regulatory requirements for safe handling of fresh fermented foods. Farms such as Njordstorp could be supported by policy instruments touching upon rural development and investment support for small-scale, food-grade fermentation facilities, either for one farm or as shared infrastructure in the region (aligned with EU CAP rural development tools), programmes that help farmers build know-how on production methods and legal frameworks, as well research programmes focusing on developing climate-suited legume varieties (e.g. fava beans) for different European climatic conditions.

Photo: Wikimedia Commons

3.2 Fermentation as nutritious / convenient food for consumers

Beyond their environmental and agricultural implications, fermentation technologies also shape how consumers engage with food. Different forms of fermentation speak to different consumer priorities: classical- and some biomass-fermented foods are associated with digestive health, nutrient quality and minimal processing[44,45], while biomass and precision fermentation can appeal to consumers seeking more environmentally conscious and convenient protein options. Rather than positioning fermentation-derived foods as a binary alternative to existing proteins, they can be seen as an additional choice for consumers wishing to diversify their protein intake and experiment with new types of food. In parallel, fermentation-derived ingredients are increasingly used in hybrid applications, enhancing both plant- and animal-based foods - for example, microbial rennet in conventional cheese production or precision-fermented components used to enhance the flavour or colour of plant-based burgers. The following section examines four illustrative fermented food products or ingredients, outlining how consumers might interact with them and through which pathways they could influence individual and public health.

To structure the discussion, health-related considerations for each product are assessed along the following dimensions:

- **Protein quality** – completeness and balance of the amino acid profile, and how easily the protein is digested and absorbed by the human digestive system.
- **Other macronutrients** – the quantity and quality of fats, carbohydrates, and fibre, and how these compare with typical dietary needs.
- **Micronutrient composition** – the presence, absence or fortification of key vitamins and minerals, and how these compare with typical dietary needs.
- **Microbiome and digestive health** – the extent to which fibres and other indigestible components act as substrates for beneficial gut microbes, and how microbial metabolites produced during fermentation (or by live cultures in the food) may directly influence gut and metabolic health.
- **Food safety** – key safety aspects such as microbial and chemical safety, allergens, and labelling, as managed within existing regulatory frameworks.
- **Public health (One Health)** – potential impacts at population level. This includes how changes in diets may affect rates of diet-related chronic disease, how different production systems may influence antimicrobial use and antimicrobial resistance (AMR), and how they may alter the risk of zoonotic diseases. It also covers environmental determinants of health, such as greenhouse-gas emissions, water quality, and biodiversity loss. These aspects are considered within a One Health perspective linking human, animal, and environmental health.

3.2.1 Tempeh: a classic Indonesian food produced by classical fermentation

Tempeh
Classical fermentation

Consumer use[46-49]

Description

Tempeh is a protein-rich food made from legumes such as soy, fermented with micro-organisms. In traditional Indonesian cuisine, it is made from fermented whole soybeans that form a firm, sliceable "cake," but is now also produced from other legumes such as chickpeas, fava beans, lentils, black beans, peas and barley. This broadens its appeal and allows the use of locally grown crops across regions. Thanks to its high protein and fibre content and its hearty, nutty flavour, consumers use tempeh not only as a meat alternative but as a versatile everyday ingredient in stir-fries, grain bowls, salads, sandwiches, stews and curries. In many European markets it is also sold pre-marinated or ready-to-cook, making it convenient for quick meals. The fermentation process improves the nutritional profile by reducing antinutrients and introducing additional vitamins, and by slightly increasing protein digestibility. In combination with the plant fibres and bioactive metabolites produced by the microbial cultures, this supports gut and microbiome health, which is an important motivation for many consumers.

Image: Wikimedia Commons

Health considerations[50,51]

Protein quality

- Complete amino acid profile, including proteins from soy or other selected crop, as well as microbial proteins.
- Exact protein content dependent on the chosen raw ingredient.
- Slightly increased protein digestibility compared to non-fermented plant-based foods.

Other macronutrients

- Low in sugar.
- Low in saturated fats.
- Rich in dietary fibre from micro-organisms and soy.
- Low in sodium; requires less salt than non-fermented plant foods for similar taste due to umami flavour.

Micronutrient composition

- Source of iron, zinc and manganese.
- In newer production methods, potentially rich in B12 after "in-situ fortification" (the inclusion of B12-producing food-grade bacteria in the fermentation process).
- Reduced amount of antinutrients (e.g. phytates, from soaking and fermentation-enhanced mineral bioavailability).

Microbiome and digestive health

- Positive effect on digestive health from plant fibres in substrate which fuel gut microbiota.
- Direct prebiotic effect from metabolites present in tempeh, produced by micro-organisms in the fermentation process.

