Genome editing technologies in microbial food and feed

Pathways to sustainable production in Norway

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Summary

This report aims to improve understanding of gene technologies in microbes and their applications in food and feed production. It outlines key advancements, explores current and future uses of gene-editing technologies, and evaluates market implications at international, EU, and Norwegian levels. The report also examines the regulatory landscape and risk assessment requirements, highlighting the need for regulatory adaptation to accommodate genome editing in microbial food and feed.

Sammendrag

Denne rapporten har som mål å gi en oversikt over bruk av genteknologier i mikrober og deres anvendelser i produksjon av mat og fôr. Den beskriver sentrale fremskritt, utforsker nåværende og fremtidige bruksområder for bruk av genredigering, og vurderer implikasjoner for markedet på internasjonalt nivå, samt i EU og Norge. Rapporten undersøker også det regulatoriske landskapet og kravene til risikovurdering, og fremhever behovet for regulatorisk tilpasning for å imøtekomme genredigering i mikrobiell-basert mat og fôr.

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Summary

This report aims to improve understanding of gene technologies in microbes and their applications in food and feed production. It outlines key advancements, explores current and future uses of genome editing technologies, and evaluates market implications at international, EU, and Norwegian levels. The report also examines the regulatory landscape and risk assessment requirements, highlighting the need for regulatory adaptation to accommodate genome editing in microbial food and feed.

Given the importance of sustainability in food and feed systems, it is essential to develop frameworks that assess the environmental impact of new technologies, their economic viability, and their contribution to social wellbeing. We give suggestions for relevant frameworks and point out the need to advocate for animal health and welfare, transparency, and ethical considerations.

This report will supplement recent reports and papers with a more detailed analysis of the potential to utilize gene-edited microorganisms in food and feed production. It is of high relevance for Norway's mission of sustainable feed, and for those pursuing microbial production of products to be used in food, feed and other uses.

The report recommends updating feed legislation to better accommodate alternative ingredients and gene-edited microorganisms. It calls for the development of clear sustainability assessment frameworks to evaluate environmental, economic, and social impacts. Research should be expanded, particularly on microbial feed for aquaculture and the use of circular resources. To support market acceptance, consumer attitudes should be studied and transparency in labelling improved. Long-term health data on synthetic proteins is needed to ensure safety. The report also highlights the importance of investigating social sustainability, including labour and community impacts. Finally, it encourages leveraging Norway's research infrastructure to scale microbial production and meet national sustainability goals.

Norsk sammendrag

Denne rapporten har som mål å gi en oversikt over bruk av nye genteknologier i mikrober og deres anvendelser i mat- og fôrproduksjon. Rapporten beskriver hovedtrekkene ved utviklingen innen bruk av mikrober i mat og fôr, diskuterer nåværende og fremtidige bruksområder for genredigeringsteknologier, og vurderer markedsimplikasjoner på internasjonalt, EU og norsk nivå. I tillegg gjennomgår den det nåværende regulatoriske landskapet og kravene til risikovurdering, og peker på at regelverket kan trenge tilpasning for å bedre ivareta genredigering i mikrobielt basert mat og fôr.

Gitt viktigheten av bærekraft i mat- og fôrsystemer, er det avgjørende å etablere rammeverk for å vurdere miljøpåvirkningen av nye teknologier, deres økonomiske levedyktighet og sosiale nytte. Vi foreslår et slikt rammeverk og understreker behovet for å fremme dyrehelse og dyrevelferd, åpenhet og transparens, samt andre etiske hensyn.

Rapporten supplerer andre rapporter og artikler med en mer detaljert analyse av potensialet for å bruke genredigerte mikroorganismer i mat- og fôrproduksjon. Den er høyst relevant for Norges samfunnsoppdrag på bærekraftig fôr, og for aktører som arbeider med mikrobielt basert produksjon av ingredienser til mat, fôr og andre formål. Rapporten anbefaler å oppdatere fôrlovgivningen for bedre å kunne inkludere alternative ingredienser og genredigerte mikroorganismer. Den etterlyser utvikling av tydelige rammeverk for bærekraftsvurdering som dekker miljømessige, økonomiske og sosiale aspekter. Forskningen bør styrkes, særlig innen mikrobielt fôr til akvakultur og bruk av sirkulære ressurser. For å støtte markedsaksept bør forbrukerholdninger gjennomføres, og produktmerking bli mer transparent. Det er behov for langtidsdata om helseeffekter av syntetiske proteiner for å sikre trygghet. Rapporten fremhever også viktigheten av å undersøke sosial bærekraft, inkludert arbeidsforhold og påvirkning på lokalsamfunn. Til slutt oppfordres det til å utnytte Norges forskningsinfrastruktur for å skalere opp mikrobiell produksjon og for å nå nasjonale bærekraftsmål.

Contents

Glossary of key terms

Aquafeed: Feed specifically formulated for aquatic animals, often containing proteins, lipids, and micronutrients.

Biomass fermentation: A fermentation process where the entire microbial biomass is harvested and used as the product, often for protein or lipid content.

CRISPR/Cas: A genome editing tool derived from bacterial immune systems that allows for precise, efficient, and cost-effective DNA modifications.

Feed additive: A substance added to animal feed to improve its nutritional value, digestibility, or health benefits.

Genetically modified microorganism (GMMs): A microorganism whose genetic material has been altered using genetic engineering techniques.

Genome-editing technologies: Technologies that allow scientists to modify an organism's DNA at specific locations. Common tools include CRISPR/Cas9, TALENs, and ZFNs.

Heterotrophic microalgae: Microalgae that grow on organic carbon sources often used in industrial fermentation for high-yield biomass production.

Life cycle assessment (LCA): A method to assess environmental impacts associated with all stages of a product's life, from raw material extraction to disposal.

Microbial fermentation: A process where microorganisms such as bacteria, yeast, or fungi convert substrates (like sugars) into valuable products such as proteins, enzymes, or vitamins.

Mixotrophic microalgae combine photosynthesis with the ability to utilize organic carbon sources, allowing them to grow under both light and dark conditions.

Novel foods: Food that was not consumed to a significant degree in the EU before May 15, 1997, including new sources, substances, or production methods.

Nutraceuticals: Products derived from food sources that provide health benefits beyond basic nutrition, often including vitamins, minerals, and bioactive compounds.

Photobioreactor (PBR): A closed system used to cultivate photosynthetic organisms like microalgae under controlled light and nutrient conditions.

Photosynthetic microalgae: Microalgae that perform photosynthesis, converting light into energy.

Precision fermentation: A form of fermentation that uses genetically engineered microorganisms to produce specific compounds (e.g., proteins, fats, vitamins) with high precision and purity.

Rest-raw materials: By-products or waste materials from other processes (e.g., food waste, slaughterhouse by-products) used as feedstock in microbial production.

Safe and sustainable by design (SSbD): A European framework for ensuring that chemicals and materials are safe and sustainable throughout their life cycle.

Single cell proteins (SCPs): Protein derived from microbial biomass (e.g., bacteria, yeast, algae) used as a nutritional supplement in food or feed.

Site-directed nuclease (SDN): Enzymes used in genome editing to create targeted DNA breaks. Categories include SDN-1 (random mutations), SDN-2 (small edits with a template), and SDN-3 (insertion of larger DNA sequences).

Sustainability assessment: A framework or methodology used to evaluate the environmental, economic, and social impacts of a product or process.

Synthetic biology: The application of science, technology and engineering to facilitate and accelerate the design, manufacture and/or modification of genetic materials in living organisms.

Qualified presumption of safety (QPS): A safety status granted by EFSA to certain microorganisms based on a history of safe use, simplifying their risk assessments.

1. Background

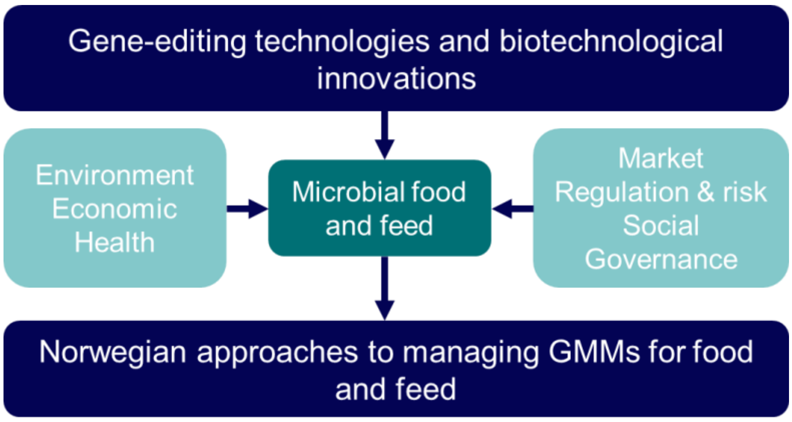
Transforming our food and agricultural systems to become more sustainable while ensuring access to adequate, safe, nutritious, and accessible foods is essential for long-term environmental, economic, and social wellbeing. Growing demand for sustainable food and feed sources are increasing the interest in gene-editing technologies and synthetic biology, particularly due to their potential to feed on residues and byproducts that reduce resource use and carbon footprint of production processes, while not compromising the nutritional value of the final products. In a Norwegian setting, these technologies are especially relevant for strengthening domestic feed production for aquaculture industry. The national 'Mission on sustainable feed' is a government initiative to provide more sustainably sourced feed ingredients for aquaculture and animal agriculture industries. The mission aims to reduce reliance on imported animal feed ingredients while reducing greenhouse gas emissions (Stortingsforhandlinger, 2022; Forskningsråd, 2023; Regjeringen, 2024; Forskningsrådet, 2025)

Microbial production is expected to play a key role in future feed systems, offering proteins, carbohydrates, oils, and micronutrients. Microorganisms can for example be used as whole microbial biomass or engineered into cell factories to produce high-value ingredients. Still, there are technical and economic challenges in their production and commercialization. To overcome these challenges, advanced gene-editing and microbial engineering can improve strain performance, enable the use of low-cost, non-competing feedstocks, and enhance the sustainability of existing production processes. Accordingly, a recent expert group under the 'mission on sustainable feed' has recommended considering genetically modified organisms (GMO) (alongside their wild-type relatives) and raw materials for the use in fish and animal feed (Forskningsråd, 2023).

The development of synthetic foods is attracting significant investments worldwide, and genome editing technologies are used to modify microbes to manufacture ingredients such as proteins and oils. In Norway, genome editing has until now only been discussed in the context of plant modification and animal breeding (including salmon aquaculture), and the use of the technology has focused on solving challenges related to pesticide use, disease outbreaks, fish farm escapes, etc. As a result, public discourse has largely overlooked recent advances in microbial food production. Within the European Union, there are ongoing processes to ease the requirements for risk assessments of genome edited organisms that do not contain genes from other organisms. While most GMOs approved for feed use today are plants, genetically modified microorganisms (GMMs) have a long history of use in the production of chemicals, materials, pharmaceuticals and food products. Their application in the food sector is now accelerating, driven by consumer demand for environmentally friendly and animal-free food alternatives.

The objective of this report is to provide an overview of the current and potential use of genome-editing technologies in microbial-based food and feed production and their possible health and societal effects, complementing previous reports and expert opinions (Figure 1). To achieve this objective, the report is organized as follow: Section 2 introduces the Norwegian political and economic relevance of the issue of genome edited microorganisms. Section 3 presents state-of-the-art microbial production and gives an overview of the most widely used microbes and their applications, with examples of emerging applications of genome editing technologies in food and feed. Section 4 offers a market assessment at the international, EU and Norwegian level. Technological innovations are closely linked to regulatory landscapes and risk assessment practices as well as sustainability requirements. Section 5 provides context for the regulatory landscape nationally and internationally of current risk assessment practices. Section 6 explores existing frameworks for and dimensions of sustainability assessments. These sections also highlight the social and ethical aspects associated with genome-editing technologies. Finally, section 7 summarizes the findings of the report and presents recommendations for researchers, funders and policy makers to support the sustainable and responsible integration of genome-editing technologies into microbial food and feed production systems.

Figure 1. The objective of the report



2. Norwegian context for microbial production of food and feed

Through international collaboration, Norway aims to make a significant contribution to solving the numerous challenges facing global food and feed systems. One such challenge is meeting established sustainability standards while catering to rising consumer demands for animal-free products. This demand has recently driven large investments in fermentation companies and biotech start-ups harnessing the potential of microorganisms, biotechnological innovation and the latest advancements in genome editing and synthetic biology in the production of novel food and food ingredients.

These developments have engendered a new international market for novel food products, one that Norwegian industry is well positioned to benefit from. Moreover, they offer technological solutions to a pressing national issue: the heavy reliance on imported feed ingredients such as soy and other vegetables in Norway´s animal agriculture and aquaculture. In 2024, the Norwegian government launched a broad, societal initiative - the 'Mission on sustainable feed' - to increase the share of domestically produced ingredients in the approximately 2 million tons of fish feed annually required in the aquaculture industry and the 2 million tons of feed concentrate used in animal agriculture (Forskningsråd, 2023). Currently, only 8% of aquaculture feed ingredients are sourced domestically (Aas *et al.*, 2022).

This report outlines key technological and economic developments in microbial food production processes that may be of importance for meeting the aquaculture industry's need for sustainable feed. While agriculture and aquaculture are both important parts of the Norwegian food system, their differing political and economic frameworks limit the potential for agriculture to supply feed ingredients to aquaculture. Aquaculture, defined as an export industry, is exempt from protective tariffs, allowing for cheaper imports of feed ingredients (Eidem, 2022). For agricultural feed ingredients, the situation is different. Norwegian agriculture is geared towards the domestic market and serves the important political goal of ensuring food security and regional settlement. Accordingly, it receives government support and is subject to 'channeling policies' ensuring that the best agricultural lands are set aside for grain production, while more challenging climatic and vegetative regions that still offer good grazing lands are utilized for animal agriculture (Eidem, 2022). Animal agricultural products are moreover protected by high custom barriers, ensuring that livestock farmers can afford to buy animal feed concentrates made from highly priced Norwegian grains. The high prices of Norwegian grain and animal agricultural products in this manner mutually support a domestic agricultural system of high political value.

