Alternative Proteins for Human Consumption

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Abbreviations

- FBS: Fetal bovine serum
- GE: Genome editing
- GHG: Greenhouse gases
- GM: Genetically modified
- GMO: Genetically modified organism
- LCA: Life-cycle assessment
- UPF: Ultra-processed foods

Executive Summary

The UK is seeing growing interest in alternative protein sources as a replacement for traditional animal-based proteins such as beef, lamb, pork, poultry, fish, eggs, and dairy, to deliver a diet that is partially or completely meat free. There is already an extensive market in alternative protein materials, however, technological advances combined with the pressure for more sustainable sources of protein has led to an acceleration of innovation and product development and introduction of a plethora of new alternative protein ingredients and products to the market. These have the potential to dramatically impact on the UK food system, with drivers for their adoption being primarily based around consumer perceptions of them being more sustainable, as well as healthier and more nutritious alternatives to their animal-based counterparts.

This report is a synthesis of desk research, based on thorough review of the academic and non-academic literature and of the alternative proteins start-up scene, and presents an analysis of the emerging market for alternative proteins, the potential implications and the potential policy responses that the FSA might need to consider.

Four main categories of alternative proteins

Four main categories of alternative proteins are presented and reviewed in this report:

Plant-based meat substitutes – Re-engineered food technology products processed into protein formulations derived from plant material that can deliver a convincing meat-like sensory experience, mostly in terms of texture and taste. Numerous products have entered the market in the past few years, but they remain relatively niche premium products at present.

Novel protein sources – Non-traditional sources of protein such as insects, seaweeds, microalgae, bacteria, and jellyfish. These are novel foods to the UK market, although not novel to the world. The way source organisms are grown at industrial scale often involves novel production technologies and exposure of these organisms to manmade environments and novel feed sources may introduce new challenges for the FSA.

Proteins and biomass biosynthesised by microorganisms – Proteins generated through biomass fermentation processes (QUORN, yeasts, fungi) or by precision fermentations using genetically modified yeasts, fungi, or microbes to generate desired protein molecules (e.g., used to produce milk and egg proteins). Currently still mostly in the pilot phase, these are expensive processes, and their production at scale is still largely underexplored.

Cultured meat – Alternatively referred to as in-vitro, lab-grown, or synthetic meat, these are mainly animal derived cells grown *in vitro*. Production is currently still in the experimental phase, and despite considerable hype, there are very few prototypes on the market to date, with unproven up-scalability.

Key findings

Key findings for each alternative protein source

1. **Plant-based meat substitutes are not equivalent to a traditional plant-based diet**. These products are often presented as a healthy, environmentally friendly alternative to meat, and while probably better for the environment than beef production, may not be as beneficial for health as the industry might want consumers to believe. Generally, they are ultra-processed foods, and although they may be fortified with beneficial nutrients, tend to be somewhat nutrient deficient, while high in sodium and synthetic additives.
2. **Novel sources of protein will have differing uptake and local impact potential.** Novel proteins such as insects and algae can be produced using lower technology solutions, can make use of organic waste streams, and can require less processing. They can represent a good option for environmental sustainability and the quality of protein is high. However, consumer acceptance in the west is a significant barrier to adoption, and there are

concerns over food safety. They seem most likely to have an impact in developing nations where there is a traditional culture of consumption.

3. **Fermentation offers the most significant potential for disruption.** Precision fermentation (production of dairy and egg protein, etc.) may prove to be the most disruptive segment over the coming decade, with the potential to upend the dairy industry and egg production, which will have knock-on effects on the viability of the meat and poultry sectors. The longer-term potential to synthesise a wide array of ingredients could profoundly change the way food is produced. However, the industry faces technological challenges to operate at scale, and success will be subject to customer perceptions and regulation with respect to the sources, for example, the use of genetically modified organisms or the media used for production.

4. **Cultured meat is still far from being a mature commercially viable technology.** Cultured meat is one of the most controversial sources and offers the most radical potential for disruption of conventional animal farming and animal-meat consumption. However, it is far from certain to prove technically or commercially viable, or to gain real acceptance with consumers. There are doubts over sustainability claims, currently nutritional content is inferior to animal meat, and there are significant technical and cost challenges. At least until the energy system is fully decarbonised, chicken, pork, fish, and novel sources such as insects and algae may be better for the planet.

