Alternative protein sources for food and feed

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Alternative proteins are of increasing interest in terms of their potential to improve food security and reduce the environmental impacts of food and feed production. This study assesses the current state and future prospects of protein production globally and in the EU to 2050, with a focus on conventional and alternative protein sources for food and feed. While projections show increased conventional protein needs up to 2050, climate change necessitates exploring non-linear scenarios and the potential of alternative proteins in the global and EU protein balance. In this context, four sources of alternative proteins – algae, insects, microbial fermentation and cultured meat – are assessed by comparing them to the conventional sources they may replace, in terms of their relative energy needs, environmental impacts, nutritional content, and their potential for being used as substitutes to conventional proteins in food and feed in the EU. The current level of R&D activity, technological and commercial readiness, and industrial capacity of the said alternatives in the EU is also examined. Finally, the study explores regulatory and technical obstacles to and opportunities for development of alternative proteins in Europe, before proposing a set of policy options that may be considered by EU policymakers for targeted support to the growth of the alternative proteins sector.

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Executive summary

Protein production in the EU is an important issue, touching on European food security, environmental sustainability, energy costs, and economic and social resilience. Interest in non-plant alternative proteins as potential substitutes for animal-based products for food and as substitutes for animal feed (e.g. soya) has grown in recent years, presenting an opportunity to contribute to the overall protein balance. The study focuses in the following four alternative protein sources: algae, insects, microbial fermentation, and cultured meat.

Current and future protein balance

Globally, most dietary protein is plant-based (57 %), followed by animal-derived sources. However, most dietary protein in Europe comes from animal sources (55-60 %). Total alternative proteins consumed in 2020 (including plant-based alternatives) were 13 million (M) metric tonnes, approximately 2 % of the animal protein market. The exact contribution from algae, insects, microbially-fermented products, and cultured meat is unknown but is estimated to be a small fraction of this total. The sources of protein used in animal feed are both non-edible (such as grass) and edible for humans (mostly grains, including cereals and pulses). The EU is almost 80 % self-sufficient for feed protein sources, and has an ample supply of roughage, which is the primary feed protein source, but lower in proteins. However, the EU only produces a quarter of the high-protein oilseed meals which account for 27 % of total feed protein used in the EU. The European 'feed protein deficit' has been a key argument for reconsidering EU feed protein sources in recent years.

The environmental impact of the current protein balance, particularly the production of animal-based proteins, is substantial. Globally, over three quarters of agricultural land and approximately two thirds of agricultural greenhouse gas emissions are associated with animal-based foods. Climate change poses additional risks to the current protein balance.

Looking to 2050, conventional protein consumption is expected to increase by 57 % for meat and 48 % for dairy, assuming continued economic growth and increasing incomes, particularly in Asia. However, the impacts of climate change on food production, already affecting protein production worldwide, necessitate the consideration of non-linear scenarios. Alternative proteins are estimated to account for 11 % of the global protein market for food up to 2035, with plant-based alternatives dominating in this period. Alternative protein sources from algae, insects, microbial fermentation, and cultured meat are also projected to contribute to the protein balance, but data on their potential contribution is limited.

Assessment of alternative protein sources

The production processes for several types of alternative proteins are energy intensive, in some cases requiring higher energy inputs than the conventional proteins they could potentially replace. Energy requirements vary considerably for both microbial fermentation and cultured meat, depending on the process and inputs used, and also reflect large uncertainties in the data.

Insects, microbial fermentation and cultured meat all require feedstocks, which contribute to their land use impacts. However, all of the alternative proteins analysed demonstrate equivalent or lower land use compared with the conventional proteins they may replace, with algae, insects and microbial proteins (in particular hydrogen oxidizing bacteria) being particularly efficient with respect to land use. Efforts to identify and use less impactful feedstock sources for alternative proteins may further reduce their land use impacts.

The review of water use across alternative proteins reveals that algae, particularly microalgae and macroalgae farmed in seawater demonstrate unequivocally better outcomes in terms of water efficiency compared with conventional proteins. While there are uncertainties in the data, notable potential for improvement is possible for microbial fermentation and cultured meat, with the latter likely to use significantly less water than beef production and potentially comparable amounts to poultry production.

Reducing greenhouse gas (GHG) emissions is a major challenge for agriculture globally and in Europe, and alternative proteins, including plant-based proteins, could play a role in mitigation efforts. As feed sources, algae production results in more emissions than soybean production, while insect production is comparable to that of other feed sources. When it comes to food, all of the alternatives demonstrate lower GHG emissions compared to beef and dairy production, although cultured meat may have emissions comparable to the most efficient poultry production systems.

Waste is not widely assessed for alternative proteins compared with conventional animal production. Where the issue is discussed, the available evidence suggests that the alternatives generate less waste compared with conventional equivalents, and that this waste is easily recycled. In some cases, alternative protein production processes could use waste from other processes, improving their overall waste footprint.

The nutrient profile of alternative proteins matters to their ability to replace conventional sources in human or animal diets. Some of the alternative protein sources offer a beneficial macronutrient profile when compared with conventional animal-based proteins, although research on their bioavailability depending on type of alternative protein, mode of production and mode of processing is ongoing. Microalgae and insects have a higher protein content than their conventional counterparts, although digestibility is lower. They also have a higher fiber content. The fat content of algae and mycoprotein is much lower than that of conventional animal-based protein sources. Algae also contain healthy fatty acids in high concentrations. Cultured meat is assumed to provide the same macronutrient profile as the conventional meat products they could replace, but the feasibility of this assumption remains uncertain. Alternative proteins have advantageous profiles when it comes to their micronutrient content. Algae, insects and mycoproteins all can provide key vitamins and minerals in higher proportions than conventional proteins. However, it is still uncertain how processing affects these micronutrients and therefore their bioavailability. The bioavailability of micronutrients in insects has been shown to be equivalent to or higher than that of beef meat. Cultured meat is assumed to provide the same micronutrient profile as the conventional meat products they could replace, but this is also still uncertain.

Nutritional content and other considerations (such as price and consumer acceptance) suggest that cultured meat and fermented alternative proteins (especially mycoprotein) could replace meat and dairy in the EU (mycoprotein is already present on the EU market, and cultured meat has been authorised in the US, Israel and Singapore), although consumer acceptance issues need to be overcome for cultured meat. Algae and insects as foods hold the most potential as alternative ingredients in multi-ingredient products, also considering consumer acceptance issues. Both alternatives present some food safety/allergenicity risks which need to be addressed through processing or during production stages (for algae). Insects and algae also have the potential to replace a proportion of feed in the aquaculture, monogastric, and ruminant sectors.

Investments in research and development (R&D), which include both private and public funding, have been increasing across all alternative protein sources in the EU. Major investments at EU or national level have been recently announced to support research as well as commercialisation in cellular agriculture, encompassing both fermentation and cultivated meat. Increased funding is also notable for algae and insects R&D, although not to the same level. The recently launched EU Algae initiative holds the promise of growing investment in that sector.

Insects, algae and mycoproteins have well-established production and processing methods, and multiple market applications, thus reaching advanced technology and commercial readiness levels (TRL 8-9 and CRI 3-4). Algae as a food source has reached a higher commercial readiness level than as feed, while the converse is the case for insects. Recombinant proteins and cultured meat have generally reached lower levels of technology and commercial readiness (TRL 5-7 and CRI 1-2). Microbially fermented dairy products have reached commercial maturity but are not yet widely available on the market (CRI 2). Cultured meat is not yet authorised on the EU market (CRI 1), but has been granted approval in the US, Israel and Singapore (CRI 2).

In the EU, the algae sector has the potential for growth but requires infrastructure investments to overcome processing limitations. The insect industry is expanding, with a focus on technological and financial developments to meet rising demand and foster circularity. While still in comparatively early development stages in the EU, cultured meat has a high level of technical expertise and pilot projects to address scale-up and commercialisation challenges. Insufficient food grade industrial capacity is a known bottleneck for microbial fermentation, in the EU and elsewhere.

Opportunities, challenges and policy options

While the alternative protein sources present opportunities to strengthen European food security and sustainability, they face considerable obstacles in scaling up technologies and achieving commercial viability against subsidised conventional sources. Common barriers include the need to optimise still-maturing technologies, expand processing and production capacity, reduce inputs and costs, address infrastructure limitations, and navigate complex regulations and legislative barriers.

The report identifies policy options to help scale up alternative protein development and production in the EU. Proposed interventions include 1) targeted research funding to advance technologies and address knowledge gaps, 2) industrial policy investments in infrastructure and processing facilities, 3) incorporating environmental considerations into regulatory approval processes, and 4) enhanced coordination across policies and stakeholders.

If pursued together, these complementary options could support sector development, enabling alternative proteins to support EU goals for a more sustainable, resilient, and self-reliant protein supply. Embedding support within a coordinated, whole-system approach to transforming EU food systems can facilitate synergistic policymaking to enhance the potential of alternative proteins for diversifying the protein supply.

Part 1: Protein balance

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1. Introduction

The EU is interested in non-plant alternative proteins as an opportunity to contribute towards multiple European policy objectives, including environmental sustainability, food security, animal welfare and human health. In this context, the European Parliament Panel for the Future of Science and Technology (STOA) has commissioned the present study. It required insights and reliable conclusions about the potential for and challenges related to alternative protein sources to support policymakers to make the best possible decisions about policy directions in the areas of food, agriculture, research, and development of industrial capabilities.

The study had five main objectives: (1) analysing the current and future projected protein balance for food and feed; (2) presenting alternative protein sources and their potential, with a focus on algae, insects, cultured meat, and microbial fermentation; (3) assessing the current state-of-the-art for the alternatives, and (4) challenges and opportunities for their adoption. Finally, (5) policy options were to be proposed to support decision-making for scaling-up development of the alternatives in the future.

Part 1 of the study supports objectives 1 and 2. It provides an analysis of current and projected protein production to 2050, globally and at EU level, the environmental costs of that production and its potential and limits in the context of climate and geopolitical challenges. Proteins of animal and plant origin are distinguished, and the role of alternative protein sources is identified. This is followed by Part 2, which addresses objective 3, and Part 3, which addresses objectives 4 and 5.

2. Methodology and resources used

The evidence and analysis supporting this Part is based exclusively on a literature review. Data on the current protein balance and projections for 2050 have been extracted from a combination of academic and grey literature. The latter includes, for example, reports published by the European Commission, FAO, OECD, and World Resource Institute, consultancies and other private sector organisations.

The information extracted was triangulated, and the most robust and recent estimates were retained. The report aims to communicate the range of data points found when several estimates were documented.

Data on the current state of play for conventional proteins are detailed for some regions (EU, US, China) but much less so at the global level, particularly for feed. Furthermore, environmental impacts in the literature tend to have been estimated for meat production alone or overall diets rather than for protein specifically. Therefore, the available evidence can only be used as a proxy for the overall impacts of the protein balance. For alternative proteins,[1] production volumes and indications of use (e.g. food vs. feed) are generally available but often come from a single source, some of which are not current. Data on the current contribution of alternative proteins to the protein

[1] Both "alternative proteins" and "alternative protein sources" are terms used in the scientific literature, often interchangeably. "Alternative proteins" tends to refer specifically to the proteins themselves, focusing on the end product. "Alternative protein sources" implies a slightly wider meaning, referring to the actual sources that generate or produce the alternative proteins. There is no universally agreed-upon terminology. For consistency, 'alternative proteins' is used in this report, as it is the more widely referenced term.

balance are not by and large available. Also, there are no exhaustive studies of the energy flows in agriculture in Europe to characterise the energy requirements of the current protein balance.

The extrapolation of the protein balance up to 2050 is based on a critical review of available projections, which are significantly more detailed and better substantiated for conventional proteins. By contrast, there are only a few projections up to 2050 of the contribution of alternative proteins to the protein balance, mostly from consultancies (i.e., non-peer reviewed). A review of these projections has sought to clarify underlying assumptions and blind spots.

3. State of play of the protein balance

Protein is essential to human and animal development, affecting growth, repair, and tissue maintenance functions. Protein forms critical enzymes, hormones, and antibodies. It acts as an energy source, assists with transporting and storing substances like oxygen and iron, and provides tissue structure. Proteins also supply essential amino acids that humans and animals cannot produce. Adequate dietary protein is critical to avoid malnutrition, impaired growth, and weakened immunity. Protein is, however, one of many nutrients essential to a healthy diet, such that different diets may achieve desirable protein intake and yet lead to very different health outcomes.

Protein production in the EU is an important issue that touches on European food security (e.g. dependence on feed from third countries), environmental sustainability, energy costs, and economic and social resilience. In this context, the European Parliament published 'A European strategy for the promotion of protein crops' (2017/2116(INI))[2] and 'European Protein Strategy' (2023/2015(INI)).[3]

More recently, non-plant alternative proteins have become salient as a potential substitute for animal-based products. As these alternatives rise in interest from consumers and industry in the EU and other countries, there is an opportunity to consider their wider potential to contribute to the overall protein balance.

This section sets out the state of play for protein in human food and animal feed from conventional animal and plant-based sources and alternative protein sources that could substitute for meat and dairy products. The current environmental costs and geopolitical challenges arising from that balance are also considered.

3.1. Conventional proteins

Conventional proteins (plant- and animal-based) dominate the global and EU protein balance.

Globally, most **dietary protein** comes from plants (57%) (mainly wheat, maize, and rice) and secondarily, from animal-derived sources (i.e. meat (18%), dairy (10%), fish and shellfish (6%), and other animal products (9%)). In Europe, however, most dietary protein comes from animal sources

[2] European Parliament, Resolution of 17 April 2018 on a European strategy for the promotion of protein crops – encouraging the production of protein and leguminous plants in the European agriculture sector (2017/2116(INI)), https://www.europarl.europa.eu/doceo/document/TA-8-2018-0095_EN.html.

[3] European Parliament, Resolution of 19 October 2023 European protein strategy (2023/2015(INI)), https://www.europarl.europa.eu/doceo/document/TA-9-2023-0375_EN.html

(55-60%), overtaking plant-based protein since the mid-1970s.[4]The ratio of protein needs in terms of recommended daily intake (hereafter RDI[5]) to consumption suggests overconsumption of proteins worldwide, on average, with estimates that the average daily total consumption of proteins is between 68g[6] and 80g per person.[7] Excess consumption globally and in Europe is estimated at about one-third more than the RDI (Fig. 1). Overconsumption has also been observed in children.[8]

4 Bonnet C, Bouamra-Mechemache Z, Requillart V, Treich N, 'Viewpoint: Regulating meat consumption to improve health, the environment and animal welfare', *Food Policy* 97: 101847, 2020.

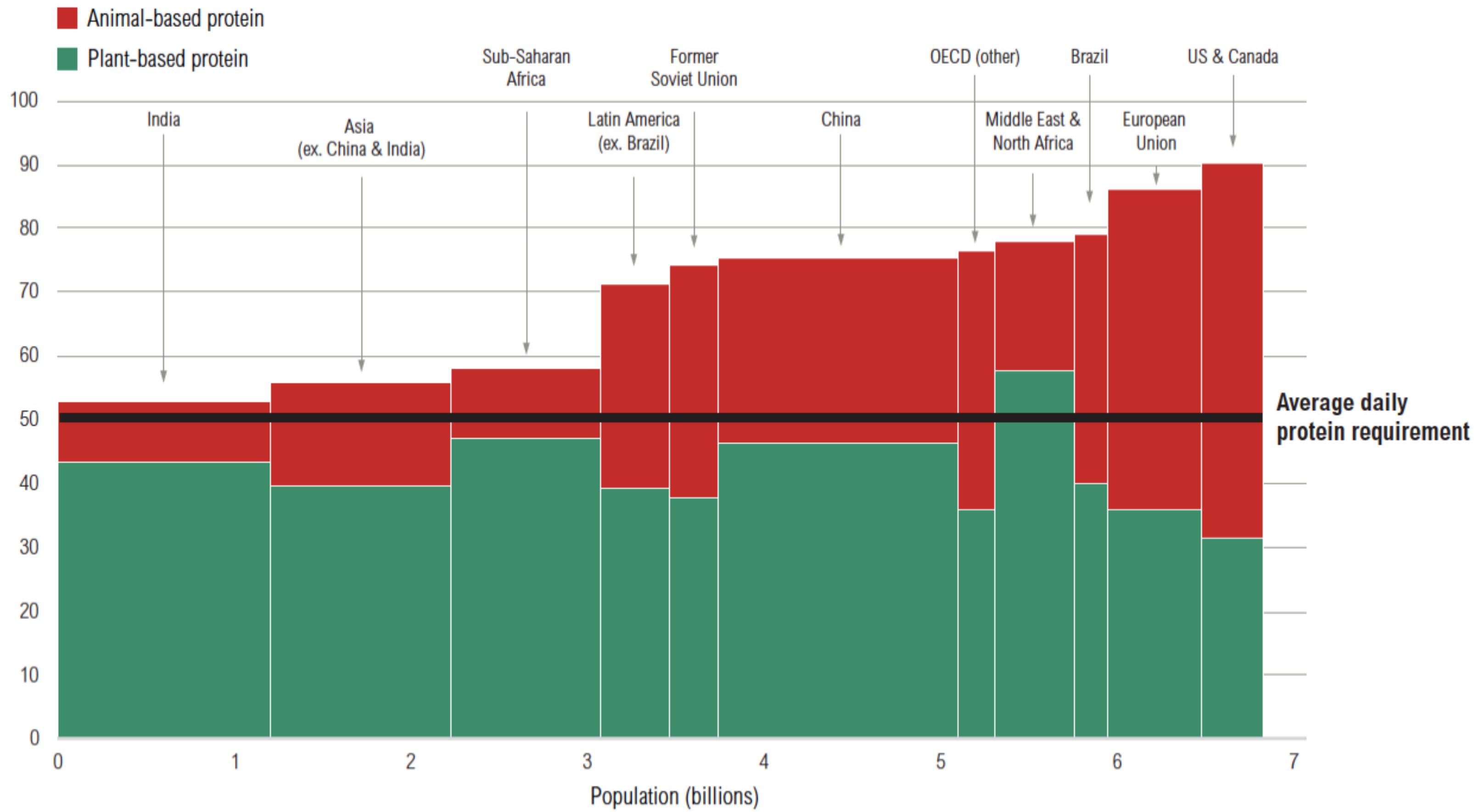
5 The recommended daily intake for adults is 0.8g of protein per kg per day. Wu G, 'Dietary protein intake and human health', *Food Funct.* 7(3):1251-65, 2016. Berners-Lee et al. assume an average of 44g per day. Berners-Lee M, Kennelly C, Watson R, Hewitt CN, 'Current global food production is sufficient to meet human nutritional needs in 2050 provided there is radical societal adaptation' *Elementa: Sicence of the Anthropocene* 6:52, 2018.

6 Ranganathan K et al 'Shifting diets for a sustainable future', Working paper, The World Resources Institute, April 2016.

7 Berners-Lee et al. 2018.

8 "In Europe, the average protein intake in 4–6-year-old children is ~55 g/day. The lowest intake seen among European children of that age (5th percentile) is 32 g/day, which is still more than twice the RDA [Recommended Dietary Allowance]." From: Mariotti F, Garnder CD, 'Dietary Protein and Amino Acids in Vegetarian Diets – A Review', *Nutrients*, 11, 2661, 2019, at page 12.

Figure 1 – Protein consumption exceeds average estimated daily requirements in all the world's regions, and is highest in developed countries, g/capita/day, 2009.



Source: GlobAgri model with source data from FAO (2015) and FAO (2011a). Width of bars is proportional to each region's population. Average daily protein requirement of 50 g/day is based on an average adult body weight of 62 kg (Walpole et al. 2012) and recommended protein intake of 0.8 g/kg body weight/day (Paul 1989). Individuals' energy requirements vary depending on age, gender, height, weight, pregnancy/lactation, and level of physical activity.

Source: Ranganathan et al. 2016.

These averages mask variations: in 2022, 1 in 10 individuals were estimated to have experienced hunger, and more than 1 in 4 individuals were severely food insecure.[9] The scale of *protein* deficiency within those populations is, however, poorly understood.[10] One source estimates that 662 million people were protein deficient in the world in 2018.[11] Comparatively, the EU (alongside the US and Canada) experience low levels of food insecurity.[12] In any case, evidence of protein overconsumption in Europe on average and by a wide margin (fig.2) suggests that European diets are not protein deficient.

Analysis published in 2021 has shown that **the EU is a net importer of proteins**, importing an estimated 26% of the protein it consumes.[13] The principal imported sources are fish and shellfish (the EU imports more than half it consumes - Norway is the biggest supplier, with 16% of the total, all other countries exporting to the EU supplying 4% or less of the total each[14]) and feed (as discussed further below). In particular, Europeans consume imported proteins by consuming meat, dairy and eggs from animals fed with imported feed.[15]

Protein sources for **feed** include sources that are edible by humans (mostly grains, including cereals, and pulses) as well as non-edible sources (e.g. grass). Total global production of these sources is estimated at more than a billion tons (1171.1 MT in 2020), with over 10% produced in the EU (152.6 MT in 2020).[16] The EU feed balance for the period 2022-2023 combines crops (cereals, oilseeds and pulses; 23%), co-products (mostly oilseed and soya-bean meals; 33%), roughage (grass, silage maize, fodder leguminous; 42%), and a residual proportion of non-plant sources (animal proteins, former foodstuffs; 2%). The EU is 77% self-sufficient overall for feed protein sources and fully self-sufficient in roughage, which is the main feed protein source, but lower in proteins; however, for oilseed meals, which represent 27% of total feed protein use in the EU and are high in proteins, the EU only produces 24% of what it needs to feed its livestock sector.[17] This is the European 'feed protein deficit',[18] which has in recent years been a key argument for reconsidering EU feed protein sources.

Concerns about Europe's feed protein deficit have increased as a result of the Ukraine war. Although the EU imports only 4% of soy (either soybeans, soybean meal or soybean oil) from Ukraine and Russia, many countries are dependent on Ukrainian and Russian protein supplies (as well as fertilisers) used in domestic protein production. The war in Ukraine has had a marked effect on

9 FAO, *The state of food insecurity and nutrition in the world*, 2023.

10 Manary MJ, Callaghan M, 'Do vulnerable populations consume adequate amounts of dietary protein?', *The Journal of Nutrition* 147(5):725-6, 2017.

11 Smith MJ, Meyers SS, 'Impact of global CO2 emissions on global human nutrition', *Nature Climate Change*, 8:834-839, 2018.

12 Ibid.

13 Schiavo M et al, 'An agroecological Europe by 2050: What impact on land use, trade and global food security?,' IDDRI, *Study* 08/21, 2021.

14 WWF, *Europe Eats the World. How the EU's Food Production and Consumption Impact the Planet*. 2022.

15 Recent estimates are that the average EU27+UK consumer thus eats a little less than 61kg of soy per year, 90% of which is embedded in animal-based products. Kuepper B and M Stravens. *Mapping the European Soy Supply Chain – Embedded Soy in Animal Products Consumed in the EU27+UK*, Amsterdam, The Netherlands: Profundo, 2022.

16 IFIF, 'Global Feed Statistics,' 2021 https://ifif.org/global-feed/statistics/

17 European Commission, Agriculture and rural development, 'Commission publishes latest forecasts on EU feed protein production and trade', 2022 https://agriculture.ec.europa.eu/news/commission-publishes-latest-forecasts-eu-feed-protein-production-and-trade-2022-11-18_en

18 Kim SW et al., 'Meeting Global Feed Protein Demand: Challenge, Opportunity, and Strategy', *Annual Review of Animal Biosciences* 7:221-43, 2019.

prices, adding to a pre-existing inflationary trend. This has highlighted the EU's dependency on third countries, either for fertilisers,[19] feed, or food, and raised the broader issue of protein self-sufficiency.

For the EU, there are two crucial dependencies worth highlighting, because they can directly threaten protein supply. The first is dependency on a handful of third countries for a significant share of the fertilisers routinely used in crop production: Russia, Belarus, Algeria, Morocco and Egypt.[20] There are significant risks attached to continued trade with these countries, either because of political tensions with the EU, or because of the potential for political instability there. The second dependency is towards soy producing countries. The EU imports about half of the soymeal (feed) it consumes from Brazil, and more than a third from Argentina and the United States.[21] In other words, the supply of soy for feed is heavily skewed towards very few exporting countries, which makes the EU's ability to produce animal based products crucially at risk of any upset in those countries or in trade relations between them and the EU.