The negative implication of this system is that Norwegian grains (and other high-protein agricultural products) generally become too highly priced to make substantial contributions to the aquaculture industry's demand for more sustainable and locally sourced feed ingredients (Eidem, 2022). Recent reports have therefore pinpointed mesopelagic fish and industrial microbial production processes as central future sources of feed ingredients for the aquaculture industry (Almås, 2020; Kari Torp, 2024). However, with increasing demands for mesopelagic fish for direct human consumption and fluctuating fish stocks, microbial technologies offer a more robust and scalable alternative. Harnessing technological inventions occurring in novel food industries could therefore play a critical role in supporting the Norwegian aquaculture industry´s transition to more sustainable feed sources. With ongoing technological advancements and declining costs, these innovations have the potential to become economically viable in the feed market soon. Consequently, deliberations regarding the management of genome-editing technologies in microbial-based food and feed production in Norway should commence (Figure 1).

2.1 The role of fermentation in food production

The production of microbes for food and feed has a long history, rooted in traditional fermentation processes. Today, these microbial systems form the basis for innovative foods and sustainable feed ingredients. Defined as the "chemical transformation of any organic matter via microbial metabolism" (Chai *et al.*, 2022), fermentation remains central in activities such as baking, brewing, winemaking, dairy processing, and fruit and vegetable processing.

Fermentation also plays a central role in modern biotechnology. Microorganisms grow and reproduce rapidly in closed, controlled systems, allowing for scalable and energy-efficient production. These systems are also for producing microbial biomass, purified compounds (such as enzymes), and alternative proteins. Several fermentation technologies exist, each with its own distinct benefits and potentialities. An overview of these technologies can be found in Box 1 (below).

Fact box 1: Fermentation technologies

Traditional fermentations apply wild-type microbial strains in the manufacture of specific products. A current example of traditional fermentation is Planterra Foods's use of shiitake mycelium to ferment rice and pea protein for their plant-based meat (Michael Carter, 2023)

Biomass fermentation makes use of microbes like fungi and bacteria that are high in protein and entails to harvests the entire biomass. Microbes used in biomass fermentation generally have a doubling time of hours and a protein content beyond 50 percent dry weight, making this a very efficient way to generate proteins (Institite, 2025)

Precision fermentation utilizes genome editing technologies to design 'microbial factories' that produce a compound of interest, such a protein, flavor molecule, vitamin, pigment, or fat" (Watson 2024). The genetic sequences are not transmitted directly from any source but synthesized from digitized databases holding the genetic coding for the original (e.g., animal) gene. At the end of the fermentation process, molecules of interest are isolated and extracted from the fermentation broth. This allows the production of food products what are often termed 'animal free'.

Traditional fermentation employs natural microorganism present in the raw food or added as a starter culture to initiate the fermentation, like in the well-known traditional Korean kimchi and German sauerkraut, and milk-based products as yoghurts and kefir. Fermentation processes can be used to produce edible microbial biomass from bacteria, yeast, fungi, and microalgae. This biomass may be used directly in end-products, either as novel food—for example, in food supplements for human consumption—or as a feed additive, such as probiotics for animal feed. In addition to whole biomass applications, fermentation is also widely used to produce purified compounds such as food enzymes, feed additives, and flavourings, - often called *precision fermentation* when utilizing genetically modified organisms (Box 1). The compounds are typically obtained from the microbial culture, either as crude extracts or after further purification, and used to enhance nutritional value, improve digestibility, or add functional properties to food and feed products. An overview of microorganism commonly used in biotechnology is found in Box 2.

Fact box 2: Types of microorganisms commonly used in industrial fermentations

Bacteria are a diverse group of prokaryotic microbes that have the capacity to produce a wide range of value-added products. Bacteria constitute an attractive protein source because of their rapid growth, and because they can utilize complex substrates as feedstocks, including anything from starch and sugars from lignocellulosic biomass to gaseous substrates (e.g., methane, CO_2) and petrochemicals (e.g., methanol and ethanol). The average crude protein content of bacteria ranges from 50-83% (Matassa *et al.*, 2016). In comparison, the currently used protein sources for aquafeed, soy and fish meal, contain about 35% and 70% crude protein, respectively. Common genera of bacteria in biotechnology include *Escherichia, Bacillus, Corynebacterium, Lactobacillus, Clostridium* and *Streptomyces (Zhang et al., 2022)*.

Fungi are a diverse group of eukaryotic microbes that are widely used due to their ability to grow on various substrates and secrete large amounts of proteins. Some species of multicellular, filamentous fungi have a long history of use, for example in the fermentation of food products like soy sauce and miso. They are also used for industrial production of specific compounds, e.g., enzymes. Species of the genera *Aspergillus, Trichoderma* and *Rhizopus* are common in industrial application. Yeast are versatile unicellular fungi that are particularly important for production of fermented food and drinks and widely used as ‘cell factories’ for production of various compounds, such as pharmaceuticals. For example, yeast converts sugars into ethanol and CO_2 used in bread and brewing. Yeast-based production systems combine the advantages of high growth rates of prokaryotic systems with the advanced protein processing machinery of eukaryotes. Species of the genera *Saccharomyces* and *Komagataella* (commonly known as *Pichia*) are examples employed in biotechnology applications (Unver and Dagci, 2024).

Microalgae belong to a diverse group of eukaryotes called algae. Most microalgae are phototrophic (derive energy from light), but some species can grow heterotrophically (derive energy from organic carbon sources) or mixotrophically (combine both strategies). These play a crucial role in aquatic ecosystems (freshwater and marine) and have gained significant attention for their potential applications in food and feed due to their pigments and beneficial lipids. Most microalgae are used to produce whole biomass or extracted lipids that can be implemented in food and feed. The genera *Chlorella, Haematococcus, Nannocloropsis* and *Spirullina* are examples of widely used microalgae. Note, Spirulina are in fact not a true alga, but rather a photosynthetic bacterium, often referred as algae from industry and consumers (Dolganyuk *et al.*, 2020; Thoré *et al.*, 2023).

In an industrial setting, bacteria, fungi, and some microalgae (heterotrophic or mixotrophic), are grown on carbon and nitrogen substrates under strictly controlled conditions. The choice of microorganism and substrate depends on the desired product and process efficiency, while parameters such as pH, temperature, and aeration are carefully optimized to maximize yield and quality. The processes are broadly classified into three main types, named after the state of the substrate available:

- **Solid-state fermentation** involves the cultivation of microorganisms in the absence or near absence of water but with sufficient moisture content to enable the growth of the fermenting organisms. The total solid content ranges from 60% to 80% and the growth substrate is available in solid form. Solid-state fermentation is common in traditional fermentation of food products involving filamentous fungi, such as bread and cheese.
- **Submerged fermentation** processes are conducted in the presence of water. The fermenting organisms grow on soluble substrates in a liquid media and the total solid content ranges from 5% to 10%. Submerged fermentation processes are the most common in biotechnological applications and the most advanced in terms of design and operation. The formerly mentioned bacteria, filamentous fungi and yeast are typically involved in this form of production.
- **Gas fermentation** involves submerged fermentation processes in which media components and microorganisms are present in the liquid media whereas the carbon and energy sources for the microbes are continuously supplied by sparging gas (syngas, methane, CO_2, H_2, etc.) through the media.

Most of the commercially relevant microalgae strains currently employed in food and industrial biotech are produced this way. However most microalgae are photosynthetic and rely on light energy and carbon dioxide, which limits their cultivation in conventional fermenters. The traditional way of cultivating microalgae are open pond systems, reducing cost of installation and operation. While cost-efficient, they offer limited control of growth condition. Today, microalgae cultivation is operated in photobioreactors (PBRs), which are enclosed systems typically made of glass or plastic that provide control over temperature, light intensity, and nutrient concentrations. PBRs can be designed in various configurations, such as tubular, flat-panel, or bubble column reactors (Huang *et al.*, 2017).

Building on these diverse cultivation strategies, synthetic biology enables microbes to be precisely engineered to produce a broader range of high-value components with greater efficiency. While microbial modification for production of enzymes, lipids, and carbohydrates has been practiced since the 1980s, recent technology advancements have opened new market opportunities for *alternative food proteins,* such as egg white protein, dairy proteins, pepsin, animal-free meat proteins such as hemoglobin and fats (Augustin *et al.*, 2024). According to the Good Food Institute (2025), the dairy alternative segment holds the largest share of the novel food market (Box 3), followed by meat, egg, and seafood alternatives (Institite, 2025). Through precision fermentation, engineered microorganisms are able to produce heme-containing protein (eg. leghemoglobin) for plant-based meat or casein for animal-free dairy.

Fact box 3: Novel food

According to EU legislation, novel food refers to food that was not significantly consumed by humans in the EU before 15 May 1997—the date when the first regulation (Regulation (EC) No 258/97) was implemented. This regulation was later replaced by Regulation (EU) 2015/2283. The novel food definition covers new foods, food from new sources, new substances used in food, as well as new ways and technologies for producing food. This includes the use of microorganisms as feed additives and flavorings.

The first introduction of a 'novel food' ingredient to the food sector was the enzyme chymosin (equivalent to rennin in rennet), which was developed in the 80s (Emtage et al. 1983; Harris et al. 1982), commercialized and approved by the EU and US. Today over 90% of rennet used for cheese production is microbially produced by fermentation (Johnson, 2017).

Any of the fermentation processes outlined in Box 1 may be utilized in the production of novel foods. The recent rise of microbial fermentation technology stabilizes the production of important compounds but has thus far only been economically viable in the pharmaceutical and biochemical sectors (RethinkX, 2019). This is now changing with a variety of synthetic and alternative proteins produced by (often genetically modified or edited) microbes that have recently entered the food market.

In addition to the recently appearing food proteins, precision fermentation is widely used to produce specialty food additives or food enzymes. Food additives are known by their E-number on ingredients lists, such as colors, antioxidants, emulsifiers, stabilizers, gelling agents and thickeners, preservatives, and sweeteners. One example is invertase (E 1103), which is an microbially produced enzyme approved as a food additive for use in baking and specialty carbohydrate production. As it remains functional in the final product labelling is required. Other compounds are classified as food enzymes, as for example amylase, often produced using genetically modified *Bacillus* strains, and used in starch processing to produce glucose syrups. As amylase is classified as a food enzyme and have no function in the final product, labelling is not required. Norwegian companies that work on microbial food ingredients based on fermentation or cultivation approaches or invests in such technologies are listed in Box 5.

2.2 The role of fermentation in feed

Microbial biomass can be produced through microbial fermentation processes and used as high-quality ingredients suitable for fish and animal consumption. Due to the high protein content of specific microorganism (Box 2), the resulting biomass is commonly referred to as single-cell proteins (SCP), even if it may also contain other components such as lipids and vitamins. SCP represents a promising alternative to traditional protein sources, like soy and fishmeal, offering a more sustainable solution (Gundupalli *et al.*, 2024).

It has been shown that heterotrophic microalgae can be fermented on organic substrates to produce omega-3 fatty acids at scale, providing a sustainable alternative to fish oil. This breakthrough in microbial ingredient production is transforming aquaculture feed by reducing reliance on wild-caught marine resources. Fermentation and microbial-based approaches are also used for speciality high-value feed ingredients, such as specific vitamins and minerals essential for fish and animal growth and health. In the aquaculture sector, microalgal-derived pigment and antioxidants such as astaxanthin and fucoxanthin, are in development for the salmon feed market where they contribute to both fish health and product quality (Nagappan *et al.*, 2021). As microbial production costs continue to decline, microbial-based approaches may extend beyond specialty applications and become increasingly viable to produce bulk feed ingredients, such as proteins and oils. This represents an important area for consideration in Norway.

Despite their potential, novel feed ingredients, such as SCP and microalgae-based pigments and oils, accounted for as little as 0.4% (8 130 tonnes) of total feed ingredients in 2020 (Innovation, 2022). This highlights the need for further innovation, regulatory adaptation, and market development to scale up their adoption in the feed industry.

In 2024, the Norwegian government launched a national mission to ensure that all feed for farmed animals and fish is sustainably sourced by 2034 (Regjeringen, 2024). This sustainability goal is particularly important for the salmon aquaculture industry, which in 2024 secured the country revenues of USD 8,1 billion and constituted 46.2% of the world's total salmon exports (Workman 2025; Sjømatrådet 2025). While feed for land-based animal agriculture is predominantly sourced domestically, the protein-rich feed required for aquaculture industry is mainly imported (Figure 2). Until slaughter, 75% of the greenhouse gas emissions from salmon production come from the import of feed ingredients (Johansen, 2022). Thus, there is a huge incentive to develop the Norwegian feed industry, particularly for the aquaculture industry.

Feed ingredients produced in Norway include wheat, barley, bran, fish oil and fishmeal (Eidem, 2022). The aim is to increase the share of feed ingredients produced in Norway from 8 to 25% in the aquaculture industry, and from 55 to 70% in animal agriculture (Regjeringen, 2024). Building a strong feed ingredient industry will make Norway more self-sufficient and reduce carbon emissions from transport of imported feed ingredients.