Key observations across the alternative protein sector

1. **Novel ingredients/foods are entering the food system**. Emerging technologies and novel food sources offer the potential to dramatically reshape the way food is produced, to optimise formulations, enhance taste, supplement nutrition, etc, but the food system, consumers, and the regulatory framework are not set up or ready for this coming change.

2. **Consumer acceptance is a significant barrier at present.** Willingness to try alternative proteins is not well aligned with the needs to address sustainability and food security, food system resilience, or even health. Highly processed foods and synthetic foods seem at odds with the trend for whole-foods and minimally refined foods seen in many affluent societies today, and although consumers seem willing to try once, the industry is struggling to generate repeat business due to high prices and disappointing experiences.
3. **Most alternative proteins require high levels of processing, which introduces risks.** High levels of processing are required either to purify proteins, or to reach the complexity of food structures demanded by consumers. Extensive processing creates issues around nutritional density value, energy consumption and GHG emissions, regulatory oversight, production control and potential risks with regard to labelling, traceability and authenticity. The nature of these alternative proteins and production processes increases uncertainty over who should be the responsible regulator.
4. **Limited understanding of nutrition and long-term health implications**. There are no longitudinal studies on the long-term health implications of intensive consumption of these alternative proteins, and there are concerns over allergens, and potential toxicity. Although nutrition falls outside of the FSA’s traditional remit, it will need to be carefully considered holistically with food safety and hygiene, and environmental sustainability factors for these alternative protein sources.
5. **The environmental case for alternative proteins is not yet fully defined.** Sustainability data is limited, difficult to compare meaningfully across the different protein types, and there are currently mixed views on the potential benefits. Although offering benefits compared to beef and dairy production in terms of methane emissions, land use, and eutrophication, the benefits over other animal and fish proteins are much less clear, and one of the key proposed benefits of reducing GHG emissions associated with animal farming will only be realised with a fully decarbonised energy system.

Macro-level perspective on alternative proteins

1. **Need to moderate consumer demand versus expanding production.** Demand management has not received much attention but may be at least as important as developing new alternative sources of protein for the future. The current diet in much of the West is excessive for many, over-consuming calories, and protein, so a reduction would be beneficial. The introduction of alternative sources raises the risk of rebound effects whereby consumers give themselves licence to consume more believing it is healthier, and better for the environment.

2. **Low-tech solutions already exist and may be better, more sustainable solutions.** Plant-based whole foods and minimally processed foods, such as traditional legumes and pulses are better for the environment and for health and require minimal packaging and cold chains for transportation and storage. Aquatic ‘blue’ food sources, although over-exploited in some areas, still offer much untapped potential.

3. **Need to focus on reducing food waste and fostering circularity.** Focusing on reducing loses in the global food system, estimated to be 30% of all produce, and 20% or higher of animal and fish protein, would make a considerable contribution to meeting emerging demands for protein and tackling GHG emissions and other environmental impacts.

4. **Alternative proteins still seem to have limited potential to address global challenges**. Expensive solutions dependent on highly skilled biochemists and engineers and protected intellectual property will not easily be deployed in developing nations and may create significant inequalities.

5. **Need to balance technological push with societal needs**. If the technologies reach the scale that proponents forecast, they are likely to be highly disruptive for the agricultural sector, rural economies, and low-skilled workers, and the related industries in non-edible animal products. The potential socioeconomic impacts are poorly understood to date, but this will require a systems-based approach to policy.

6. **Shifting the narrative from 'alternative protein' to 'protein diversification'.** Alternative proteins are rightly receiving much attention, but rather than focusing specifically on the development of these alternatives, consideration of the full spectrum of dietary proteins, both existing and emerging may be more beneficial for the planet.

Implications and recommendations for the FSA

The majority of the protein sources discussed in this report in one way or another fall under Novel Food regulation, from jelly fish which are consumed elsewhere in the world but new to the UK, to protein ingredients and products resulting from novel processes and innovations from laboratories in the UK and worldwide. There are still considerable uncertainties around the likely nutritional profile of these protein sources, the extent to which they represent genuinely sustainable choices, their cost and hence accessibility, and risks that might result from production processes and long-term consumption. The research also shows that consumer acceptance remains one of the most immediate challenges for novel protein sources, at least in western societies with a strong tradition of animal husbandry and meat and dairy based diets.