Food safety

- Extended shelf life of legume used as base crop.
- Potential adverse health effect of histamine for consumers with histamine intolerance.
- Not suited for people with allergies to soy or other base crops used in the process.
- Subject to conventional EU food safety protocols (HACCP) to secure safe production and consumption.

Public health (One Health)

- Diversification of consumption patterns from animal- to more plant- and fermented foods reduces antibiotics dependency, antimicrobial resistance and zoonoses, while lowering pressure on the planet.
- This diversification of consumption patterns is typically linked to a lower disease burden and better population health.

3.2.2 Mycoprotein: a protein source produced by biomass fermentation

Mycoprotein
Biomass fermentation

Consumer use[52-54]

Description

Mycoprotein is a protein-rich food based on fermented fungal biomass, used to enrich a meal's nutritional quality by partially or fully replacing a meat product on the plate. It is a well-established whole-food produced through biomass fermentation of filamentous fungi, yielding biomass that is rich in both fibre – with functional fibres such as beta-glucans and chitin – and protein, completing the amino acid profile. In practice, consumers mainly encounter mycoprotein through branded products such as Quorn™, sold across Europe in formats including mince, burgers and sausages. They can be used much like meat in familiar dishes such as Bolognese, curries, stir-fries and sandwiches. These products are typically sold chilled or frozen, often pre-seasoned or ready-to-cook, which makes them convenient for quick meals. Newer forms of mycoprotein (for example neutral-tasting powders) are being developed for use in a wider range of foods but are not yet widely available. Mycoprotein's nutritional profile – high in protein and fibre and low in saturated fat with no cholesterol – is at the heart of growing evidence linking its consumption to improved satiety, blood lipid profiles and cardiometabolic effects, making it a fitting choice for health-conscious consumers.

Image: Wikimedia Commons

Health considerations[52-58]

Protein quality

- Complete amino acid profile, proteins from fungal biomass.
- Higher protein digestibility than non-fermented plant foods.

Other macronutrients

- Low in sugar.
- Low in saturated fats (and cholesterol).
- Rich in fibre (chitin, β-glucans) from fungi.
- Low in sodium.

Micronutrient composition

- Source of selenium, manganese, calcium and zinc.
- In newer production methods, potentially rich in B12 after "in-situ fortification" (the inclusion of B12-producing food-grade bacteria in fermentation process).

Microbiome and digestive health

- Mild positive effect on digestive health from fungal fibres in mycoprotein which fuel gut microbiota.
- Mild direct prebiotic effect from metabolites present in mycoprotein, produced by micro-organisms in the fermentation process.

Food safety

- Potential adverse health effect of histamine for consumers with histamine intolerance.
- Need for heat treatment to bring RNA content below acceptance threshold
- Subject to conventional EU food safety protocols (HACCP) to secure safe production and consumption.

Public health (One Health)

- Diversification of consumption patterns from animal- to more plant- and fermented foods reduces antibiotics dependency, antimicrobial resistance and zoonoses, while lowering pressure on the planet.
- This diversification of consumption patterns is typically linked to a lower disease burden and better population health.

3.2.3 Casein and omega-3: animal-like nutrients produced by precision fermentation

Casein
Precision fermentation

Consumer use[59-64]

Description

Casein is one of the two main protein groups found in milk, alongside whey. Together, these milk proteins are used across a broad range of foods such as dairy products, baked goods, infant formula, supplements and plant-based “dairy-style” products. It is a nutritious protein, known for its contribution to the structure, texture and body of cheese. Precision fermentation makes it possible to produce casein (and other milk proteins) without farmed animals, by programming micro-organisms to secrete molecules that are bioidentical to their bovine or human counterparts. This unlocks opportunities to reach critical texture and taste enhancements in plant-based or hybrid cheeses, spreads and other “dairy-style” foods. This speaks to environmentally and animal-welfare-conscious consumers interested in “animal-free” products with familiar taste and texture while associated with lower animal and environmental impacts. At the same time, casein’s applications are of interest to lactose-intolerant consumers who would benefit from formulations that contain milk proteins but not lactose; and caregivers who may be attracted to casein-enriched infant formulae that more closely resemble human milk.

Image: Public Domain

Health considerations[59,60,63-65]

Protein quality

- High quality and highly-digestible protein, used as an ingredient in foods such as cheese.
- Same characteristics as its animal-based equivalent.