To support the mission, the Research Council of Norway (RCN) has established an expert committee tasked with identifying key barriers and opportunities. The committee's report highlights three main challenges hindering the development of a strong, sustainable feed ingredient industry in Norway:

1. Inadequate regulatory frameworks that are not yet adapted to novel feed sources such as insects, seaweed, or microbial biomass,
2. Gaps in biological and technological knowledge, particularly regarding the nutritional value, safety, and environmental impact of alternative feed ingredients, and
3. Limited circular use of bioresources, where by-products and waste streams from agriculture, fisheries, and food industries are underutilized.

RCN emphasizes that large-scale national missions like this require broad collaboration across sectors, including research institutions, industry, government agencies, and civil society. The mission is inspired by the EU's mission-oriented research model and is designed to be interdisciplinary, solution-driven, and societally relevant. The initial report that framed the mission (Forskningsråd, 2023) also stressed the importance of concrete actions to remove systemic barriers. These include updating legislation, incentivizing sustainable practices, and investing in innovation ecosystems that can accelerate the development and commercialization of new feed technologies.

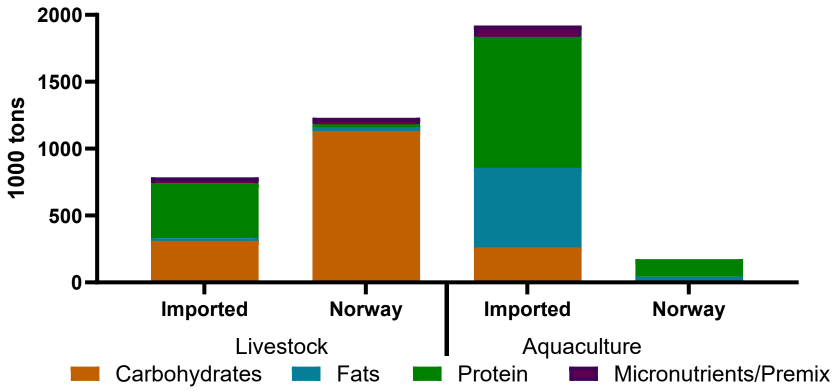


Figure 2: Feed ingredients imported or produced in Norway for Livestock or aquaculture feed (produced based on table 8 from (Eidem, 2022)

The report Råvareløftet (2022) was developed by a large consortium of salmon farming and feed producing companies in Norway, coordinated by the environmental NGO, Bellona (Silje Båtsvik Risholm, 2022). This report gives 21 action points for more sustainable production of salmon feed. It moreover suggests which challenges limit the production of 15 important feed ingredients, including yeast, bacteria, and both hetero- and phototrophic microalgae. Råvareløftet estimates that, if actions are taken, it will be possible to produce 1 106 000 tons of new feed ingredients in Norway by 2040, which lifts the domestically produced share of feed ingredients in the salmon industry to 64%. A similar report suggests a self-sufficiency rate of 50% for feed protein by 2050 (Almås, 2020). To reach a high share of Norwegian feed ingredients, all governmental organs must to be prepared to support and guide research and industry towards more circular use of biological resources in feed production. Specifically, this implies that:

1. The life cycle of all new feed ingredients needs to be mapped and assessed, and impact on fish welfare must be studied; and
2. The aquaculture industry needs incentives to accept and adopt new feed ingredients.

Regarding microorganisms specifically, the report states that research and development needs to be prioritized, particularly on the identification of appropriate growth substrates and possibilities of up-scaling production processes. It further argues that the use of rest raw materials, e.g. slaughterhouse by-products and human food waste, needs to be prioritized. Improved use of rest-raw materials in feed will contribute to the transformation of residue materials into high-value products, and to the development of more circular production systems. The latter may be of importance for market and social acceptance of the final products (Silje Båtsvik Risholm, 2022).

One of the many technically viable solutions suggested to enhance access to new feed resources is the microbial manufacture of bulk feed ingredients, such as proteins, lipids, micronutrients, and whole microbial biomass. It may be wise to consider if or how gene-editing of microbes increases the potential to realize the mission's aims, especially in terms of sustainability. In the Råvareløftet report (2022), the potential volumes for aquaculture feed produced from microorganisms have been estimated to be highest for bacteria (30.000-100.000 tones) and phototropic microalgae (50.000-200.000 tonnes) (Silje Båtsvik Risholm, 2022). Almås et al. (2020) give similar estimates, in which microbial production has the potential to reach 300 000 tonnes by 2050 (Figure 3)(Almås, 2020). Microbial production is regarded as an area-efficient alternative form of production and a good and relevant source of fat, proteins, essential nutrients, and other important feed ingredients. The microbes used in this production can utilize different sources of carbon and energy, and in this manner contribute to new developments in the biotechnological feed industry. The challenge is, however, the need for renewable energy.

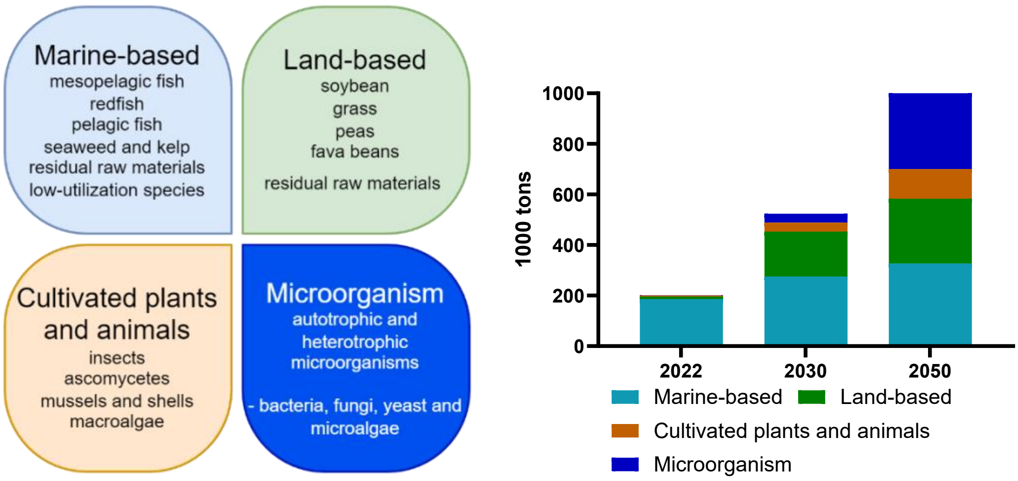


Figure 3. Overview of sources for feed and their potential production per year, (Almås, 2020).

To be able to meet the production estimates of "Råvareløftet", there is a need for more knowledge about which microorganisms are most relevant to produce fish feed, and how these can be tailored to more efficiently produce the desired feed ingredient. This is where gene-editing technologies can play an important role.

We have identified several Norwegian companies that work on microbial feed ingredients based on fermentation or cultivation approaches, including proteins, pigments and algal oils. While large-scale fermentation industries have already been established in Denmark and the Netherlands, the Norwegian activities in this field are still in their early stages and slowly expanding. According to Almås et al. (2020, 2023), Norway is particularly well suited to house such industries due to its unique access to large land areas, freely available cooling water, and high domestic demand for aquaculture feed, which together allows the establishment of a large internal marked (Almås, 2020).

3. Technological advancements

Advancements in synthetic biology, including microbial engineering, genome engineering and genome-editing technologies, may improve the sustainability of existing food and feed production systems by allowing the effective and rapid engineering of microorganisms and overcoming current production and commercialization challenges. This may result in improved productivity, nutritional quality, and functionality for microbial food and feed. In this section, we present state-of-the-art methodologies, an overview of commonly used industrial microbes, and insights into how to up-scale their production.

3.1 State-of-the-art genome editing technologies

Synthetic biology can be described as “the application of science, technology and engineering to facilitate and accelerate the design, manufacture and/or modification of genetic materials in living organisms” (EFSA, 2020). Genome editing techniques are used as tools for the design and construction goals of synthetic biology. The past two decades have seen the development of several new genomic techniques. In a study by the (Commission, 2021), the term new genomic techniques (NGTs) are used to refer to new gene technologies that have mainly been developed after 2001 (e.g. after the implementation of Directive 2001/18/EC)(Commission, 2021). They involve site directed nucleases (SDNs) like clustered regularly interspaced short palindromic repeats (CRISPR) and a CRISPR-associated protein (Cas, hereafter collectively referred to as CRISPR/Cas); transcription activator-like effector nucleases (TALENs); zinc finger nucleases (ZFNs); oligonucleotide directed mutagenesis (ODM) and mega nucleases (Figure 5). NGTs differ from pre-2001 gene technologies in that they refer to mutagenesis techniques that target specific locations in the genome of a wide range of organism. This report focuses on NGTs that act primarily on DNA within microbial systems.

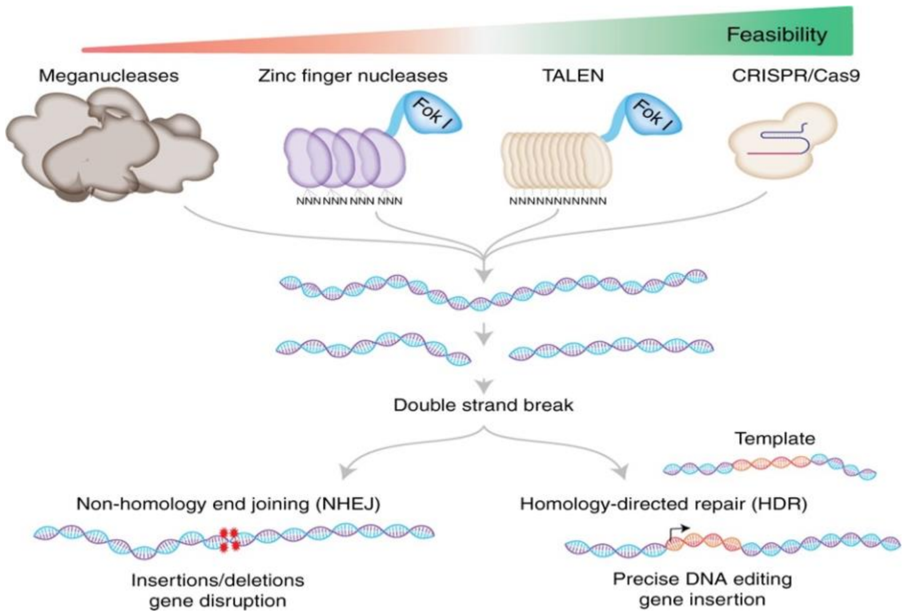


Figure 5: Gene-editing technologies and their repair mechanisms (figure from (Maddali, 2024))

In microbial systems, the most used genome-editing technique is CRISPR/Cas – a tool derived from the bacterial adaptive immune system (Jinek *et al.*, 2012). Its popularity stems from its relative ease of use, low cost and high efficiency. Genome editing technologies like CRISPR/Cas can be engineered to direct the nuclease to a specific genomic site, where they introduce double strand-breaks in the DNA. These breaks trigger the cell's DNA repair mechanism, which can lead to a targeted mutation.

There are several variants of CRISPR/Cas, the most advanced being CRISPR/Cas9. CRISPR/Cas9 makes double-strand cuts at specific target sites on the DNA, inducing a repair of the cut sites by the cell´s endogenous DNA repair mechanisms, either homologous directed repair (HDR) or non-homologous end joining (NHEJ). The NHEJ is error prone, leading to alteration of the DNA sequence during the repair process in the form of deletion(s), insertion(s), or substitution of nucleotides, thus making the NHEJ most suitable for knockout mutations in eukaryotes like microalgae and fungi. The processes of NHEJ are not well characterized and not generalized in bacterial systems, as revealed by studies in mycobacterium, *Pseudomonas, Bacillus* and *Agrobacterium (Shuman and Glickman, 2007; Selle and Barrangou, 2015).* Conversely, HDR, which is less prone to errors in its repair process is more suitable for targeted insertion of nucleotides. Variants of CRISPR technology, like CRISPR activation (CRISPRa) and CRISPR interference (CRISPRi), are methods that can result in the transient transcriptional activation or repression of a gene-of-interest, respectively. Additionally, prime editing and base editing are powerful CRISPR-Cas-based genome editors that expand the toolbox without inducing double strand breaks in the host genome and bypass the need for donor DNA (Anzalone *et al.*, 2020; Wang *et al.*, 2021).

In microbes, the application of synthetic biology has led to the integration of complex biosynthetic pathways (EFSA, 2020; Mullins *et al.*, 2022) and *de novo* protein generation using machine learning approaches (Zhang *et al.*, 2025). The extent of genetic modification or editing in synthetic biology products can vary widely, ranging from being very similar to those produced by conventional genetic engineering techniques to exhibiting entirely new characteristics at the genetic or phenotypic level, as seen in the case of synthetic organisms. By using synthetic biology, it is also possible to create novel genetic sequences or biological functions, either through the synthetization of entirely new (*de novo*) genetic material or by modifying existing naturally occurring DNA modules.

The ease of use of the CRISPR/Cas system has catalyzed a surge in its adoption across research and innovation projects, to the point that the technology is now almost synonymous with genome editing. However, the CRISPR/Cas system is not universally optimal for all genome-edited events. Depending on the goal of an editing event, e.g., where minimizing off-target mutations is highly desirable or, for practical reasons, where a particular technology has long been optimized for a specific event, alternative site-directed nucleases (SDNs) may be preferable. In microbial biotechnology, the CRISPR/Cas technique is widely used for the development of microbial cell factories (Section 3.23.1). Until now, the patent hurdle has probably limited CRISPR/Cas-based product commercialization (van der Oost and Patinios, 2023). However, the future promises more CRISPR-edited products on the market.