Hence the need for development of a cohesive regulatory framework that can accommodate the novelty of these foods as well as the rapid pace of their market entry, provide the necessary consumer guidance and public health protection, and prepare and adapt agriculture and associated industries towards building a resilient food system while minimising its impact on the environment. In this complex setting regulation has a strong and vital role to play, and increasingly the role of regulation particularly in the food industry is moving from a watchdog for industry conduct, to a facilitator of a multi-stakeholder, complex, and rapidly changing environment, with the responsibility to safeguard the interests of consumers/end-users.

Key strategic considerations for the FSA:

- Regulation may need to go beyond determining toxicity and hygiene and encompass the wider effects of these highly refined molecules in food compositions, nutritional value, and on human health. This may lead to the requirement for a more sophisticated regulatory approval system resembling pharmaceuticals regulation.

- Balancing the industry demand for faster/easier approval processes with potential long-term consumer and population health interests represents one of the dilemmas the FSA will face going forward.
- Establishing a clear sustainability credential for the novel proteins entering the market is not a straightforward task at present. There is a need to establish who will be the responsible regulator and to develop suitable frameworks for assessment and transparency.
- By developing a clear language and messaging and avoiding the hype language coined by the industry PR when addressing the industry and the public can bring considerable clarity to internal discussions as well as external negotiations required for building a functional regulatory framework.
- The interconnected nature of supply chains and industries means that the FSA may be required to support regulators of other industries with direct or indirect impact on food supply chains.
- Specific focus will need to be brought to:
    - Food approvals process
    - Data gathering standards
    - Certification, monitoring, and audit of novel processes
    - Framework for labelling
    - Managing consumption levels
    - Reducing consumer food waste

FSA priorities for the short, medium, and long-term

Although not all these recommendations sit within the FSA remit, the FSA can play a role in supporting wider government, including the Department of Health and Social Care, and DEFRA, on these issues. Priorities include:

Short-term (within 3 years)

- Food safety, food authenticity.
- Building further knowledge and expertise to address emerging complexity of food production and supply.
- Initiating the design and testing of new approval frameworks and processes for novel foods.
- Building connections with regulatory bodies in other relevant industries.

Medium-term (3 – 5 years)

- Understanding actual environmental and climate impact of novel protein sources – establish measurement metrics.
- Continuous adaptation of testing and new approval frameworks for emerging novel foods.
- Continuous relationship with regulatory bodies in other relevant industries.
- Managing industry expectations and lobbies in favour of a systems approach to regulation.
- Considerations for creating a regulatory framework for demand management to reduce consumption of high calorie foods, which will include animal proteins as well as highly processed foods.
- Creating a framework for food security and supply resilience in an interconnected world.

Long-term (5 - 10 years)

- Understand impact of novel foods on long-term health.
- Safeguarding industrialised food systems from system failure.
- Finding a balance between continuation of traditional agriculture and wholesale industrialisation of the food system.
- Continuous adaptation and updating of regulatory framework for demand management to reduce over-consumption of high calorie foods, which will include animal proteins as well as highly processed foods. Including consumer education, advertising restrictions, and taxation/subsidies to shift behaviours.

1. Introduction

1.1 Background

Recent years have seen a growing interest in new protein sources as a replacement for animal-based proteins such as beef, lamb, pork, poultry, fish, eggs and dairy, to deliver a diet that is partially or completely meat free. There is already an extensive market in alternative protein materials, such as grain-based materials reprocessed to resemble meat in the form of sausages and burgers, or materials such as tofu and mycoprotein, which can be used as protein ingredients in more traditional meals. However, two trends in particular are emerging in the alternative proteins market for human consumption in the UK.

Firstly, the introduction of new alternative proteins, from more or less conventional sources, such as peas, algae and insects. Although some of these may have been consumed elsewhere in the world, they tend to be new to the UK market. Secondly, the introduction of laboratory cultivated meat, fish, and dairy proteins. This is currently being produced by a relatively small number of start-ups, with no large-scale commercial availability yet.