Other macronutrients

- *Not applicable as casein is isolated from the fermentation medium and the micro-organisms. As a single protein, casein itself does not contain fibre or other macronutrients.*

Micronutrient composition

- *Not applicable as casein is isolated from the fermentation medium and the micro-organisms. As a single protein, casein itself does not contain micronutrients.*

Microbiome and digestive health

- *Not applicable as casein is isolated from the fermentation medium and the micro-organisms. As a single protein, casein itself does not contain components associated with digestive health.*

Food safety

- Limited or no adverse health effect of histamine for consumers with histamine intolerance, as casein is isolated from the fermentation medium and the micro-organisms.
- Enabler of milk and dairy alternatives for adults and infants with cow- or animal-milk allergies.
- Subject to conventional EU food safety protocols (HACCP) to secure safe production and consumption.

Public health (One Health)

- Increased adoption of hybrid plant-based and fermented dairy – thanks to similar functionality as conventional products – reduces antibiotics dependency, antimicrobial resistance and zoonoses, while lowering pressure on the planet.
- Depending on the products, increased consumption of hybrid plant-based and fermented dairy might be linked to a lower disease burden and better population health.

Omega-3

Precision fermentation

Consumer use[68-70]

Description

Omega-3 is a fatty acid, and an essential micronutrient that is present in marine foods, algae and certain plant sources. It is commonly used to fortify protein-rich foods such as margarines, milks and yoghurts, and is naturally present in foods like oily fish, flaxseed and rapeseed oil. It can also be consumed as food supplements, available in formats such as capsules or liquid oils. Omega-3 cannot be synthesised in sufficient quantity by the human body and therefore needs to be integrated in diets in one of these ways. Precision-fermented omega-3 – usually produced from microalgae – targets several consumer segments: people who avoid fish for ethical, religious or taste reasons; environmentally- and animal-welfare-conscious consumers seeking alternatives to fish-derived oils; and those concerned about contaminants in marine products, such as heavy metals or persistent organic pollutants. Fermentation-derived omega-3 is increasingly used in supplements and fortified foods, where it can be incorporated without a strong "fishy" taste, allowing consumers to increase intake in a convenient and potentially more sustainable way.

Image: Wikimedia Commons

Health considerations[68,69,71]

Protein quality

- *Not applicable as omega-3 is not a protein but a family of fatty acids. It can be an important component of specific types of protein-rich food or feed.*

Other macronutrients

- *Not applicable as omega-3 is isolated from the fermentation medium and the micro-organisms. Omega-3 itself does not contain fibre or other macronutrients.*

Micronutrient composition

- Important micronutrient (fatty acid), present in marine foods, algae and certain plant sources.
- Same characteristics as its animal-based equivalent.

Microbiome and digestive health

- *Not applicable as omega-3 is isolated from the fermentation medium and the micro-organisms. Omega 3 itself does not contain components associated with digestive health.*

Food safety

- Limited or no adverse health effect of histamine for consumers with histamine intolerance, as omega-3 is isolated from the fermentation medium and the micro-organisms.
- Enabler of omega-3 intake without risks of marine pollutants found in certain seafoods.
- Subject to conventional EU food safety protocols (HACCP) to secure safe production and consumption.

Public health (One Health)

- Intake of precision-fermented omega-3 as supplement can prevent nutritional deficiencies for consumers, especially children.
- Empowerment of consumers shifting to plant-rich lifestyles that reduce externalities of overfishing and aquaculture such as antibiotics dependency, antimicrobial resistance and zoonoses, environmental and marine pollution.

4. Conclusion

Based on the quantitative and qualitative analysis in this report, **fermentation food and feed applications** emerges as an **essential building block of the European Union's future protein system.** Taken together, the findings suggest that scaling classical, biomass and precision fermentation could:

1. **Significantly reduce the environmental footprint of EU protein consumption in food and feed** across greenhouse gas emissions, land use, and freshwater use.

2. Provide **socio-economic opportunities** alongside their perceived challenges, by

    a. offering **farmers** new income streams, valuable feed products and rural value-creation projects through feedstock supply, use of co-products and on-farm fermentation; and

    b. providing **consumers** with additional options for healthy and convenient foods and ingredients, often associated with benefits for planetary and public health

In light of these results, fermentation merits consideration as an essential component of the EU's protein and food future. After recognizing the importance of fermentation in the latest Bioeconomy Strategy[19], EU policymakers can further operationalise its role through upcoming files such as the Biotech Act I and II, the Competitiveness Fund, the Common Agricultural Policy, and other innovation-focused instruments. By providing clear, science-based regulation, targeted public–private investment in infrastructure and innovation, and integration into core agricultural and food policies, the EU can maximise the environmental and socio-economic benefits of fermentation and position it as a flagship of the European bioeconomy and a strategic lever for a more resilient, competitive and sustainable protein future.