Another key rationale for reconsidering the current protein balance, globally and in the EU, is its considerable **environmental** impact. The impact of producing animal-based proteins is a particular concern, encompassing both animal rearing and feed production.[22] Globally, more than three-quarters of agricultural land and about two-thirds of agricultural greenhouse gas emissions are estimated to be associated with the production of animal-based foods.[23]

The production of animal-based proteins also consumes vastly more **water** than that of plant-based proteins.[24] For example, Poore and Nemecek found that it takes about 2,714 litres of freshwater withdrawal per kilogram of beef (dairy herd), 1,451 litres per kilogram of beef (beef herd), 648 litres per kilogram of wheat, 397 litres per kilogram of peas, and 216 litres per kilogram of maize.[25]

There is thus a marked discrepancy between the environmental impact of animal protein production and their contribution to protein intake. A recent assessment of diets in the UK as a proxy for the dominant protein mix in Europe provides the strongest evidence to date of the significantly greater environmental costs of sourcing proteins from animals as opposed to plants.[26] Accordingly, altering the current protein balance globally and in the EU, is widely seen by the scientific community as imperative to tackling climate change.[27] A particularly contentious issue is the use of edible proteins to feed animals. This is a highly inefficient process, due to the 7-12% conversion rate of plant-to-animal protein.[28]

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19 A significant proportion of fertiliser imported into the EU originates from Russia and Belarus, as well as Morocco, Algeria and Egypt. Source: Fertilizers Europe, *Fertilizer Industry Facts & Figures 2022*.

20 Ibid.

21 Reuters, 'Update 1-EU 2022/23 soybean imports at 9.79mln T, rapeseed 6.37 mln T', 2023 https://www.reuters.com/article/eu-oilseeds-imports-idAFL8N36L545

22 Pexas G, Kyriazakis I, Doherty B, The Future of Animal Feed, Report to the Food Standards Agency, London, 2023.

23 Ranganathan et al 2016.

24 Poore J, T Nemecek. 'Reducing food's environmental impacts through producers and consumers' *Science* 360, 987-992, 2018.

25 https://ourworldindata.org/grapher/water-withdrawals-per-kg-poore drawing from Poore J, Nemecek T, 'Reducing food's environmental impacts through producers and consumers', *Science* 360: 987-992, 2018.

26 Scarborough P et al. 'Vegans, vegetarians, fish-eaters and meat-eaters in the UK show discrepant environmental impacts', *Nature Food*, 4:565-574, 2023.

27 e.g. Ivanovich CC et al. 'Future warming from global food consumption', *Nature Climate Change* 13:297-302, 2023.

28 As reported in Berners-Lee M et al. 2018.

It is generally accepted that the increased reliance for protein (and diet more generally) on animal-based products rather than plant-based products has been associated with increasing dependence on **energy** inputs.[29] There are no estimates for the overall energy consumption of the EU protein balance; however, as of 2019, 34% of the energy consumed by the overall EU food sector corresponded to primary production, and 24% to processing. An estimated 70% of the overall energy consumed by the food sector in 2019 was from fossil fuels.[30] Some estimates have shown the profound difference between plant-based and animal-based products in terms of energy input: for example the energy input for growing wheat can be up to 30 times less than the energy input for rearing dairy cows.[31]

Climate change risks highlight the fragility of the current protein balance. Yield stagnation[32] and decline have already been documented in relation to warming temperatures and more frequent extreme weather events. Rainfed agriculture is fundamentally vulnerable to climate change, and therefore, so is plant protein production. Animal rearing for protein production (meat and dairy) on land has experienced growing challenges and particularly thermal stress.[33] Climate change also affects the supply of fish and shellfish for food and feed. Historical data suggests growing challenges to wild fish populations as well as aquaculture.[34]

In sum, from a global and EU perspective, there are geopolitical and environmental reasons for questioning the current protein balance, and whether it can or should be maintained. A different protein balance could involve not only a different ratio of plant-to-animal-based proteins but also the use of alternative proteins. The next section explores the current state of play for alternative proteins, globally and in the EU.

3.2. Alternative proteins

While the EU is not deficient in protein for food or feed per se, alternatives to conventional animal proteins are increasingly being considered, both from the perspective of health and nutrition and environmental sustainability, and to increase resilience in EU food security. The range of alternative proteins considered in a European context belongs to three main groups: (1) plant-based

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29 Usubiaga-Liano A, P Behrens, V Daioglou, 'Energy use in the food system', *Journal of Industrial Ecology* 24(4), 830-840, 2020.

30 Bortoloni M et al, 'Chapter 10 – Assessing energy requirements in the European (EU-28) food sector', *Sustainable Development and Pathways for Food Ecosystems*, 2023, pp.259-272. https://doi.org/10.1016/B978-0-323-90885-6.00008-9; see also Bajan B, J Lukasiewicz, A Mrowcynska-Kaminska, 'Energy Consumption and its Structures in Food Production Systems of the Visegrad Group Countries Compared with EU-15 Countries', *Energies* 14(13), 3945, 2021. https://doi.org/10.3390/en14133945. More recent data for the food sector are not available. Overall, in the EU, the contribution of renewable energy sources to overall energy consumption has been increasing, from 4.3% in 1990 to 11.8% in 2021; during this period the amount and share of solid fossil fuels in final energy consumption fell from 9.6% in 1990 to 2% in 2021; Eurostat, 'Energy statistics – an overview', 2023. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#Final_energy_consumption

31 Monforti-Ferrario F et al, *Energy use in the EU food sector: State of play and opportunities for improvement*. Joint Research Centre, European Commission, 2015.

32 e.g. Hawkins, E et al. 'Increasing influence of heat stress on French maize yields from the 1960s to the 2030s,' *Global Change Biology, 19(3): 937, 2013.*

33 Cheng M, McCarl B, Chengcheng F, 'Climate change and livestock production: a literature review', *Atmosphere*, 13(1): 140, 2022.

34 Barange M et al (eds), *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge adaptation and mitigation options*, FAO Fisheries and Aquaculture Technical Paper No 627, Rome, FAO, 2018; Free CM et al. 'Impacts of historical warming on marine fisheries production', *Science*, 363(6430): 979-983, 2019.

alternatives to conventional animal proteins[35], (2) protein alternatives that are relatively new to the EU but have been important in other cultures and contexts, and (3) protein alternatives that are entirely new to human and animal diets.

Total alternative proteins consumed in 2020 were estimated at 13 million (M) metric tonnes, approximately 2% of the animal protein market, and this includes plant-based alternatives.[36] The exact percentage of protein derived from algae,[37] insects, microbially-fermented products, and cultured meat is unknown but is together estimated to be a fraction of this total, both globally and at the EU level. The extent to which each of these alternative protein groups currently contributes to the protein balance in the EU and globally varies accordingly. This section outlines the categories of alternatives and where data are available, the contribution of those alternatives to the protein balance globally and in the EU specifically.

3.2.1. Plant-based alternatives

Plant-based alternatives to meat and dairy products aim to replicate at least to some degree the taste and textures of conventional animal proteins. These exist on a spectrum: from plants high in protein that are unprocessed or minimally processed, such as peas and lentils, to more processed products such as soy-based tofu and highly processed plant-based products that use biotechnology advances to replicate as closely as possible the taste and texture of meat and dairy products.[38] Projections for alternative proteins imply that most are currently plant-based and will continue to dominate to 2030.[39]

3.2.2. Non-plant-based alternatives

The second group of alternative proteins are relatively new to the EU or specifically for protein production, but there are long-running precedents for their use in other cultures and contexts: these include micro- and macro-algae cultivation and insects. The third group includes alternatives that are entirely new in the sense that they have not until very recently been a protein source for human or animal diets anywhere: they are microbial fermentation and cultured meat. Each of these alternatives is considered in turn.

[35] Plant-based alternatives refers to plant proteins (e.g. wheat, soy, peas and lentils, nuts and seeds) that are used as a direct substitute for animal-based products, particularly where they are trying to mimic conventional animal-based protein sources in taste, texture and/or nutritional composition.

[36] Witte B, Obloj P, Koktenturk S, Morach B, Brigl M, Rogg J, Schulze U, Walker D, Von Koeller E, Dehnert N, Grosse-Holz F. Food for Thought: The Protein Transformation, 2021 BCG. https://web-assets.bcg.com/a0/28/4295860343c6a2a5b9f4e3436114/bcg-food-for-thought-the-protein-transformation-mar-2021.pdf The authors do not define the range or types of alternatives that comprise this total, although plant-based 'meats', and alternatives that mimic meat made from microorganisms are referenced.

[37] Algae is sometimes included with plants in estimates of the protein balance for food (e.g. https://www.expertmarketresearch.com/reports/europe-plant-protein-market), complicating an assessment of its current role in global and EU diets.

[38] World Economic Forum (WEF). Meat: the Future series – Alternative Proteins, 2019. https://www3.weforum.org/docs/WEF_White_Paper_Alternative_Proteins.pdf

[39] Frezal C, Nenert C, Gay H. Meat Protein Alternatives: Opportunities and Challenges for Food Systems' Transformation, *OECD Food, Agriculture and Fisheries Papers*, No. 182, OECD Publishing, Paris, 2022. https://doi.org/10.1787/387d30cf-en.

Algae

Algae include both seaweed (macroalgae) and microalgae, and they have been an important human food for thousands of years.[40] However, their use has varied over time, including in several European countries. Today algae are primarily consumed in Asia; consequently, more than 97% of world algae production is also in this region. Approximately 30 of the estimated 30,000 – 1 million algae species that have been identified worldwide are regularly cultivated or harvested commercially, only 6 of which represent most of the algae intended for human consumption.[41]

In Europe, most commercial seaweed is wild-harvested rather than cultivated. However, two kelp species are currently cultivated on a commercial scale in Europe (i.e. *Saccharina latissima* and *Alaria esculenta*). Furthermore, only a few members of the group of organisms classed as microalgae are cultivated commercially worldwide.[42] Global production data from the microalgae sector indicates that *Arthrospira* (commonly known as Spirulina) is the most produced type, followed by *Chlorella* and *Dunaliella*. Spirulina and *Chlorella* are predominantly used in the EU.[43]

Consumption history affects the regulatory status of algae products in the EU. Species that were used as food in the EU before 15 May 1997 fall under the General Food law. However, species that were not consumed in the EU before this date require authorisation under the Novel Foods Regulation (EU) 2015/2283.

Globally, total algae biomass production (macro- and microalgae combined) was estimated at 35.82M tonnes (fresh weight) in 2019.[44] Of this, more than 99% (35.76M tonnes) was seaweed (macroalgae) and the rest (0.056M tonnes) was microalgae, and of the microalgae produced, 99% was Spirulina and the rest a combination of green microalgae. Of the total volume, 0.8% was produced in Europe, and of this more than 99% was seaweed and the rest primarily Spirulina.[45]

Although now dated, a 2012 article estimated that 76% of seaweed production worldwide was for direct human food consumption.[46] A 2022 study estimates that between 31% and 38% is consumed directly as food, with most of the rest used as food additives or functional food ingredients.[47] Van

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40 Wells ML, Potin P, Craigie JS *et al*. 'Algae as nutritional and functional food sources: revisiting our understanding', *J Appl Phycol* 29, 949–982, 2017. https://doi.org/10.1007/s10811-016-0974-5

41 Bjerregaard R, Valderrama D, Radulovich R, Diana J, Capron M, Mckinnie CA, Cedric M, Hopkins K, Yarish C, Goudey C, Forster J. *Seaweed aquaculture for food security, income generation and environmental health in Tropical Developing Countries (English)*, Washington, D.C. : World Bank Group, 2016. http://documents.worldbank.org/curated/en/947831469090666344/Seaweed-aquaculture-for-food-security-income-generation-and-environmental-health-in-Tropical-Developing-Countries; Guiry MD, 'How many species of algae are there?' *J Phycology* 48, 5, 2012. https://doi.org/10.1111/j.1529-8817.2012.01222.x

42 Amorim ML, Soares J, Sélia dos Reis Coimbra J, de Oliveira Leite M, Teixeira Albino LF, Arêdes Martins M. 'Microalgae proteins: production, separation, isolation, quantification, and application in food and feed', *Critical Reviews in Food Science and Nutrition*, 61:12, 1976-2002, 2021. https://doi.org/10.1080/10408398.2020.1768046

43 Henchion M, Hayes M, Mullen AM, Fenelon M, Tiwari B. 'Future Protein Supply and Demand: Strategies and Factors Influencing a Sustainable Equilibrium', *Foods*, 6, 53, 2017. https://doi.org/10.3390/foods6070053

44 FAO. Global seaweeds and microalgae production, 1950-2019. WAPI factsheet, 2021. https://www.fao.org/3/cb4579en/cb4579en.pdf

45 Ibid.

46 Chopin T. 'Seaweed aquaculture provides diversified products, key ecosystem functions. Part II. Recent evolution of seaweed industry', *Global Aquaculture Advocate*, 15, 24-27, 2012. https://www.researchgate.net/publication/269994844_Seaweed_aquaculture_provides_diversified_products_key_ecosystem_functions_Part_II_Recent_evolution_of_seaweed_industry

47 Naylor R.L., Hardy R.W., Buschmann A.H. *et al*. 'A 20-year retrospective review of global aquaculture.' *Nature* 591, 551–563 (2021). https://doi.org/10.1038/s41586-021-03308-6

der Spiegel et al[48] estimate that 30% of algae production is for feed (of which the vast majority is seaweed).

A 2022 study indicates that seaweed production in Europe is also primarily directed at food (34-36%) and food-related applications (15%), such as supplements. An estimated 10% is sold for animal feed.[49] No estimates were found regarding the contribution of algae to the protein balance for food or feed.

Insects

Insects, like algae, have been consumed in many parts of the world for centuries. The focus on their use as a potentially important source of food and feed is a relatively recent trend in western countries.[50] This was propelled by factors that include, amongst others, policy work carried out by the FAO, which has since 2013 identified insects as a source of alternative proteins that might contribute to global food and feed security.[51] Nevertheless, the regulation and use of insects as food and feed vary considerably worldwide.[52]

Global production data show that cricket is the most farmed insect for human nutrition.[53] In the EU, to date formulations of four insect species have been authorised as novel food applications: house cricket (*Acheta domesticus*); lesser mealworm (*Alphitobius diaperinus*); migratory locust (*Locusta migratoria*); and yellow mealworm (*Tenebrio molitor*).[54]

Processed animal proteins (PAPs) derived from seven insect species are used in the EU for animal nutrition, including yellow mealworm and black soldier fly, which can be fed to certain food-producing animals (i.e. farmed fish, pigs and poultry).[55]

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48 Van der Spiegel M., Noordam M.Y., van der Fels-Klerx H.J, 'Safety of novel protein sources (insects, microalgae, seaweed, duckweed and rapeseed) and legislative aspects for application in food and feed production', Compr. Rev. Food Sci. Food Saf. 12, 662–678, 2013. https://doi.org/10.1111/1541-4337.12032

49 Vazquez Calderon F, Sanchez Lopez J. *An overview of the algae industry in Europe: Producers, production systems, species, biomass uses, other steps in the value chain and socio-economic data*. Guillen J, Avraamides M eds. Publications Office of the European Union, Luxembourg,2022. https://doi.org/10.2760/813113; Araújo R, Vázquez Calderón F, Sánchez López J, Azevedo IC, Bruhn A, Fluch S, Garcia Tasende M, Ghaderiardakani F, Ilmjärv T, Laurans M, Mac Monagail M, Mangini S, Peteiro C, Rebours C, Stefansson T and Ullmann J. Current 'Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconom',. Front. Mar. Sci. 7:626389, 2021. https://doi.org/10.3389/fmars.2020.626389

50 FAO. *Looking at edible insects from a food safety perspective. Challenges and opportunities for the sector.* Rome (2021) https://doi.org/10.4060/cb4094en

51 van Huis A, van Itterbeek J, Klunder H, Mertens E, Halloran A, Muir G, Vantomme P *Edible insects: future prospects for food and feed security*. Food and Agriculture Organization of the United Nation, Rome, 2013. https://www.fao.org/3/i3253e/i3253e.pdf

52 Montanari F, Pinto de Moura A, Cunha LM, *Production and Commercialization of Insects as Food and Feed: Identification of the Main Constraints in the European Union*, Springer, 2021.

53 Meticulous Research, *Edible Insects Market*, 2022.

54 Two additional species - black soldier fly (*Hermetia illucens*) and honeybee drone brood (*Apis mellifera male pupae*) - are subject to authorisations that are currently pending at EU level (European Commission 2023). European Commission's Q&A - Approval of fourth insects as novel food https://food.ec.europa.eu/safety/novel-food/authorisations/approval-insect-novel-food_en (accessed on 19 July 2023).

55 IPIFF, *EU Legislation. Insect producers must conform with the same general rules that apply to operators in other sectors*. https://ipiff.org/insects-eu-legislation/ (accessed on 19 July 2023)

In 2019, the EU produced 500 tonnes of insects intended for food and 5,000 tonnes intended for feed.[56] In 2022, EU production of insects as animal feed totalled 9,495 tonnes.[57] Insects intended for use in aquaculture and as pet food account for the largest share (50%) of EU insect production as feed. Black soldier fly is by far the most farmed species for use as feed internationally. In Europe, together with the yellow mealworm, it accounts for 95% insect-based feed production.[58] No estimates were found regarding the contribution of insects to the protein balance for food or feed.

Microbial fermentation

Microbial fermentation for alternative protein production encompasses three at times overlapping processes: traditional fermentation, which has been used for thousands of years and includes alternative proteins such as tempeh and tofu; biomass fermentation, which uses microorganisms to scale up protein production; and precision fermentation, which uses microbes as 'cell factories' to produce functional ingredients.[59] The microbes involved can include fungi, algae and bacteria. For the purposes of this study, we focus primarily on biomass and precision fermentation, as traditionally fermented products are often included under plant-based alternatives since many of these are soya-derived.

The regulatory landscape in the EU for microbially fermented foods is complex and evolving. Precision-fermented products are generally considered to be novel foods under Regulation (EU) 2015/2283. If the product is obtained through the use of genetically modified organisms (GMOs), it must be authorised under Regulation (EC) No 1829/2003 on genetically modified food and feed if rDNA from the GMO is still present in the fermentation product.

Fungal proteins have for many years been produced from biomass fermentation. Quorn is one of the earliest and most successful producers of microbial proteins for food.[60] In 2017, Quorn sold 22,000 tonnes of its microbial protein product.[61]

Precision fermentation, with the aid of synthetic biology, and algal, fungal and bacterial cells can be optimised to increase yield, quality and the nutritional content of fermented foods. Precision fermentation has been used for many years in other sectors (e.g. healthcare and industrial applications) and as a food ingredient (notably, the enzyme chymosin, and hemp flavouring for some plant-based meat analogues), but its potential to create alternative protein sources is still emerging.

Microbial protein has shown promise as a fishmeal replacement in aquaculture, and has been tested in terrestrial livestock as feed (i.e. the primary food source) and as a feed additive (e.g. nutritional

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[56] IPIFF, *The insect sector milestones towards sustainable food supply chains*, updated May 2020. Available at https://ipiff.org/wp-content/uploads/2020/05/IPIFF-RegulatoryBrochure-update07-2020-1.pdf (accessed on 19 July 2023).

[57] IPIFF, *Overview of the European insect feed market*, version 2, November 2023.

[58] Ffoulkes C., Illman H, O'Connor R, Lemon F, Behrendt K, Wynn S, Wright P, Godber O, Ramsden M, Adams J, Metcalfe P, Walker L, Gittins J, Wickland K, Nanua S and Sharples B, *Development of a roadmap to scale up insect protein production in the UK for use in animal feed,* Technical report prepared by ADAS and Michelmores for WWF-UK and Tesco, 2021.

[59] Good Food Institute (GFI) *Fermentation: Meat, seafood, eggs and dairy. 2022 State of the Industry Report*, 2022 https://gfi.org/wp-content/uploads/2023/01/2022-Fermentation-State-of-the-Industry-Report-1.pdf

[60] Graham AE, Ledesma-Amaro R. The microbial food revolution. *Nat Commun* 14, 2231, 2023. https://doi.org/10.1038/s41467-023-37891-1

[61] Henchion et al. 2017.

supplement),[62] although historically low prices for soybean have restricted growth of microbial proteins in this sector.[63] The most recent estimates available are from 2014-2016 indicating global production volumes for different microbial proteins totalling approximately 3.1M tonnes per year, including both food and feed (compared to approximately 330M tonnes of conventional animal protein in that period).[64]

Cultured meat

Cultured meat (also referred to as cell-based meat) involves *in vitro* meat production using animal cells. It represents an entirely new approach to producing alternative proteins, as compared to algae, insects and microbial fermentation, for which there are historical precedents as a food source.

The method for producing cultured meat encompasses several key phases: cell sourcing, where muscle or stem cells are taken from live animals; cell cultivation, where these cells are cultivated in a controlled environment to proliferate and differentiate; and tissue formation, where cells mature to form muscle tissues resembling traditional meat. The approach has evolved rapidly in recent years, driven by advancements in cell biology and biotechnology.

Cultured meat is not yet authorised in the EU, but has been authorised for consumption in Singapore since 2020, and in the US in 2023. In both countries, this is for cultured chicken, produced by one company for the market in Singapore. In the US, two companies have received approval to produce cultured chicken, but products are not yet commercially marketed. Although recent commercial and regulatory attention has been focused on chicken, the original application of the method was for beef, which is remains a major focus of industrial development. Applications for pork, fish and seafood are also being explored. There are no known applications of cultured meat, or animal cell technology more generally, for feed,[65] and none is produced for this purpose.[66]

3.3. Summary of the protein balance

In summary, globally, most dietary protein comes from plants (57%, and primarily grains) and secondly from animals (43%, and primarily meat, dairy and fish). In the EU, by contrast, over half of proteins consumed are animal-based, exceeding plant-based proteins since the 1970s. There is evidence of protein overconsumption in the EU by around a third above the recommended daily intake. Moreover, the EU has a 'feed protein deficit', importing 61% of processed proteins for animal feed (including a quarter of the feed high in protein, such as soy) highlighting the region's import dependency in this area. The current protein balance has major environmental impacts, with animal production responsible for two-thirds of agricultural emissions globally despite providing less than 20% of overall protein intake. Climate change also threatens future supply.

Geopolitical and environmental pressures have led many to reconsider the conventional protein balance and expand alternative proteins in the EU and globally. The main alternative protein sources

[62] Graham AE, Ledesma-Amaro R, 2023.

[63] Matassa S, Boon N, Pikaar I, Verstraete W. Microbial protein: future sustainable food supply route with low environmental footprint. *Microbial Biotechnology*, 9, 5, 2016. https://doi.org/10.1111/1751-7915.12369

[64] Ibid.

[65] GFI. *Cultivated meat and seafood. 2022 State of the Industry Report*, 2022. https://gfi.org/wp-content/uploads/2023/01/2022-Cultivated-Meat-State-of-the-Industry-Report-2-1.pdf

[66] Cultured meat is not considered in this study as a protein source for animal feed due to its high cost of production (including to 2050). There are no known examples of cultured meat being fed to animals and no studies were found that considered the potential for cultured meat to be used as animal feed in the foreseeable future.

considered for the EU in this study are algae, insects, microbial proteins from fermentation, and cultured meat. Globally, algae production is 35.8 million tonnes, but under 1% is in the EU. Insects for feed are increasing, with black soldier fly dominating. Quorn produces about 22,000 tonnes of microbial protein yearly but overall this sector is very small. Cultured meat is not yet commercially available. Plant-based proteins dominate alternatives currently and likely will continue to do so. The exact contribution of each non-plant source is uncertain, but together are a fraction of the 13 million tonne alternative protein market (itself only 2% of animal proteins).

4. Projections to 2050

Projections for the protein balance in future years can support better decision-making for alternatives versus conventional sources. Looking ahead to 2050 offers an opportunity to consider different scenarios in this context. This section assesses the future potential protein balance for conventional proteins and alternatives.

4.1. Conventional protein projections to 2050

Trends in meat production and consumption since the 1960s indicate a continuous increase worldwide,[67] with the most recent growth occurring in Asia. This is mirrored by an increase in feed production, where Asia leads.[68] Europe and North America may, by contrast, be approaching 'peak meat', i.e. the point when absolute consumption of meat begins to decline.[69]

Projections from those trends from 2005 to 2050 taking into account expected population growth suggest an increase in meat consumption by 57% and dairy by 48%.[70] Another estimate anticipates a growth of 79% in total consumption of all animal proteins between 2006 and 2050.[71] A third study suggests an overall increase in protein production of 119% by 2050 to match expected needs.[72]

These are business-as-usual scenarios. Meat consumption growth is mapped against average global economic growth assumptions, with expectations that continued increases in incomes (e.g. in Asia) will drive further meat consumption, and therefore meat production.[73]

There are strong reasons to consider non-linear scenarios to 2050. A major argument for doing so is climate change, which albeit frequently mentioned in the literature, has generally not been incorporated in 2050 protein projections. Climate change is already affecting protein production worldwide in the form of simultaneous extreme weather events,[74] and there are convergent

67 Our World in Data, 'Meat production by livestock type, World, 1961 to 2021', https://ourworldindata.org/grapher/global-meat-production-by-livestock-type [accessed 17 October 2023].