Both trends have the potential to have a dramatic impact on the UK food system, with drivers for their adoption being primarily based around consumer perceptions of them being more sustainable, and healthy and nutritious alternatives to meat. However, there are still considerable issues and uncertainties around the likely nutritional profile, the extent to which they do represent genuinely sustainable choices, their cost, risks that might result from production processes and long-term consumption, and consumer acceptance.

1.2 Objectives

This report presents findings of an assessment of the emerging alternative proteins for human consumption and their likely development within the UK over the next 10 years, based on assimilation and synthesis of existing research. The report looks specifically at the anticipated impact of these alternative proteins on the safety and nutritional value of the food, consumer choice, environmental and social sustainability of the value chains, and the emerging challenges and opportunities that these foods may present. This study will enable the FSA to identify key issues that need to be prepared for as novel sources of protein enter the market, and consider how these might affect its operations, partners and stakeholders, consumers, and the food regulatory framework. Work has previously been undertaken within the FSA looking at emerging technologies including alternative proteins impacting the food system (Short et al., 2021), and that work is included in the inputs to this report alongside evidence from other sources.

1.3 Research questions

This report seeks specifically to address the following research questions:

i. What types of alternative protein will become available over the coming decade and in what timescales?

ii. How commercially viable, affordable, and available are they likely to be, bearing in mind issues such as production and retail cost and consumer acceptability/desirability?

iii. Are there any specific risks to consumers and public health that might be associated with the production and consumption of these products?

iv. To what extent are the various alternative proteins able to provide more sustainable and climate friendly food than current main sources of protein?

1.4 Methodology

This research took the form of an evidence assessment and synthesis of the available academic literature, news articles, industry reports, and a review of the alternative protein start-up scene, including several food sector start-up focused databases (e.g. Food Navigator, 2021; Forward Fooding, 2021). The research process consisted of desk-based research, and analysis and review were undertaken using qualitative and quantitative analysis where appropriate.

This report draws upon the recent increase in studies of the potential pros and cons of these emerging alternative protein sources, but the knowledge base, and particularly detailed life-cycle assessments (LCA) and longitudinal nutrition and health studies, remain mixed and limited (Tso et al., 2021). Where possible, we sought to identify multiple, most recent articles on each topic of interest to ensure a balanced perspective, and gave preference to more highly cited articles, or those from leading global institutions and research groups, and government agencies.

1.5 Structure of the Report

The following section (chapter 2) of this report presents an overview of the food industry context and the drivers of change that are generating interest in alternative proteins. Chapter 3 presents innovation in the sector, and identifies four main categories of interest, and discusses the investment scene and predicted growth in each of these. Each of these four categories are then discussed in depth in the subsequent sections: Plant-based meat substitutes (chapter 4); Novel sources of protein (chapter 5); Fermentation-based biosynthesized proteins (chapter 6); and Cultured meat (chapter 7). For each category an assessment is presented of the state of development and timing to market, technical and commercial viability, consumer acceptance, food safety and public health, sustainability benefits, and emerging regulatory considerations. Chapter 8 then presents key findings from the research based on a synthesis and comparative analysis of the emerging proteins. Chapter 9 then concludes the report with recommendations for policy and regulatory strategy for FSA and closes with suggested areas for further research.

2. Food industry context and drivers of change

The global food system is undergoing rapid change, with innovation across the value chain in products, processes, and services. Accelerating the adoption of novel sophisticated food technologies offers the promise of improved quality, variety, and nutritional content, and enhanced efficiency, productivity, and environmental benefits. Alternative proteins from non-animal sources represent a key area of innovation, with the goal of offering multiple new, affordable, and sustainable proteins for all. While proteins from alternative sources are not anticipated to replace animal-proteins entirely, they may help to alleviate growing global demand for meat proteins in the short-term, and offer the potential for far-reaching change across the food system value chain and for consumers in the longer term (DigitalFoodLab, 2021a).