5. Appendix

5.1 Results breakdowns

Feed ingredient	Environmental impact per kg of protein		
	GHG (kg CO_2e/kg)	Land use (m^2·yr/kg)	Water use (L/kg)
Grass hay	1.6	3.8	15.1
Grass silage (fermented)	1.2	2.6	3.8
Difference (%)	*-23%*	*-31%*	*-74%*
Conventional bulk protein	1.7	3.3	80.0
BF bulk protein	5.6	0.4	29.0
Difference (%)	*225%*	*-88%*	*-64%*
Animal whey protein	55.2	*no data*	3,795.0
PF whey protein	2.71	*no data*	73.9

Figure A1 *Environmental impact of feed ingredients per kg of protein, fermented product compared with non-fermented equivalent and percentage difference.*

5.2 Methodology

This section describes the main building blocks of the quantitative assessment performed for this report: 1) the projected EU production of biomass- and precision fermented products; 2) the collection of environmental impact data for greenhouse gas emissions, land use and water use; 3) the calculation of total impacts of biomass and precision fermented products, combining 1 and 2.

5.2.1 Projected production of fermented products

Projected production of fermented products is derived from an estimate of their potential global market size, itself based on current animal-product consumption and assumed substitution rates. The underlying assumptions and input data used for these projections are outlined below.

Volumes of animal product consumption

Current and projected EU consumption of animal products for 2025–2040 was sourced from the FAO, which provides data in four categories: meat, seafood, dairy and eggs. The projection reflects a business-as-usual trajectory based on existing dietary patterns and population growth, without any assumed uptake of alternative proteins. This makes it a suitable baseline for modelling the adoption of fermented products described below[72].

Volumes of plant-based substitutes

Current consumption of plant-based animal-product substitutes was taken from country-level GFI analyses for 2024[73], covering roughly 70% of the EU population. EU-wide consumption was then estimated by scaling these volumes linearly to the total EU population. Projected volumes were modelled similarly to fermented products, explained below.

Uptake of fermented products – S-curve approach with three adoption scenarios

For our calculations, we used uptake estimates for fermented products from a forthcoming publication written by Systemiq, with the support of the Good Food Institute Europe[74]. There, EU consumption of fermented products is modelled as substitution of the FAO business-as-usual consumption of animal products. Substitution rates were specified separately for biomass and precision fermented proteins and for each of the animal product categories described above. To reflect uncertainty in these projections, three scenarios were modelled: low, medium and high adoption.

The future uptake of fermented products was projected using an S-curve adoption approach, based on the historic uptake of novel technologies. The S-curve is characterised by three phases:

- Initial phase: slow adoption due to high costs and limited awareness.
- Growth phase: accelerated uptake as novel food processes become more efficient and public acceptance increases.
- Saturation phase: market maturity and adoption plateau as the maximum market potential is realised.

The S-curve parameters tipping point, growth rate and maximum market potential are aligned with global and EU market and technology dynamics. The tipping point, defined as the moment a technology reaches price-performance parity, varies by technology, animal product category and scenario. For biomass-fermented products, it is estimated to occur between 2028-2030 under the medium scenario, depending on the animal product category replaced. For precision fermented products, the tipping point is between 2035-2040, reflecting their lower technological maturity. These assumptions were informed by expert input and assessments of the addressable market.

Market size estimates use category-specific future price assumptions. For biomass fermentation, prices are set to match those of the animal products they replace, as these are full-product substitutes (e.g., Quorn). For precision-fermented ingredients, we assume prices decline from current product prices, up to the tipping-point year, reaching per-kilogram price parity with comparable animal-based products (as reported by the European Commission). After the tipping point, prices are held constant at parity, with any additional cost reductions treated as producer margin rather than passed through to prices.

Production projections for domestic and export market

Projected EU production of fermented proteins is derived from the consumption estimates above, combined with assumptions on self-sufficiency and export rates. Domestic production shares are proxied using the EU's current self-sufficiency level in animal products, 86% in the medium scenario. The EU export share is likewise based on the animal-product market, currently 8% of global consumption.

Scenario variation reflects shifts in competitiveness: in the low scenario, both export share and self-sufficiency fall by 25%; in the high scenario, exports rise by 25% and self-sufficiency by 15%. Total EU production is the sum of production volumes for domestic consumption and exports.

5.2.2 Collection of environmental impact data

Environmental impact values were compiled for fermented products and the animal products they are projected to substitute. The focus was on greenhouse gas emissions, land use and water use, expressed per unit of output.

The assessment draws on publicly available corporate Life Cycle Assessments (LCAs), direct engagement with producers of fermented proteins and a peer-reviewed study. A deliberately conservative approach was applied to avoid underestimating impacts: values based on average grid mixes were used instead of 100% renewable scenarios, and crop-based feedstocks were preferred over waste-stream inputs. Impact values were cross-checked across sources, underlying assumptions were verified with study authors when unclear, and grid-mix corrections were applied where required.