68 China has seen a very rapid increase in feed production; https://ifif.org/global-feed/statistics/ consulted on 24/7/2023.

69 Witte et al. 2021.

70 Alexandratos, N. and J. Bruinsma, World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Rome, FAO, 2012.

71 Ranganathan K et al 2016.

72 Berners-Lee et al. 2018.

73 OECD/FAO, *OECD-FAO Agricultural Outlook 2023-2032*, OECD publishing, Paris, 2023, https://doi.org/10.1787/08801ab7-en.

74 "Primary production and the whole food supply chain are highly vulnerable to the impacts of climate change and biodiversity loss. Changes in weather patterns induced by climate change are already jeopardising food production in Europe, and the impacts will worsen in the coming years. The consequences for regional agriculture production

scientific warnings that extreme weather may trigger multiple breadbasket failures in the near future.[75] Pollinator losses, water availability issues, and higher CO2 concentrations are also expected to reduce yields and protein content in plant-based food and feed.[76] The latest studies point to climate impacts on food production occurring sooner than previously estimated (i.e. before 2040).[77] These trends bring into question the continued *availability* of different protein sources.

An alternative scenario for the protein balance to 2050 might consider the possibility that conventional protein availability becomes an issue, globally and in the EU. This could occur, for example, in the aftermath of, or in the form of a climatic "existential shock" by the end of the 2020s, as assumed in the latest foresight report of the Joint Research Centre of the European Commission.[78] From that point onwards, existing drivers of continued production increases – economic and population growth – would compete with other drivers – availability and scarcity issues – to shape the protein balance. Here we consider the potential effects of climate change impacting on protein projections for conventional animal and plant-based proteins.

4.1.1. Animal-based proteins

Heat stress, water scarcity, reduced feed crop and forage quality, and diseases are some of the challenges to livestock induced by climate change. Those are expected to reduce feed intake, which impacts growth, reducing milk production and increasing mortality. Indirectly, heat stress reduces protein content and yield in feed.[79] Fisheries and aquaculture are also threatened by climate change, and although the expected impacts are mixed, they tend to be negative.[80]

These combined issues will make it more challenging in the future to produce equivalent, let alone greater quantities of animal-sourced proteins. Major events such as a prolonged heatwave affecting major producing countries could trigger a shift. Animal protein production worldwide and in the EU could rapidly change depending on how different production systems respond to climatic and economic conditions.

Conventional production in uncontrolled and monoculture environments is likely to result in greater variations in output, leading low-margin operations (typically, dairy farms) to shut down at

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and food habits will be significant. Furthermore, the largest socio-economic and food security impacts will occur in regions where the natural resources needed for production are under particular stress." (COM 2023: 8)

75 Gaupp F et al. 'Changing risks of simultaneous global breadbasket failure', *Nature Climate Change*, 10:54-57, 2020; Hasegawa T, Wakatsuki H, Nelson GC, 'Evidence for and projection of multi-breadbasket failure caused by climate change', *Current Opinion in Environmental Sustainability*, 58:101217, 2022; Kornhuber K et al., 'Risks of synchronized low yields are underestimated in climate and crop model projections', *Nature Communications* 14, 3528, 2023; Qi W et al. 'Increasing concurrent drought probability in global main crop production countries', *Geophysical Research Letters*, 49(6), 2022.

76 Ehrlich PR, Harte K, 'To feed the world in 2050 will require a global revolution', *PNAS* 112(48): 14743-14744, 2015.

77 Jägermeyr J et al, 'Climate impacts on global agriculture emerge earlier in new generation of climate and crop models', *Nature Food* 2:873-885, 2021.

78 Matti J, Bontoux G, Pistocchi S, *Towards a fair and sustainable Europe 2050: social and economic choices in sustainability transitions*, Publications Office of the European Union, Luxembourg, 2023.

79 Cheng M, McCarl B, Chengcheng F, 'Climate change and livestock production: a literature review', *Atmosphere*, 13(1): 140, 2022; Escarcha JF, Lassa JA, Zander KZ, 'Livestock under climate change: a systematic review of impacts and adaptation', *Climate* 6(3):54, 2018; Rojas-Downing M et al, 'Climate change and livestock: impacts, adaptation, and mitigation', *Climate Risk Management* 16, 145-163, 2017.

80 Maulu S et al., 'Climate change effects on aquaculture production: sustainability implications, mitigation, and adaptations', *Sustain. Food Syst.*, 5, 2021; Tigchelaar M et al. 'Compound climate risks threaten aquatic food system benefits', *Nature Food*, 2:673-682, 2021; Barange et al. 2018.

an accelerated pace. Meat and dairy production could continue operating in mixed-farming environments (particularly when animal rearing is combined with agroforestry, which provides passive cooling to animals during heat waves[81]). Livestock production could also continue operating in controlled environments (indoors). Growth may continue in both mixed farming and controlled environments but this will translate into higher costs, particularly for the latter because of increasing cooling needs and energy use, and higher feed costs (reduced yields leading to price increases).

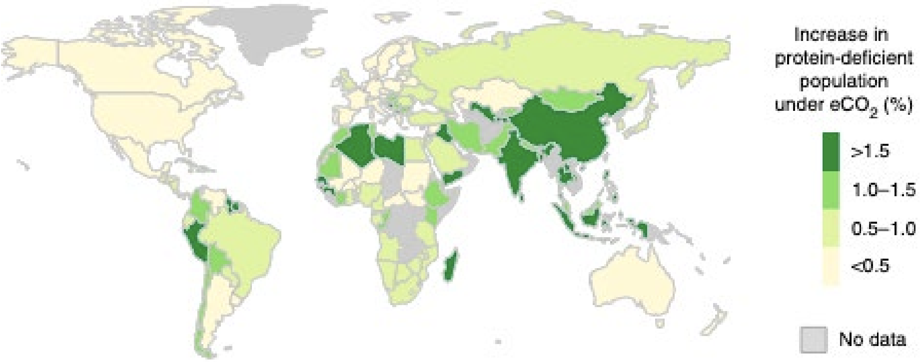
Cost increases across dairy and meat products may dampen demand for animal proteins, especially meat, in favour of plant-based or other alternative proteins. The issue of feed availability and quality (in terms of protein content) would be particularly acute for production in controlled environments and would create a major opportunity for feed protein alternatives.

4.1.2. Plant-based proteins

Projections of plant-based protein production to 2050 have often been drawn under the assumption of a shift in diets, away from meat and towards plant-based food.[82] Such a shift could be encouraged by a protein availability crunch in the period to 2030. This would entail redirecting land use towards producing protein-rich food. However, increased atmospheric CO2 is projected to reduce protein content in plant-based staple foods and thus increase protein deficiency by 0.8% in Europe, under an assumption of stable diets (see Fig. 2).[83] The impact in Europe would be greater as diets shift towards more plant-based proteins.

Furthermore, the combination of increased heat and greater variations in moisture is expected to negatively impact yields (although projected impacts remain too uncertain to be quantified).[84] Since alternative proteins are produced in controlled or aquatic environments, they may provide a complementary source to address variations in the supply of conventional proteins produced by rainfed agriculture.

Figure 2 – Impact of atmospheric CO_2 increase on protein deficiency.[85]



Source: Smith and Meyers, 2018.

[81] Lal R, 'Integrating animal husbandry with crops and trees', *Front. Sustain. Food Syst.* 4, 2020.

[82] e.g. Berners-Lee et al. 2018; Ranganathan et al. 2016.

[83] Smith MJ, Meyers SS, 'Impact of global CO2 emissions on global human nutrition', *Nature Climate Change*, 8:834-839, 2018.

[84] Lesk C et al., 'Compound heat and moisture extreme impacts on global crop yields under climate change', *Nature Reviews Earth & Environment* 3, December, 872-889, 2022.

[85] Ibid.

4.2. Alternative proteins projections to 2050

One study[86] estimates that, by 2035, alternative proteins (including plant-based alternatives) will account for 11% of the global protein market for food, and may reach up to 22%. That considers Europe and North America the most mature markets for alternative proteins, with the biggest potential in Asia-Pacific. The latter market is estimated to account for two-thirds of global consumption of alternatives by 2035. In that assessment, Europe could reach 15M metric tonnes of alternative proteins[87] by 2035 in the base case scenario, or 22% of the market currently occupied by conventional animal proteins, with an upside scenario of 33M metric tonnes (34%) if Europe reaches 'peak meat' consumption in 2025, and assuming significant technological and regulatory step-changes in favour of the alternatives.[88] Such a path could be facilitated by challenges with conventional protein production within the next decade, as described above.

4.2.1. Algae

Algae production worldwide has grown rapidly since 2017; Greene et al. suggest that considering protein demands and sustainability concerns alongside limited market penetration to date, algae could contribute more than the total projected protein demand to 2050.[89] Henchion estimate that algae could potentially replace up to one third of soybean meal in pig and poultry diets.[90]

4.2.2. Insects

The insect market for food and feed is forecast to reach an estimated production volume of 3.1M tonnes by 2030. As the EU market for insects opens progressively following the first authorisations of insects as novel foods, the production potential for insects as food is estimated to reach 260,000 tonnes by 2030.[91]

The future potential of insects as feed is expected to be much greater than for food. A review of alternative protein sources suggests that, depending on the fish species, fishmeal in aquafeed can be partially replaced by 25-30% insect meal: for Atlantic salmon even up to 100% replacement without compromising quality. For pigs and poultry, 10% of conventional protein can be replaced by insect meal.[92] Insect feed production is thus projected to grow at least up to 2.7M tonnes by 2030.[93] In that period, the share of insects intended for use in aquaculture and as pet food are expected to increase, from 50% at present to over 80% of the share of EU insect production as feed.[94]

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86 Witte et al. 2021.

87 Including plant-based meat alternatives, as well as animal-cell-based (cultured meat) products and those produced using micro-organisms (including microalgae). Insect proteins are not mentioned.

88 Barriers and opportunities for alternative proteins are assessed in Parts 2 and 3.

89 Greene, CH, Scott-Buechler CM, Hausner ALP, Johnson ZI, Lei XG, and Huntley ME. 'Transforming the future of marine aquaculture: A circular economy approach'. *Oceanography* (2022) 35, 2:26–34, https://doi.org/10.5670/oceanog.2022.213.

90 Henchion et al. 2017.

91 IPIFF *The insect sector milestones towards sustainable food supply chains*, updated May 2020. Available at https://ipiff.org/wp-content/uploads/2020/05/IPIFF-RegulatoryBrochure-update07-2020-1.pdf (accessed on 19 July 2023).

92 Gasco L, Renna M, Bellezza Oddon S., Rezaei Far A, Naser El Deen S and Veldkamp T, *Insect meals in a circular economy and applications in monogastric diets*, Animal Frontiers 2023 Vol. 13 Issue 4, p. 81-90.

93 IPIFF 2020.

94 IPIFF 2023.

4.2.3. Microbial fermentation

Witte et al.[95] assess the potential for alternative proteins derived from microorganisms to contribute to the protein balance for food. In their base case scenario, they estimate that microorganism-based alternatives to meat will reach 22M metric tonnes globally by 2035, or 2.5% of the global protein market for meat and meat alternatives. This assumes price parity with conventional meat products is reached by 2025.

4.2.4. Cultured meat[96]

Only one study was identified that makes projections for cultured meat production as far into the future as 2050.[97] Despite variations, projected production volumes were generally low, with an aggregated 54% probability that less than 100,000 tonnes of cultured meat would be sold (at any price point) before the end of 2051. In a context where annual production of conventional meat in 2018 was 346M tonnes, and seafood in 2015 was 200M tonnes, it would take at least 50M tonnes of cultured meat to represent 5-7% of the meat demand estimated in 2051. The projected probability of >50M metric tonnes of cultured meat sold globally in 2051 was less than 10%.

These projections are considerably lower than those made by consultancies that have produced assessments to 2030 and 2035. Brennan et al.[98] estimate that by 2030, cultured meat could provide up to 0.5% of the world's meat supply.[99] Witte et al.[100] also estimates that price parity with conventional products will be reached in the next decade (by 2032), with reference to the EU and US for illustration, and that by 2035, production of cultured meat products will reach 6M metric tonnes in the base case scenario.[101]

95 Witte et al. 2021.

96 Food only; our assumption is that cultured meat will not be cost-effective as a feed input in the timeframe of this study.

97 The study looked at three time horizons: 2031, 2036 and 2051. Forecasts were made by experts regarding the probabilities that production volumes reach different levels by the target years and considering a variety of factors such as the funding landscape, trained researchers in the field, potential sales and public support for the technology. The study looked at the potential for cultured meat where cultured animal cells make up more than half of the product (rather than serving as an ingredient in a primarily plant-based product). It did not account for the possibility of transformative AI to affect the industry.

Dullaghan N, Linch. Forecasts estimate limited cultured meat production through 2050. Effective Altruism Forum, 2022. https://forum.effectivealtruism.org/posts/2b9HCjTiFnWM8jkRM/forecasts-estimate-limited-cultured-meat-production-through

98 Brennan T, Katz J, Yossi Q, Spencer B. Cultivated meat: Out of the lab, into the frying pan. McKinsey & Company Agriculture Practice (2021) https://www.mckinsey.com/industries/agriculture/our-insights/cultivated-meat-out-of-the-lab-into-the-frying-pan#/

99 The analysis relies on assumptions about the potential for production processes to be sufficiently scaled and costs to decrease to parity with conventional products, but without providing an explanation or underpinning evidence for these assumptions

100 Witte et al. 2021.

101 The analysis is based on expert interviews and a review of industry data, but no details are provided on the underpinning assumptions.

5. Conclusions

This report examines the current and projected protein balance, focusing on conventional and alternative protein sources.

The current protein balance is dominated by conventional proteins. There are strong reasons – health, climate, environment, geopolitics – for questioning whether the current distribution of animal and plant based proteins, and their relative contributions to the overall intake globally and in the EU **can** and **should** be maintained.

Alternative proteins, including algae, insects, microbial fermentation, and cultured meat, offer potential to contribute towards a more sustainable and resilient protein balance. However, their current contribution is minimal and data on their usage, particularly in an EU context, are limited and sometimes outdated. These non-traditional protein sources are still emerging, and their future contribution largely depends on various factors including technological advancements, regulatory frameworks, and market dynamics.

The protein balance globally and in the EU to 2050 will be greatly influenced by population growth and climate impacts on food production. Protein needs will increase, while protein production may suffer from greater fluctuations in weather conditions. Significant behavioural shifts before then could lead to a major redistribution of food and feed protein sources.

Sustainability concerns and climate threats to animal feed production may provide a significant opportunity for growing the scale of alternative proteins for feed, and particularly insects (which can be reared in controlled environments).

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Part 2: Assessment of alternative protein sources

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1. Introduction

Part 2 provides an assessment of alternative protein sources, covering their energy requirements, environmental impacts and nutritional quality, as well an appraisal of their potential to substitute for their conventional counterparts. The alternatives are further assessed according to EU research and development activity, technological and market readiness, and industrial capability.

2. Methodology and resources used

The evidence and analysis supporting this Part is based exclusively on a literature review. Data supporting the assessment of alternative sources has been extracted from academic literature primarily as well as grey literature. The latter includes, for example, reports published by the UN Food and Agriculture Organisation (FAO), industry bodies, research organisations, and other private sector organisations.

The information extracted was triangulated, and the most robust and recent estimates were retained. The report aims to communicate the range of data points found when several estimates were documented.

The assessment of alternative proteins relative to conventional proteins requires comparing two very different data sets. Conventional animal proteins and their impacts are well studied, whereas the alternatives belong, for the most part, to nascent industries (and specifically in an EU context, with respect to algae). Their processes are many (for instance, microalgae are produced either in photobioreactors, open pools, or fermenters[102]) evolving rapidly and their impacts are comparatively much less studied.[103] As a result, where estimates on the alternatives are presented, they often appear as wide ranges, reflecting the unsettled nature of methods and the variety of processes involved.

Moreover, conventional animal proteins are also produced through a wide range of processes (intensive, extensive, organic, etc.), and impacts vary accordingly, although most estimates used in the literature tend to refer to the more widespread, intensive processes. Modes of production are also evolving and will likely change in the near future: for example, conventional protein production is changing to reduce its environmental impacts, while alternative protein sectors are undergoing rapid transformation as the industry develops.[104]

Assessments of energy use and environmental impacts of cultured meat are generally based on life cycle analyses. As the technologies are still under development, the results reported are based on modelling and assumptions about the type of bioreactor, growth medium, and energy sources,

[102] Araújo R, Vázquez Calderón F, Sánchez López J, Azevedo IC, Bruhn A, Fluch S, Garcia Tasende M, Ghaderiardakani F, Ilmjärv T, Laurans M, Mac Monagail M, Mangini S, Peteiro C, Rebours C, Stefansson T, Ullmann J, 'Current Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy' *Front Mar Sci* 7 (1247), 2021. doi:10.3389/fmars.2020.626389.

[103] Smetana et al., 'Meat substitutes: Resource demands and environmental footprints', *Resources, Conservation & Recycling* 190: 106831, 2023.

[104] Nowacka M et al., 'Developments in Plant Proteins Production for Meat and Fish Analogues', *Molecules*, 28: 2966, 2023, https://doi.org/10.3390/molecules28072966 .

among other factors, and in the case of some studies, supplemented with confidential data from industry start-ups.[105] There is, therefore, significant uncertainty in the estimates.[106]

Regarding microbial fermentation, we have selected the following alternatives for the analysis, based on data availability: for meat alternatives, mycoproteins which are produced by fungi (*Fusarium venenatum*), and for dairy alternatives, recombinant proteins, namely proteins cloned via the proliferation of host non-animal cells. For the latter, there are multiple approaches considered in the literature, which contributes to uncertainty in the data, and particularly affects estimates of nutritional quality.

Lifecycle assessments of alternative dairy proteins produced using cellular agriculture often compare the impacts of cellular agriculture to the impact of extracting dairy proteins from milk. These assessments therefore tend to compare dairy alternatives to processes that have a greater environmental footprint than the production of milk itself.

Waste is a poorly studied parameter in studies of alternative protein sources, with generally very little to no data to compare them to conventional protein sources.

Finally, there are other important considerations in realtion to alternative protein sources, such as consumer acceptance, biodiversity, farmers' livelihoods and the future of farming as a profession, life in rural areas, the emergence of new business models and new actors in agriculture. However, while these should be part of the discusion about alternative protein sources in a wider context, they fall beyond the scope of present study.

3. Assessment of the alternative protein sources

Protein production in the EU is important, affecting European food security, environmental sustainability, energy costs, and economic and social resilience. While there has been much policy and investor interest in plant-based alternatives, interest in non-plant alternative proteins as potential substitutes for animal-based products has grown in recent years, presenting an opportunity to contribute to the overall protein balance.

This section evaluates four non-plant alternative protein sources based on common criteria compared to conventional animal products and soy. The alternatives considered are algae, insects, microbial fermentation and cultured meat, which are described in the preceding Part. The assessment covers energy requirements and environmental impacts, including land use, water use, greenhouse gas emissions, and waste production. This is followed by an assessment of the nutritional quality. A selected set of alternative sources was chosen for the comparison based on the availability of data on the alternatives in the literature and their relevance to the EU context.

Table 1 summarises the comparison of energy use and environmental impacts and Table 2 summarises the comparison of nutritional quality across the alternative sources. Cells in table 1 have been colour coded as follows: dark green=significantly lower environmental impact than conventional sources; light green=lower; yellow=similar; orange=higher; red=significantly higher; grey=uncertain/mixed relative outcomes depending on process or data source. There is no colour coding of the results in table 2, since the relative nutritional merits of protein sources depend on their relative contribution to the overall human or animal diet that they are a part of.

105 Sinke P et al., 'Ex-ante life cycle assessment of commercial-scale cultivated meat production in 2030,' *Intl. J. Life Cycle Assess.* 28:234-254, 2023. https://doi.org/10.1007/s11367-022-02128-8.

106 Tuomisto HL, Allan SJ, Ellis MJ, 'Prospective life cycle assessment of a bioprocess design for cultured meat production in hollow fiber bioreactors', Sci. Total Environ., 851(1), 158051, 2022. https://doi.org/10.1016/j.scitotenv.2022.158051.

Table 1 – Energy and environmental impacts of the alternative protein sources

Type of protein	Source	Comparison with conventional protein sources			
		Energy	Land use	Water use	GHG emissions
Algae	Sugar kelp (*Saccharina latissima*)	Higher to much higher than soy protein	Lower to significantly lower than all conventional proteins	Much lower than conventional proteins	Higher than soy protein; lower than dairy and chicken; significantly lower than beef
	Spirulina or *Chlorella*	Lower to higher than beef depending on the production process	Lower to significantly lower than all conventional proteins	Much lower than all conventional proteins	Significantly higher than soybean; higher than dairy and chicken; significantly lower than beef
Insects	Mealworm	Slightly higher than dairy and chicken; lower than beef	Significantly lower than beef and similar to chicken and feed formulations	Higher than beef and significantly higher than chicken and feed formulations	Significantly lower than beef; slightly lower than poultry and similar to feed formulations
	Black soldier fly	Higher to much higher than soy protein depending on animal diet	Similar to feed formulations	Significantly higher than feed formulations	Similar to feed formulations
Microbial fermentation	Mycoprotein (*Fusarium venetatum*)	Lower, similar to or higher than meat and soy protein depending on method and assumptions.	Lower than chicken; significantly lower than beef	Significantly lower to higher than meat depending on the method and assumptions	Lower than chicken; significantly lower than beef
	Dairy alternative	Lower, similar to or higher than dairy depending on method and assumptions	Significantly lower than dairy	Lower, similar to or higher than dairy depending on assumptions	Lower to significantly lower than dairy depending on method/source
Cultured meat	Cultured chicken	Higher to much higher than conventinoal chicken depending on method and assumptions	Similar to or lower than chicken	Higher or similar to chicken depending on method	Higher than chicken
	Cultured beef	Slightly lower to much higher (up to 3 times higher) than beef depedning on method and assumptions	Significantly lower than beef	Significantly lower than beef	Lower to much lower than beef beef

Table 2 – Nutritional quality of the alternative protein sources

Type of protein	Source	Comparison with conventional protein sources							
		Protein	Fiber	Fat	Carbohydrates	Vitamin A and B12	Calcium	Iron	Zinc
Algae	Sugar kelp (*Saccharina latissima*)	Sig. lower than all conventional proteins	Sig. higher than all convention al proteins	Sig. lower than chicken and beef	Sig. higher than chicken and beef	Higher than all conventional proteins	Sig. higher than all conventional proteins	Higher than all conventional proteins	Higher than chicken, dairy, soy protein; similar to beef
	Spirulina or *Chlorella*	Higher than all conventional proteins, but less digestible	Sig. higher than all convention al proteins	Lower than chicken and beef	Sig. higher than chicken and beef	Higher than all conventional proteins	Sig. higher than all conventional proteins	Sig. higher than all conventional proteins	Lower than all conventional proteins
Insects	Mealworm	Similar to all conventional proteins	Sig. higher than all convention al proteins	Higher than all conventiional proteins	Higher than chicken and beef; similar to dairy	Higher than beef, dairy, soy; similar to chicken	Higher than beef, dairy, soy; similar to chicken	Higher than beef, dairy, soy; similar to chicken	Higher than beef, dairy, soy; similar to chicken
	Black soldier fly	Similar to soy	Similar to soy	Higher than soy	Lower than soy	Higher than soy	Higher than soy	Lower than soy	Lower than soy
Microbial fermentation	Mycoprotein (*Fusarium venetatum*)	Slightly lower than chicken and beef	Higher than chicken and beef	Similar to chicken and beef	Higher than chicken and beef	None: lower than chicken and beef	Higher than chicken and beef	Much higher than chicken and beef	Lower than chicken and beef
	Dairy alternative	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Cultured meat	Cultured chicken	Assumed similar to chicken	Assumed similar to chicken	Assumed similar to chicken	Assumed similar to chicken	Assumed similar to chicken	Assumed similar to chicken	Assumed similar to chicken	Assumed similar to chicken
	Cultured beef	Assumed similar to beef	Assumed similar to beef	Assumed similar to beef	Assumed similar to beef	Assumed similar to beef	Assumed similar to beef	Assumed similar to beef	Assumed similar to beef

3.1. Energy use

The production processes for several types of alternative proteins are energy intensive, in some cases requiring greater energy inputs than the conventional proteins they could potentially replace. Energy requirements vary considerably for both microbial fermentation and cultured meat, depending on the process and inputs used, and also reflect large uncertainties in the data.