3.2 New genetic tools in microbial production systems

Challenges in biomanufacturing are often related to the scalability of the process to industrial scale, the stability of the strain in long operations, and the profitability of the process (Hassoun *et al.*, 2024). Strain stability, biological conversion rates and yields can be improved through intentional strain design and optimization using modern genome-editing technologies such as CRISPR/Cas in the selection and design of targets (Clomburg *et al.*, 2017; Karim *et al.*, 2025).

The most used species in production of food and feed include the bacterial genera *Escherichia,* and *Bacillus,* and the fungal genera *Aspergillus, Trichoderma*, and *Saccharomyces (Karim et al., 2025)*. Given their long history of safe use, it is expected that species of these genera will serve as first line microorganisms to which gene-editing technologies will be applied in production for food and feed. Engineering selected strains through genome-editing technologies will enable sustainable processes to use different feedstocks and improve biomass and protein production yields.

Genome editing for improved food and feed products

Microorganisms (Box 2) are increasingly important in the production of novel foods (Box 3) and feed additives. Currently, additives and flavorings are largely produced chemically or via extraction from plants, but there is high interest increasing the efficiency and specificity of microbial production through the use of the gene technologies (Sun *et al.*, 2021). Genome editing of microbes may also be used to alter the protein composition, such as the amount of specific essential amino acids, of desired food/feed ingredients.

The CRISPR/Cas system has been successfully applied to engineer strains of yeast to improve their production capacities. The genetics and physiology of *Saccharomyces cerevisiae* are well understood, and a wide range of genetic tools for strain engineering are well established. *S. cerevisiae,* including genetically modified (GM) versions, are largely used for production of feed additives. GM strains of *K. pastoris* are researched for production of feed additives, food enzymes and flavorings (Irani *et al.*, 2016). They are also used in the production of the soybean leghemoglobin protein which is adding meat flavor to the ‘Impossible foods’ plant-based burger (Jin *et al.*, 2018). Another commercially significant example of microbial protein production is *Fusarium venenatum*, a filamentous fungus used to produce a meat alternative, Quorn™, a well-known SCP product.

CRISPR/Cas-mediated genome editing is most applied in the bacterial genera *Escherichia*, *Bacillus*, *Streptomyces* and *Clostridium (Karim et al., 2025). Escherichia coli* is the most widely used host for synthetic biology. As far back as the 1980s, it was utilized to produce the enzyme chymosin (or rennin), a protease found in rennet, which is still used today in cheese production (Emtage *et al.*, 1983). Lactic acid bacteria that are currently used as probiotics have a high natural occurrence of the CRISPR-Cas system. Zbiotics is a US-based company that markets a probiotic product from genetically engineered *Bacillus subtilis* with an acetaldehyde dehydrogenase gene to decompose acetaldehyde for the purpose of reducing the effects of alcohol consumption. Researchers have developed and applied CRISPR/Cas9-mediated gene-editing to *B. subtilis* to improve its protein-producing ability (Altenbuchner, 2016) and to eliminate its ability to form spores, which pose a contamination risk in industrial fermentation due to their resistance to sterilization (García-Moyano *et al.*, 2020). There is ongoing research aimed at producing simplified single-component proteins that replicate key functions of more complex natural products. One example of this is the production of milk-related oligosaccharides for application in infant formula and supplements for gut health and as prebiotics (Walter and PINEL, 2022). For instance, *E. coli* has been gene-edited to produce lacto-N-neotetraose, a human milk oligosaccharide with prebiotics effects. Similarly, *B. subtilis* has been edited through CRISPR interference (CRISPRi) to enable the metabolic engineering of lacto-N-neotetraose (Fang *et al.*, 2018).

Microalgae are predominant producers of the omega-3 fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). Specifically, heterotrophic microalgal species such as *Schizochytrium* and *Thraustochytriidae* are essential producers of DHA with up to 38% of the total fatty acids (Morita *et al.*, 2006; Jovanovic *et al.*, 2021). The Dutch company Corbion has scaled fermentation of microalgae and has become the most recognized suppliers globally of algal omega-3 ingredients to aquafeed. Photosynthetic microalgae, such as *Nannochloropsis* primarily produce EPA up to 42% of the total fatty acids (Jovanovic *et al.*, 2021; Xu, 2022). Given the fact that these rely on solar light and fixation of CO2, they are attractive in an environmental perspective. Genome-editing technologies hold enormous potential to enhance the production yield of important omega-3 fatty acids (Nymark *et al.*, 2016; Wang *et al.*, 2016; Poliner *et al.*, 2018). Major firms, like DSM IP Assets B.V., own patents on these advances (WO2017194683A1). It can therefore be anticipated that such products may enter the market in the future.

Fact box 4: Milk protein as example of a synthetic food product

Traditionally, milk proteins are obtained through human nursing or from drinking animal sourced milk from cows and goats. Milk is very nutritious, and is typically composed of almost 90% water, 1% protein, 3.8 % fat and 7% lactose (Yi and Kim, 2021). The two latter provide most energy. Milk has two main proteins, whey and casein. Whey proteins include lactoferrin, alpha-lactalbumin, and secretary IgA, and many more that are less abundant. Milk moreover contains important carbohydrates, such as lacto-N-neotetraose and 2'-fucosyllactose.

Since milk protein encoding genes are not naturally found in microorganisms like fungi, the microbes need to be genetically modified to express them. A US-based company in the market, Perfect Day, uses GM filamentous fungi, such as *Trichoderma reesei*, designed for the synthesis of recombinant milk protein, in their production process. As they grow, the microorganisms performing the fermentation with nutrients and sugar and produce their endogenous proteins in addition to the novel milk proteins. Later, spent medium and microbes are removed.

Precision fermented milk proteins can be incorporated into plant-based dairy alternatives, such as milk, cheese, yoghurt, and ice cream. Moreover, they can be included in nutritional supplements and sports nutrition, such as protein powders, bars, and shakes. They can also be incorporated into non-dairy foods, like bread, snacks, and ready-to-eat meals. Some notable companies that produce milk proteins are Perfect Day, Motif FoodWorks, New Culture, ProProtein and Geltor. They typically recommend their milk proteins to be used in products like creamy cheeses, whipped cream, egg replacer, ice cream, protein bars and snacks, yoghurts, confectionary and sour cream. They can also be blended or mixed into beverages (even as milk).

Genome editing for the utilization of alternative raw materials

The use of genome editing technologies to enable microbial growth on sustainable raw materials is attracting attention. This approach holds significant potential to reduce overall environmental impacts and production costs. This was the case for the microalgae *Aurantiochytrium* sp., which was transformed with the inulinase gene from *Kluyveromyces marxianus* to convert fructose from inulin hydrolysis into DHA, thereby reducing the production costs and environmental pollution associated with inulin-rich materials (Diao *et al.*, 2020). The modification of common microbial production systems running on sugar-based carbon sources is of particular interest in this connection, as their reliance on this raw material puts them in direct competition with other human food production systems. To achieve more sustainable outcomes, sugar-based carbon sources should be avoided in microbial fermentations. Alternative carbon-sourced feedstocks include side streams from forestry (e.g., cellulose), aquaculture and fisheries, or one-carbon (C1) compounds, namely natural gas (mostly methane), methane (CH_4), methanol (CH_4OH), carbon monoxide (CO), carbon dioxide (CO_2), or the combination of sunlight and CO2. Biogenically sourced carbon - i.e., carbon absorbed into, stored in, and emitted by organic matter - should be preferred over carbon from fossil fuel for environmental sustainability.

Genome editing tools in future microbial production systems

As indicated in the above, recent literature indicate the following factors to be of importance to the development and profitability of microbial production systems: the selection and design of targets, strain optimization, bioprocess development, feedstock improvement, and final product formulation and production (Siddiqui *et al.*, 2023). Additionally, process integration and intensification can boost the profitability of fermentation processes (Clomburg *et al.*, 2017). Fermentation processes involving microorganisms possess an inherent complexity that make their monitoring, control, and optimization a challenging task. By digitalizing the process, and introducing the use of sensors, process control software and data collection, the performance of the fermentation process can be boosted (Noll and Henkel, 2020). What is sometimes referred to as ‘the fourth industrial revolution’ (or Industry 4.0) combines physical, digital, and biological domains, and includes technologies like artificial intelligence (AI), machine learning, big data, cloud computing, the Internet of thing (IoT), smart sensors, robotics, as well as digital twins. The implementation of these tools to fermentation process to improve process efficiency, enhance the smart production, facilitate process optimization and design novel processes is gaining momentum and will likely be the future trend in automation and digitalization (Hassoun *et al.*, 2023).

Recent progress in photobioreactor design has contributed to overcoming some of the obstacles associated with the up scaling of biomass production systems, including the high processing costs and low efficiency of conventional cultivation systems. The use of advanced digital technology, such as wireless sensor-based monitoring (Hermadi *et al.*, 2021), IoT (Wang *et al.*, 2022) and automation of the microalgae cultivation operation (Erbland *et al.*, 2020) promise more precise and efficient microalgae biomass production. Moreover, AI techniques can be used to develop optimal cultivation methods without extensive laboratory trials, saving time and resources (Zakir Hossain *et al.*, 2022). The use of AI to analyze and systematize data from fermentation processes may further provide a learning platform through which mistakes can be avoided and efficiency improved.

Possible hurdles for application

The smells and textures associated with microbial biomass depend on the application and may be incompatible with the human palate. This problem may be solved if of genome editing is used to improve sensory characteristics such as the flavor, fragrance, and functional attributes of plant-based products or cultivated meat. This could be achieved through a combination of genome editing of strains, selective breeding, or the formulation of blends and co-cultures to achieve more pleasant organoleptic qualities. For example, one challenge for the industry has been that the processing of biomass can contribute to the generation of short chain peptides that consumers perceive as bitter. This challenge has been met by “Equii's bread”, which uses microbial fermentation SCP to enhance their product and give the bread a more "buttery" mouthfeel. Another example is the synthetic production of proteins such as hemoglobin, which contribute to the distinctive taste and aroma of meat (Jin *et al.*, 2018), and whose integration into plant-based products mimics the sensory characteristics of traditional meat-based products. Genome editing can also enable the creation of custom-designed ingredients with specific nutritional profiles to meet dietary and health requirements. For example, designed protein ingredients can be used for dietary supplements, as nutrient enhancements, and functional foods, collectively termed nutraceuticals. Such novel products can meet market niches with high consumer willingness to pay.

4. Assessment of markets and investments

While most of the marketed microbial feed products contain native microorganisms, GMMs constitute the vanguard of food product innovation, and may influence future feed markets. Here we also map Norwegian investments and research and innovation activities to indicate Norwegian competitive abilities in the market of microbially produced food and feed products.

4.1 The International market of microbial products

The global precision fermentation market size was valued at USD 1.6 billion in 2022 and is projected to increase to USD 67.9 billion by 2032, growing at a compound annual growth rate (CAGR) of 46% over the forecast period (Research, 2024) (Precedence Research[1]). With Europe being the largest market, and US markets growing, the Asia-Pacific is anticipated to have the greatest CAGR in the years to come. At present, most of the companies involved are start-ups, although some larger food and life science companies are already well established (Augustin *et al.*, 2024).

The dairy alternative segment contributed most to the 2022 market, with 58.65% of revenue share, followed by meat, egg, and seafood alternatives. Specifically, whey and casein proteins accounts for most of the market, as these are popular ingredients for dietary supplements in the sports market. The casein protein segment held a revenue share of 40% in 2022, followed by collagen, egg white and heme proteins. While the precision fermentation market is divided into yeast, algae, fungi, and bacteria, the yeast segment accounted for the highest market share in 2022.

According to the Good Food Institutes (GFI) 2024 report on the state of the fermentation industry (Institite, 2025), capital investments in fermentation is at current 651$ MM, up 43% since 2023. GFI reports over 160 companies in this new fermentation area.

Global NGOs and alliances exist to support market access. GFI is an international NGO and non-profit think tank established in 2016 that works to accelerate plant-based cultivation and fermentation technologies by advocating for investments, developing regulations and policies, promoting open-access research, and raising awareness of new products. GFI has offices in Europe, Asia Pacific, Brazil, India, Israel and the US. Partnerships such as the Fungi Protein Association[2] and the Precision Fermentation Alliance[3] have been established to build capacity, transparency in policies, regulations, marketing, and awareness, etc.

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[1] https://www.precedenceresearch.com/precision-fermentation-market
[2] https://www.fungiprotein.org/
[3] https://www.pfalliance.org/

4.2 European markets and investments

In 2022, Europe held the largest market share (40.44%) of microbial products, with Germany, the United Kingdom, and France as major contributors to the market. The region is projected to maintain its position in the market over the next ten years. With 55 out of 136, Europe in 2022 also had the highest number of companies engaging the production of microbial food ingredients.

GFI reports that, in 2023 and 2024, activity grew in Europe, Israel, and the United Kingdom, indicating potential innovation hubs or newly emerging target markets. In 2022, the Netherlands announced a record-breaking $64MM investment in cell agriculture, and the completion of one of the world's largest protein facilities. The Danish company Novozymes and the international Arla Food company have entered a collaboration on precision fermentation to bring innovative new protein products to market[4]. In France, the Bel Group (known for the Babybel cheese) has partnered with Standing Ovation, a company that produces animal-free casein[5]. These are some recent examples of large, well-known actors entering the synthetic protein market.

NGOs and alliances to support market access have also appeared in Europe. The international GFI has a European office. The partnership EIT Food established in 2022 an EIT Food Diversification Think Tank[6] focusing on the transformative shift in how we produce and consume protein. The think tank has published several policy recommendations. Recently, the industry alliance Food Fermentation Europe[7] was launched to update current regulatory processes, especially those relating to the novel food regulation. They are also tackling labelling, nomenclature, and industrial-scale fermentation capacity issues to strengthen market access.