Biomass-fermented products

Per unit impact values were taken from three LCAs:

- Quorn (2022): This publicly available LCA reports an average across five products, is corrected to an average grid mix and uses wheat-starch glucose as the feedstock[21].
- Solar Foods (2021): This publicly available LCA uses an average grid mix and is based on hydrogen-oxidising bacteria[22].
- Dutch producer (2025): This LCA was provided through direct communication and uses an average grid mix and glucose derived from carbohydrate-rich crops[26].

Precision-fermented products

Three sources were used for the per unit impact values:

- Perfect Day (2021): This publicly available LCA uses the average US grid mix and corn-starch feedstock[23].
- Behm et al. (2022): This peer-reviewed study uses sugar-beet feedstock and the German average grid mix[24].
- Onego Bio (2024): This LCA uses the average US grid mix and corn-starch feedstock[25].

Comparative products

Comparative impact values are based on animal product values from Poore & Nemecek[15], which provides the most comprehensive and harmonised global dataset for animal-product footprints. Impacts are expressed per kilogram of product for biomass-fermented comparisons, reflecting that these are whole-product substitutes, and per kilogram of protein for precision-fermented comparisons, as these ingredients replace specific functional proteins rather than the full product. This aligns functional units across categories and ensures methodological consistency.

Authors can be contacted for further detail on the underlying impact values.

5.2.3 Environmental impact assessment

The analysis calculates the total net environmental impact resulting from producing fermented products and from the substitution of animal-based products. This captures both the impacts of new production and the impacts avoided when conventional products are displaced. To quantify these effects, the production projections described above are multiplied by the per-unit impact data collected for greenhouse gas emissions, land use and water use.

Headline emissions, land-use and water-use savings reflect fermented products displacing animal products consumed in the EU and exported abroad, a material share of land demand for EU production is embodied in overseas inputs (e.g., pre-processed animal products and feed). To distinguish impacts occurring within EU border we attributed to the impacts into three categories: (a) EU consumption supported by EU-based inputs (b) EU consumption supported by overseas inputs, and (c) overseas consumption met via EU exports. For reporting EU-border impacts, we treat (a) as the only land saving we can confidently attribute to the EU, since (b) occurs outside the EU supply chain footprint and (c) primarily reflects displaced non-EU livestock production with limited traceability back to EU land.

6. References

1. Living History Farms. Beyond sauerkraut: a brief history of fermented foods. 2014. Available from: https://www.lhf.org/2014/03/beyond-sauerkraut-a-brief-history-of-fermented-foods

2. Mannaa M, Han G, Seo Y-S, Park I. Evolution of food fermentation processes and the use of multi-omics in deciphering the roles of the microbiota. Foods. 2021;10(11):2861. Available from: https://www.mdpi.com/2304-8158/10/11/2861

3. Markov S. Industrial fermentation. EBSCO Knowledge Advantage. 2024. Available from: https://www.ebsco.com/research-starters/science/industrial-fermentation

4. The Good Food Institute. 2024 state of the industry: fermentation for meat, seafood, eggs, dairy and ingredients. 2024. Available from: https://gfi.org/wp-content/uploads/2025/04/2024-Executive-summary-Fermentation-for-meat-seafood-eggs-dairy-and-ingredients.pdf

5. Planet A Ventures. Introducing precision fermentation: accelerating the plant-based meat revolution. 2023. Available from: https://planet-a.medium.com/introducing-precision-fermentation-accelerating-the-plant-based-meat-revolution-bad1dfd9cb04

6. EuropaBio. Joint industry definitions of fermentation and precision fermentation. 2025. Available from: https://www.europabio.org/joint-industry-definitions-of-fermentation-and-precision-fermentation

7. The Protein Project and Wageningen University

8. Whittaker JA, Johnson RI, Finnigan TJA, Avery SV, Dyer PS. The biotechnology of Quorn mycoprotein: past, present and future challenges. Grand challenges in fungal biotechnology. 2020:59-71.

9. The Good Food Institute. Fermentation metabolism and feedstocks: a technical deep-dive. 2025. Available from: https://gfi.org/science/the-science-of-fermentation/deep-dive-fermentation-metabolism-and-feedstocks

10. RethinkX. Rethinking food & agriculture 2020–2030: the second domestication of plants and animals, the disruption of the cow, and the collapse of industrial livestock farming. 2019. Available from: https://www.rethinkx.com/food-and-agriculture

11. van Dijk M, Morley T, Rau ML, Saghai Y. A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. Nature Food. 2021; 2:494-501.