Conventional livestock production involves energy intensive processes. The cultivation of feed crops and energy needs for heating, cooling and lighting in animal rearing, combined with processing and transport of animal products, collectively contributes to the substantial energy footprint of animal-based proteins.

3.1.1. Algae

Energy use in algae production varies greatly between microalgae (Spirulina, *Chlorella*) and macroalgae (sugar kelp), and depending on the production method (i.e. in open ponds or in bioreactors). Electricity is required at all microalgae production stages: cultivation, water treatment, harvest, washing, pasteurisation, and packaging. For macroalgae, energy is used to power boats for accessing cultivation sites and mostly to operate drying and freezing equipment after harvest.[107] The evidence suggests that the energy use of sugar kelp production is higher to much higher than in soy protein production.[108] Spirulina production in open ponds has been found to be lower than that required to produce beef,[109] but it may be higher with other production methods.[110]

While drying and freezing make up a significant share of the energy used, anaerobic fermentation provides a much less energy intensive alternative for conservation. However, reliable fermentation protocols for the commercial production of cultivated macroalgae are not yet established.

3.1.2. Insects

Insect farming occurs in temperature-controlled environments, making it an energy-intensive activity. Energy use in insect production significantly varies depending on the animals' diet.

For instance, it has been estimated that larvae of black soldier fly grown on high quality feed substrates account for energy use equal to 174 mega joules (MJ) for producing 1 kg of proteins. Conversely, when fed on waste and by-products, their energy use levels are much lower

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107 Koesling M et al., 'Environmental impacts of protein-production from farmed seaweed: Comparison of possible scenarios in Norway', Journal of Cleaner Production, 307:127301, 2021; Thomas J-BE, Sodré Ribeiro M, Potting J, Cervin G, Nylund GM, Olsson J, Albers E, Undeland I, Pavia H, Gröndahl F, 'A comparative environmental life cycle assessment of hatchery, cultivation, and preservation of the kelp *Saccharina latissima*.' 78 (1):451-467, 2020. doi:10.1093/icesjms/fsaa112.

108 Koesling M et al., 'Environmental impacts of protein-production from farmed seaweed: Comparison of possible scenarios in Norway', Journal of Cleaner Production, 307:127301, 2021; Philis G, Gracey EO, Gansel LC, Fet AM, Rebours C, 'Comparing the primary energy and phosphorus consumption of soybean and seaweed-based aquafeed proteins – A material and substance flow analysis.' *J Clean Prod* 200:1142-1153, 2018, .

109 Tuomisto HL, Texeira de Mattos MJ, 'Environmental impacts of cultured meat production', Environ Sci Technol., 2011, Jul 15, 45(14):6117-23, doi: 10.1021/es200130u.

110 Smetana S et al. 2023.

comparatively (26–84 MJ). If fed with soybean meal and fishmeal, energy use are in the range of 9-44 MJ.[111]

Rearing mealworms requires energy use of 173 MJ for producing 1 kg of proteins, which is slightly higher than the energy use levels needed for milk and chicken production and lower than for beef.[112]

3.1.3. Microbial fermentation

Fermentation for the production of food or feed proteins consumes energy in two main ways: for the production of feedstocks and for powering the production process itself (external electricity). There is high uncertainty regarding those impacts, and a wide range of estimates are found in the literature, reflecting the effect of different assumptions and methods.[113] As a result, the relative energy use of microbially fermented proteins would not appear as unequivocally better or worse than that of the conventional proteins they may replace. Nevertheless, the high energy intensity of producing mycoprotein is frequently noted.[114]

3.1.4. Cultured meat

Lifecycle analyses have estimated different energy use levels for cultured meat compared to their conventional counterparts, depending on the underpinning assumptions including the type of bioreactor and growth medium used.[115] Estimated energy use ranges from slightly lower than conventional beef but similar to or slightly higher than poultry[116] to as much as three times higher than conventional beef.[117] These estimates have levels of uncertainty.

Whilst energy use is similar to or higher for cultured meat than for its conventional counterparts, this is in the form of industrial energy rather than consisting of a trade-off between using human

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[111] Bosch G, Van Zanten HHE, Zamprogna A, Veenenbos M, Meijer NP, Van der Fels-Klerx HJ, and Van Loon JJA. 'Conversion of organic resources by black soldier fly larvae: legislation, efficiency and environmental impact', J. Clean Prod., 2019, 222:355–363. doi:10.1016/j.jclepro.2019.02.270.

[112] For instance, Oonincx DGAB and de Boer IJM, 'Environmental impact of the production of mealworms as a protein source for humans – a life cycle assessment', PLoS One 7(12):e51145, 2012, p. 1–5.

[113] Diaz-Bustamante ML et al., 'Trends and prospects in dairy protein replacement in yogurt and cheese', Helyon 9: e16974, 2023; Smetana et al. 2023. Hadi J, Brightwell G, 'Safety of alternative proteins: technological, environmental and regulatory aspects of cultured meat, plant-based meat, insect protein and single-cell protein', Foods 10: 1226, 2021; Diaz-Bustamante et al., 2023; Behm K, Nappa M, Aro N, Wleman A, Ledgard S, Suomalainen M, Hil J, 'Comparison of carbon footprint and water scarcity footprint of milk protein produced by cellular agriculture and the dairy industry', *The International Journal of Life Cycle Assessment*, 27:1017-1034, 2022, https://doi.org/10.1007/s11367-022-02087-0.

[114] e.g. Smetana et al., 2023.

[115] Tuomisto HL, 'The eco-friendly burger: Could cultured meat improve the environmental sustainability of meat products?' 20: e47395, 2019, https://doi.org/10.15252/embr.201847395.

[116] Tuomisto HL, Teixeira de Mattos MJ, 'Environmental Impacts of Cultured Meat Production', *Environ. Sci. Technol.* 45(14), 6117, 2011. https://doi.org/10.1021/es200130u; Sinke P, et al., 2023.

[117] Mattick CS et al., 'Anticipatory Life Cycle Analysis of In Vitro Biomass Cultivation for Cultured Meat Production in the United States', *Environ. Sci. Technol.* 49(19) 11941, 2015. https://doi.org/10.1021/acs.est.5b01614; Tuomisto HL, Ellis MJ, Haastrup P, 'Environmental Impacts of Cultured Meat: Alternative Production Scenarios', *Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector*, 2014. https://core.ac.uk/download/pdf/38629617.pdf; Tuomisto HL, 'Challenges of assessing the environmental sustainability of cellular agriculture,' *Nature Food*, 3:801-803, 2022, https://doi.org/10.1038/s43016-022-00616-6; Mazac R, Jarvio N, Tuomisto HL, 'Environmental and nutritional Life Cycle Assessment of novel foods in meals as transformative food for the future,' *Science of The Total Env.*, 876, 2023, https://doi.org/10.1016/j.scitotenv.2023.162796.

edible energy for livestock production.[118] Moreover, cultured meat production replaces energy use for biological processes in animals (calorie conversion) with energy in the form of electicity and heat. The latter can be produced sustainably, with greater potential improvements in this area over time as compared to conventional agriculture.[119]

3.2. Environmental impacts

3.2.1. Land use

Insects, microbial fermentation and cultured meat all require feedstocks, which contribute to their land use impacts. However, all of the alternative proteins analysed demonstrate equivalent or lower land use compared to the conventional proteins they may replace, with algae and insects being particularly efficient with respect to land use. Efforts to identify and use less impactful feedstock sources for alternative proteins may further reduce their land use impacts.

Agriculture currently uses one third of the available land globally. Livestock production accounts for 70% of all agricultural land, while cropland occupies the remaining 30%.[120] Yet livestock provide less than 20% of calories humans get from food.

Competition for land for the cultivation of soy for food and feed uses has been growing in some countries and regions (e.g, South America). Currently, soy production accounts for 131 million hectares of land used globally. This has resulted not only in the conversion of land already exploited for other agricultural uses, but also in the significant reduction of natural habitats and ecosystems (e.g., rainforests). Intensive farming practices and use of plant protection products in soy cultivation are also associated with soil erosion.[121]

Algae

There is minimal land use associated with the culture of microalgae, especially if onshore production is located on marginal, non-arable lands.[122] Some microalgae production happens in fermenters, which require feedstocks for growth, including sugars, the production of which requires land.[123] Macroalgae do not require land use except for onshore processing, which is minimal. For both sugar kelp and Spirulina or *Chlorella*, land use is lower to significantly lower than conventional sources of protein.[124]

Insects

Overall, the operation of insect farms, including large-scale farms, requires comparatively smaller infrastructure and facilities than for other animal-rearing operations. Feed substrates (e.g., grains and carrots) account for the largest portion of land use in insect production. Insects are generally reared in closed environments using vertical farming solutions or modern technologies (e.g.,

118 Human edible energy refers to. crops used as animal feed that could be used as human food; Mattick CS et al., 2015.

119 Sinke P, et al., 2023.

120 FAO, *Land statistics and indicators 2000–2021*, FAOSTAT ANALYTICAL BRIEF 71, 2021.

121 FAO, 'The future of food and agriculture. Alternative pathways to 2050', 2018, Available at: http://www.fao.org/3/CA1553EN/ca1553en.pdf

122 Tzachor et al., 2022.

123 Araujo et al., 2021.

124 Parodi A, Leip A, DeBoer IJM, Slegers PM, Ziegler F, Temme EHM, Herrero M, Tuomisto H, Valin H, Van Middelaar CE, Van Loon JJA and Van Zanten HHE, 'The potential of future foods for sustainable and health diets,' *Nature Sust.* 1:782-789, 2018, https://doi.org/10.1038/x41893-018-0189-7.

bioreactors).[125] Recent studies indicate that the land use impact of insect production is 0.36–3.6 m^2 per 1 kg of biomass as opposed to 23.1 m^2 in the case of beef, 4.64 m^2 for chicken and 1.48 m^2 for feed formulations.[126]

Microbial fermentation

The land use impact of microbial fermentation depends principally on feedstocks. Just like meat production, some microbial fermentation relies on crops. Glucose from refined maize or sugar cane is used to feed the organisms that ferment, whether they are bacteria or fungi. Nonetheless, land use for growing mycoprotein is lower than beef or chicken meat production,[127] and land use for growing dairy alternatives is less than conventional dairy.[128] Land use for feedstocks of microbial fermentation could decrease even further in the future as other feedstocks are considered.[129] Microbial fermentation can also rely partially or completely on gas as feedstock (e.g. CO_2), which results in only minimal land use.

Cultured meat

The land use requirements of cultured meat production depend on the sources of feedstock used to provide nutrients for the cells. Estimates that rely on highly efficient production systems for cultured meat (e.g. using blue-green algae as a source of nutrients) indicate that land use requirements would be lower for cultured meat compared to beef and chicken.[130] But the results are more uncertain if conventional 'feed' inputs to cultured meat, such as soy and corn, are used.[131] Compared to livestock production, land use is lower than for beef and poultry,[132] but if the protein content of the product is taken into account, land use for poultry is similar to cultured meat due to the high stocking densities of modern poultry production.[133]

3.2.2. Water use

The review of water use across alternative proteins reveals that algae, particularly microalgae and macroalgae farmed in seawater demonstrate unequivocally better outcomes in terms of water efficiency compared to conventional proteins. While there are uncertainties in the data, notable potential for improvement is possible for microbial fermentation and cultured meat, with the latter likely to use significantly less water than beef production and potentially comparable amounts to poultry production.

Water is an essential resource for global food security. According to the FAO, it takes 3,000 litres of water to produce food for one person's daily needs, whereas up to 15,000 litres are needed for the

[125] Jiang G, Ameer K, Kim H, Lee EJ, Ramachandraiah K, Hong GP, *Strategies for Sustainable Substitution of Livestock Meat,* Foods, 2020, 9(9), 1227.

[126] Smetana S, Bhatia A, Batta U, Mourim N, Tonda A, 'Environmental impact potential of insect production chains for food and feed in Europe', Animal Frontiers, Volume 13, Issue 4, 2023, p. 112–120, https://doi.org/10.1093/af/vfad033.

[127] Parodi et al. 2018.

[128] Tuomisto HL, 2022, Diaz-Bustamante et al, 2023.

[129] e.g. Upcraft T et al., 'Protein from renewable resources: mycoprotein production from agricultural residues', *Green Chemistry* 23(14): 5150-5165, 2021.

[130] Sinke P et al., 2023.

[131] Tuomisto HL, 2019.

[132] Tuomisto HL, 2022 and 2019.

[133] Santo RE, Kim BF, Goldman SE, Dutkiewicz J, Biehl EMB, Bloem MW, Neff RA, Nachman KE, 'Considering Plant-Based Meat Substitutes and Cell-Based Meats: A Public Health and Food Systems Perspective,' *Front. Sustain. Food Syst.* 4, 2020, https://doi.org/10.3389/fsufs.2020.00134.

production of 1 kg of meat.[134] Other data sources find 2,714 litres of freshwater withdrawal per kilogram of beef (dairy herd), 1,451 litres per kilogram of beef (beef herd), 660 litres per kilogram of poultry meat, and 628 litres per kilogram of milk.[135] These different estimates relate to scoping differences, depending on whether they focus on blue water (surface and ground freshwater) footprint only, or include also green water (soil moisture from precipitation used by plants) and grey water (used water that contains impurities) footprint. The cultivation of soy also requires a large amount of water. While water use can be reduced when rainwater is available, the soy global water footprint is currently estimated to be 2,145 litre/kg.[136]

Algae

The main use of freshwater for the production of microalgae is for cultivation – freshwater provides the environment in which microalgae grow – and washing the biomass acquired after filtration. This has been shown to consume only small amounts of freshwater per kilogram of product compared to beef meat production, which itself consumes more water than any other protein source.[137] Macroalgae, by contrast, is grown in seawater, yet is washed and blanched in freshwater post-harvest, to clean it and reduce iodine content.[138] Blanching in seawater enables reducing iodine content too, and is being adopted by kelp producers in Europe. While explicit comparisons with conventional sources are lacking, it is highly likely that freshwater use required for sugar kelp is less than for conventional proteins.

Insects

Together with feeding substrates and antiobitics, water usage is one of the few main agricultural inputs that farming insects requires. To date most studies evaluating the water footprint of insect production have focussed on insects grown on conventional diets. Their findings indicate that the lowest insect water fooprint is in the range of 0.4-0.8 m^3 per 1 kg of insects biomass, which is higher than conventional protein sources.[139]

Microbial fermentation

The evidence on the use of freshwater for microbial fermentation suggests that it is significant, although the literature shows a wide range of estimates, which are sometimes higher, equivalent to, or lower than water use for conventional proteins.[140] It is therefore difficult to conclude on that matter.

Cultured meat

Estimates of the potential water use of cultured meat depend on the water footprint method used (i.e. the mix of green water (rainwater), blue water (extracted surface- and ground water) and grey water (wastewater)).[141] Available life-cycle assessments (LCAs) indicate that, similar to land use, this

134 https://www.fao.org/water/en/

135 https://ourworldindata.org/grapher/water-withdrawals-per-kg-poore drawing from Poore J, Nemecek T, 'Reducing food's environmental impacts through producers and consumers', *Science* 360: 987-992, 2018.

136 Mekonnen MM and Hoekstra AY, *The green, blue and grey water footprint of crops and derived crop products*, Hydrology and Earth System Sciences, 15(5), 2011, p 1577-1600.

137 Tzachor A, Smidt-Jensen A, Ramel A, Geirsdottir M, 'Environmental Impacts of Large-Scale Spirulina (*Arthrospira platensis*) Production in Hellisheidi Geothermal Park Iceland: Life Cycle Assessment' *Maritime Biotechnology* 24: 991-1001, 2022, https://doi.org/10.1007/s10126-022-10162-8.

138 Wirenfeldt CB et al, 'Post-harvest quality changes and shelf-life determination of washed and blanched sugar kelp (*Sacharina latissima*)' *Sec. Food Biotechnology*, 2, 2022, https://doi.org/10.3389/frfst.2022.1030229

139 Smetana S, et al., 2023.

140 Diaz-Bustamante et al., 2023; Smetana et al., 2023, Tuomisto 2022, Behm et al., 2022.

141 Tuomisto HL, 2019.

production process will use significantly less water than for beef production.[142] However, it may be higher than or similar to poultry production.[143]

3.2.3. Greenhouse gas emissions

Reducing GHG emissions is a major challenge for agriculture globally and in Europe, and alternative proteins, including plant-based proteins, could play a role in mitigation efforts. As feed sources, algae production results in more emissions than soybean production, while insect production is comparable to that of other feed sources. When it comes to food, all of the alternatives demonstrate lower GHG emissions compared to beef and dairy production, although cultured meat may have emissions comparable to the most efficient poultry production systems.

Livestock production is currently accountable for a significant share of all anthropogenic GHG emissions (between 11 and 19% depending on the source).[144] In this regard, it has been estimated that 100 g of beef has the highest environmental impact in terms of CO_2 equivalents (a mean of 50 kg), followed by pork (7.6 kg) and poultry meat (5.7 kg).[145] With regard to soy, land conversion for its cultivation and its global trade have resulted in the release of more GHG emissions in the atmosphere: currently, the carbon footprint of soybeans is estimated to be 3.9 kg CO_2 equivalents.[146] When considered with reference to the amount of protein produced, however (rather than total weight), emissions to produce soybean proteins are less than to produce any animal-based protein.[147]

Algae

Emissions from macroalgae production vary greatly depending on location, as they tend to be adapted to local conditions. They include the production of ropes and buoys, as well as operation of boat transportation and processing (drying and freezing).[148] Current modes of protein-production have been shown to have a significantly greater global warming potential than soybean production, although the potential for lower impact than soybean production has been anticipated.[149] Claims that seaweed supply chains could have a net negative carbon impact have been disputed.[150] However, as a food source, the production of microalgae or macroalgae currently results in fewer emissions than the animal-based conventional protein sources considered (beef, chicken, dairy).[151]

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142 Tuomisto HL, Ellis MJ, Haastrup P 2014; Tuomisto HL and Teixeira de Mattos MJ 2011.

143 Tuomisto HL, 2019.

144 https://thebreakthrough.org/issues/food-agriculture-environment/livestock-dont-contribute-14-5-of-global-greenhouse-gas-emissions, accessed January 2024.

145 Poore J, Nemecek T, 'Reducing food's environmental impacts through producers and consumers', Science, 2018, 260:987-992.

146 Ffoulkes C, Illman H, O'Connor R, Lemon F, Behrendt K, Wynn S, Wright P, Godber O, Ramsden M, Adams J, Metcalfe P, Walker L, Gittins J, Wickland K, Nanua S and Sharples B, 'Development of a roadmap to scale up insect protein production in the UK for use in animal feed', Technical Report, WWF UK and Tesco, 25 June 2021.

147 Parodi et al. 2018.

148 Hasselström L, Thomas J-BE 'A critical review of the life cycle climate impact in seaweed value chains to support carbon accounting and blue carbon financing.' Clean Environ Syst 6:100093, 2022. https://doi.org/10.1016/j.cesys.2022.100093.

149 Koestling et al., 2021.

150 Hasselström L, Thomas JBE, 'A critical review of the life cylce climate impact in seaweed value chains to support carbon accounting and blue carbon financing', Cleaner Environmental Systems, 6: 100093, 2022.

151 Parodi et al 2018; Tzachor et al. 2022.

Insects

GHG emission levels in insect production are largely influenced by the substrates used to feed the animals. These can be further reduced by feeding insects on organic waste, for example.[152] The carbon footprint of insect farming has been estimated to be on average in the range of 0.3 – 3.0 kg CO_2 equivalents per 1 kg of insect biomass, which is lower than conventional alternatives, and broadly equivalent to feed formulations.[153]

Microbial fermentation

Emissions associated with fermentation are largely caused by feedstocks. Most production relies on either refined sugars from crops (maize or sugarcane) or gas (generally nitrogen). Gases used as feedstocks are themselves produced through a very energy intensive process that consumes large quantities of fossil fuels and emits high levels of CO_2.[154]

The evidence indicates that GHG emissions of mycoproteins productions are lower than those of chicken and significantly lower than those of beef[155], while those of dairy alternatives are lower to significantly lower than those of conventional dairy proteins.[156]

Cultured meat

Cultured meat production is a highly energy intensive process, with consequent potential impacts in terms of CO_2 emissions. Some estimates suggest that when factoring in the relevant emissions, cultured meat production could have a lower GHG footprint than beef – potentially by more than 75%.[157] But the emissions could be higher than for the most efficient poultry production systems.[158] Using renewable energy sources during the production process could reduce emissions further, but cultured meat is still expected to emit similar levels to conventional chicken.[159] However, the efficiencies of cultured meat production may be improved with technological developments.

3.2.4. Waste

Waste is not widely assessed for alternative proteins compared to conventional animal production. Where the issue is discussed, the available evidence suggests that the alternatives generate less waste compared to conventional equivalents, and that this waste is easily recycled. In some cases, alternative protein production processes could use waste from other processes, improving their overall waste footprint.

Meat processing generates large quantities of waste, which consist primarily of organic by-products, including offal, processing streams (e.g. wastewater) and packaging material, among others. While for some meat by-products specific management strategies allowing their mimisation, reuse or recycle can be applied, other by-products are inevitable for technical or regulatory reasons and must

[152] Smetana S, 'Circularity and environmental impact of edible insects', J Insects Food Feed, 2023, 9(9), p. 1111-1114.

[153] Smetana S, et al., 2023.

[154] https://cen.acs.org/environment/green-chemistry/Industrial-ammonia-production-emits-CO2/97/i24; also Järviö N, Netta-Leena M, Kobayashi Y, Ryynänen T, Tuomisto HL, 'An attributional life cycle assessment of microbial protein production: A case study on using hydorgen-oxidizing bacteria', *Science of the Total Environment*, 2021, 776, 145764, https://doi.org/10.1016/j.scitotenv.2021.145764.

[155] Hadi and Brightwell 2021.

[156] Diaz-Bustamante et al., 2023;, Behm et al .,2022.

[157] Santo RE et al., 2020.

[158] Tuomisto HL, Allan SJ, Ellis MJ, 2022; Sinke P et al., 2023; Tuomisto HL, 2022; Mattick et al., 2015.

[159] Sinke P et al., 2023

be therefore disposed of. [160] Unlike meat, soy production (soy bean meal and soy oil) generates a limited amount of residues, which can be used as animal feed, incinerated or applied back into the soil.[161]

Algae

Minimal waste is generated from algae production. That consists principally of wastewater following cultivation (microalgae), washing (microalgae and macroalgae) and blanching (macroalgae).

Insects

The main by-product of insect farming is frass, which can be used as a fertiliser, for soil improvement and crop protection.[162] Uneaten feeding substrates are also a by-product of insect production. Insects have significant potential in terms of circular economy. Most species can be fed on organic waste (e.g., manure, kitchen waste etc.), thereby valorising by-products that otherwise would not be exploited, and used for human and/or animal consumption.[163]

Also, insect feed conversion ratios (FCRs) – that is the amount of feed required to produce 1 kg of edible meat – are better than that of other food-producing animals. Depending on the diets they are fed, the FCR of black soldier fly may range from 1.4 up to 2.6, while in the case of yellow mealworm from 3.8 up to 6.1. Consequently, such species perform better than beef (FCR = 8.8), whereas only the black soldier fly compares to poultrymeat (FCR= 2.3).[164]

Microbial fermentation

The production of single-cell proteins via fermentation has been identified as a solution for recycling waste from other processes, particularly those from conventional agriculture.[165] There is little evidence available on waste generated from microbial fermentation, apart from wastewater, which was explored in a case study.[166] In recombinant protein (e.g. milk proteins) production processes using microbial fermentation, the left over microbial biomass is potentially a waste product. As the microbes are genetically modified, the microbial biomass cannot be used as food or feed in the EU countries.[167]

Cultured meat

The potential waste streams from cultured meat production are lactate and ammonia that are byproducts of cell metabolism, leftover nutrient medium and wastewater from washing the bioreactors.[168] The lactate and ammonia can be potentially extracted and used for other production

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160 Jiang G, Ameer K, Kim H, Lee EJ, Ramachandraiah K, Hong GP, 2020.