Non-meat sources of protein are certainly not new, and the food industry has long catered to demands of vegetarian, vegan, and other specialty diets, so what is driving this new interest in alternative sources of protein? Unlike traditional vegetarian and vegan, the emerging industry is targeting a much broader market of flexitarians and those seeking to reduce their meat consumption, rather than substituting meat entirely, with products aiming to closely mimic the varied tastes and textures of traditional meats and seafood. The literature identifies four main drivers of change in the sector (e.g., Avelar et al., 2022; Doumeizel, 2019; Henchion et al., 2021; Karmaus & Jones, 2021; Smith et al., 2019):

i. Food security and the challenge of delivering adequate nutrition for a growing population (discussed in section 2.1).
ii. Greater awareness of food-related health outcomes (section 2.2).
iii. Concerns over climate change and environmental sustainability (section 2.3).
iv. A dynamic foodtech sector and strong technology/investor push (section 2.4).

While ethics and animal welfare concerns are often a consideration for vegetarian and vegan consumers, they do not appear to rank highly with consumers or industry as a driver of change (Bashi et al., 2019).

2.1 Food security

The global food system faces unprecedented challenges over the decades ahead in providing adequate nutrition for all within planetary boundaries. Despite continuous innovation and productivity improvements, the global food system is still failing to provide sufficient amounts and quality of nutrition to the world – 690 million people were considered undernourished in 2019, and two billion suffer food insecurity and lack of safe access to food (FAO et al., 2020). Moreover, global population growth (forecast to reach 9.8 billion by 2050), and rising affluence around the world are leading to a steep rise in demand for more and better-quality nutrition and particularly meat products (Avelar et al., 2022; Henchion et al., 2021). Demand for animal proteins increased by approximately 2% per year over the past decade and will almost double by 2050 if current rates of adoption are maintained (Bashi et al., 2019), as illustrated in Figure 1 (Godfray et al., 2019).

Meat production as a source of nutritional proteins is often portrayed as an inefficient use of resources, with livestock having an inefficient conversion rate of crop calories to meat calories (it takes about 23 calories of crops to produce one calorie of beef), using 80% of the world's arable land, and over 70% of fresh water (FAO, 2020c). See Figure 2 for illustration of land use for livestock meat and dairy. With much of the world's agricultural system already approaching resource limits on land and freshwater, the potential for significant further increase in animal-based protein production is greatly constrained, making the current growth trajectory unsustainable.

Given the challenges with meeting global demand, alternative sources of protein from non-animal sources utilising better crop conversion ratios and more efficient means of production could be an important part of the solution to provide food security to meet future global nutritional needs and improve universal access to safe and nutritious food.