4.3 Norwegian investments

Several Norwegian companies apply fermentation as a core technology to produce feed and food ingredients (Box 5). Most use traditional fermentation to stabilize, modulate and process final products, or use biomass fermentation to produce microbes that contain a large fraction of proteins or lipids. Moreover, several companies are involved in R&D projects developing technologies to enhance the efficiency of fermentation processes, indicating a growing interest in the market (Box 6).

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[4] https://www.arla.com/company/news-and-press/2023/pressrelease/novozymes-and-arla-foods-ingredients-join-forces-to-harness-power-of-precision-fermentation/
[5] https://www.groupe-bel.com/en/newsroom/news/bel-group-and-standing-ovation-form-a-strategic-partnership-to-meet-the-challenge-of-proteins-for-the-future/
[6] https://www.eitfood.eu/projects/eit-food-protein-diversification-think-tank
[7] https://www.foodfermentation.eu/

Fact box 5: Norwegian companies involved in precision fermentation for food proteins

Sifotek is a Stavanger-based company founded in 2021 based on patented precision fermentation technology to produce animal-free milk and bee-free honey, ultimately leading to reduction of greenhouse gas emissions compared to conventional food technologies.

Vectron biosolutions, located in Trondheim, is a company based on microbial strain development and protein production. Although not solely working on precision fermentation, they have, since 2022, been partnering with Motif FoodWorks, a Boston-based food technology company making plant-based food better tasting and more nutritious (Works, 2022).

Orkla alternative proteins, a subsidiary of Norwegian Orkla, has invested in two international startup (Lidman, 2022)

- Change foods is a US based startup from 2019 that produces cheese proteins based on precision fermentation. The aim is to produce various dairy products like yoghurt, butter, ice cream and milk.

- Arkeon biotechnologies is an Austrian startup from 2021 aiming to produce alternative proteins from CO2 in a sustainable and cost-effective way. They have identified a unique microorganism that produces essential and non-essential amino acids and peptides that will increase the quality of plant-based products. The company aims to convert CO2 to food.

NoMy, is a biotechnology company based in Oslo that transforms food industry side streams into sustainable, high-value ingredients for food and aquafeed. Using fungal fermentation technologies, NoMy produces mycoprotein—a nutritious, scalable, and cost-effective protein alternative. Their approach is rooted in circular bioeconomy principles, leveraging the natural power of fungi to create impactful, regenerative solutions for the food system.

Norwegian research institutions and companies are increasingly active in the development of microbially produced food products and alternative proteins. While food applications have so far received most attention, the potential to utilize microbial production processes in the development of new feed ingredients to the aquaculture industry – a key sector in Norway's bioeconomy – is great. Several technological developments within the food industry, such as the microbial production of proteins, allergen-free ingredients, and fermentation-based flavorings, can be adapted for feed and aquaculture.

Fact box 6: Selected Norwegian research projects in microbial biotechnology

Arrival of cellular agriculture – enabling biotechnology for future food production. The project will use lab-cultivated meat and precision fermentation to produce milk, eggs, and meat proteins. Also included is scaling up the cell-based meat production and research on which materials are suitable to use as a framework for the muscle cells. With the help of yeast or other microorganisms, scientists will use precision fermentation to make edible proteins such as egg white and milk protein. The project is also investigating societal possibilities and challenges. The project is funded by the Research Council of Norway (grant ID: 336136) and led by Nofima during the period 2023–2027.

SafePhaeO_3 - Data-driven engineering of microalgal biofactories for safe and efficient omega-3 production. This project focuses on developing safer, precisely engineered microalgae cell factories to produce high-value bio-based products, with a particular emphasis on omega-3 fatty acids. By combining AI-driven analysis with advanced omics data, it aims to identify novel target genes and regulatory networks, enhance production efficiency, and ensure phenotypic stability from lab to pilot scale. SafePhaeO3 also addresses regulatory, safety, and environmental concerns through risk mitigation strategies, creating a versatile platform for sustainable, cost-effective bioproduction. The project is funded by the Research Council of Norway (grant ID: 353213) and led by NORCE during the period 2025-2028.

Precision food production. The project covers precision food production through novel biotech processes, smart sensors, and data analytical tools. Novel biotech processes include development and studies of new processes based on combinations of enzymatic protein hydrolysis, precision fermentation and culturing of meat. The project is funded by The Agricultural and Food Industry Research Funds (grant ID: 314111), a strategic programme for Nofima during 2021–2024.

Single cell protein production by anaerobic respiration. Based on an invented precision fermentation method for oxygen-independent (anaerobic) cultivation of dense bacterial cultures (patent pending). The basic research project will identify relevant organisms and further develop anaerobic cultivation strategies with future industrial implementation in mind. The project is funded by Novo Nordisk Fonden and led by NMBU during 2021–2026.

SmartSense4Protein. Bringing together expertise in photonics, robotics and AI research, this project aims to develop a smart sensor platform for the analysis of proteins and peptides applicable in industrial settings. The platform will be based on new, miniature size, tunable laser technology paired with a sample interaction module and a hybrid digital twin concept for data modeling. It will enable the monitoring, development and control of production processes involving alternative proteins from new raw materials. The project is funded by the Research Council of Norway (grant ID: 353091) and led by NMBU during 2025-2029.

To meet the ambitions of Råvareløftet, future research should prioritize the development of single-cell proteins (SCPs) and microbial oils tailored for aquaculture. Lessons learned from the food sector, especially in the application of precision fermentation, can be leveraged to create a stable, high-quality supply of domestically sourced raw materials. These could supplement marine resource flows and reduce reliance on imported feed ingredients, thereby enhancing the sustainability and resilience of Norwegian aquaculture and contributing to the global food system. The infrastructure to promote such research ventures exists and should be used to its fullest. Norway has several labs and pilot infrastructure for the optimisation of design and for the scaling up of microbial production systems from laboratory to pilot scale (Box 7). The facilities in Norway form a robust ecosystem for microbial innovation. As exemplified in the collaboration between Finnfjord AS and UiT, Norway has seen successful collaborations between local industries and research institutions. These pilots demonstrate the value of co-developing microbial production platforms that are both economically viable and environmentally sustainable.

Fact box 7: Relevant Norwegian research infrastructure for microbial production

The National bioprocessing and fermentation centre at NORCE is an open research infrastructure for the development of new bioresources and bioproducts supporting Norway's strategy on the bioeconomy. The NBioC includes equipment like fermenter ranging from 1L to 1500 L for stepwise scale up, microbial platform and gas fermentation systems tailored for the use of gases as feedstocks. It is a landmark facility for fermentation process design. optimization and scale up from laboratory to pilot scale.

The food pilot plant Norway housed by NMBU and Nofima consists of several different processing halls, and includes a dairy hall, a brewery hall and a lab pilot for biorefining on a 30-50 litre scale.

The biorefining laboratory at NMBU includes equipment like a steam explosion unit, hydrolysis reactors, fermenters, ultra/nanofiltration equipment and a spray dryer.

The fermentation laboratory at SINTEF has robotic equipment for miniaturized cultivation, large capacity incubators for shake flasks, laboratory fermenters (1-3 L) equipped for extensive process control and monitoring, and a pilot plant with two fermenters (50 and 300 L) for scale-up studies and small productions.

The fermentation research lab at UIB includes lab-scale equipment for aerobic and anaerobic submerged fermentation at temperatures up to 80oC, solid-state fermentation and continuous monitoring of efflux gases (TRL 3-4). Connected to the national Aquafeed Technology Centre.

The National algae pilot at Mongstad owned by UIB offers a microalgae production test facility (TRL 5-6) for process optimization, scale-up, and the production of large quantities of biomass for further testing and development of new products (food, feed, chemicals). The facility consists of a 200 m2 greenhouse with various types of photobioreactors (from 40L to 3200L photobioreactors), and a basic laboratory and office as well as the related infrastructure (water treatment, harvesting equipment) in the annex. The facility is operated in close collaboration with NORCE and is connected to the national Aquafeed Technology Centre.

Biotep at Nofima in Tromsø is a national facility for industrial biotechnology, Biotep offers pilot-scale fermentation and downstream processing capabilities. It enables companies and researchers to scale up microbial processes from lab to industry, supporting innovation in food, feed, and biobased materials.

Finnfjord is a ferrosilicon producer in Northern Norway, that has developed a process involving using CO_2 and NO_x from the factory's flue gas to grow microalgae, diatoms, for use in feed and other products. They operate the world's largest vertical column photobioreactor, with a capacity of 300,000 liters. This setup allows for efficient production of lipid and protein-rich biomass, which is used primarily as fish feed. At the industrial site, UiT- The Arctic University of Norway has established a laboratory, and the collaboration has facilitated funding for scale up and the testing of biomass products in fish feed.

In support of the investments in research and technological development listed above, the Research Council of Norway has also funded research projects investigating the possible societal impacts of the introduction of alternative proteins on the Norwegian market. These include: **Protein 2.0 - The biosynthetic protein transition: assessing impacts, outcomes and opportunities of Norway's post-animal bioeconomy,** led by Ruralis (RCN grant ID: 294777; project period 2019-2022) and **Meating the Anthropocene: Barriers and opportunities for alternative proteins in Norway**, led by UiO (part of Include – Research centre for socially inclusive energy transitions, financed by RCN; project period 2021-2025). Much of the information presented in chapter 5 originates in this kind of research in the social sciences and humanities, nationally and internationally.

The future potential of microbial fermentation technologies, particularly those involving genome editing, will depend heavily on the regulatory landscape. In Europe, regulations on genome-edited organisms are currently under revision. The outcome of this process will significantly influence the pace and scope of innovation in Norway and beyond.

5. Regulatory landscape and risk assessment

This section will outline the regulatory frameworks that are relevant for the safe use of genome editing technologies in microorganisms. It will describe the requirements for risk assessment of the organisms involved as well as of the finalized food and feed products in European and Norwegian legislation. The final section will focus on current processes to revise existing legislation to facilitate the application of recent developments in biotechnology in the production of sustainable food and feed.

5.1 EU and Norwegian regulation

GMOs for contained use and EFSA´s qualified presumption of safety

Within the European Union, a complex system of regulations and directives is in place to ensure that neither the processes nor the final (food or feed) products arising from precision fermentations pose a threat to human or environmental health. While Directive 2009/41/EC on the contained use of genetically modified microorganisms sets the conditions under which this production may occur, Regulation (EC) No. 1829/2003 on genetically modified food and feed is there to ensure "a high level of protection of human life and health, animal health and welfare, environment and consumer interests in relation to genetically modified food and feed" on a well-functioning European market (Article 1, objective a). If the final food or feed product contains viable cells (or microbial 'cell factories'), the authorization of this product to enter the European market needs to be evaluated according to Directive 2001/18/EC on the deliberate release into the environment of genetically modified organisms.

Table 2 gives an overview of relevant EU regulations and guidance documents published by EFSA (the European Food Safety Authority).

References	Title
1. Directive 2001/18/EC	Directive 2001/18/EC of the European Parliament and of the Council of 12 March 2001 on the deliberate release into the environment of genetically modified organisms
2. Regulation (EC) No 1829/2003	Regulation (EC) No 1829/2003 of the European Parliament and of the Council of 22 September 2003 on genetically modified food and feed
3. Directive (EU) 2018/350	Commission Directive (EU) 2018/350 of 8 March 2018 amending Directive 2001/18/EC of the European Parliament and of the Council as regards the environmental risk assessment of genetically modified organisms
4. EFSA GMO Panel (2010)	Guidance on the environmental risk assessment of genetically modified plants
5. EFSA GMO Panel (2011a)	Guidance on the risk assessment of genetically modified microorganisms and their products intended for food and feed use
6. EFSA ANS Panel (2012)	Guidance for submission for food additive evaluations
7. EFSA FEEDAP Panel (2023)	Guidance on the assessment of the safety of feed additives for the users

8. EFSA FEEDAP Panel (2017a)	Guidance on the assessment of the safety of feed additives for the target species
9. EFSA FEEDAP Panel (2017b)	Guidance on the safety of feed additives for consumers
10. EFSA FEEDAP Panel (2018a)	Guidance on the characterization of microorganisms used as feed additives or as production organisms
11. EFSA FEEDAP Panel (2018b)	Guidance on the assessment of the efficacy of feed additives
12. EFSA FEEDAP Panel (2019)	Guidance on the assessment of the safety of feed additives for the environment
13. EFSA CEP Panel (2021)	Scientific Guidance for the submission of dossiers on Food Enzymes
14. EFSA (2021)	EFSA statement on the requirements for whole genome sequence analysis of microorganisms intentionally used in the food chain
15. EFSA BIOHAZ Panel (2023)	Scientific Opinion on the update of the list of qualified presumption of safety (QPS) recommended microorganisms intentionally added to food or feed as notified to EFSA.
16. EFSA GMO Panel (2017)	Guidance on allergenicity assessment of genetically modified plants
17. EFSA FAF Panel (2021)	Scientific guidance for the preparation of applications on smoke flavouring primary products

Table 2. Existing legislation and guidelines covering the risk assessment of micro-organisms or their products relevant for this mandate. https://efsa.onlinelibrary.wiley.com/doi/10.2903/j.efsa.2024.8895

Microorganisms enjoying Qualified Presumptions of Safety

The mentioned regulations and directives are important in establishing the terms and methods for the assessment of risks to human and environmental health of novel products allowed on the European market. For food and feed products generated through precision fermentation, the use of microorganisms and of genome editing technologies both come with risks. This is evident in the EU novel food regulation (EU 2015/2283) which regulates "foods consisting of, isolated from or produced from microorganisms, fungi or algae" and "foods consisting of, isolated from or produced from cell culture or tissue culture derived from animals, plants, microorganisms, fungi or algae". Even products containing single cell proteins (SCP) produced without the introduction of genomic modifications of any kind come under this legislation (Fytsilis et al., 2024) see figure 7.