161 Ffoulkes C, et al., 2021.

162 Hénault-Ethier L, Reid B., Hotte N., Paris N., Quinche M., Lachance C, et al., *Growth Trials on Vegetables, Herbs, and Flowers Using Mealworm Frass, Chicken Manure, and Municipal Compost,* ACS Agricultural Science & Technology 2023, https://doi.org/10.1021/acsagscitech.2c00217 and Wantulla JJ A, van Loon A and Dicke M, *Soil amendment with insect exuviae causes species-specific changes in the rhizosphere bacterial community of cabbage plants*, Applied Soil Ecology 2023 Vol. 188, p. 104854, https://doi.org/10.1016/j.apsoil.2023.104854.

163 Wang Y and Shelomi M, *Review of Black Soldier Fly (Hermetia illucens) as Animal Feed and Human Food*, Foods 2017, 6, 91.

164 Oonincx DGAB, van Broekhoven S, van Huis A, van Loon JJA, *Feed Conversion, Survival and Development, and Composition of Four Insect Species on Diets Composed of Food By-Products*, PLoS One, 2015 Dec 23;10(12):e0144601.

165 Onyeaka H et al., 'Single Cell Protein for Foods and Feeds: A Review of Trends', *The Open Microbiology Journal*, 16, 2022.

166 Järviö N et al., 'An attributional life cycle assessment fo microbial protein production: A case study on using hydrogen-oxidizing bacteria', *Science of the Total Environment*, 776, 145764, https://doi.org/10.1016/j.scitotenv.2021.145764.

167 Behm et al 2022.

168 Tuomisto et al 2022.

processes. Possibilities for recycling the unused medium are being investigated. One LCA estimated that the risk of eutrophication[169] from cultured meat is substantially lower than for beef production but not compared with poultry.[170]

3.3. Nutritional quality

3.3.1. Macronutrient content

Some of the alternative protein sources offer a macronutrient profile that is is similar to or more nutrient dense compared to conventional animal-based proteins, although research on their bioavailability – i.e. whether they come in a form the human body can absorb and use – depending on type of alternative protein, mode of production and mode of processing is ongoing. Microlgae and insects have a higher protein content than their conventional counterparts, although digestibility is lower. They also have a higher fiber content. The fat content of algae and mycoprotein is much lower than that of conventional animal-based protein sources. Algae also contain healthy fatty acids in high concentrations. Cultured meat is assumed to provide the same macronutrient profile as the conventional meat products they could replace.

Conventional sources of protein for food, and particularly meat, are rich sources of protein. They also contain fat, but no or little carbohydrates or dietary fiber. Ruminant products (beef meat, dairy) also contain trans-fatty acids, while meat from monogastric species (pork, chicken) does not. They are a core source of amino acids (building blocks of proteins) in omnivorous diets. Conventional sources of protein for feed, especially soya, provide a mix of protein, saturated fats and dietary fiber. The very high protein content of soya is a major factor for its use in animal feed.

Algae

The literature highlights both the high nutritional quality of algae, and the need for further studies on the specific nutritional profile of different varieties, the bioavailability of the nutrients they contain, and how those vary depending on modes of production and processing.[171] The digestibility of proteins found in macroalgae is generally low,[172] whereas that of proteins found in microalgae is inferior to that of milk proteins.[173] Thanks to their dietary fiber content, the potentional for algae to contribute to gut health is perceived as high, although research into this matter is ongoing. Their fat content is low, and they contain healthy fatty acids in high concentrations.[174]

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169 Eutrophication is the over-enrichment of nutrients in a water body, often due to run-off from land. The resulting dense growth of algae and macrophytes can create 'dead zones' by depleting the surrounding areas of oxygen, killing fish and other organisms.

170 Mattick CS et al., 2015.

171 "[D]espite highly accurate and precise analytical determinations of food content, current knowledge of the nutritional or functional food value of algal products remains largely qualitative", in Wells ML, Potin P, Craigie JS, Raven JA, Merchant SS, Helliwell KE, Smith AG, Camire ME, Brawley SH, 'Algae as nutritional and functional food sources: revisiting our understanding', *J Appl Phycol* 29 (2):949-982, 2017. doi:10.1007/s10811-016-0974-5.

172 Bikker P, Stokvis L, van Krimpen MM, van Wikselaar PG, Cone JW, 'Evaluation of seaweeds from marine waters in North-western Europe for application in animal nutrition', Anim Feed Sci Technol 263:114460, 2020; Krogdahl Å, Jaramillo-Torres A, Ahlstrøm Ø, Chikwati E, Aasen I-M, Kortner TM, 'Protein value and health aspects of the seaweeds Saccharina latissima and Palmaria palmata evaluated with mink as model for monogastric animals' Anim Feed Sci Technol 276:114902, 2021; Øverland M, Mydland LT, Skrede A, 'Marine macroalgae as sources of protein and bioactive compounds in feed for monogastric animals' J Sci Food Agric 99:13–24, 2019.

173 Parodi et al., 2018.

174 Barbier et al. PEGASUS - PHYCOMORPH European Guidelines for a Sustainable Aquaculture of Seaweeds, COST Action FA1406 (M. Barbier and B. Charrier, Eds), Roscoff, France, 2019. https://doi.org/10.21411/2c3w-yc73.

Insects

The nutritional quality of insects depends on various different factors, including species, development stage, their diet as well as environmental or abiotic factors (i.e., non-living chemical or physical elements of the environment, such as acidity, salinity, humidity, radiation, etc.)[175] Macronutrients and notably proteins have been more researched compared to micronutrients.

On average, the crude protein (dry weight) content of mealworms is 43%-53%, while for the black soldier fly is 32%-48%, which is almost similar to that of beef and chicken.[176] Amino acid composition and digestibility are generally considered key indicators to assess protein quality.[177] Overall, data available singles out farmed insects as a high-quality protein source for the human diet. [178] The protein content of the insect species under analysis as a feed source is also generally considered of good quality. In particular, their essential amino acid profiles are comparable to that of soybean meal.[179] Because of their palatability, they are suitable replacements for soybean meal for feeding certain animal species (e.g., broilers, pigs).[180] However, with the exception of fish, recent studies conducted on black soldier fly larva meal fed to food-producing animals indicate that only partial replacement might be advisable as otherwise growth performance of the animals might be affected.[181]

Insects can be also source of other macronutrients. In the case of the yellow mealworm, fiber, fats and carbohydrates are present in higher quantities than in almost all conventional protein sources.[182] Compared to soy, the black soldier fly has a higher fat content, while its fiber content is similar and carbohydates content lower.[183]

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175 van Huis A, *Potential of Insects as Food and Feed in Assuring Food Security*, Annual Review of Entomology Volume 58, 2013, p. 563-583.

176 Selaledi L, Mbajiorgu CA and Mabelebele M, *The use of yellow mealworm (T. molitor) as alternative source of protein in poultry diets: a review*, Tropical Animal Health and Production 2019 Vol. 52, p. 7-16, https://doi.org/10.1007/s11250-019-0203 and Wang YS and Shelomi M, *Review of Black Soldier Fly (Hermetia illucens) as Animal Feed and Human Food*, Foods 2017, Vol. 6, Issue 10, p. 91, doi:10.3390/foods6100091.

177 Malla N, Nørgaard JV and Roos N, *Protein quality of edible insects in the view of current assessment methods*, Animal Frontiers, 2023 as well as FAO, *Dietary protein quality evaluation in human nutrition*, Report of an FAQ Expert Consultation, Food and Nutrition Paper 92, 2011, available at https://www.fao.org/ag/humannutrition/35978-02317b979a686a57aa4593304ffc17f06.pdf.

178 Malla N and Roos N, *Are insects a good source of protein for humans?*, J Insects Food Feed, 2023, 9(7), p. 841-844.

179 Pinotti L, Giromini C, Ottoboni M, Tretola M,and Marchis D., *Review: Insects and former foodstuffs for upgrading food waste biomasses/streams to feed ingredients for farm animals*, Animal, 13(7), 2019, p. 1365-1375.

180 Makkar HPS, Tran G, Heuzé V, Ankers A, *State-of-the-art on use of insects as animal feed,* Animal Feed Science and Technology, Volume 197, November 2014, p. 1-33.

181 Facey H, Kithama M, Mohammadigheisar M, Huber H, Shoveller AK, Kiarie EG, *Complete replacement of soybean meal with black soldier fly larvae meal in feeding program for broiler chickens from placement through to 49 days of age reduced growth performance and altered organs morphology*, Poultry Science, Volume 102, Issue 1, January 2023, 10229; Gasco L., Renna M, Bellezza Oddon S, Rezaei Far A, Naser El Deen S and Veldkamp T, *Insect meals in a circular economy and applications in monogastric diets*, Animal Frontiers, 2023, Vol. 13, Issue 4, p. 81-90, https://doi.org/10.1093/af/vfad016 and Alfiko Y, Xie D, Astuti RT, Wong J and Wang L, *Insects as a feed ingredient for fish culture: Status and trends*, Aquaculture and Fisheries 2022, Vol. 7, Issue 2, p. 166-178, https://doi.org/10.1016/j.aaf.2021.10.004

182 Toviho O.A., Bársony P. *Nutrient Composition and Growth of Yellow Mealworm (Tenebrio molitor) at Different Ages and Stages of the Life Cycle*, Agriculture 2022, 12(11), 1924; https://doi.org/10.3390/agriculture12111924-

183 Lu S et al., *Nutritional Composition of Black Soldier Fly Larvae (Hermetia illucens L.) and Its Potential Uses as Alternative Protein Sources in Animal Diets: A Review*, Insects. 2022 Sep; 13(9): 831, 2022 Sep 13. Doi: 10.3390/insects13090831.

Microbial fermentation

Mycoprotein have been noted for their high fibre and protein and low fat content. While the digestibility of protein in mycoprotein is lower than that of milk casein,[184] it is still considered a robust source of protein. Mycoprotein is also high-fiber, which contributes various benefits, in particular to gut health.[185]

Besides mycoprotein, other alternative proteins generated through microbial fermentation – such as dairy proteins in the example discussed in this report – can be produced via the cultivation of different host organisms: yeast, bacteria, animal or plant cells. The nutritional value of the harvested produce depends on the host organism.[186]

Cultured meat

The macronutrient content and related nutritional quality of cultured meat are not well-known.[187] No studies were identified that assess this in human or animal subjects. Life cycle analyses and other studies of cultured meat have generally assumed that the macronutrient profile – and especially the protein levels – of cultured meat products would be similar to that of the conventionally produced product of the animal from which the cultured meat cells were derived, whether beef, chicken, pork or fish.

In principle, the protein content of cultured meat should be similar to its conventional counterpart, but the length of the cell cultivation process may affect protein concentration and quality. The fat content and quality can be controlled as fat is added to cultured meat or fat cells can be co-cultured with muscle cells. Theoretically it is possible to produce meat with lower levels of saturated fats and higher levels of omega-3 fatty acids.[188] This is speculative, however, as there are no research studies available to confirm this.

3.3.2. Micronutrient content

Alternative proteins have advantageous profiles when it comes to their micronutrient content. Algae, insects and mycoproteins all can provide key vitamins and minerals in higher proportions than conventional proteins. However, it is still uncertain how processing affects these micronutrients and therefore their bioavailability.[189] However, the bioavailability of micronutrients in insects has been shown to be equivalent to or higher than that of beef. Cultured meat is assumed to provide the same micronutrient profile as the conventional meat products they could replace.

Conventional proteins are important sources of micronutrients. It is an important source of zinc, iron, potassium, phosphorus, selenium, copper, A, B and D vitamins. By contrast its contribution to dietary

[184] Parodi et al., 2018.

[185] Souza Filho PF, Andersson D, Ferreira JA, Taherzadeh MJ, ' Mycoprotein: environmental impact and health aspects', *World Journal of Microbiology and Biotechnology*, 35(147), 2019, https://doi.org/10.1007/s11274-019-2723-9.

[186] Diaz-Bustamante et al., 2023.

[187] Correspondence with cultured meat expert.

[188] Fraeye I, Kratka M, Vandenburgh H, and Thorrez L, 'Sensorial and Nutritional Aspects of Cultured Meat in Comparison to Traditional Meat: Much to Be Inferred,' *Front. Nutr.*, 7, 2020, https://doi.org/10.3389/fnut.2020.00035; Zaraska M, 'Is Lab-Grown Meat Good for Us?' *The Atlantic*, 2013, https://www.theatlantic.com/health/archive/2013/08/is-lab-grown-meat-good-for-us/278778/ (accessed 27 October 2023).

[189] Parodi et al., 2018.

fiber, magnesium, and vitamins C and E is poor.[190] Dairy products contribute a large share of micronutrient needs, and particularly calcium, vitamins A, B5, B12, phosphorus and potassium.[191]

Algae

Algae present high vitamin and mineral content relative to conventional protein sources. They are particularly high in A, K, and B12 vitamins. While Vitamin B12 is high in macroalgae and microalgae, that found in Spirulina is in a form not absorbable by the human body.[192] Seaweeds are also high in magnesium, calcium, iron and iodine, which enables their contribution as supplements to the human diet.[193] Sugar kelp in particular has a high iodine content, and some concern has been expressed that consumers could be getting excessive iodine if kelp was to become a common staple.[194] Trials of the integration of algae as a supplement in feed have shown that it can contribute to animal diets (with different types of algae proving useful to different species), although palatability issues (which is due to the high mineral content) may limit that potential.[195] Processing, and particularly blanching, can lead to losing some minerals and soluble carbohydrates.

Insects

Insects can also be a source of important micronutrients for both human and animal diet, although, significant differences can be observed across species.

From a food perspective, mealworms perform better than their conventional counterparts in terms of overall vitamin content, with this being more evident for beef and dairy but less for chicken. The same can be said for the overall mineral content, with the notable exception of beef that has comparatively higher levels of iron, zinc and potassium, among others.[196, 197]

From a feed perspective, not all insect species are rich in micronutrients that are essential for animal requirements. For instance, most species present relatively low levels of calcium, with the black soldier fly being an exception.[198] In addition, when reared indoors, mealworms may present lower levels of Vitamin D.[199] When compared to soybean meal, insects perform better in terms of overall vitamin content, while the former presents, on average, higher levels of minerals.[200] Studies have

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190 Smith NW, Fletcher AJ, Hill JP, McNabb WC, 'Modeling the Contribution of Meat to Global Nutrient Availability' *Front Nutr.* Feb 2;9:766796, 2022. doi: 10.3389/fnut.2022.766796.

191 Smith NW, Fletcher AJ, Hill JP, McNabb WC. 'Modeling the Contribution of Milk to Global Nutrition' *Front Nutr.* Jan 13;8:716100, 2022. doi: 10.3389/fnut.2021.716100.

192 Parodi et al., 2018.

193 Barbier et al., 2019.

194 EFSA, Dujardin B, Ferreira de Sousa R, Gomez Ruiz JA, 'Dietary exposure to heavy metals and iodine intake via consumption of seaweeds and halophytes in the European population', EFSA Journal, 2023, 21 (1):e07798. doi:https://doi.org/10.2903/j.efsa.2023.7798.

195 Ibid.

196 Orkusz A, *Edible Insects versus Meat—Nutritional Comparison: Knowledge of Their Composition Is the Key to Good Health*', Nutrients. 2021 Apr; 13(4): 1207.

197 Dairy UK, The nutritional composition of dairy products: https://milk.co.uk/nutritional-composition-of-dairy/milk/ (accessed on 13 October 2023).

198 Spranghers T, Ottoboni M, Klootwijk C, Ovyn A, Deboosere S, De Meulenaer B, Michiels J, Eeckhout M, De Clercq, P and De Smet S, *Nutritional composition of black soldier fly (Hermetia illucens) prepupae reared on different organic waste substrates,* J Science Food and Agriculture 97, 2017, p. 2594-2600.

199 Oonincx DGAB and Finke MD, *Insects as a complete nutritional source,* J Insects Food Feed, 2023, 9(5), p. 541-543.

200 Orkusz A, 2021, and Soybean meal nutrition: calories, carbs, GI, protein, fiber, fats https://foodstruct.com/food/soybean-meal (accessed on 13 October 2023).

shown the bioavailability of micronutrients in insects to be equivalent or higher than that found in beef meat.[201]

Microbial fermentation

Mycoprotein is a source of useful minerals, such as zinc, calcium and iron, in comparable or higher concentration than conventional protein sources. By contrast, it is low in vitamins present in convention protein sources.

The micronutrient content of proteins produced through microbial fermentation, such as dairy alternatives, depends on the microorganisms used in cultivation, which may include bacteria, yeast, animal or plant cells.[202]

Cultured meat

The micronutrient content of cultured meat is unknown, although as with the macronutrient profile, it is generally expected to be the same as for its conventional counterparts. Observers have particularly noted that theoretically, the heme iron – which is better absorbed by the human body but also may increase the risk of cancer, stroke, heart disease and metabolic syndrome when consumed in high quantities - could be substituted with non-heme iron, which is naturally found in plant-based foods.[203]

3.4. Potential of the alternatives as substitutes for conventional animal proteins

Cultured meat and fermented alternative proteins (especially mycoprotein) could replace meat and dairy in the EU (mycoprotein is already present on the EU market, and cultured meat has been authorised in Singapore, Israel and the US), although consumer acceptance issues need to be overcome for cultured meat. Algae and insects as foods hold the most potential as alternative ingredients in multi-ingredient products, also considering consumer acceptance issues. Both alternatives present some food safety/allergenicity risks that must be addressed through processing or during production stages (for algae). Nutritional quality is also a consideration where alternative proteins are used as ingredients or supplements in procesed foods. Insects and algae also have the potential to replace a proportion of feed in the aquaculture, monogastric, and ruminant sectors.

Non-plant alternative proteins have the potential to substitute for conventional animal-based products, in some cases as a complete replacement and in others partially, for example, as an ingredient or supplement in human or animal diets. This section considers the opportunities and constraints associated with the four alternatives as substitutes for animal proteins. Potential substitution is assessed in light of factors including diet-related mortality risks, nutrient bioavailability, food safety, required processing levels, price and consumer acceptance.

Algae

The potential for algae to become a widely consumed substitute for conventional protein sources in Europe is limited due to several constraints. These include food safety concerns, a lack of consumer awareness regarding the environmental benefits of consuming algae, and aversion

201 Parodi et al., 2018.

202 Diaz-Bustamante et al., 2023.

203 Fraeye I, et al., 2020; Zaraska M, 2013.

towards the taste, texture, odour and colour of some algae-based foods,[204] although seaweed added to food formulations has been found to have beneficial effects on consumer response.[205]

Safety is a particular concern for microalgae due to the presence of heavy metals and toxins, which can result from the growing substrate used. As far as iodine is concerned, it is generally acknowledged that iodine deficiency is a bigger issue in the EU than overexposure.[206] Microalgae may also expose consumers to bacterial and viral infections. The minimal use of heat in microalgae processing requires that alternative strategies are found to make the product safe for consumption.[207]

Their allergenicity is considered low.[208] Consumer acceptance is another significant hurdle for developing the market of algae as food in Europe, as European consumers being less accustomed to the odour, appearance or *umami* taste of algae than, for example, Asian consumers.

Insects

Current consumption patterns and studies of consumer acceptance indicate that the complete substitution of conventional animal-based foods with insects in the short to medium term is unlikely.[209] The potential to be incorporated into compound foods as a substitute for a conventional animal-based ingredient is greater due to their high protein quantity and quality. Among all insect food applications, their use as ingredients in sports foods (e.g., protein bars), food supplements and other functional foods is expected to experience the highest growth by 2030.[210]

However, insect protein digestibility by the human body may be negatively affected by the presence of chitin, a carbohydrate polymer contained in insect exoskeletons. Although chitin has recognised beneficial health properties (e.g. antioxidant, antimicrobial) in addition to being an important source of fibre, it might need to be removed during processing to guarantee the preservation of insect protein quality.[211]

In addition, certain insect protein components (i.e., tropomyosin and arginine) may pose a food safety risk as they may trigger allergenic reactions in consumers sensitive to crustaceans and derived products, and dust mites.[212] For this reason, in the EU, food containing mealworms must display specific allergen warnings on the labelling. [213]

The edible insect market is still at an early stage of development, and consumer prices for insect-based foods on the EU market are, on average, relatively high, making them a premium food

[204] Mendes MC et al., 'Algae as food in Europe', *Foods* 11: 1871, 2022.

[205] Figueroa V, Farfán M, Aguilera JM, 'Seaweeds as Novel Foods and Source of Culinary Flavors' Food Reviews Inernational, 2023, 39(1): 1-26. doi:10.1080/87559129.2021.1892749.

[206] EFSA et al 2023.

[207] Hadi J, Brightwell G, 2021.

[208] Diaz-Bustamante et al., 2023.

[209] See, for instance, Mancini S, Sogari G, Espinosa Diaz S, Menozzi D, Paci G and Moruzzi R, 'Exploring the Future of Edible Insects in Europe', Foods 2022, 11(3), p. 455.

[210] Meticulous research, https://www.meticulousresearch.com/pressrelease/795/europe-edible-insects-market-2030 (accessed on 27 October 2023).

[211] Belluco S, Losasso C, Maggioletti M, Alonzi CC., Paoletti MG, Ricci A, 'Edible Insects in a Food Safety and Nutritional Perspective: A Critical Review', Volume 12, Issue 3, May 2013, p. 296-313 and Ojha S, Bekhit AED, Grune T, Schlüter OK, 'Bioavailability of nutrients from edible insects', Volume 41, October 2021, p. 240-248.

[212] Belluco S et al., cited above.

[213] See, for instance, Table 1 of Annex to Commission Implementing Regulation (EU) 2023/58 of 5 January 2023 authorising the placing on the market of the frozen, paste, dried and powder forms of Alphitobius diaperinus larvae (lesser mealworm) as a novel food and amending Implementing Regulation (EU) 2017/2470, OJ L 5, 1.6.2023, p. 10.

category. In the long run, higher consumer demand combined with the scaling up of their production and the lowering of production costs may contribute towards reducing their market price.

Regarding insects for animal nutrition, as indicated under Section 3.1., their protein quality makes them a suitable partial replacement for soybean in livestock feed.

Microbial fermentation

At present, the large scale production and commercialisation of mycoproteins as meat alternatives throughout the EU – the most notable example of which is Quorn – has not raised any significant food safety concern. Furthermore, the proximity between mycoprotein and the texture and taste of meat have made it easy to accept by consumers.[214] Health benefits have been reported for the consumption of mycoproteins, in particular positive effects on blood cholesterol concentration and glycemic response.[215] Meat alternatives produced from cultivated mycoproteins have been associated with potential allergenic risks, while future efforts to switch to alternative sources of carbon for feedstock could be associated with mycotoxins.[216]

Recombinant dairy proteins present a high nucleic acid content, which could influence their potential to replace dairy proteins. Treatments to reduce nucleic acid content come at a higher environmental cost.[217] Lifecycle studies of the production of dairy alternatives via cellular agriculture have concluded that they would generally have an equivalent footprint to the production of dairy proteins directly extracted from raw milk. This suggests that dairy proteins produced via cellular agriculture could compete with conventional dairy proteins in the more developed dairy markets of the EU, especially if renewable rather than fossil fueled energy was to become widespread, and the costs of conventional dairy production were to rise.[218] However, at present, "the economics of food-grade precision fermentation is nowhere near competing with commodity dairy".[219]

There are many applications of microbial fermentation beyond mycoprotein for meat alternatives and cultured dairy alternatives. Gas-fermented microbes to incorporate into multi-ingredient products may offer substitutes for animal-based protein ingredients with a much lower environmental footprint.[220]

Cultured meat

In principle, cultured meat has the potential to directly substitute for conventional animal proteins (rather than as a supplement to or ingredient in other foods, as in the case of insects, for example). The taste, smell, texture, appearance and nutritional composition could be – if not identical – at least very similar to animal proteins since cultured meat is produced from animal cells.

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214 Souza Filho et al. 2019.

215 Ibid.

216 Hadi J, Brightwell G 2021.

217 Diaz-Bustamante et al., 2023.

218 Behm et al., 2022

219 Tuomisto H, 2023

220 Mazac R, Järviö N, Tuomisto H, 'Environmental and nutritional Life Cycle Assessment of novel foods in meals as transformative food for the future, Science of the Total Environment 876: 162796, 2023, http://dx.doi.org/10.1016/j.scitotenv.2023.162796.

For these reasons, diet-related risk factors from meat consumption,[221] and particularly from red meat, could also exist for cultured meat if intake values for cholesterol, heme iron and saturated fat are replicated in the same proportions as for the equivalent animal product. Notably, cultured meat is still at an early stage of development, so data on nutrient bioavailability is not available to verify this assumption.