12. Henchion M, Hayes M, Mullen AM, Fenelon M, Tiwari B. Future protein supply and demand: strategies and factors influencing a sustainable equilibrium. Foods. 2017;6(7):53.

13. Our World in Data. Per capita sources of protein. 2022. Available from: https://ourworldindata.org/grapher/per-capita-sources-of-protein?time=latest&country=OWID_WRL~Africa+%28FAO%29~Asia+%28FAO%29~Europe+%28F~OWID_EUR

14. Aiking H. Protein production: planet, profit, plus people? American Journal of Clinical Nutrition. 2014;100 Suppl 1:483S-9S.

15. Poore J, Nemecek T. Reducing food's environmental impacts through producers and consumers. Science. 2018;360(6392):987–992.

16. Food and Agriculture Organization of the United Nations. The state of world fisheries and aquaculture 2022. 2022. Available from: https://openknowledge.fao.org/items/11a4abd8-4e09-4bef-9c12-900fb4605a02

17. Kuepper B, Stravens M. Mapping the European Soy Supply Chain. 2022. Available from: https://wwfeu.awsassets.panda.org/downloads/mapping_the_european_soy_supply_chain_e4c.pdf

18. Bidoglio G, Schwarzmueller F, Kastner T. A global multi-indicator assessment of the environmental impact of livestock products. Global Environmental Change. 2024;87:102853.

19. European Commission. Bioeconomy strategy. 2025. Available from: https://environment.ec.europa.eu/strategy/bioeconomy-strategy_en

20. FAOSTAT. Consumption data for food type and country consolidated by food group and region. 2020. Available from: https://www.fao.org/faostat/en/#data/FBS

21. Carbon Trust. Quorn footprint comparison report. 2023. Available from: https://www.quorn.co.uk/assets/files/content/Carbon-Trust-Comparison-Report-2023.pdf

22. Järviö N, Maljanen N-L, Kobayashi Y, Ryynänen T, Tuomisto HL. An attributional life cycle assessment of microbial protein production: a case study on using hydrogen-oxidizing bacteria. Science of the Total Environment. 2021;776:145764.

23. Perfect Day. Comparative life cycle assessment of Perfect Day whey protein production to dairy protein. 2021. Available from: https://perfectday.com/wp-content/uploads/2022/01/Comparative-Perfect-Day-Whey-LCA-report-prepared-by-WSP_20AUG2021_Non-Confidential-1.pdf

24. Behm K, Nappa M, Aro N, Welman A, Ledgard S, Suomalainen M, Hill J. Comparison of carbon footprint and water scarcity footprint of milk protein produced by cellular agriculture and the dairy industry. The International Journal of Life Cycle Assessment. 2022;27:1017-1034.

25. Järviö, N. Ovalbumin production using Trichoderma Reesei. 2023. Available from: https://static1.squarespace.com/static/61cad38f755fec2450afb224/t/67632e8b42d962529484ac78/1734553227832/Onego-LCA-2024-digital.pdf

26. Dutch biomass fermentation producer. Life Cycle Assessment Results. 2025. Direct communication with producer (confidential, not publicly available)

27. Jungbluth N, Chudacoff M, Dauriat A, Dinkel F, Doka G, Faist Emmenegger M, Gnansounou E, Kljun N, Schleiss K, Spielmann N, Stettler C, Sutter J. 2007: Life Cycle Inventories of Bioenergy. Available from: https://esu-services.ch/fileadmin/download/jungbluth-2007-17_Bioenergy.pdf

28. Matassa S, Boon N, Pikaar I, Verstraete W. Microbial protein: future sustainable food supply route with low environmental footprint. Microbial Biotechnology. 2016;9(5):568–575.

29. Numidia. Available from: https://numidiadairy.com/whey-protein-concentrate-feed-grade

30. European Whey Products Association. Available from: https://ewpa.euromilk.org/wp-content/uploads/2024/05/Whey_in_Animal_Nutrition_-_A_Valuable_Ingredient__EWPA_B.pdf

31. European Commission. EU agricultural outlook 2024–2035. 2024. Available from: https://agriculture.ec.europa.eu/document/download/48b04248-de6c-4608-bbcf-f2c9e0ed9d2b_en?filename=agricultural-outlook-2024-report_en.pdf

32. Blasi A, Verardi A, Lopresto CG, Siciliano S, Sangiorgio P. Lignocellulosic agricultural waste valorization to obtain valuable products: an overview. Recycling. 2023;8(4):61.

33. Usmani Z, Sharma M, Diwan D, Tripathi M, Whale E, Jayakody L, Moreau M, Thakur VK, Tuohy M, Gupta VK. Valorization of sugar beet pulp to value-added products: a review. Bioresource Technology. 2022;346:126580.