As a rule, all novel food and feed products developed using the mentioned microorganisms pose potential toxicological threats to consumers and must be subject to risk assessments according to procedures set by EFSA prior to market authorization. However, EFSA oversees a list of "recommended biological agents" (including bacterial, algal, yeast and virus strains) that have been assessed as safe for the intentional addition to food or feed in the EU market. This assessment is based on the known history of safe use of the microorganism in question. It involves the consideration of the taxonomic identity of the microorganism, the related body of knowledge and potential safety concerns. Microorganisms passing this assessment receive a Qualified Presumption of Safety (QPS) status and are entered on EFSA´s QPS list. Applications for market authorization of products containing strains of microorganisms on this list qualify for fast-track safety assessment.

Figure 6 illustrates the process by which EFSA evaluates and establishes the Qualified Presumption of Safety of microorganisms in novel food applications.

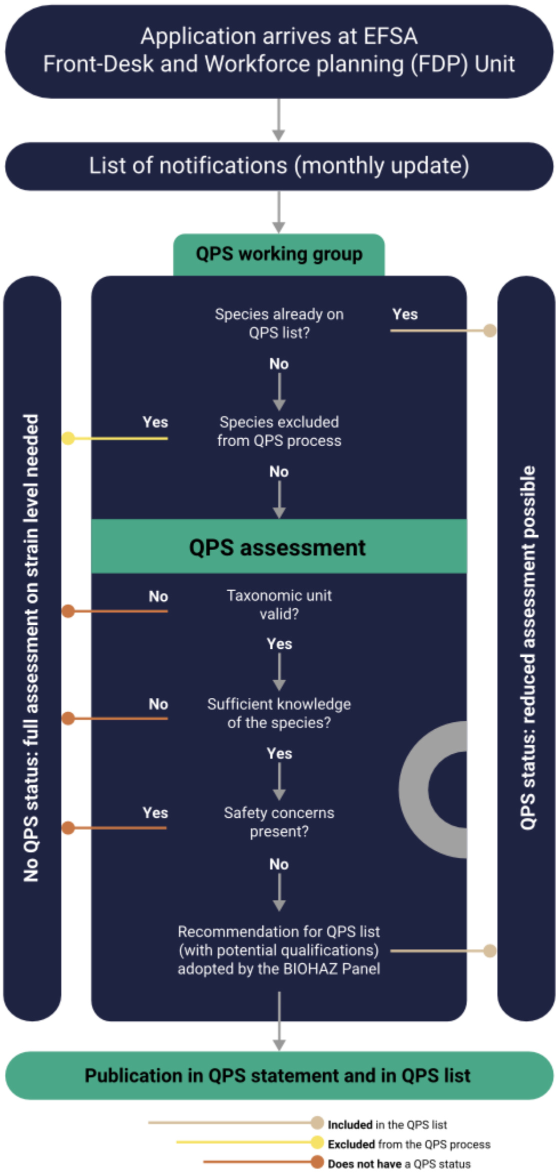

Figure 6: Illustration of EFSA's work to establish the Qualified Presumption of Safety for microorganisms in applications for market authorization of novel food products. (Available at https://www.efsa.europa.eu/en/applications/qps-assessment)

The QPS assessment is conducted independently of the safety assessment of the product itself (performed by the relevant EFSA panel) and the QPS status applies to the taxonomic strain of (the) microorganism(s) and not to the product containing it/them (Koutsoumanis *et al.*, 2023).

Possible risks related to the "formulation or processing" of the final product are part of the EFSA safety assessment. This means that QPS status is granted independently of the concentration levels of the microorganism in the product. In cases in which data is lacking on the effect of "the direct exposure of humans and animals to viable cells" but a well-documented body of knowledge exists on "the safety of their fermentation products and/or their biomasses in the food and/or feed chain", the QPS status covers "production purposes only" and the application must include data to confirm that no viable cells exist in the final product (EFSA QPS). For products containing microorganisms without QPS status, full safety assessments are demanded. Among such microorganisms we find those that are not well defined; those for which safety concerns are identified; and those for which it is not possible to conclude whether they pose a safety concern to humans, animals, or the environment.

Per December 2024, the QPS list contains 117 microbial species and viral families, where most (91) are bacteria (Hazards et al., 2023; Allende et al., 2025) Some of the commonly used microbial strains in industry are briefly outlined in chapter 3.

According to EFSA, the QPS approach can be extended to genetically modified microorganisms (GMM) serving as "production strains, biomass or active agents" as long as "the species of the parental/recipient strain has QPS status" and "the genetic modification does not raise safety concerns" (EFSA QPS). The latter issue is covered in the safety assessment of genetically modified organisms (under Directive 2001/18/EC) or genetically modified food and feed (under Regulation (EC) No. 1829/2003). Figure 7 illustrates the information required in the authorization procedure for novel foods (tissue engineered or SCP) and GMM derived foods, respectively, as presented in a recent publication by (Fytsilis et al., 2024) on the toxicological risks of dairy proteins produced through cellular agriculture.

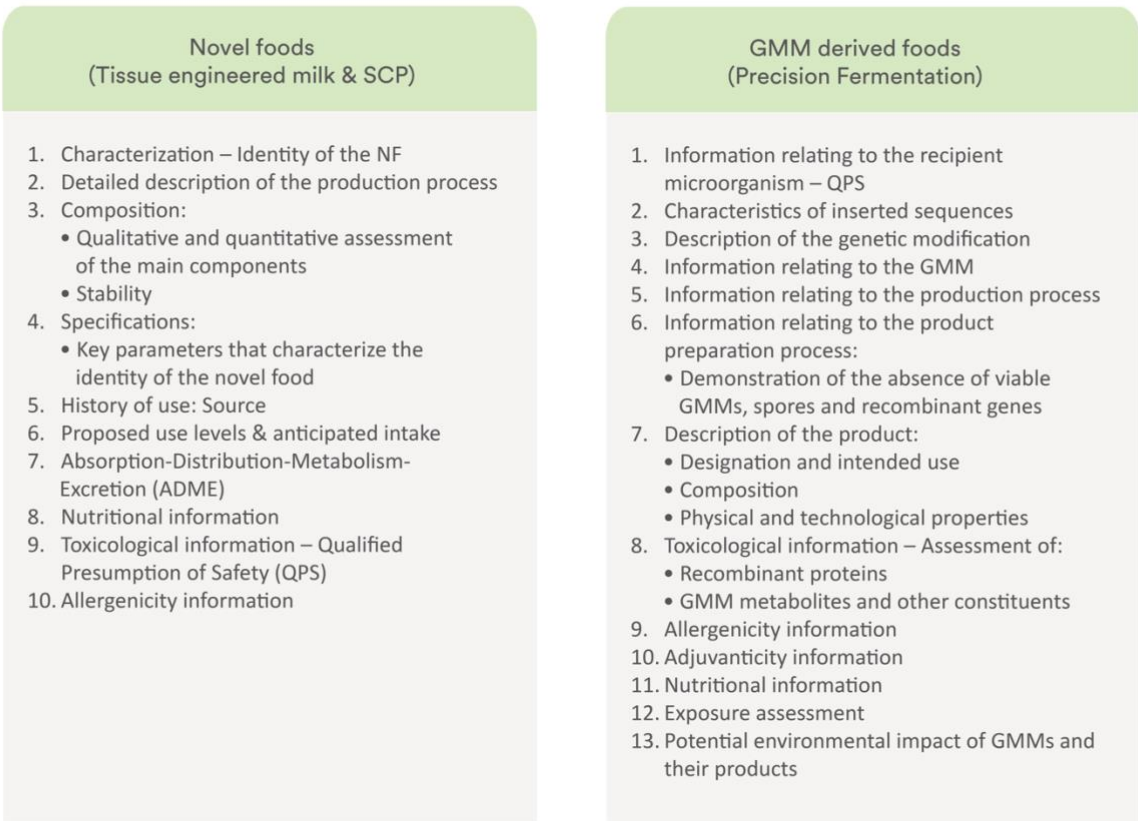

Figure 7: Overview of the required information in the authorization procedure as laid down in the EU Novel Food Regulation and the GMO regulation (adopted *from* (Fytsilis et al., 2024)

In summary, the extent of regulation of genome edited (GMM) or synthetic microorganisms from contained production lines will depend on 1) the history of safe use of the microorganism in question, and 2) whether its utilization has involved the use gene technologies.

The collaboration between EFSA and VKM

Norway's GMO regulation is harmonized with EU and follows guidelines established by the European Food Safety Authority (EFSA). EFSA has produced the guidance document EFSA Panel on Genetically Modified Organisms (GMO) 2011) to aid risk assessments of GM microorganisms (GMM), including microorganisms defined as bacteria, filamentous fungi, yeasts, and microalgae. The risk assessment for GMMs is based on a stepwise approach (EFSA 2011) (see stepwise approach in Figure 6):

1. Microbial and molecular characterization: aimed to identify the GMM and its parental organism and to identify and characterize related hazards (e.g. antimicrobial resistance (AMR), virulence, pathogenicity, toxin production).
2. The safety of the genetic modification: focused on the intended and predicted unintended effects of the genetic modification and potential additional hazards derived from the GMM.
3. The environmental risk assessment (ERA): targeted to assess potential adverse effects to humans, animals and the environment resulting from the deliberate release of the GMM into the environment. ERA is further complemented with post-market environmental monitoring.
4. Safety for humans and animals, including intended and unintended effects.

The aspects on the molecular characterization of GMMs in the guidance from 2011 have been superseded in 2018 and 2019 and replaced by the guidance of the EFSA CEP panel from 2019. Of relevance here is that EFSA has included a step in the risk assessment with the requirement of whole genome sequencing (WGS) analysis for characterization of microorganisms (including GMMs) used as feed additives or as production organisms, and toxicological studies of the feed additive in the animal with a specific focus on metabolites that can affect the consumer. Additional EFSA guidance documents are also available for food enzymes, food additives, food flavorings and feed additives (Jaime Aguilera and Kovalkovicova, 2021). An EFSA report from 2022 points out that there are no clear criteria for differentiating between GMM and a synthetic organism (Rychen et al., 2018; More et al., 2022). The report recommends the inclusion of 'omics' high-throughput experimental studies and the application of bioinformatics tools in the risk assessment.

The Norwegian Scientific Committee for Food and Environment (VKM), which collaborates closely with EFSA, adheres to the EFSA guidance documents. VKM carries out independent risk assessments for the Norwegian Food Safety Authority (Mattilsynet) for products produced under contained conditions, and for the Norwegian Environment Agency (Miljødirektoratet) for products on the market or released into the environment that contain GMOs. The VKM has stated that the EFSA guidance on risk assessment of GMOs and their products intended for food and feed is suitable for genome edited microorganisms, although their regulatory landscape can be considered complex due to the various uses of microorganisms and their products (VKM and Marthe Ganes Jevnaker, 2021). EFSA has, however, in 2024 pointed out that some of their guidance documents need to be updated to be better adapted to recent applications in genome editing.

Through the EEA agreement, Norway has negotiated the right to supplement risk assessments of GMOs that falls under GMO Directive (2001/18/EC), e.g. living GMOs to be released into the environment with assessments of the ethical implications, societal utility and sustainability aspects of their use. The legal framework in this sense provides support and direction for the use of new genome editing technologies in the microbial production of sustainable feed and novel foods.

Suggested changes to the regulation of GMOs

Countries around the world are discussing existing GMO regulations and accompanying guidance documents. Several have initiated processes of de-regulation of genome edited organisms. Generally, there are two main trends in the global regulatory landscape: i) countries regarding genome edited organisms as GMOs but aim to simplify regulations, and ii) countries excluding genome edited organisms where no foreign DNA is inserted from the scope of regulations (defining them as non-GMOs) but requires confirmation (Tachikawa and Matsuo, 2023).

In 2020, the Norwegian government inaugurated a public committee mandated to carry out a broad review on the production and use of GMOs and assess risks and ethical dilemmas. The committee concluded their work in 2023 with the report «Genteknologi i en bærekraftig fremtid» ("Gene technology in a sustainable future"). The members agreed that any new proposal for regulating products of organisms developed with genome editing should take into account consumer interests, transparency and stimulate research and innovation (Genteknologiutvalget, 2023). However, the committee members disagreed on how risks posed by organisms developed with gene technologies should be assessed in regulatory decision-making. Most of the members argued for significant restructuring of the regulatory framework, while a minority argued for adaptation and updating current regulation and practice. The Norwegian government has recently approved a revised Gene Technology Act, with more lenient regulation for GMM medical products and for research purposes. The revised law emphasizes support for innovation and research, and states that Norway will align with possible future revisions decided by the EU.

In the EU, there are ongoing processes to relax what is regulated under the current GMO Directive (2001/18/EC). These processes focus on plants and suggest a new directive for the regulation of new genomic techniques (including genome editing) (EFSA, 2020; Commission, 2021; Jaime Aguilera and Kovalkovicova, 2021; Eidem, 2022; More *et al.*, 2022; Hazards *et al.*, 2023). One can assume that the same deliberation may also influence future regulation of GMMs and NGTs in micro-organisms. As EFSA is currently revising the guidelines for GM animals, one may further expect revisions to the guidelines for risk assessment of GMMs, established by EFSA in 2011. This may include an elaboration of the relevance of the proposed changes to the EU regulation of genome edited plants for the regulation of genome edited microorganisms, including the possibility that some categories of the latter are taken out of the GMO scope.