However, the nutritional profile of cultured meat could be adjusted during the production process – which is not possible for conventional meat. In theory, cholesterol levels could be lowered, non-heme iron replaced with heme iron[222] and the fat content controlled, including the levels of saturated compared to polyunsaturated fats.[223] Omega-3 fatty acids could replace other types of fats.

In theory, food safety could also be improved for cultured meat as compared to its conventional equivalent since there are no digestive organs that could contaminate the meat with intestinal pathogens such as *E. coli, Salmonella* or *Campylobacter* as can occur with livestock at slaughter.[224] The use of antibiotics and vaccines could also be greatly reduced or no longer required, thereby reducing the risk of antimicrobial resistance (AMR).[225] However, antibiotics may need to be used for cultured meat to prevent contamination and so the mitigating effects of cultured meat on AMR are unknown.

Replicating the complex structure and variety of tissues found in conventional meat is a significant challenge for the production of cultured meat. The texture, marbling, and overall appearance of cultured meat are areas where significant research and development are still required to achieve a product that is indistinguishable from conventional meat.

The estimated price of cultured beef remains high compared to conventional beef, if it were available on the EU market.[226] R&D funding is targeted at bringing the production costs down to achieve a price comparable with an equivalent animal product (see section 5).

Finally, consumer acceptance will be essential for cultured meat to substitute for conventional animal products successfully. Price will be a significant factor alongside taste, appearance, ethical considerations, and perceived health benefits. Consumer acceptance of cultured meat is generally low (only insects score lower).[227] However, attitudes towards cultured meat are still evolving and there is currently a lack of widespread familiarity with it.

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221 Etemadi A, et al., 'Mortality from different causes associated with meat, heme iron, nitrates, and nitrites in the NIH-AARP Diet and Health Study: population based cohort study,' *BMJ*, 2017, 357, https://doi.org/10.1136/bmj.j1957; Hooda J, Shah A, and Zhang Li, 'Heme, an Essential Nutrient from Dietary Proteins, Critically Impacts Diverse Physiological and Pathological Processes,' *Nutrients* 6(3): 1080-1102, https://doi.org/10.3390/nu6031080.

222 Heme iron is better absorbed by the body than non-heme iron, but heme iron has been shown to increase the risk of disease when consumed in excess quantities.

223 Chriki S, Hocquette JF, 'The Myth of Cultured Meat: A Review,' *Sec. Nutrition and Food Science Technology*, 2020, 7, https://doi.org/10.3389/fnut.2020.00007.

224 Shapiro P., 'Clean meat: how growing meat without animals will revolutionize dinner and the world,' *Science*, 2019, 359:399, https://www.science.org/doi/10.1126/science.aas8716

225 Chriki and Hocquette, 2020.

226 Kools F, 'What's been going on with the 'hamburger professor,' Maastricht University News, 2019, https://www.maastrichtuniversity.nl/news/what%E2%80%99s-been-going-%E2%80%98hamburger-professor%E2%80%99.

227 Onwezen et al., 'A systematic review on consumer acceptance of alternative proteins: Pulses, algae, insects, plant-based meat alternatives, and cultured meat,' *Appetite*, 2021, 159, https://doi.org/10.1016/j.appet.2020.105058.

3.5. EU R&D activity

Investments in R&D, which include both private and public funding, have been increasing across all alternative protein sources in the EU. Major investments at EU or national level have been recently announced to support research as well as commercialization in cellular agriculture, encompassing both fermentation and cultivated meat. Increased funding is also notable for algae and insects R&D, although not to the same level. The recently launched EU Algae initiative holds the promise of growing investments in that sector.

Research and development (R&D) activity is a critical component in the advancement of alternative proteins, encompassing the contributions from research institutions, universities, startups, and established companies. These entities support innovation through a variety of means, including the publication of scientific studies, filing of patents, and initiation of research projects. The volume of these activities provides insight into the level of interest and investment in the field, while the presence of major EU grants and funding initiatives further supports the growth and development of the sector for each alternative. Collectively, the scope and maturity of the R&D ecosystem plays a significant role in determining the pace and direction of progress for the alternative proteins, influencing their potential for success and sustainability in the market.

Algae

The commercial landscape of algae production in Europe has been growing steadily in recent years. The number of European seaweed start-ups has reportedly nearly tripled in the past 10 years,[228] most seaweed companies being found in France, and then the United Kingdom, Ireland, Norway and the Netherlands, Spain, Denmark. The growing trend in the algae sector more broadly is noticeable since the mid-2000s, and has benefited both the seaweed and microalgae sectors.[229]

R&D on algae production for food and feed has been receiving both private and public funding. Investments into European SMEs and start ups have been channelled through the BlueInvest platform[230] as well as other routes. Grant funding has played a major role in funding the sector as a whole so far, representing 75% of investment into the algae sector in 2019.[231] Indeed, EU funding has supported at least 300 algae related projects to date, and it is planning to allow algae businesses to tap into a EUR 500 million "InvestEU Blue Economy" fund.[232] Further funding is being made available through the Horizon programme, and the European Maritime, Fisheries and Aquaculture Fund (EMFAF).

There is a general need, recognised in the recent EU communication "Towards a strong and sustainable EU algae sector" (also known as the EU Algae Initiative)[233] for greater EU support to the sector. Ongoing research seeks to improve the economic feasibility of large scale cultivation of macroalgae in the Northern Atlantic, while seeking to optimise practices and develop further applications for algae across food, feed, pharmaceuticals and biomaterials.

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228 De Chaisemartin et al., *The case for seaweed investment in Europe*, Seaweed for Europe, 2021.

229 Araujo et al. 2021.

230 https://maritime-forum.ec.europa.eu/theme/investments/blueinvest_en.

231 De Chaisemartin et al., *The case for seaweed investment in Europe*, Seaweed for Europe, 2021.

232 https://www.foodnavigator.com/Article/2022/11/16/food-innovators-welcome-ec-s-pioneering-algae-plan

233 https://oceans-and-fisheries.ec.europa.eu/publications/communication-commission-towards-strong-and-sustainable-eu-algae-sector_en

Public funding for research and development has played a significant role in the development of the Norwegian algae industry. Indeed, Norway's strategy, which has combined encouraging research and development in seaweed cultivation and delivering licenses for cultivation is credited for the high number of seaweed aquaculture companies found there.[234]

Insects

Only few years ago insect companies were largely concentrated in Northern Europe.[235] However, with the progressive removal of regulatory barriers to access the EU market, insect companies are now more evenly distributed across the EU territory. For instance, the majority of companies that are members of the International Platform for Insects as Food and Feed (IPIFF) are currently based in France (9), Germany (6), Spain (5) and Italy (3).[236]

In the edible insect segment, Protix, Ynsect and AgroNutris are currently major players on the EU market, with successfully submitted novel food authorisations for specific insect applications and securing their exclusive commercial exploitation for five years - the maximum period allowed under EU legislation. In the feed insect segment, Protix, Entomo and InnovaFeed are amongst the major players on the EU market.

In the EU, over the past two decades R&D activity targeting insects as food and feed has been conducted by various research institutions located in different EU Member States, including the Netherlands, Belgium, Italy, Denmark, Germany and Spain. [237]

R&D related to insects has also recently benefitted from EU funding under the Horizon 2020 programme. For instance, concluded in 2023, with a duration of four years and a consortium of 35 organisations, SUSINCHAIN (SUStainable INsects CHAIN) investigated ways to overcome existing barriers to the scaling up of the insect value chain through the application of emerging technologies as well as the development of strategies to ensure higher levels of consumer acceptance. To this effect, the project received an EU net contribution of EUR 1 653 005,00.[238] Additionally, Insect Doctors is a joint Ph.D. programme that aims at training fifteen future pathologists to deal with insect diseases in mass-rearing establishments to avoid economic losses as well as their spreading to humans. This project has benefitted from an EU net contribution of EUR 4 201 844,76.[239]

Therefore, over the last few years the EU R&D ecosystem has evolved favourably for insects as food and feed both in terms of number and geographical distribution of market players and public funding. For this reason, at present funding opportunities are not regarded as a key driver for the growth of the European insect sector unless if directed at helping companies to scale up.[240]

If one considers intellectual property rights associated with R&D activity, globally China and South Korea are the countries with the highest number of patented innovations involving edible insects (together they account for 94% of all such patents). While a majority of patents belong to private

234 Araujo et al., 2021.

235 See, for instance for insects as food, Pippinato L, Gasco L, Di Vita G and Mancuso T, *Current scenario in the European edible-insect industry: a preliminary study*, Journal of Insects as Food and Feed, 2020, 6 (4), p. 371 – 381.

236 https://ipiff.org/ipiff-members/?location=Ipro

237 See, for instance, Boukid F, Sogari G and Roselli CM, *Edible insects as foods. Mapping scientific publications and new product launches in the global market (1996-2021)*, Journal of Insects as Food and Feed, 2023, Volume 9 (3) 2023, pp. 353-368.

238 https://cordis.europa.eu/project/id/861976.

239 https://cordis.europa.eu/project/id/859850.

240 IPIFF, *IPIFF perspectives on the evolution of the European insect sector towards 2030: current EU regulatory status, existing opportunities and propsects for development,* Brussels, November 2023.

companies, the Korean Rural Development Administration, a government institution, is the entity that has obtained more patents for insect-based food applications.[241]

Microbial fermentation

Globally, investments (both public and private) in fermentation (and particularly precision fermentation) have increased significantly, and recently on a level close to the amounts invested in plant-based alternatives. There is evidence of a trend since 2019, after only occasional investments in those sectors in the years previously.

Of those investments, most have gone into microbial fermentation, rather than biomass or traditional fermentation.[242] These have been overwhelmingly made in Northern America, however, with Europe a distant second: USD 2.9 billion have been invested in fermentation in Northern America during the period 2013-2022, versus USD 0.4 billion in Europe over the same period.

By contrast, Europe has been leading *public* funding into research and commercialization of fermentation. That includes both EU and national funding:

- EUR 13.1 millions in EU funding have been budgeted for the HealthFerm research collaboration.
- EUR 34 millions in funding from Finland have been granted to Solar Foods.
- EUR 10 millions have been allocated by Norway to a five year program on cellular agriculture and precision fermentation.
- EUR 60 millions has been announced by the Netherlands to invest in a full cellular agriculture ecosystem.
- EUR 16.9 millions in EU funding have contributed to the construction of one of the largest protein facilities in the Netherlands, dedicated to mycoprotein production.

The commercial landscape for fermentation is a dynamic one, with a steady increase in the number of companies across the biomass and precision fermentation landscape since 2013: there were 132 companies identified by the Good Food Institute in those sectors in 2022, against only seven before 2013 (not all of those companies would produce alternative proteins for food, however). A little under half of them are found in Europe, which has more companies in the sector than North America does. A notable trend is the growing involvement of conventional protein companies in those new ventures, with of the well-known food and feed multinationals (e.g. Nestle, Cargill, GeneralMills, KraftHeinz, etc.) having in one way or another become participants in the growth of the sector.

Cultured meat

Global investments in cultured meat (and seafood) companies tripled on average annually from 2016 to 2022, for a total of USD 2.8 billion in those six years. In Europe, investments in cultured meat increased in 2022 as compared to 2021, despite a decrease globally.

[241] Lordelo Guimarães Tavares PP et al, *Innovation in Alternative Food Sources: A Review of a Technological State-of-the-Art of Insects in Food Products*, Foods. 2022 Dec; 11(23): 3792, doi: 10.3390/foods11233792.

[242] GFI, 'Fermentation: Meat, seafood, eggs, and dairy, 2022 State of the Industry Report,' 2023, https://gfi.org/wp-content/uploads/2023/01/State-of-the-Industry-Report-Fermentation-2022.pdf.

In 2022, more than 150 companies were exclusively focused on cultured meat (and seafood) worldwide.[243] Of these, 24 are based in the EU, concentrated in Germany (6), the Netherlands (5) and France (3).[244] Major diversified food companies are also involved in the cultured meat industry through investment, acquisition, partnership, or R&D and manufacturing of inputs. This includes companies headquartered in the EU or EFTA countries such as CP Kelco ApS, Kerry Group, Merck KGaA, and Nestlé.

The Dutch government announced EUR 60 million in funding for cultured meat and precision fermentation in 2022, which represents the largest public sector investment in these alternative proteins to date.[245] Since 2005, R&D support for cultured meat at EU level and in the member states has been pivotal, with key investments including:[246]

- EUR 2.7 million to BioTechFoods' 'Meat4all' project in 2020, marking the EU's first public investment in cultured meat.[247]
- EUR 2.5 million to ORF Genetics in 2020 for growth factor research.[248]
- EUR 2 million to Mosa Meat's 'Feed for Meat' project in 2021, to lower cell culture media costs.[249]
- EUR 10 million seed-funding to Gourmey in 2021, co-funded by the European Commission and Bpifrance.[250]

At the Member State level, funding and co-funded R&D programmes include:

- EUR 5.2 million in 2021 from the Spanish government to BioTech Foods to assess health benefits of cultured meat.[251]
- EUR 3 million in 2019 through Eurostars to Meatable to manufacture meat cells without the need to slaughter an animal as the precursor to cell differentiation and growth.[252]
- EU 3.6 million to a Belgian consortium to grow fat and liver cells for producing foie gras.

The European Institute of Innovation & Technology (EIT) also launched the 'Cultivate Meat Innovation Challenge' in 2022, and will award EUR 100,000 to each of four projects in an effort to

243 GFI, 2023. This is an underestimate as it does not include companies in 'stealth mode', when start-ups operate in secret to prevent competitors from learning about their business models, technologies or products before release.

244 GFI, 2023.

245 https://www.tudelft.nl/en/2022/tnw/dutch-government-confirms-eur60m-investment-into-cellular-agriculture; https://gfieurope.org/blog/netherlands-to-make-biggest-ever-public-investment-in-cellular-agriculture/

246 https://proveg.com/blog/the-european-union-funds-research-in-cellular-agriculture/

247 https://www.foodnavigator.com/Article/2020/10/14/EU-assigns-first-ever-funds-for-cultured-meat-project

248 https://icelandmonitor.mbl.is/news/news/2020/08/01/icelandic_biotech_firm_receives_large_european_gran/

249 https://proveg.com/blog/the-european-union-funds-research-in-cellular-agriculture/; https://www.greenqueen.com.hk/mosa-meat-nutreco-eu-grant/

250 https://www.bloomberg.com/news/articles/2021-07-14/lab-grown-foie-gras-receives-french-government-support-tastes-delicious; https://techcrunch.com/2020/10/14/lab-grown-meat-project-gets-first-taste-of-eu-public-funds/

251 https://www.foodnavigator.com/Article/2021/01/20/Spanish-government-invests-5.2-million-in-cultured-meat-project.

252 https://app.dealroom.co/companies/meatable; https://techcrunch.com/2019/12/06/dutch-startup-meatable-is-developing-lab-grown-pork-and-has-10-million-in-new-financing-to-do-it/.

incentivise research that will drive down the cost of cell culture media. The initial funding round is expected to lead to 'substantially more funding'.[253]

While Europe has made significant contributions to cultured meat developments, countries like the US, Singapore, and Israel are also leading in investments and technological advancements. The US is responsible for more than 60% of all investments in cultured meat – more than all other countries combined, followed by Israel (almost 22%), the Netherlands (almost 6%) and Singapore (almost 5%).[254] The European approach has been more focused on public-private collaborations, while the US, for instance, has seen larger private investments (CRS 2023).

Start-ups in this sector face both opportunities and challenges. While there is significant investment and growth potential in the sector, the survival and growth rates of startups depend on factors such as their ability to secure funding, reduce production costs, and scale up operations effectively. The high costs of cell culture media and the need for suitable bioreactors are among the challenges that startups face. The fate of these start-ups often relies on technological breakthroughs, market acceptance, and regulatory landscapes (Chodkowska, Wodz and Wojciechowski 2022). Patent filings for cultured meat technology are led by the US and Asian countries. Only three of the top ten companies filing patents in Europe are based there.[255]

3.6. EU production potential

3.6.1. Technological and commercial readiness

Insects, algae and mycoproteins have well-established production and processing methods, and multiple market applications, thus reaching advanced technology and commercial readiness levels (TRL 8-9 and CRI 3-4). Algae as a food source has reached a higher commercial readiness level than as feed, while the converse is the case for insects. Recombinant proteins and cultured meat have generally reached lower levels of technology and commercial readiness (TRL 5-7 and CRI 1-2). Microbially fermented dairy products have reached commercial maturity but are not yet widely available on the market (CRI 2). Cultured meat is not yet authorised on the EU market (CRI 1), but has been granted approval in the US, Israel, and Singapore (CRI 2).

Technology Readiness Level (TRL) and the Commercial Readiness Index (CRI) are two assessments used to gauge the maturity and market readiness of a technology or product. The TRL system provides a consistent metric to help determine how close a technology is to being ready for its intended use, with a scale ranging from 1 to 9 that measures the developmental progress of a technology, from conceptualisation to full operational deployment.[256]

Progression through the TRLs represents the path from idea conception to operational application, aiding stakeholders in evaluating and managing technological risks:

1. **Early Stage Research** (TRLs 1-3): Initial scientific exploration of basic principles, further formulation of technology concepts, and proof-of-concept demonstration through analytical and experimental work.

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[253] https://eit.europa.eu/our-activities/opportunities/cultivated-meat-innovation-challenge.

[254] https://www.fdbusiness.com/report-reveals-countries-poised-to-seize-the-worlds-lab-grown-meat-market/

[255] https://www.govgrant.co.uk/sector-research/how-well-is-europe-playing-the-cultured-meat-game/ ; https://www.fdbusiness.com/report-reveals-countries-poised-to-seize-the-worlds-lab-grown-meat-market/

[256] EURAXESS, 'About Technology Readiness levels,' no date, https://euraxess.ec.europa.eu/career-development/researchers/manual-scientific-entrepreneurship/major-steps/trl (accessed 30 October 2023).

2. **Development and Demonstration** (TRLs 4-6): Validation of components in controlled and relevant environments, progressing to a prototype demonstration in a relevant or simulated setting.

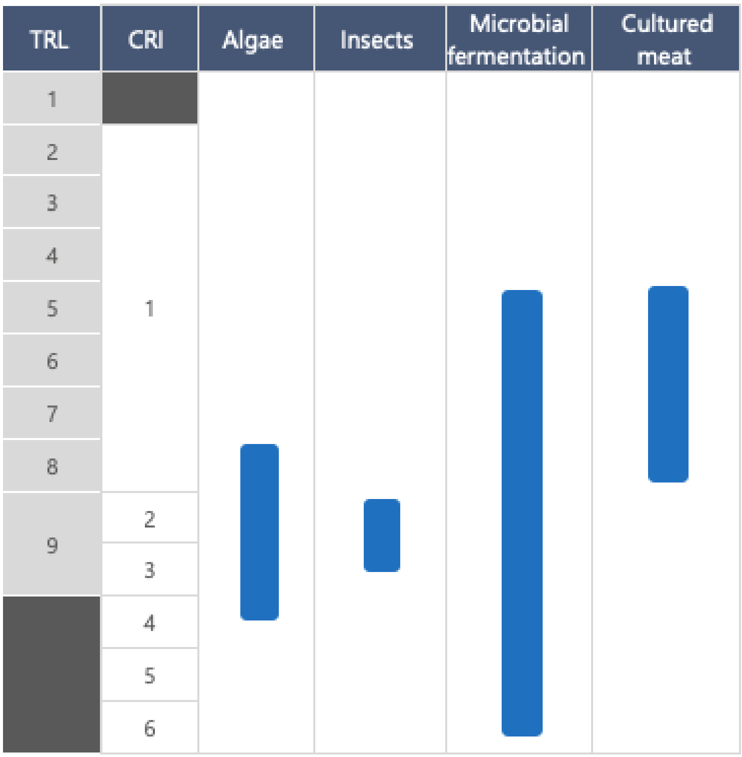
3. **System, Test, Launch, and Operations** (TRLs 7-9): Prototype testing in operational environments, final system completion and qualification, culminating in proven performance through successful operations.

CRI evaluates the extent to which a product is ready for commercialisation. CRI is a less well-established metric compared to TRL and there are different scales used for CRI; the one adopted for this study ranges from 1-6.[257] CRI considers factors such as regulatory approvals, market demand, and production scalability:

1. **Early Stage Commercialisation** (CRI 1-2): Initial hypothetical commercial propositions driven by technology advocates, transitioning into commercial trials lacking empirical commercial value evidence.
2. **Development** (CRI 3-4): Commercial scale-up with risky financing, evolving into multiple commercial applications with decreasing subsidisation and new financing attracted by public information availability.
3. **Market Maturity** (CRI 5-6): Competitive market driving widespread technology deployment, culminating in a "bankable" grade asset class with well-understood commercial performance minimizing financial decision risk.

Together, TRL and CRI provide an overall understanding of a technology or product's viability and potential success in the market.

Table 3 – TRL and CRI of the alternative protein sources



[257] Heder M, 'From NASA to EU: the evolution of the TRL scale in Public Sector Innovation,' *The Public Sector Innovation Journal*, 2017, 22(2).

TRI score description: 1 = Basic principles observed (conceptual stage); 2 = Technology concept formulated (evaluation & proof of concept); 3 = Experimental proof of concept (lab tested or simulated); 4 = Technology validated in a lab (testing & optimisation ongoing); 5 = Technology validated in relevant environment (incl. performance & reliability testing); 6 = Technology demonstrated in relevant environment (successful prototype); 7 = Prototype demonstrated in operational environment (incl. performance & reliability testing; 8 = Technology system complete & qualified through testing & demonstration (final system in place); 9 = Technology proven in operational environmental (full-scale deployment & commercialisation).

CRI score description: 1 = Hypothetical commercial proposition (conceptual stage, w/ product design, some market analysis, and business plan developed); 2 = Commercial trial (technology tested on the market); 3 = Commercial scale up (manufacturing processes est., w/ quality control measures, ready for wider distribution); 4 = Multiple commercial applications (additional marketable functions or uses); 5 = Market competition driving widespread deployment; 6 = 'Bankable' grade asset class, w/ stable economic value & future prospects.

Algae

Seaweed and microalgae has been used as a food source and in supplements for many years in the EU and are considered to be at TRL 8-9 for these applications, with well-established harvesting, processing, and consumption patterns. This was confirmed in a study of 223 European-based start-ups and SMEs, which found that 85% of them had a TRL of 8 or 9, already generating revenues, with most of them involved in food and feed production.[258]

Algae as a food source has reached CRI 4. Seaweed is a traditional food source in many cultures and has a well-established market in the EU, particularly as a specialty food item. There is also growing interest in seaweed as a health food, leading to increased commercialisation. Similarly, microalgae such as Spirulina and *Chlorella* are widely available in the EU as dietary supplements and are increasingly being used as ingredients in health food products due to their high protein content and nutritional quality.

Algae as a feed source has reached CRI 3-4. Algae-based feeds, especially for aquaculture, are commercially available and used as a source of essential nutrients. The EU has several producers of algae-based aquaculture feed, reflecting a maturing market (CRI 4). While there is significant interest in using microalgae as a feed for livestock, this market is not as developed as the aquaculture feed market. There are operational trials and some commercial activity, but it is not yet fully mainstream (CRI 3).

Insects

Following the regulatory approval of the most common edible insects as novel foods, including mealworms, and the expansion of the list of food-producing animals that can be fed with insects, the EU market has reached the highest level of technology readiness (i.e., TRL 9) and is now undergoing industrial and market scaling up. However, the scaling up is at a more advanced stage for insects as feed (CRI 3) as compared to insects as food (CRI 2) .

Edible insects are still subject to few key legal constraints that are slowing down market developments. As already referred above, the novel food authorisations that have been approved to date can only be exploited commercially by the respective applicants. While other food companies can buy approved insect formulations directly from those applicants or their licensees, this situation may limit in practice technology repeatability by other competitors and market entrants for a few years. In addition, there are a few other insect species whose approval as novel foods is still pending at EU level (e.g, *Gryllodes sigillatus*, *Apis mellifera*).

[258] De Chaisemartin et al, *The case for seaweed investment in Europe*, Seaweed for Europe, 2021.

Also, now that several insect-based food products are on the EU market the question as to whether and to what extent consumers will buy and include them in their diets remains to be seen. Lastly, while consumer research has so far generally focussed on consumer willingness to try edible insects, very few studies analyse consumer willingness-to-pay for those products.[259] Considering current consumer prices of food products containing edible insects, future research in this area may contribute towards a better understanding of market demand vis-à-vis these food innovations.

Microbial fermentation

The microbial fermentation sector is complex and diverse. As a result, has reached different levels of technological maturity and commercial readiness for different applications.