Figure 1 Trends in consumption of meat – regional and global

Source: Godfray et al. (2019) based on data from FAOStat

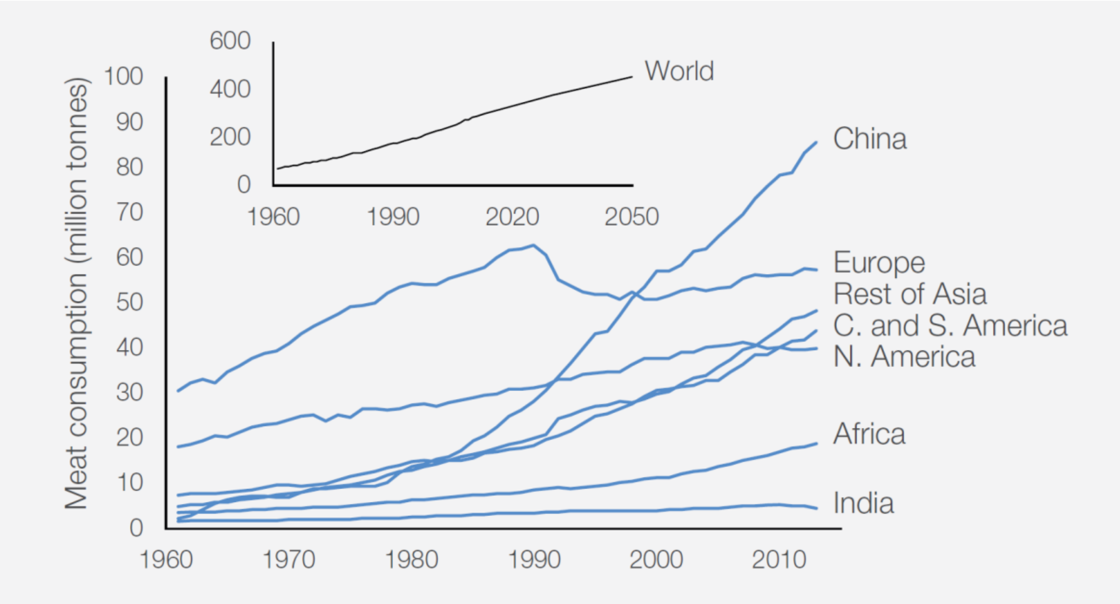
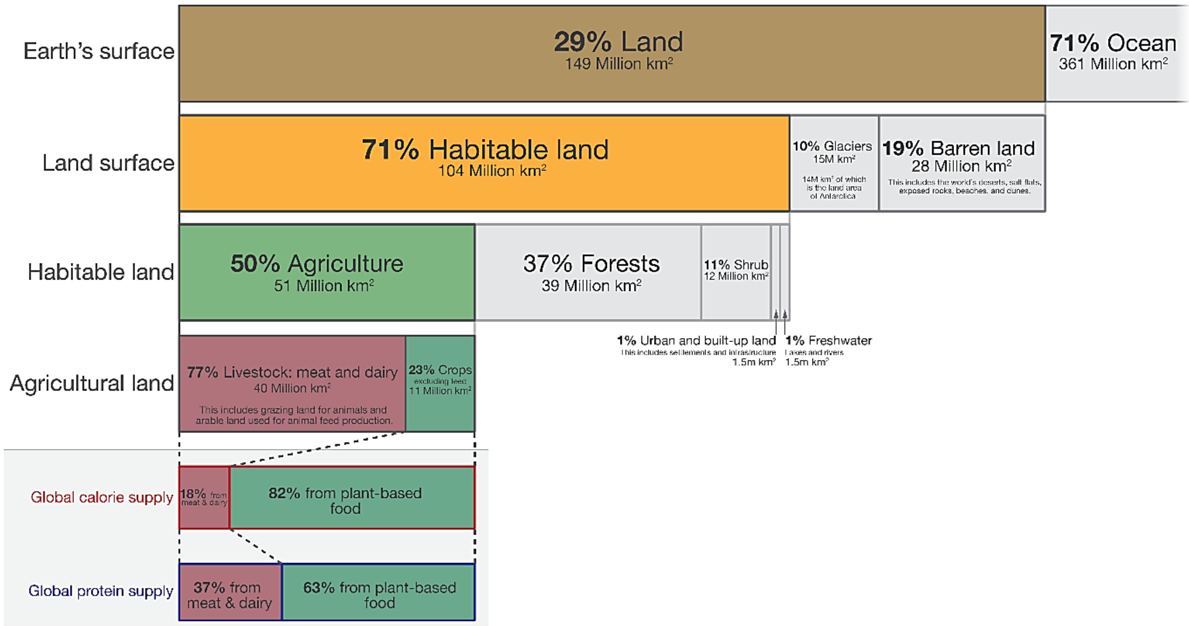


Figure 2 Global land use for food production

Source: Our World in Data; Ritchie & Roser (2019) based on data from UN Food and Agriculture Organisation (FAO)



2.2 Food-related health outcomes

The alternative protein sector is supported by mainstream general dietary recommendations that now commonly advise against consuming meats, particularly red meat, and processed meats. The National Food Strategy in the UK is aiming to nudge consumer habits with the ambition to deliver a 30% reduction in meat consumption, 30% increase in fruit and vegetables consumption, and a 50% increase in fibre consumption over the coming decade (Global Academy of Agriculture and Food Security, 2021; National Food Strategy, 2021); and in early 2022 the EU labelled red meat a cancer risk and advised that food promotions should encourage consumers to shift towards a more plant-based diet (Moran, 2022).