6. Assessment of environmental and social sustainability

Genome editing technologies may contribute substantially to the development of sustainable food and feed production systems. Expectations are that these technologies will help amend the negative environmental impacts related to climate change, prevent fossil resource depletions, improve the use of land and water resources, and contribute to positive socio-economic development. The use of these technologies is, however, still in its early stages. Accordingly, it is important to critically assess whether the products developed through these technologies are delivering on their promises, ensuring that potential benefits outweigh any environmental, health, or socio-economic risks.

This section provides some examples of frameworks to assess the sustainability of food and feed products, and production systems based on precision fermentation. The potential environmental, health and welfare, ethical and economic implications of implementing GMM foods and feed are also included in this section.

6.1 Sustainability framework and methodologies

A sustainability framework serves as a guiding structure for the evaluation of whether a product, process or a system is sustainable. It brings together diverse approaches and perspectives for assessing environmental, economic and social dimensions in an integrated way.

Life cycle sustainability assessment (LCSA) is such a conceptual framework that seeks to incorporate environmental life cycle assessment (LCA), social life cycle assessment (sLCA) and life cycle costing (LCC) (UNEP, 2020). While LCSA offers a structured way to address the environmental, societal and economic dimensions of a system, its application in emerging sectors such as microbial production is still under development. For microbial production, relevant impact categories must be carefully selected to reflect the technology's stage of development, data availability and the fundamental characteristics of the study. LCA is more developed than sLCA and LCC, and therefore often used independently. LCA is the most applied sustainability model used in the microbial field. It has been applied to compare milk protein produced through fermentation processes to milk protein from the traditional dairy industry (Behm *et al.*, 2022). LCAs show that PF-derived protein can outperform established protein systems in sustainability, but further gains rely on feedstock sourcing and energy sources for fermentation (Eastham and Leman, 2024).

Alternative frameworks exist that could be considered. The European Commission´s Joint Research Centre recently published criteria for a safe and sustainable by design (SSbD) framework to aid the European Union´s Chemicals Strategy for Sustainability (European Commission 2024). The SSbD framework aims to ensure that materials and chemicals are safe and sustainable throughout their life cycles. The assessment initially covers hazards, production and processing risks, as well as health and environmental risks at the use stage, in addition to a more extensive assessment of environmental sustainability (by LCA) and an optional socio-economic assessment. While this framework does not apply to feed and food applications, its adaptation and validation for food systems could be explored, especially given that it integrates *safety* with sustainability at the earliest stages of development. Although microbial productions occur in closed containment (i.e., in bioreactors) from which escapes are unlikely, accidents may still occur in which genome edited organisms are released into the environment.

Five ecological principles have been put forth by (Muscat *et al.*, 2021), to guide biomass use towards circular economy in ways that are beneficial to land-based food systems. They include safeguarding and regenerating the health of our (agro)ecosystems, avoiding non-essential products and the waste of essential ones, prioritizing streams for basic human needs, utilizing and recycling by-products and using renewable energy.

FAO has developed a framework for the assessment of sustainability of food systems, the SAFA (Sustainability assessment of food and agriculture) (FAO, 2014). This framework guides the assessment of the several ways in which food and agricultural systems impact people and the environment. SAFA seeks to harmonize themes, terms and definitions used in various frameworks, and tailor these to food and agriculture processes. The SAFA framework is extensive and operates within the four dimensions *good governance*, *environmental integrity*, *economic resilience* and *social. well-being* (see figure 8). Within these dimensions, it specifies twenty-one overarching themes (universal sustainability goals), 58 sub-themes (sustainability objectives specific to supply chains) and 116 measurable indicators that are key to measure performance and progress (FAO, 2014; Zarbà *et al.*, 2025). While the SAFA framework cannot be used for certification purposes, it constitutes a valuable tool with which to perform holistic assessments of the impact of microbial productions on the many dimensions and intricate workings of existing food systems. Its inclusion of a fourth sustainability dimension, *good governance*, further enables assessments of the possible of influence of the introduction and regulation of novel food and feed products on citizens' trust in producers, authorities and managerial systems.

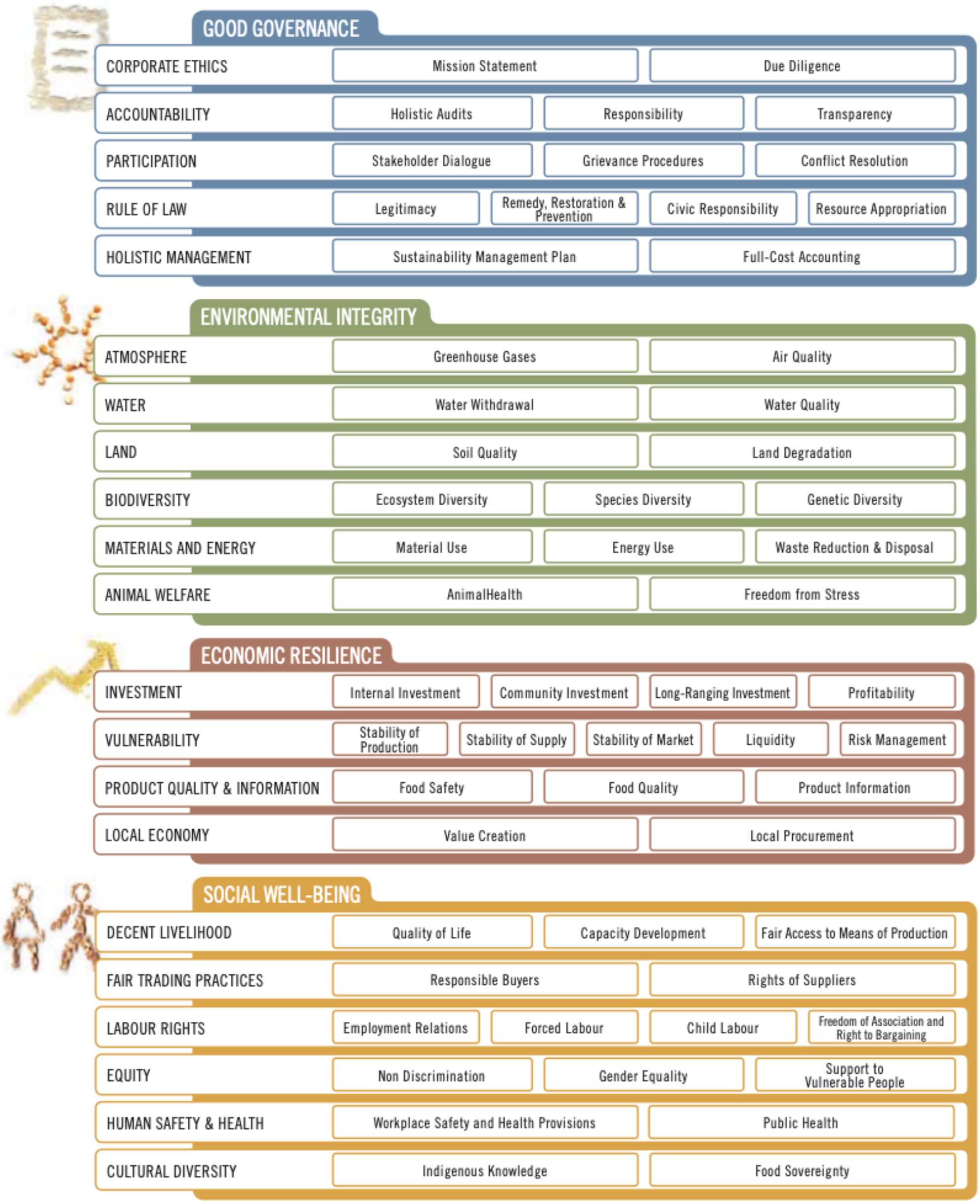

Figure 8: The four dimensions and twenty-one themes of the SAFA framework (adopted from (FAO, 2014)

6.2 Environmental promises and risk

The advantage of using microbial production in the development of food and feed products lies in the scalability and efficiency of the production processes compared to traditional agriculture or aquaculture. A US scenario report predicts that precision fermentation can lead to a 75% reduction of greenhouse gas emissions from animal agriculture (a drop in net emissions of 65%), a fall in water usage of 75% (a net reduction of 60%) and envisions that land freed for reforestation can lead to capture of more than 5.5 bill tons CO2 eq. by 2035 (RethinkX, 2019). The same report addresses consumers' environmental concerns by highlighting the benefits of reduced need for traditional livestock farming. The potential contribution of microbial production technologies in decreasing the need for traditional livestock is supported in some scientific literature (Järviö *et al.*, 2021; Teng *et al.*, 2021; Augustin *et al.*, 2024) but contested in other sources (Behm *et al.*, 2022).

Faced with novel technologies, responsible pre-assessments should always consider whether there are alternative solutions which could solve the same problems. Moreover, different geographical regions may have different reasons for adoption, e.g., animal welfare may be a driver connected to the potential to reduce the use of animals in industrial animal agriculture in Germany, whereas health aspects connected to improved food production drive may adoption in Singapore and the US (Ye *et al.*, 2025). Further, new bioproduction infrastructure and supply chains require physical areas to different degrees depending on the species and processes involved. This may have positive impacts if food and feed can be produced in industrial areas and lead to a reduction in land-use conflicts.

While industry points to a range of environmental gains, there are also environmental concerns associated with the introduction of novel forms of food and feed production. Many assessment results and LCAs are presented by private companies, and underlying data are not accessible. Moreover, LCA studies often rely on data from pilot scale studies and focus on a selection of indicators, leading to variability in the results. Most studies expect the consumption of sugar used for fermentation media and of electricity for production processes to be the main contributors to impact (Järviö *et al.*, 2021; Behm *et al.*, 2022). Nevertheless, there seems to be agreement in the literature that because the use of feedstocks may be expanded in microbial production lines (to include substrates like methanol, CO_2, marine or forestry side streams) and because such production lines may utilize renewable energy sources, they hold the potential to mitigate some of the greenhouse effect (Järviö *et al.*, 2021; Behm *et al.*, 2022; Shi *et al.*, 2022). For example, there are opportunities for microbes growing on hydrogen and methanol, which can be made with renewable electricity, combined with water, carbon dioxide and a very small amount of fertilizer.

6.3 Human health and animal welfare considerations

A comprehensive sustainability assessment must also consider social aspects, including human health, nutrition, and animal welfare. Evaluation helps to ensure that microbial feed and food are not just resource-efficient, but also safe, ethical and beneficial to society.

One may start with the nutritional completeness of microbially produced proteins, particularly when they are intended to replace complex natural products. For example, a single synthetic dairy protein produced through microbial fermentation (Fact box 3) does not replicate the full complexity of natural milk. Unlike animal-derived milk, microbial production typically does not include other key components such as lipids, carbohydrates, minerals, and vitamins (Yi and Kim, 2021). This is especially important to consider in sensitive applications like infant formula, where nutritional balance is critical. For comparative assessments of milk protein from precision fermentation and conventional agriculture, the functional unit should reflect the nutritional value delivered, rather than simply mass, to ensure meaningful evaluation of protein quality and dietary contribution.

As with all food proteins, there is a potential for allergenicity, particularly for individuals with existing protein-related allergies. However, studies on specific applications, such as those by (Jin *et al.*, 2018; Reyes *et al.*, 2021), have indicated a low risk of allergenic response, though this must be evaluated on a case-by-case basis, as current regulations require. Importantly, protein engineering offers the possibility to reduce allergenic potential, just as it does in conventional food production. Nonetheless, as with any food processing method, there remains a small possibility of residual or unintended allergenic proteins being present. Since the use of synthetic proteins in food is still relatively new, long-term safety data is limited, and continued research will be essential to fully understand their health (Wood *et al.*, 2023) and ethical implications.

Alternative proteins promise other, more direct, benefits to animal welfare. Limited but promising attempts have been made to replace fish meal with microbial proteins. In Atlantic salmon, 55% fish meal has been successfully replaced with bacterial proteins (SCP) without compromising growth performance while also improving the apparent digestibility of several essential amino acids (Tlusty *et al.*, 2017). In rainbow trout, replacement of up to 10% of soybean meal with proteins from *Methylorubrum extorquens* had no negative effect on growth and even resulted in a significant increase in fish survival (Hardy *et al.*, 2018). Higher inclusion rates in rainbow trout fry, up to 50%, could be achieved and were associated with improvement in growth performance (Zamani *et al.*, 2020). While microalgae are rich in omega-3 that are known to be beneficial for fish health, studies have shown that replacing fish meal with 20% microalgae (using the microalgae *Nannochloropsis oceanica*) leads to reduction in feed intake. This leads to a poorer feed conversion ratio (FCR) and lipid and energy retention (Sørensen *et al.*, 2017). This can be alleviated using pre-treatment to rupture the microalgal cell wall to obtain extracts, or purified components.

Cod aquaculture, which is currently trying to (re)establish itself to become a major contributor to the Norwegian aquaculture industry, faces challenges related to gut disorders (intestinal strangulation) in the domesticated fish (Skedsmo *et al.*, 2024). A recent report by Nofima describes this as the largest cause of death in the ocean fish pens. The condition afflicts all age groups and causes animal welfare and economic problems – the latter partly because particularly the larger fish are afflicted. While it is at present uncertain whether genetic or environmental factors (or a combination) are the main cause of these gut disorders, feed is demonstrated to have an effect on gut health (Albrektsen *et al.*, 2006; Grisdale-Helland *et al.*, 2008). Accordingly, the sector is seeking new and better feed ingredients catering to the specific needs of cod, including components made from single cell proteins (SCP) and algal oils. Like for the other forms of aquaculture mentioned, further refinement of microbial feed ingredients and assessments of their impact on fish health are still needed.