Mycoproteins for meat substitutes have been commercially available for several decades. The technology behind mycoproteins is well-established, with these products widely available in supermarkets and used in a variety of foods. The TRL for mycoproteins is thus at level 9, which indicates that the technology is proven and accepted in operational environments.

Recombinant protein technology for food applications is more varied in its TRL. Many recombinant proteins are still in the development or early commercial stages, In general, the TRL for recombinant proteins is 5 to 7, indicating that the technology has been validated in relevant environments and is beginning to be deployed in pilot projects or limited market releases.

Some recombinant proteins, such as those used in alternative dairy products, are also reaching commercial maturity, though not as widespread as mycoproteins. These products have reached TRL 8-9 with the technology proven and in some cases available commercially (CRI 2), but not as widely integrated across all potential markets and applications as mycoproteins.

Cultured meat

Cultured meat technology has advanced beyond the initial research and concept phase (TRLs1-4), including the basic understanding of biological processes to produce meat in vitro, such as cell culture and tissue engineering. A number of companies and research institutions have successfully produced cultured meat in a laboratory setting, which includes growing muscle cells in a bioreactor and forming them into edible products. Thus cultured meat production, in general, has reached TRL 5.

Some companies have moved beyond the lab and produced cultured meat in environments that more closely resemble commercial production facilities, reaching TRL 6. This is a critical step in proving that the technology can be scaled up for widespread consumption.

Another small number of companies have reached the stage of having prototype products that are close to what could be sold commercially (TRL 7). These prototypes are used for testing and refinement before full commercialisation. The products have also reached a stage where they are available for private tasting events, including in the EU.[260]

Two companies have received approval for cultured meat (chicken meat) for the US market, but it is not yet available commercially (TRL 8). Israel approved the first cultured beef in 2024 (TRL 8). A cultured chicken meat product has been approved in Singapore and has been sold to consumers in a limited number of venues (TRL 8-9).

259 See, Mancini S, Sogari G, Espinosa Diaz S, Menozzi D, Paci G and Moruzzi R, 'Exploring the Future of Edible Insects in Europe', cited above.

260 GFI, 2023.

The main obstacle to advancing cultured meat is scaling-up production, which would support lower costs. This requires developing new bioreactor facilities and other infrastructure. The regulatory lanscape is also in development, with no cultured meat products approved on an EU market or outside of the US, Israel and Singapore globally. Cultured meat is also unfamiliar to many consumers, with uncertainty related to trust and consumer acceptance, which is important for industry to advance development of this technology. In Singapore, the CRI for cultured chicken is 1-2, while in the EU it remains at 1 since there are no products on the market yet.

3.6.2. Industrial capability

In the EU, the algae sector has the potential for growth but requires infrastructure investments to overcome processing limitations. The insect industry is expanding, with a focus on technological and financial developments to meet rising demand and foster circularity. While still in comparatively early development stages in the EU, cultured meat has a high level of technical expertise and pilot projects to address scale-up and commercialisation challenges. Insufficient food grade industrial capacity is a known bottleneck for microbial fermentation, in the EU and elsewhere.

Industrial capability encompasses the collective ability of an industry or sector to develop, produce, and market a product, drawing upon available technology, production capacity, and technical expertise. In the context of alternative proteins, this includes understanding the main EU firms involved in product development and commercialisation, and assessing the availability and adequacy of production facilities, workforce expertise, and the degree of integration and scalability of supply chains and logistics infrastructure.

Algae

The population of industrial players in European algae production is rapidly growing. Data on the size of the sector is inconsistent, however, with low and high estimates varying by an order of 10.[261] There is apparent consensus on the lack of processing capacity across the sector, largely due to the high capital investment costs required. "Landing facilities for the processing of cultivated seaweed biomass"[262] and "biorefineries"[263] are called for to expand processing capacity in the EU, and thus achieve both scale and the ability to generate numerous applications for food, feed, and beyond.

A large share of algae production in the EU relies on wild harvesting, whereas globally aquaculture dominates by far: EU aquaculture production represented 0.001% of global seaweed aquaculture in 2021.[264] Seaweed aquaculture is developing in Europe, while the sustainability of wild harvesting has been questioned.[265]

The JRC has concluded in 2023 that for algae production to really take off in Europe, many knowledge gaps in technology, biology and markets need to be tackled first. This applies to aquaculture in particular, including the development of durable structures for large scale

[261] Avitabile et al., *Biomass production supply & use in the EU*, Joint Research Centre of the European Commission, 2023.

[262] Stévant P, Rebours C, "Landing facilities for processing of cultivataed seaweed biomass: a Norwegian perspective with strategic considerations", Journal of Applied Phycology, 33: 3199-3214, 2021.

[263] De Chaisemartin et al., 2021.

[264] Avitabile et al., 2023.

[265] Araújo et al., 2021.

production in the Northern Atlantic.[266] Mechanisation and automation of several stages, including harvest, could also improve the economic outlook for large-scale seaweed cultivation.[267]

The algae sector in Europe has been called "immature",[268] operating currently with high production costs and at a limited scale. More generally, these issues were recognised in the Roadmap for the Blue Economy published in 2020, and again in the report on the future of the EU algae sector.[269]

Insects

The EU insect sector has been steadily expanding in terms of industrial capability over the last decade for both food and feed though at a different speed and with distinct patterns.

Regarding the insect food market, according to IPIFF, in 2020 the vast majority of the operators of this market segment were micro-companies (81%) very often with a total investment below 500,000 EUR. In the same year, the European workforce of this market segment amounted to less than 500 employees, while forecasts indicate that the sector could generate a total of 4,000 jobs by 2030. The current level of vertical integration of the insect food sector is low. A majority of business players in this market segment only operate in the processing stage (notably, secondary processing aimed at formulating insect products for the final consumer), whereas less than a third cover all relevant production stages (i.e, insect farming, secondary processing, and sales). Initially, in the absence of a EU harmonised regulatory framework for insects as food, most companies concentrated their activities in national markets where production and trade were allowed. Now, following the first raft of novel food authorisations regarding insects, the EU market has become the main target market.[270] The further upscaling of the insect food sector depends on a combination of technological, financial and market factors, which include increased automation of large-scale insect farms, availability of subsidies and investments, and higher stability of the demand for insect-based products.[271]

Concerning insects as feed, operators of this market segment were either already active in the pet food business or are newly established players. According to data from IPIFF, in 2021 insect feed operators were present in 20 European countries employing about 1,000 FTEs with 25,000 jobs forecast to be created by 2030. Currently, the large majority of insect feed businesses are SMEs, but by 2030 larger companies are expected to dominate the market. The growth of the insect feed industry has been supported by significant private investments mainly to test products and build production facilities, which are estimated to be EUR 3 billion by 2025. Most insect feed operators are targeting national markets at present, but in the medium term are likely to pursue opportunities in international markets, including outside Europe. The further upscaling of the insect feed sector is largely dependent on the possibility to use cheaper organic waste as substrates for insect rearing as

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266 Bak UG, Gregersen Ó, Infante J, 'Technical challenges for offshore cultivation of kelp species: lessons learned and future directions', *Bot Mar* 63 (4) :341, 2020. Doi :https ://doi.org/10.1515/bot-2019-0005

267 Araújo et al., 2021.

268 Ibid.

269 https://op.europa.eu/en/publication-detail/-/publication/7e963ebb-46fc-11ea-b81b-01aa75ed71a1/language-en ; Kuech A, Breuer M, Popescu I, *Research for PECH Committee – The future of the EU algae sector*, European Parliament, Policy Department for Structural and Cohesion Policies, Brussels, https://www.europarl.europa.eu/RegData/etudes/STUD/2023/733114/IPOL_STU(2023)733114_EN.pdf.

270 IPIFF, Edible insects on the European market, 2020, available at https://ipiff.org/wp-content/uploads/2020/06/10-06-2020-IPIFF-edible-insects-market-factsheet.pdf.

271 Yang Y and Cooke C., 2020, 'Exploring the barriers to upscaling the production capacity of the edible insect sector in the United Kingdom', British Food Journal 123(4): 1531-1545 and Niyonsaba HH, Höhler J, , van der Fels-Klerx HJ, Slijper T, Alleweldt F, Kara S, Zanoli R, Costa AIA, Peters M and Meuwissen MPM, 'Barriers, risks and risk management strategies in European insect supply chains', Journal of Insects as Food and Feed, 2023. 9 (6), p. 691 – 705.

a way to contribute towards full circularity, meet the demand of low-carbon footprint food products and reduce production costs.[272]

Microbial fermentation

There is a global lack of industrial capacity to scale up microbial fermentation. Indeed, existing fermentation facilities tend to have been designed many years ago for other purposes than the production of food. Significant investments have been going into the construction of such facilities, although most have been planned for facilities based eslewhere than in Europe, and notably in Northern America or the Middle East.[273]

Cultured meat

The production capacity and facilities for cultured meat are still in development. Pilot-scale processing facilities for cultured meat are operating worldwide, including in the EU, offering proof-of-concept capabilities to demonstrate product yield and assess costs.[274] In 2022, there were 27 such pilot-scale (or larger) facilities identified worldwide. Demonstration-scale and industrial-scale facilities would enable significantly larger production volumes, but facilities at this scale are not yet operating in an EU context and there are only a small number worldwide. In 2022, Gourmey, a cultured meat startup based in France, announced plans to construct a commercial production facility in Paris.

Likewise, supply chain integration and scalability are also in the process of being developed, with challenges in scaling up production and sourcing fundamental ingredients. Logistics infrastructure is also a challenge, since cultured meat needs to be produced and distributed in a way that preserves its quality and safety; this infrastructure is not yet in place.

The technical expertise in the cultured meat industry is high, including in an EU context, with many companies employing scientists and engineers with backgrounds in cell biology, tissue engineering, and food science. Cultured meat was pioneered at the University of Maastricht and Mosa Meat is a startup spin-off from the university.[275]

The current industrial capability for commercializing cultured meat in the EU is still in the development stage. While there are several key players in the industry and a strong base of technical expertise, challenges remain in terms of production capacity, facilities, supply chain integration, and scalability. The TRL and CRI for cultured meat in the EU are relatively low, indicating that there are still significant gaps that need to be addressed before cultured meat can be a viable alternative to conventional meat.

4. Conclusions

Alternative protein sources, including algae, insects, microbial fermentation, and cultured meat, present a promising opportunity to alleviate the environmental burdens associated with conventional livestock production, which is characterized by high energy and water consumption, significant greenhouse gas emissions, and considerable waste generation.

[272] IPIFF, An overview of the European market of insects as feed, April 2021, available at https://ipiff.org/wp-content/uploads/2021/04/Apr-27-2021-IPIFF_The-European-market-of-insects-as-feed.pdf.

[273] GFI, 2023

[274] GFI, 2023.

[275] https://www.labiotech.eu/interview/interview-mark-post-cultured-meat/

While alternative proteins generally require less water and land and produce fewer greenhouse gas emissions compared to conventional animal proteins, there are variations and complexities within each alternative that necessitate further research and optimization. For example, the energy use in producing some alternative proteins can be equivalent to or even higher than their conventional counterparts, and specific feed sources for alternatives such as insects and algae can result in higher greenhouse gas emissions compared to soybean. Moreover, while alternative proteins tend to generate less waste, with some even offering circular economy benefits by utilising waste as an input, the full extent of their sustainability potential is yet to be fully realised and requires further investigation.

Some of the alternative protein sources offer a beneficial macronutrient profile when compared to conventional animal-based proteins, although research on their bioavailability depending on type of alternative protein, mode of production and mode of processing is ongoing. Alternative proteins have advantageous profiles when it comes to their micronutrient content, although there too the impact of different production processes and processing deserves further investigation.

The potential of alternative proteins to replace conventional protein sources hinges on their nutritional contribution to people's and animals' diets, besides their price, regulation, and consumer acceptance. The level of investment in R&D, commercial and technological maturity and industrial capacity further point to how the future of alternative proteins may play out. The outlook as it emerges from this study is summarised below, for each category considered.

Algae as an alternative protein presents less potential for food rather than feed. That is principally due to low consumer awareness and the limited possibilities for generating wholesome food products from algae. By contrast, there is more support for its potential as a supplement to feed. The EU algae sector has not joined in the aquaculture expansion that has characterised it elsewhere in the world. There are knowledge gaps and industrial capacity to address before the industry may scale up. The current costs of producing seaweed protein ingredient is too high to be competitive with conventional alternatives (e.g. soy protein), especially for species with low protein content, such as sugar kelp. Substantial investments in cultivation and processing infrastructure as well as co-extraction of protein and high-value compounds would be needed to sustain the development of the emerging European seaweed industry,[276] while innovative methods could be implemented for lowering the environmental impact of seaweed protein ingredients.[277]

Insect production for food and feed is less land-intensive and can have lower greenhouse gas emissions than traditional livestock, especially when insects are fed organic waste. Energy use varies but can be significantly lower compared to beef. GHG emissions are influenced by diet, but emissions are generally lower than conventional proteins, while water use is generally higher. Nutritionally, insects offer high-quality protein with a better feed conversion ratio than beef and similar to poultry. Their amino acid profiles are comparable to soybean meal, making them suitable for feeding certain livestock, although only as a partial replacement for optimal growth performance.

Insects hold the most potential as a supplement for compound foods, especially sports foods and functional foods, as a feed supplement. The EU is seeing growth in insect farming, supported by R&D and regulatory advancements, but faces hurdles in market development and competitive pricing. Challenges include achieving consumer acceptance and managing potential allergens like chitin alongside scaling up production sustainably.

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[276] Emblemsvåg J, Kvadsheim NP, Halfdanarson J, Koesling M, Nystrand BT, Sunde J, Rebours C, 'Strategic considerations for establishing a large-scale seaweed industry based on fish feed application: a Norwegian case study.' *Journal of Applied Phycology*, 32 (6):4159-4169, 2020. doi:10.1007/s10811-020-02234-w.

[277] Koesling M et al., 2021.

Microbial fermentation offers the potential to reduce environmental impacts, in particular land use and GHG emissions. Mycoproteins are best understood in terms of their contribution to nutritional needs, offering a palatable and nutritious alternative to meat, with the added benefit of beneficial micronutrients. The potential of microbial fermentation largely lies principally with the provision of useful food ingredients, with some alternatives already mature and many others at early stages of development and commercialisation. Insufficient food grade industrial capacity is a known bottleneck for the expansion microbial fermentation, in the EU and elsewhere, although an influx of investments (both public and private) in recent years have begun to fund the construction of large scale production capacity.

Cultured meat offers potential environmental benefits compared to conventional animal proteins, particularly relative to beef production. While it is an energy-intensive production process, cultured meat uses industrial energy that in principle can be generated sustainably, requires less land and water, and may emit fewer greenhouse gases. Nutritional profiles of cultured meat are likely to be similar to conventional equivalents, but in theory can also be adjusted to reduce undesirable components like cholesterol and saturated fats.

Cultured meat still faces significant challenges in scaling up production, reducing costs, and achieving consumer acceptance. Whilst regulatory approval has been granted in other terrorities, no cultured meat products have been approved for the EU market. The technology is still in development, with pilot-scale facilities operating worldwide and a need for commercial production facilities in the EU. Despite increased investment and R&D funding, the industry still faces challenges in production capacity, facilities, supply chain integration and scalability. Consumer acceptance will be crucial for successful substitution of conventional animal proteins with cultured meat.

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Part 3: Opportunities, challenges and policy options

Table of contents

1. Introduction

This Part provides a summary of EU regulatory and technical obstacles and incentives for the alternative protein sources that affect their wider uptake. Policy options to scale-up the development and production of the alternatives in the EU are proposed and their potential impacts assessed.

2. Methodology and resources used

The evidence and analysis supporting this Part is based on a synthesis and analysis of evidence gathered in earlier stages of the study to support Parts 1 and 2 of the study. This evidence was primarily obtained from literature review and complemented by stakeholder interviews. Data supporting the assessment of alternative sources has been extracted primarily from academic literature as well as grey literature. The latter includes, for example, reports published by the UN Food and Agriculture Organisation (FAO), industry associations, research organisations, and other private sector organisations.

Semi-structured interviews with selected industry experts and European Commission officers were conducted with the aim to collect informed views about technical and regulatory opportunities and challenges, and to provide insights on feasibility, advantages and disadvantages of the policy options. A total of nine interviews have been conducted.

Four interviews were conducted with representatives from industry associations Cellular Agriculture Europe, Food Fermentation Europe (FFE), the International Platform of Insects for Food and Feed (IPIFF) and the European Algae Biomass Association (EABA).

Five interviews were conducted with the European Commission staff from DG MARE, DG RTD and DG SANTE (DG SANTE Units A1 – Antimicrobial Resistance, Human Nutrition, E2 – Food Processing Technologies and Novel Foods, and G5– Food hygiene, Feed and Fraud; DG MARE Unit A2 - Blue Economy Sectors, Aquaculture and Maritime Spatial Planning; DG RTD Unit B2 – Bioeconomy and Food Systems and B4 – Ocean and Waters). DG SANTE Unit G2 – Animal Health was invited to participate in an interview, but declined.

The development, production and wider uptake of alternative proteins sources assessed in this study raise various social, economic and ethical issues, including implications for farmer livelihoods, rural development, biodiversity and consumer acceptance, among others. However, as these aspects were not the main focus of the study, they are discussed in this report only where relevant.

3. Key technical and regulatory obstacles and opportunities

Protein production in the EU is affecting European food security, environmental, economic and social sustainability and resilience. While there has been much policy and investor interest in plant-based alternatives in recent years, interest in non-plant alternative proteins as potential substitutes for animal-based products has grown in recent years, presenting an opportunity to contribute to the overall protein balance.

This section outlines the key technical and regulatory obstacles and opportunities relating to the wider uptake of alternative protein sources for human and animal nutrition. It draws on information detailed in the preceding Part, supplemented with insights from stakeholder interviews.

While benefiting from increasing consumer awareness and substantial private capital investment, the alternative protein sector in the EU faces considerable obstacles. These relate to scaling up technologies and achieving commercial viability against conventional sources benefiting from subsidies and consumer familiarity. However, these alternative sources might contribute to strengthening European food security and sustainability if existing barriers to their uptake were overcome.

Common technical hurdles include optimising technologies still requiring advancement, expanding production capacity and reducing inputs and operational costs. Infrastructure limitations are challenging for all alternative sources, with insufficient processing and production facilities impeding scale-up. Energy-intensive processes and reliance on high-emission feedstocks for some of the alternatives are also challenges that, if unaddressed, could add to the EU food system's energy and environmental footprint.

While specifics differ, the complex set of regulations applicable to food and feed applications of alternative proteins, the limited capability (skills and resources) of SMEs and start-ups to address EU regulatory requirements, and lengthy processes for reviewing regulatory approval applications hinder EU approval and/or marketability of the alternatives.

There are several policy/regulatory opportunities for incorporating alternative proteins into the protein balance in the EU: recent preparatory work on a European Commission's EU Protein Strategy, the Farm to Fork Strategy, a Sustainable Food System legislative framework, the circular economy principles in the Green Deal, and more broadly, the revised EU Industrial Strategy, which does not mention food, yet aims to reduce the EU's dependence on imports across a range of strategic sectors.

Several technical opportunities could be seized across the EU. The infrastructure for production could be adapted to grow alternative proteins (i.e. existing infrastructure could be retrofitted to produce alternative proteins[278]). Energy infrastructure in the process of being decarbonised may provide the clean energy they require. Finally, conventional agriculture may find new markets and substitute for declining existing markets by growing some of the feedstocks for alternative protein production.

3.1.1. Algae

The conditions of the Northern Atlantic differ substantially from the extensive shallow water areas found in Asia, the main producing region. Therefore, cultivation methods and equipment for growing algae in Europe differ, and more R&D is needed there to scale up production. Furthermore, stabilisation and processing methods are still lacking, which represents perhaps the most important bottleneck for the sector.

Furthermore, the EU algae sector requires substantial capital investments to overcome high production costs (e.g. due to manual rather than mechanised harvesting) and limited scale. There is demand for more landing facilities and biorefineries to enhance processing capacity and achieve the broader potential of algae for food, feed and other sectors (e.g. bioplastics).

Several safety issues with microalgae are technical obstacles (such as heavy metals accumulation and high levels of toxins, which depend on the growing substrate), which must be resolved at production or processing stages. When arsenic content is a concern, that tends to be overwhelming organic arsenic, which is harmless, although EU regulation on this matter currently ignores the distinction between organic and inorganic forms. There are also regulatory obstacles regarding high iodine content in seaweeds. Iodine content is not subject to harmonised EU limits at present,

[278] EIT Food, *Accelerating Protein Diversification for Europe*, Discussion paper, 2023.

although it is generally understood that the EU population is iodine deficient overall. Significant regulatory obstacles lie outside the remit of the EU, and relate to licensing regimes, which are under the responsibility of Member State authorities. Climatic conditions in the Northern Atlantic, as well as expanding offshore infrastructures (wind farms) provide opportunities for further growth of the sector in the EU.

3.1.2. Insects

Some key technical issues for the EU insect sector include proving the safety of certain former foodstuffs (e.g., meat, fish) as insect feed substrates, which is currently prohibited by EU regulations. Also, despite the circularity potential of using insect frass as organic fertiliser, some EU Member States allow this, while others do not.

Automation and scaling up of insect farms is needed to reduce production costs, as the sector is dominated by small companies with limited investment capacity. The sector also has limited vertical integration with most companies focusing only on insect processing rather than the whole value chain.

There are also technical obstacles to completely substituting conventional animal-based food and feed with insects. Concerning food, insect protein digestibility may be negatively affected by chitin, requiring its removal during processing. While insects can induce allergic reactions in consumers sensitive to crustaceans and dust mites through ‘cross-sensitisation’, it is unclear if they can also directly trigger allergic reactions (‘direct sensitisation’). Complete substitution of animal feed like soybean meal with insect meal may negatively affect animal growth.

Legal constraints also slow insect food and feed market development. Under the current novel food legal framework, product authorisations may limit commercial exploitation to specific applicants for a maximum of 5 years, if an applicant so requires, thus hindering technology replicability and market entry. Few additional insect species (i.e., black soldier fly, honeybee drone brood) are currently being risk-assessed and awaiting for novel food approval at EU level. As it is the case for other products of animal origin, harmonised EU hygiene rules specific to insects may eventually be needed in the future as this may support a greater level playing field between EU and non-EU operators.

The principles of the circular economy applied to insects production (namely, the possibility to feed insects with products that are currently prohibited) could present major opportunities for reducing input costs and boosting the further scale up of the sector. The EU-approved use of insect feed in aquaculture and for other food-producing animals also offers a major opportunity for sector growth in terms of overall production and employment creation.

3.1.3. Microbial fermentation

A lack of sufficient food-grade industrial capacity and infrastructure to scale up commercial production (and of the capital investment that it requires) is a technical obstacle to the growth of the microbial fermentation sector and uptake in the EU. Addressing large scale processing challenges more generally will be required for strains and production processes that are at this stage less mature.

Fermentation processes, especially downstream processing, rely on feedstocks such as refined sugars. The sector seeks lower-footprint alternatives, e.g. agricultural residues, waste streams, or gas as feedstocks instead of refined crops. Water use for microbial fermentation has been flagged as another obstacle, which, if unaddressed, would undermine the “green” ambitions of the sector and its claims.

In the EU, a complex regulatory framework applies to products obtained through microbial fermentation, which includes novel foods, GMOs and food improvement agents, among others.

This combined with the length and complexity of approvals process for such products is an obstacle to the further evolution of the sector in the EU, warranting more streamlined processes and a faster response from EFSA on applications. Existing restrictions in labelling and marketing – such as reserved terms for dairy products, which are also relevant to some microbial fermentation products – are also challenges for sector expansion.

3.1.4. Cultured meat

Replicating the complex structure, texture, and overall appearance of conventional meat is a significant challenge for the cultured meat sector. Achieving a product that is indistinguishable from conventional meat still requires considerable research and development.

Significant challenges in scaling up production, reducing costs, and achieving consumer acceptance persist. Investment is needed in production facilities (to shift from pilot to commercial scale), cell line development, scaffolding, and bioprocess design.

Although the nutritional profile of cultured meat, including its protein content, cholesterol, iron, and fat content, is expected to be the same or similar to conventional products, this has not been extensively studied. Regulatory approvals in the US primarily evaluate safety and manufacturing practices. The nutritional profile is assessed to ensure a product meets FDA standards, which may include comparisons with conventional animal-based equivalents. As production methods continue to advance, more data on the nutritional attributes of culture meat will likely become available. The ability to adjust the nutritional profile during production is a theoretical advantage, but data on nutrient bioavailability is not yet available. Assumptions of nutritional equivalence between cultured and conventional meat still require confirmation through detailed nutritional analysis.