34. Boyd CE, McNevin AA, Davis RP. The contribution of fisheries and aquaculture to the global protein supply. Food Security. 2022;14(3):805-827.

35. Alagawany M, Elnesr SS, Farag MR, Abd El-Hack ME, Khafaga AF, Taha AE, Tiwari R, Yatoo MI, Bhatt P, Khurana SK, Dhama K. Omega-3 and omega-6 fatty acids in poultry nutrition: effect on production performance and health. Animals. 2019;9(8):573.

36. Glencross B, Ling X, Gatlin D, Kaushik S, Øverland M, Newton R, Valente LMP. A SWOT analysis of the use of marine, grain, terrestrial-animal and novel protein ingredients in aquaculture feeds. Reviews in Fisheries Science & Aquaculture. 2024;32(3): 396-434.

37. Bromm J, Tokach M, Woodworth JC, Goodband RD, DeRouchey JM, Hastad CW, Post ZB, Flohr JR, Schmitt RA, Zarate Ledesma JF, Gebhardt JT. Effects of increasing omega-3 fatty acids on growth performance, immune response, and mortality in nursery pigs. Translational Animal Science. 2024;8.

38. Food and Land Use Coalition. Growing better: ten critical transitions to transform food and land use. 2019. Available from: https://www.foodandlandusecoalition.org/wp-content/uploads/2019/09/FOLU-GrowingBetter-GlobalReport.pdf

39. Carr BT, et al. The importance of essential fatty acids and their ratios in aquafeeds to enhance salmonid production, welfare, and human health. Frontiers in Animal Science. 2023;4.

40. Expana. Precision fermentation: a disruptor for fermentation-based feed additive industries? 2020. Available from: https://www.feedinfo.com/our-content/insight-precision-fermentation-a-disruptor-for-fermentation-based-feed-additive-industries/210597

41. Jeločnik M, Veljković S, Gligorević K, Martinov M. Competitiveness of sauerkraut production. Western Balkan Journal of Agricultural Economics and Rural Development. 2019;1(2):113-123.

42. Materia VC, Linnemann AR, Smid EJ, Schoustra SE. Contribution of traditional fermented foods to food systems transformation: value addition and inclusive entrepreneurship. Food Security. 2021;13(5):1163–1177.

43. EU CAP Network. Promoting fermented vegetables as gut-friendly, nutritious superfood. Available from: https://eu-cap-network.ec.europa.eu/good-practice/promoting-fermented-vegetables-gut-friendly-nutritious-superfood_en

44. Diez-Ozaeta I, Astiazaran OJ. Fermented foods: An update on evidence-based health benefits and future perspectives. Food Research International. 2022;156:111133.

45. Sproten A, Wei R, Roosen J. Report on consumer perception of fermented foods.2025. Available from: https://www.domino-euproject.eu/wp-content/uploads/2025/03/Report-on-consumer-perception-of-FFs.pdf

46. Barlee's. Available from: https://barlees.eu/en/product/tempeh-barley-and-peas-bio-200g-marinated/?srsltid=AfmBOoomBXV5x8ldhL_KNugeDxPwr8-j6AhiTK4DkxcWyWbl_Mkq-aul&utm

47. Goyal S, Degieter M, Ott D, Torreiro MG, Matteucci C, Zannini E, De Steur H. Tempeh powder production from different substrates: carbon footprint, land-use change, economic feasibility and eco-efficiency. British Food Journal. 2025. Available from: https://doi.org/10.1108/BFJ-04-2025-0492

48. Dixon, R. "It's actually a superfood!" Why tempeh is suddenly on every menu – and coming to a supermarket near you. The Guardian. 2025. Available from: https://www.theguardian.com/food/2025/sep/28/its-actually-a-superfood-why-tempeh-is-suddenly-on-every-menu-and-coming-to-a-supermarket-near-you?utm

49. Signorelly, A. This plant-based food has more protein than eggs. Vogue. 2025. Available from: https://www.vogue.com/article/tempeh-benefits?utm_source=chatgpt.com

50. Cleveland Clinic. Is tempeh just tofu? Not exactly – but here's why it's so good for you. 2024. Available from: https://health.clevelandclinic.org/tempeh-nutrition-and-benefits

51. Teoh SQ, Chin NL, Chong CW, Ripen AM, How S, Lim JJL. A review on health benefits and processing of tempeh with outlines on its functional microbes. Future Foods, Volume. 2024;9:100330.

52. Derbyshire, E. Fungal-derived mycoprotein and health across the lifespan: a narrative review. Journal of Fungi. 2022; 8(7):653.