6.4 The protein debate: Balancing benefits and impacts

The use of precision fermentation technologies utilizing the productive potential of microorganisms is often advanced as a response to the increasing need for protein to support a growing global population, and to fight malnutrition. Genome editing tools are moreover considered to support democratic food production practices, as they are cheaper and more efficient than older tools of gene modification and should thus be more available to small-scale producers. The RethinkX think tank argues that new technologies of protein production may decentralize the food sector by enabling any country with any kind of climate' to produce food locally. Allowing the production of food in urban areas in which the costs of transportation and distribution are less, this shift could lead to reduced price volatility and increased security for consumers (RethinkX, 2019). It could moreover reduce the reliance on imports and large corporate players.

While RethinkX foresees the introduction of alternative proteins on the US market to cause severe disruptions to the country's animal agriculture industry, a recent scenario analysis predicts an increase in market shares of alternative protein-based food products (dairy and cultured meat) on Norwegian markets to have little impact on Norwegian animal agriculture (Mittenzwei *et al.*, 2025). While a reduction in the number of animals is likely, this reduction will be mitigated by a reduction in imports, leading to an increase in national self-sufficiency. Because markets tend to bifurcate under substitution transitions, the analysis predicts that if current policy regimes do not radically change, "the structure of relatively extensive production and small farm units could place [Norway] in a position to become a global supplier of high-end natural products in the future"(Mittenzwei *et al.*, 2025). The transition to alternative proteins, the authors argue, is likely to have less impact in countries with a protected agricultural sector, like Norway, than in neoliberal countries dependent on animal agriculture exports.

Complementing the many publications on the promises and possibilities of the transition to alternative proteins is a recent literature review by (Duluins and Baret, 2024) critiquing the reductionisms involved in publications on this transition. Such reductionisms include the tendencies to reduce food to a single macronutrient (proteins) and to foster (mis)conceptions about the nutritional interchangeability of proteins. They further involve the depiction of animals and alternative proteins in terms of comparable and exchangeable protein delivery systems. In response to this, the review aligns with a series of recent publications emphasizing the significance of animal production systems beyond their nutritional value, arguing for the importance of animals in supporting ecosystem services (nutrient cycling, landscape management etc.), providing co-products (like manure for fertilizers and leather), and sustaining rural livelihoods and cultural meaning (Dumont *et al.*, 2019; Alders *et al.*, 2021; Wood *et al.*, 2023). Concerns have also been addressed by for example Patti Whaley, Trustee of the UK Food Ethics Council, who claims that the argument of feeding the world more protein is not valid, as the problem of hunger relates to a poor distribution of food, and not a matter of food production volumes (Whaley, Patti, n.d.). Also, without subsidies, the price point for fermentation-created dairy products volumes is higher than for ordinary dairy products (high or even unstable). The Finnish research institute VTT has estimated that the production cost of synthetic egg white protein may be 10 EUR per kilo (VTT, 2020). Cost is a key factor for market uptake and a bottleneck for deployment of the industry. In addition to factors like transportation and distribution mentioned above, the cost of alternative proteins is influenced by the scale of production, the fermentation technology, and the production efficiency of the wild-type or genome-edited microorganisms.

6.5 Transparency and traceability

Labelling ensures the traceability of an ingredient or product back to the source. This is specifically important when it comes to synthetic proteins, as they may not be structurally and functionally identical to the origin. Lack of clarity in labelling laws and the use of terms on products can bring inaccurate and potentially misleading information to consumers. Moreover, consumers today are exposed to a profusion of product claims around synthetic food, such as lactose-, hormone-, GMO-, antibiotic-, cholesterol-, and/or pesticides-free. These are added to packaging to provide positive product statements and are not enforced by regulations. While reflecting and responding to consumers' concerns for health and environmental impacts, and sometimes providing valuable information, such label claims can potentially also mislead or confuse. Moreover, as this kind of labelling is not enforced by regulation, it is rarely investigated for accuracy.

Gene modification or editing of microorganisms can be carried out using a diversity of techniques, but not all these falls under regulatory definitions of GMO. According to Regulation (EC) No 1830/2003, food substances processed with a genome edited microorganism do not require GMO-labelling if they do not contain the GMO, whereas food produced from a genome edited microorganism must be GMO-labelled if the microbe or its genetic material is present. Regulatory discrepancies exist as products with detectable engineered genetic material need to have a label informing consumers of the ingredient, while products made with extremely processed bioengineered ingredients with no detectable DNA from the GMO do not have to disclose it (Poinski, 2022). Additionally, there are differences between the labelling regulations globally, bringing further risk of inconsistencies (Hanlon and Sewalt, 2021).

6.6 Market and Consumer acceptance

Microbial food and feed products have the potential to be more environmentally and economically sustainable than similar products from other sources. This leads to the need to know more about the conditions for social acceptance. Novel food products can be accepted or rejected for various reasons, including their health effects, taste profile, , and cultural or emotional attitudes to the product. Products containing alternative proteins will often be highly processed, leaving their market uptake dependent on public debates on the (negative) health effects of ultra-prossesed foods (Malila *et al.*, 2024). Microalgae are a common ingredient in food in many parts of the world but constitute a relatively new type of ingredient in Europe. Studiesnonetheless indicate Europeans' acceptance for low inclusions of microalgae in food (Olsen *et al.*, 2024). (Banovic and Grunert, 2023) have studied the determining aspects of consumer acceptance of and attitudes to food products generated by fermentation technology. They found that framing the products as *natural* instead of *sustainabl*e, and emphasizing the similarity of their production to conventional methods, affected consumer acceptance positively. This caused them to argue for the need to align the regulation of novel precision fermentation products with existing regulations for nutritional claims and labeling of natural products (1924/2006, 2006; 1047/2012, 2012). When it comes to precision fermentation, some products such as synthetic egg white, are likely to find a substantial proportion (51–61%) of consumers willing to try the product, with vegetarians and vegans displaying the highest enthusiasm (Zollman Thomas *et al.*, 2023).

In a study on insects and microalgae in feed, (Weinrich and Busch, 2021) found that the more clearly the environmental impact is perceived, the more positively the feed is regarded. Recently, stakeholder interviews in the Norwegian aquaculture sector was conducted to identify what engenders the social license to operate in the aquaculture feed industry.

Because feed ingredients and their respective production processes are key to sustainability improvements, stakeholders placed great emphasis on utilizing waste- and by-products in the industrial production of single-celled proteins, mussels, seaweed, insects, as well as protein sources lower down in the food chain. They further considered it important to identify new feed ingredients that promote animal health and improve growth and feed efficiency.

Public surveys performed by (Farstad and Remøy, 2024) identified Norwegians' general lack of knowledge about what is used in animal feed. Respondents appreciated use of Norwegian feed raw materials but were only moderately willing to pay extra for this. There was relatively high acceptance of the use of insect-based feed in livestock and salmon farming, also been confirmed in another study.

Historically, consumers have had various reactions to the use of biotechnology and gene technologies depending on their use and assumed benefits and risks. While use within medical or pharmaceutical fields has been considered acceptable, the use within food and environmental systems has met more skepticism. For example, people have expressed concerns regarding GMO plants and animals in connection with their potential risk to human or environmental health, the potential monopolization by large biotechnology companies, and other ethical issues (Helliwell *et al.*, 2017; Hermadi *et al.*, 2021; Kjeldaas *et al.*, 2021). Within Norway, two surveys have been conducted, presenting somewhat conflicting findings. The report issued by the Biotechnology Advisory Board in collaboration with the Geneinnovate-project points out that the majority of respondents are positive to the use of genome editing in agriculture and aquaculture if this is beneficial for society or contributes to sustainability. In this study, many of the respondents were concerned about risk but trusted that Norwegian authorities would only approve safe products. Although Bugge's study confirmed increasing acceptance for the marketing of GM-based food products in Norway, it revealed that skeptical attitudes to GMOs remain (Bugge, 2020). Skepticism is mainly connected to risk but also related to other (environmental and/or ethical) values (Bugge, 2020). None of these studies included questions connected to the use of genome editing in microorganisms. And it remains difficult to investigate consumer acceptance and attitudes to products which (barely) exist or are far removed from the everyday life of consumers (e.g., aquafeed) (Weinrich and Busch, 2021). The substitution of an ingredient in a final food or feed product, for example of a natural with a synthetic protein, is typically driven by economic concerns rather than by consumer preferences (RethinkX, 2019). However, for society to fully harness the benefits of new food and feed products, consumers must have confidence in the food they eat as well as in the regulatory framework for approval. Future consumer acceptance of fermented food products will probably depend on the benefits of the product itself as well as on the context of its production process - for example to what extent it contributes to improving animal welfare in intensive industries (Banovic and Grunert, 2023; Zollman Thomas *et al.*, 2023) or removes the use of higher animals completely. This complements what has been found in surveys on genome editing; that the intention behind the application of the novel technology impacts social acceptance.

7. Conclusion and recommendations

This report has brought together a multitude of issues relating to the possibilities and benefits of employing precision fermentation technologies in the production of novel and more sustainable food and feed products.

In describing the Norwegian industrial actors, research activities and infrastructures involved, the report may contribute to increased collaboration among the different actors and to the further development and application of precision fermentation technologies within a Norwegian context. Our investigations reveal that although research and development projects exist, there is a need to strengthen efforts, particularly in what relates to the microbial production of feed to the aquaculture industry and the circular use of resources.

In describing recent technological developments together with the many agents involved, the report highlights the complex environmental, societal and ethical contexts these technologies are part of, and that should be considered in any discussion of the potentialities of the technologies themselves.

Clear, adequate and fit-for-purpose regulation is important for the predictability of industry actors wishing to invest in industrial transitions. For the public, the main concern is to have updated, regulatory frameworks ensuring that risk assessments cover all novel risks to human, animal and environmental health: those emerging from the use of novel biological agents (microorganisms) and novel genome editing technologies as well as those arising from novel forms of processing. Future changes to existing regulations must continue to ensure this. This means that further research efforts and regulatory frameworks alike and must employ a holistic understanding of the food system and of the health and nutritional aspects of old and novel food products. Research efforts must be broader, and the scope and methods of risk assessments updated. It will also be necessary to collect long-term data on the health effects of synthetic proteins and other novel food (and feed) products. The important work of updating existing regulations will likely take much time and effort but will - as exemplified in EFSA's work with the QPS list - become easier as information is accumulated with experience.

As evidenced in the sustainability frameworks presented and in the scenario analysis of the possible impact on novel proteins on Norwegian agriculture, the successful development of sustainable food systems relies on slow, partial and closely monitored transitions. Full sustainability assessments are demanding and, if implemented, likely to slow the introduction of novel products. They are, however, important to ensure that developments within the food system cover all four dimensions of sustainability, including the important dimension of good governance, which is of fundamental importance to the Norwegian public's trust in novel food and feed products, as well as in authorities and managerial systems. To ensure social sustainability, further efforts to predict and - even more importantly - to monitor, the effect of introductions of novel products and industrial processes on local communities and working conditions will be important. The economic sustainability of these products and processes will moreover depend on policy regimes, the cost of production and dissemination, and consumer acceptance (the latter whose dynamisms should be the focal point of further research). Thus, there is a need to develop clear and targeted frameworks for sustainability assessment that cover the all the aspects of sustainability: the environmental, the economic, the social and good governance.

Within both the aquaculture and the animal agriculture industries, an important principle will be to use novel fermentation technology in the benefit of animal health and welfare; to reduce the number of animals being subjected to highly intensive and unsustainable production systems and to improve the (digestive and physical) health of those in remaining (but altered) systems. The possible bifurcation of the protein market may allow investments in more sustainable, industrial production systems as well as in the refinement of existing, small-scale forms of production of traditional ('natural') meat, fish and dairy products with higher prices on the market. The largest gains seem nonetheless possible within the aquaculture industry, where the use of precision fermentation technologies may improve the quality of fish feed and help the development of feed better tailored to the different species' health and nutritional needs.

7.1 Recommendations

Based on the observations made in this report, we offer the following recommendations aimed at guiding Norwegian authorities, enterprises and research actors towards the sustainable and responsible development of genome editing technologies in microbial food and feed production.

Research and innovation

- Expand the knowledge base on microbial feed, especially for new marine organisms in commercial production.
- Prioritize research on microbial strain development, upscaling, and use of rest-raw materials (e.g., food waste, slaughterhouse by-products).
- Encourage interdisciplinary collaboration across sectors to support national missions like sustainable feed.

Health and safety

- Generate more data on the long-term safety and health implications of microbial proteins.
- Address allergenicity and nutritional completeness in synthetic food products.

Strategic Development

- Support the development of Norwegian infrastructure and industrial pilots for microbial production.
- Advance food and feed strategies to meet national self-sufficiency targets.

Regulatory adaptation

- Investigate the specific needs for and future frameworks of feed legislation tailored to alternative feed ingredients.
- Address the heterogeneity of the regulatory landscape, especially concerning gene-edited microorganisms. Ensure that regulations support safe and sustainable innovation.

Sustainability frameworks

- Refine, and validate robust sustainability assessment frameworks to guide evaluation of environmental, economic, and social impacts
- Promote sustainability frameworks that include animal welfare, transparency, and ethical considerations.

Societal and ethical considerations

- Fill assessment gaps by investigate the economic and social sustainability of microbial production
- Integrate ethical considerations into the development of the microbial industry.

Market and consumer acceptance

- Investigate the conditions for market and social acceptance of microbial food and feed.
- Conduct consumer studies to understand perceptions of native and genome-edited microbial products.
- Improve public awareness and transparency around novel food technologies and labelling.

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