No regulatory applications for approval of cultured meat products have been made to date in the EU. Given uncertainties, it is unclear at this stage whether evidence on cultured meat products would suffice to satisfy EU regulatory requirements. Similarly to microbial fermentation, the length and complexity of the regulatory approval for cultured meat as novel food, and existing labelling and marketing restrictions may discourage applications too. Some EU Member States are considering banning cultured meat production and marketing and restricting the use of commercial designations traditionally associated with meat products, which could also hinder sector growth.

4. Scaling up the development and production of alternative proteins in the EU

The study has identified four overarching policy options and related suboptions that could be considered to address the main issues for the alternative protein sectors. A baseline has been developed that reflects the current situation, and is used as a benchmark for the assessment of the alternatives.

4.1. Baseline

Food consumption trends – There is a continued drive to consume proteins in the EU, much of which is currently from animal sources, which account for 55-60% of dietary proteins. There is an increasing interest in alternative proteins, including non-plant-based sources, as substitutes for animal-based products. Some substitution from conventional animal-based sources to alternative proteins is gradually taking place, primarily led by plant-based alternatives. This trend is largely driven by availability and price but also by environmental concerns and consumer awareness, as well as industry innovation and marketing strategies.

Regulatory trends – The current EU regulatory framework is focused on food and feed safety. Regarding food, separate authorisations (e.g., as a novel food, GMO, additive, etc.) are required for most alternative protein sources covered by this study before they can access the EU market. Authorisation decisions are based on scientific risk assessments, but the process is considered to be lengthy and complex, especially for SMEs. Labelling rules and product classifications also constrain alternative protein marketing in some cases (e.g. microbial fermentation and cultured meat). Regarding feed, some regulatory barriers exist that limit the upcycling of food as feed for the development of certain alternative proteins (insects).

There are also political and technical challenges with the development of a sustainable food framework at EU level: there have been political disagreements over EU sustainability policies, and difficulties generating measures that would operationalise sustainability in its various dimensions. Nevertheless, efforts are underway to address the environmental impact of the current protein balance, particularly concerning animal-based proteins. The European Parliament's report calling for an EU protein strategy recognises the need to change dietary patterns, influenced by market dynamics and consumer choices.

Feed consumption trends – The EU's dependence on imported feed protein sources is likely to slightly decrease until 2030, reflecting the growing production and use of authorised alternatives (insects).

Protein production trends – Climate and geopolitical dynamics affect both the supply of imported feed proteins and the production of animal and plant-based proteins in the EU. The EU algae and insect sectors are growing, driven by Member State initiatives to support R&D and scaling operations, indicating a shift towards more sustainable protein production practices.

R&D trends – There is an increase in R&D investment targeting alternative protein sources, both plant and non-plant-based. This investment is driven by the potential of these alternatives to contribute to a more sustainable and resilient protein supply within the EU.

Market trends – The development of cultured meat and microbial fermentation products continue outside the EU, with market authorisation in several non-EU countries. While some of these products are not yet authorised in the EU, progress in third countries leads to the establishment (or strengthening) of major non-EU players. Additionally, the EU market for insects, microbial fermentation, and algae is poised for growth, contingent on technological breakthroughs and regulatory developments, as well as consumer acceptance.

4.2. Policy options

The four overarching options are: increased and targeted research and development funding, industrial policy investment, regulatory support, and policy coordination. The options and corresponding suboptions are presented, along with a description of their objectives and main features, as well as where they fit within the overall EU policy framework and their feasibility. This is followed by observations of the advantages and disadvantages of the options.

4.2.1. Increased, targeted R&D funding

Greater targeted research funding would support addressing uncertainties and knowledge gaps, helping to mitigate some of the risks associated with investing in alternative protein development. It could also be instrumental in driving the necessary innovations that may address the most problematic aspects of some of the alternative protein sources such as energy consumption, texture and taste optimisation and scale-up processes.

This option would provide direct EU funding through Horizon Europe or successor programmes for targeted research:

- Advancing alternative protein production and processing technologies. The aims are to improve alternative protein properties related to texture, taste, safety, production costs and efficiency, and environmental sustainability.
- Assessing the impacts of alternative proteins in areas where knowledge gaps currently exist, such as safety, environmental sustainability, nutritional profiles, and challenges related to processing methods and scaling up production. Improvements to lifecycle assessment standards and methods would also aid environmental impact assessments.

Grants would support academic and industry consortia to undertake projects from basic research through piloting and demonstration levels. Knowledge and technologies developed would be made available through open access publishing and data requirements to inform better decision-making by authorities and policy makers.

Funding would complement existing national programmes and help coordinate efforts for greater impact. Multi-disciplinary consortia and private-sector participation would be essential.

This option aligns with EU research policy focused on challenge-driven, collaborative projects generating accessible results. It complements the European Green Deal, Farm to Fork Strategy, the Circular Economy Action Plan, the Zero Pollution Action Plan, Public-Private Partnerships supported by the EU Industrial Strategy, and other initiatives promoting sustainable and resilient food systems.

The European Commission DG RTD would lead policy design and implementation, with inputs from other DGs and EU agencies (e.g. EFSA, EEA) on priority research areas.

As an expansion of existing Horizon Europe funding or integration into successor programmes, this option leverages familiar and feasible implementation mechanisms. As a demand-driven opportunity, funded projects are likely to address alternative protein innovation needs.

Advantages

- High relevance to all four alternative protein sectors, targeting all relevant aspects of R&D needs
- Accelerates advancement of production and processing technologies through strategic investment
- Provides missing evidence to clarify regulatory pathways
- Promotes knowledge diffusion through open-access provisions
- Fosters public-private collaboration
- Facilitates comparing alternatives to inform policymaking on sustainable protein transitions
- Provides flexibility to fund projects on multiple alternative proteins based on research quality
- Operates within the existing legislative framework

Disadvantages

- Risks overlap with existing national-level funding initiatives
- Depends on engaging industry experts needed to design robust research
- Businesses may be reluctant to engage in research they could not appropriate / patent the results from
- Businesses may resist openly sharing some proprietary data

Outcomes

It will directly assist in developing and advancing technological innovations that enhance product quality and commercial viability, and produce evidence and data to support regulatory approval and mainstream adoption.

Beneficiaries

It provides direct support to alternative protein companies to accelerate development, and insights to authorities and policymakers guiding sustainability transitions.

4.2.2. Increased investment in industrial capacity

Public investments would address some of the industrial obstacles to growing the alternative proteins sector in the EU. The option would contribute to financing scaling up in the alternative protein sector. This would include support to infrastructure for producing alternative proteins (as well as other food products[279]) at scale. That includes biorefineries (for algae, microbial fermentation, cultured meat and insects) as well as landing facilities for processing of seaweed. The latter are particularly relevant for small operators. This can correspond to both building new infrastructure and retrofitting existing, suitable infrastructure (e.g. dairy, chemical or petrochemical infrastructure for microbial fermentation). The costs involved may sometimes be very large.[280] They would be partially covered by either co-financing (subsidies) or loan guarantees.

The option would activate existing tools for EU and Member State financial support to industry, such as the Important Projects of Common European Interest (IPCEI) scheme. It is also coherent with the Capital Markets Union 2020 Action Plan, which incorporates a number of measures to support access to finance.

Member States and the European Commission would play a key role in implementing the option, which may be developed in a coordinated manner through dedicated, sector-specific initiatives (such as the EU Algae Initiative – see option 4). It is practically feasible. Politically, some Member States would likely oppose subsidies going to some sectors, in particular cultured meat. However, projects enabling pooling contributions from a group of Member States would not require all Member States to participate.

Advantages

- High relevance to microbial fermentation, algae and cultured meat sectors
- Accelerates the maturation of the alternative protein sector in the EU
- Does not require new legislation

Disadvantages

- Could establish infrastructures having high environmental impact unless criteria were set to restrict funding for certain technologies

Outcomes

It supports the development of physical infrastructure suitable for the sector's needs.

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279 Biorefineries enable isolating several distinct compounds from the raw product, some of which would be used as food.

280 Interviews with industry associations; EIT Food, *Accelerating Protein Diversification for Europe*, Discussion paper, 2023.

Beneficiaries

It provides direct support to alternative protein companies to finance scaling up.

4.2.3. Regulatory support

The EU legal framework applying to the alternative protein sector, including the novel food regulation, can be made more supportive and efficient, thus removing burdens hindering decision-making within the sectors while protecting consumer interests and the environment.

1. Include environmental impacts in risk assessments informing authorisation processes for alternative proteins

The policy would require regulatory change to add environmental criteria to the current policy regime for authorising the production and commercialisation of alternative proteins, where such criteria are not foreseen or very detailed (e.g., novel food regulation).

In so doing, the policy would reflect market trends observed in the EU and elsewhere in recent years where most innovations in the field of alternative proteins are driven by environmental sustainability considerations rather than by other factors such as food safety or nutrition.

This policy would entail a significant change in the current approach followed by the EU regarding risk assessment as the latter is largely focused on safety aspects. Overall, environmental impacts are considered only in part and merely from a risk standpoint, thus not taking into account potential benefits in terms of sustainability.

This regulatory change would require extensive public consultations with stakeholders (e.g., EU Member States, industry associations, consumer and environmental NGOs, academia etc.) to:

- identify the appropriate environmental criteria that EFSA should consider when risk-assessing alternative proteins; and
- determine the relative weight that should be allocated to the environmental impacts identified (e.g., vis-à-vis food safety aspects).

Such consultations should also help establish whether this policy should be limited to alternative proteins or could be usefully extended to other food innovations requiring pre-market authorisation in the EU. In this context, consideration should also be given as to whether it would be fair to subject to such environmental impact assessments alternative proteins (and other food innovations) but not food products already on the market.

This policy is likely to involve a complex legislative process, requiring the introduction of changes to well-established EU regulations (notably, the General Food Law, novel food framework etc.) and possibly to other legal acts under preparation (e.g., the Sustainable Food System Framework).

Advantages

- Highly relevant to microbial fermentation, cultured meat, insects, and microalgae, considering some of the environmental impacts of certain production systems; less so to seaweed
- Ensures EU risk assessment follows a more holistic value-chain approach
- Promotes research on environmental impacts in support of EU authorisations
- Contributes to reducing the environmental impact of the EU food system
- Strengthens the role of the EU as a global leader in the sustainability of food systems

Disadvantages

- Requires a complex consultation and legislative process
- Requires strengthening EU (EFSA) assessment capabilities, particularly with regard to Life Cycle Assessment methods
- Environmental criteria are likely to be generic for all food innovations rather than specific to alternative proteins
- Implementation might be challenging as the assessment of environmental impacts depends upon several different elements and details
- Likely to result in additional costs for applicants
- Likely to slow down regulatory approval processes

Outcomes

It fosters the production of alternative proteins that are safe and sustainable, thus contributing to reducing their negative externalities on the environment.

Beneficiaries

It provides for a scenario that, by supporting sustainable food innovations, ultimately benefits the environment as well as the public at large.

2. Improve implementation of the EU framework for alternative proteins (novel foods, GMOs, etc.)

The current EU framework applicable to alternative proteins includes various legal acts governing regulated food products such as novel foods, GMOs, and food improvement agents. Such a framework would be made more efficient by developing tailor-made guidance alongside the provision of additional resources in the EU budget for the submission of EU-level applications for regulated products.

Sector-specific guidance would address the specific characteristics and needs of the alternative protein sector.

Besides EU legislation on novel foods, alternative proteins may be subject to other regulatory regimes requiring prior approval (e.g., GMOs in the case of certain products resulting from microbial fermentation; food improvement agents in the case of algae as well as products obtained through precision fermentation).

Therefore, providing practical guidance (e.g., in the form of a decision-tree) would enable future applicants to identify the correct approval pathway and regulatory requirements from the start, securing faster access to the EU market.

The guidance may also identify the type of scientific studies and primary data that applicants must present when submitting an application and secondary sources and data that can be used to that effect. It might also explain the main requirements and bottlenecks of the authorisation procedures, including:

- the need to notify EFSA in advance of scientific studies supporting an application to make sure that the latter is deemed valid;
- how to handle requests for additional information from EFSA throughout the procedure; and

- how to guarantee legal protection of confidentiality and proprietary data covered by an application.

As the development of technical guidance is quite common in the area of regulated products at EU level, this policy does not present any major feasibility issues. It would be coherent with the existing policy framework.

Advantages

- Highly relevant to cultured meat (because of the current lack of EU authorisations), microbial fermentation and algae (in both cases, because of the complexity of the EU legal framework that applies to them); less so to insects (because their legal framework is clear and first approvals have been obtained)
- Greater legal certainty / awareness for potential applicants, particularly SMEs
- Could lead to a higher number of applications covering alternative proteins
- Reduces the costs associated with applications, notably for SMEs

Disadvantages

- Producing and maintaining updated guidance imposes an additional administrative burden on public authorities

Outcomes

It aims to resolve knowledge obstacles faced by alternative protein companies to complying with EU regulatory requirements.

Beneficiaries

It supports alternative protein companies, particularly SMEs, to understand their obligations under the EU regulatory framework and secure faster market access.

4.2.4. Policy coordination

The overall protein balance at EU level relates to multiple distinct policies and regulatory issues: industrial policy, nutrition, food safety, food security, marine development, agriculture, climate and environment, research and development, innovation, intellectual property. Addressing EU needs in this area is a complex challenge. The principle of substitution of one source of protein for another is logically necessary to address EU goals, yet politically sensitive: trade-offs are on the menu. Therefore, a new degree of policy coordination at the EU level is required to achieve a more diverse protein balance that ensures food security while reducing environmental harm.

This option aims to increase the suite of coordination tools the EU and Member States can use. In the baseline, there are already several tools in place: the EU Algae Initiative, the Farm to Fork Strategy, and interservice meetings at the European Commission. The option would add to these tools and seek greater integration between them, whether for monitoring purposes or decision-making.

Policy cooperation would unfold at three complementary levels:

- **Specific initiatives would be developed targeting each alternative protein source.** The EU Algae Initiative would serve as a blueprint for parallel efforts on insects, microbial fermentation and cultured meat. Initiatives are suitable for exploring and addressing the wide range of issues (scientific, technical, economic, social) hindering potential development, taking a sector-wide approach. They articulate together multiple interventions that do not require changes to legislation: research projects, guidance and information sharing, funding support, engagement with Member State authorities and industry associations, etc. They evolve as progress is achieved.

- **An EU Protein Strategy** would benefit from inputs of relevant initiatives and policies, articulated together by a dedicated commission overseeing the strategy's implementation. All four initiatives mentioned earlier, to the extent they address food and feed dimensions (the EU Algae Initiative addresses other dimensions too), would also reflect the orientations set in the EU Protein Strategy. A common set of metrics (on the contribution of individual sources to the EU's protein balance, environmental impacts, etc.) would be used to monitor evolutions and assess progress against targets (if/when targets have been set).
- The specific alternative protein initiatives and the EU Protein Strategy **would be harmonised and integrated within the overall framework of the EU Farm to Fork Strategy**. Protein-focused efforts would be tied to a whole system approach to food and feed, one that considers overall nutrition and diet beyond protein intake, and works towards a food system working within planetary boundaries.

This option aligns with existing policies and further contributes to policy coherence by driving further integration and coordination.

Individual DGs would develop protein specific initiatives. Monitoring of the implementation of the EU Protein Strategy would involve all DGs in scope, as well as JRC, EIT Food (to ensure continuous link to research and industry), and the European Parliament.

Views differ among stakeholders on the need for greater coordination in this space. The case for better coordination would need to be made to ensure this option would be politically feasible. An initiative on cultured meat could be opposed by some, although the low key nature of an "initiative" may alleviate the risks of political opposition.

Advantages

- High relevance to all protein alternatives
- Provides better governance for current and future policies on alternative proteins
- Ensures protein objectives are pursued as part of a broader approach to the EU food system

Disadvantages

- May slow down decision-making by setting a higher coordination requirement

Outcomes

It aims to link actions on alternative proteins to a holistic food system approach in the EU.

Beneficiaries

It supports all stakeholders by ensuring participation and recognition of the diverse objectives at stake: food security, environmental impacts, nutrition, trade, etc.

5. Conclusion

The set of options proposed in this report are complementary rather than alternative. Together, they form a set of interventions which address most regulatory and technical challenges and opportunities identified in earlier stages of the study:

- Production and processing issues affecting costs, taste, texture, safety;
- Knowledge gaps on nutrition, environmental impacts, and safety;
- Inadequate/non-existent production and processing infrastructure at scale;
- Potential for protein production with a lower environmental footprint than conventional proteins;
- Large environmental impacts and energy use of some modes of current production/processing (likely to evolve for the better as technologies progress); and
- Lack of capability to address EU regulatory requirements for market authorisations (particularly for SMEs).

Furthermore, they address the risk of siloed policymaking when it comes to diversifying the protein balance in the EU.

These options are, for the most part, non-regulatory in nature. In other words, they are not putting forward any major changes to the EU regulatory framework, with the exception of the arguably complex but potentially consequential introduction of environmental considerations in regulatory risk assessments for novel foods.

Instead, most options proposed would activate existing dispositions, whether regulatory (e.g. rules on subsidies for SMEs or public funding of strategically important projects) or not (e.g. research funding).

The options include a governance dimension: a framework for coordinating current and future actions related to alternative proteins with interventions on conventional and plant-based alternatives. Such coordination would also cut across policies to ensure the important dimensions this study did not explore – consumer acceptance and information, overall diet and nutrition, and social impacts – are considered alongside environmental and food security objectives. It would also facilitate synergistic policymaking to realise the potential of non-plant alternative proteins within a whole-system approach to food production and consumption in the EU. This largely relies on existing and forthcoming tools and broad strategic orientations at EU level (whether related to industrial policy, sustainable food systems, or protein supply and independence), providing a favourable environment for diversifying the protein supply.

Annex 1 – Interview guide

This annex includes the information shared with interviewees (officers at the European Commission and representatives of business associations) and the questions that guided the interviews.

Arcadia has been commissioned by the European Parliamentary Research Service (EPRS) to conduct a study on the future of alternative protein sources in sustainable animal and human nutrition. The EPRS has requested a review of the potential for four alternative sources of protein – algae, insects, microbial fermentation, and cultured meat – to substitute for conventional food and feed. Arcadia is now consulting with the European Commission and business associations involved in these sectors to collect views on possible future policy interventions at EU level.

Four themes have been identified for defining policy options:

*1. **Research and Development** – Greater targeted research funding would support addressing uncertainties and knowledge gaps. It could also be instrumental in driving the necessary innovations that may address the most problematic aspects of some of the alternative protein sources (e.g., energy needs).*

*2. **Industrial policy** – Industrial policy can contribute to supporting start-ups as they struggle to scale up while steering the private sector towards more sustainable and circular industrial solutions and away from unsustainable approaches.*

*3. **Regulation** – The implementation of the EU legal framework on novel foods applying to the alternative protein sector can be made more efficient, thus removing burdens hindering decision-making within the sectors while protecting consumer interests and the environment. Changes to the regulatory framework may also be considered under this option.*

*4. **Policy coordination** – The overall protein balance at EU level relates to a multitude of distinct policies and regulatory remits. Achieving a more diverse protein balance that provides food security and sustainability will require a whole-systems approach and, therefore, a new degree of policy coordination at the EU (and national) level.*

Questions:

1. Do these 4 themes address the dimensions you consider relevant? Are there any you would dismiss? Are there any you would add?

2. Of these themes, which one(s) would you like to focus on? What are the main challenges with alternative proteins that you are focusing on? And what are the main opportunities?

3. What are the main knowledge gaps regarding the potential use of alternative proteins in food that would need to be prioritized in future research?

4. Should future research funding prioritise specific alternative proteins (algae, insects, microbial fermentation or cultured meat)? If so, why?

5. Which programmes / what kinds of funding instruments should be used to finance future research (EU and/or national)? Why?

6. Which solutions or instruments could best support the alternative protein sector in developing an infrastructure that fits its needs?

7. Is there a role for the EU in supporting the way start-ups finance scaling up? Which one?

8. How can policy ensure that the sector contributes to reducing the food system's environmental footprint while scaling up?

9. What do you identify as the main regulatory and technical obstacles to the growth of alternative proteins in food [these can refer to areas for regulatory change, but also areas for private sector's progress to match regulatory requirements]? What interventions could best tackle these obstacles?

10. How can we ensure that the EU regulatory framework for alternative proteins takes into account the needs of SMEs, farmers, and farmers' organisations?

11. What would any efforts at greater policy coordination in this domain need to focus on most? What interventions would be desirable here? Are there any best practices at national or international level that could be replicated in the EU?

Annex 2 – Summary table

This table provides a synthetic account of the options proposed, their advantages and disadvantages.

Policy option	Advantages	Disadvantages	Outcomes	Beneficiaries
1. Increased, targeted R&D funding	• Highly relevant to all alternative proteins • Accelerates advancement of production technologies through strategic investment • Provides missing evidence to clarify regulatory pathways • Promotes knowledge diffusion through open-access provisions • Fosters public-private collaboration • Facilitates comparing alternatives to inform policy-making • Provides flexibility to fund projects on multiple alternative proteins based on research quality • Operates within the existing legislative framework	• Risks overlap with existing national-level funding initiatives • Depends on engaging industry experts needed to design robust research • Businesses may be reluctant to engage in research they could not patent the results from • Businesses may resist sharing some proprietary data	• Directly assist in developing and advancing technological innovations that enhance product quality and commercial viability • Produce evidence to support regulatory approval and mainstream adoption	• Alternative protein companies • Authorities and policymakers

2. Increased investment in industrial capacity	• Highly relevant to microbial fermentation, algae, and cultured meat sectors • Will accelerate the maturation of the alternative protein sector in the EU • Does not require new legislation	• Could establish infrastructures with high environmental impact unless criteria were set to restrict funding for certain technologies	• Enable physical infrastructure suitable for the alternative protein sector's needs	• Alternative protein companies
3. Regulatory support				
3.1. Include environmental impacts in risk assessments informing authorisations of alternative proteins	• Highly relevant to microbial fermentation, cultured meat, insects, and microalgae - less so to seaweed • Ensures EU risk assessment follows a holistic value-chain approach • Promotes research on environmental impacts in support of EU authorisations • Contributes to reducing the environmental impact of the EU food system • Strengthens EU's role as a global leader in the sustainability of food systems	• Requires a complex consultation and legislative process • Requires stronger EU assessment capabilities (notably LCA methods) • Environmental criteria likely to be generic for all food innovations • Implementation likely to be challenging owing to the multiple elements / details to be taken into account when carrying out environmental impacts • Likely to result in additional costs for applicants • Likely to slow down regulatory approval	• Fosters the production of safe and sustainable alternative proteins	• The environment • The public at large

3.2. Improve implementation of the EU framework for alternative proteins (through dedicated guidance)	• Highly relevant to cultured meat, microbial fermentation and algae) - less so to insects • Greater legal certainty / awareness for applicants (notably SMEs) • Likely to lead to a higher number of applications on alternative proteins • Reduced costs associated with applications (notably for SMEs)	• Additional administrative burden for public authorities ensuing from producing and updating guidance	• Resolve knowledge obstacles faced by alternative protein companies to complying with EU regulatory requirements	• Alternative protein companies (notably SMEs)
4. Policy coordination	• Highly relevant to all protein alternatives • Provides better governance for current and future policies on alternative proteins • Ensures protein objectives are pursued as part of a broader approach to the EU food system	• May slow down decision-making by setting a higher coordination requirement	• Can link actions on alternative proteins to a holistic food system approach in the EU	• All stakeholders

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Alternative proteins are of increasing interest in terms of their potential to improve food security and reduce the environmental impacts of food and feed production. This study assesses the current state and future prospects of protein production globally and in the EU to 2050, with a focus on conventional and alternative protein sources for food and feed. While projections show increased conventional protein needs up to 2050, climate change necessitates exploring non-linear scenarios and the potential of alternative proteins in the global and EU protein balance. In this context, four sources of alternative proteins – algae, insects, microbial fermentation and cultured meat – are assessed by comparing them to the conventional sources they may replace, in terms of their relative energy needs, environmental impacts, nutritional content, and their potential for being used as substitutes to conventional proteins in food and feed in the EU. The current level of R&D activity, technological and commercial readiness, and industrial capacity of the said alternatives in the EU is also examined. Finally, the study explores regulatory and technical obstacles to and opportunities for development of alternative proteins in Europe, before proposing a set of policy options that may be considered by EU policymakers for targeted support to the growth of the alternative proteins sector.

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