53. Finnigan TJA, Wall BT, Wilde PJ, Stephens FB, Taylor SL, Freedman MR. Mycoprotein: the future of nutritious nonmeat protein, a symposium review. Current Developments in Nutrition. 2019;3(6):nzz021.

54. Elhalis H, See XY, Osen R, Chin XH, Chow Y. The potentials and challenges of using fermentation to improve the sensory quality of plant-based meat analogs. Frontiers in Microbiology. 2023;14:1267227.

55. Bottin JH, Swann JR, Cropp E, Chambers ES, Ford HE, Ghatei MA, Frost GS. Mycoprotein reduces energy intake and postprandial insulin release without altering glucagon-like peptide-1 and peptide tyrosine-tyrosine concentrations in healthy overweight and obese adults: a randomised-controlled trial. The British Journal of Nutrition. 2016;116(2):360-74.

56. Pavis GF, Revuelta Iniesta R, Roper H, Theobald HE, Derbyshire EJ, Finnigan TJA, Stephens FB, Wall BT. A four-week dietary intervention with mycoprotein-containing food products reduces serum cholesterol concentrations in community-dwelling, overweight adults: A randomised controlled trial. Clinical Nutrition. 2024;43(3):649-659.

57. Jacobson MF, DePorter J. Self-reported adverse reactions associated with mycoprotein (Quorn-brand) containing foods. Annals of Allergy, Asthma & Immunology. 2018;120(6):626-630.

58. Dzeladini L, Chan D, Kummerow M. A case report of mycoprotein allergy. Internal Medicine Journal. 2017;47(S5):17.

59. Eastham JL, Leman AR. Precision fermentation for food proteins: ingredient innovations, bioprocess considerations, and outlook - a mini-review. Current Opinion in Food Science. 2024;58:101194.

60. Knychala MM, Boing LA, Ienczak JL, Trichez D, Stambuk BU. Precision fermentation as an alternative to animal protein, a review. Fermentation. 2024;10(6):315.

61. Banovic M, Asioli D, Sogari G. Cross-cultural consumer valuation of precision fermentation milk: effects of information, individual traits, and labelling preferences. Food Quality and Preference. 2025;131:105570.

62. Food Standards Agency. A rapid evidence review on consumer responses to precision fermentation. FSA Research and Evidence. 2025;1-55.

63. Buxton, A. Consumers are ready for animal-free dairy, new study finds. The Green Queen. 2022. Available from: https://www.greenqueen.com.hk/consumers-ready-for-animal-free-dairy/?utm

64. Brück WM. Chapter 8 - the benefits of alpha-lactalbumin in early childhood. In: Dairy in human health and disease across the lifespan. Academic Press. 2017;117-126.

65. Doughman SD, Krupanidhi S, Sanjeevi CB. Omega-3 fatty acids for nutrition and medicine: considering microalgae oil as a vegetarian source of EPA and DHA. Current Diabetes Reviews. 2007;3(3):198-203.

66. Jin J, den Besten HMW, Rietjens IMCM, Widjaja-van den Ende F. Chemical and microbiological hazards arising from new plant-based foods, including precision fermentation-produced food ingredients. Annual Review of Food Science and Technology. 2025;16:171-194.

67. Fytsilis DV, Urlings MJE, Schooten F-J, de Boer A, Vrolijk MF. Toxicological risks of dairy proteins produced through cellular agriculture: current state of knowledge, challenges and future perspectives. Future Foods. 2024;10:100412.

68. Food and Agriculture Organization of the United Nations. Fats and fatty acids in human nutrition: report of an expert consultation. 2010. Available from: https://www.fao.org/fileadmin/user_upload/nutrition/docs/requirements/fatsandfattacidsreport.pdf

69. Restivo, J. Omega-3 foods: Incorporating healthy fats into your diet. Harvard Health Publishing. Available from: https://www.health.harvard.edu/nutrition/omega-3-foods-incorporating-healthy-fats-into-your-diet

70. Bomkamp C, Panescu P, Eastham L. Omega-3 ingredient use in alternative meat and seafood products. Good Food Institute. 2024. Available from: https://gfi.org/wp-content/uploads/2024/09/Omega-3-report.pdf

71. Kunj P, Sahu S, Singh G, Arya SK. A review on algal oils as a sustainable source of essential omega-3 fatty acids. Bioresource Technology Reports. 2025;30:102154.

72. FAOSTAT: Food Balance Sheets. Food and Agriculture Organization of the United Nations. Available from: https://www.fao.org/faostat/en/#data/FBS

73. The Good Food Institute. Plant-based food retail market insights. 2025. Available from: https://gfieurope.org/european-plant-based-sales-data/

74. Systemiq, with the support of the Good Food Institute Europe. Seizing the economic opportunity of alternative proteins in Europe. Forthcoming.