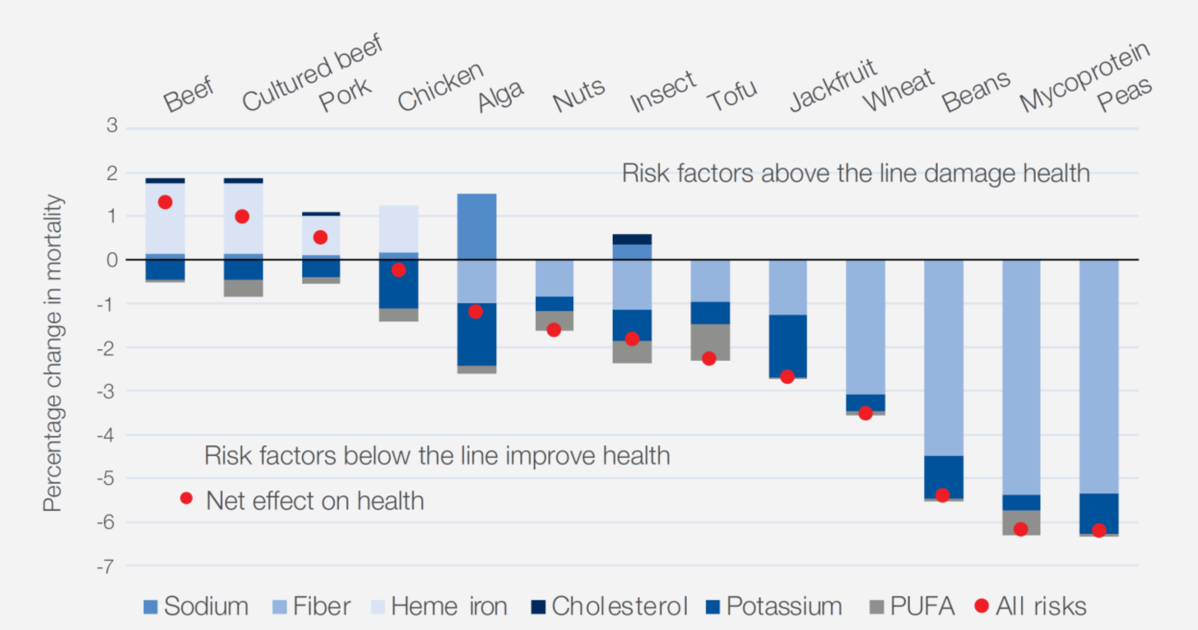
2.2.1 Health implications of a meat-based diet

The negative health implications of eating red meat, and highly-processed meat which is often high in sodium and nitrates, have been studied extensively, and longitudinal studies have shown strong epidemiological evidence of a link between their consumption and colorectal cancer (Knuppel et al., 2020; Papier et al., 2020; World Cancer Research Fund, 2018). Some studies suggest a link with diabetes, cardiovascular disease, and dementia associated with red meat consumption, but the evidence is inconclusive, and even less so for white meat consumption (Boada et al., 2016; Dyer, 2019; Leroy & Cofnas, 2020; Papier et al., 2020; Vernooij et al., 2019).

Conversely, meats typically contain higher protein content and higher biological value protein than plants, and are a good source of essential nutrients, (Godfray et al., 2019), some of which are more bioavailable than in alternative food sources (Wyness, 2015). Meats are also a rich source of amino acids, and lean meat can form part of a varied and healthy diet, and contribute to weight control (Bohrer, 2017). Considering the positive and negative together, Figure 3 presents a comparison of the potential health implications on mortality of consuming additional portions of various different proteins (Godfray et al., 2019).

Figure 3 Health effects of consuming an additional portion of different proteins

Source: Godfray et al. (2019)



2.2.2 Health implications of a plant-based diet

Health benefit claims for plant-based diets are derived from health data of a traditional vegetarian diet (Heard & Bogdan, 2021; Tso et al., 2021), which can provide the necessary nutrients for a balanced diet, are lower in saturated fats and sugars, and can have beneficial effects on the gut microbiota (Fasolin et al., 2019). However, these should be distinguished from novel plant-based meat and protein substitutes, which in many cases are often ultra-processed foods (UPF) and have been found to fall below the levels of calcium, potassium, magnesium, zinc and Vitamin B12 compared to weight equivalents of meat, and are often high in saturated fats, salt and sugar (Tso & Forde, 2021). UPFs in general have been associated with nutritional deficiencies and higher prevalence of diet-related disease such as diabetes (Martínez Steele et al., 2017; Poti et al., 2017), although the nutritional deficits of some alternative meat substitutes can potentially be alleviated by fortifying with supplementary nutrients.

2.3 Climate change and sustainability

The third driver, and a key argument of the proponents for alternative proteins, or “sustainable proteins”, is delivering environmental sustainability. The food sector is recognised as a major contributor to climate change and agricultural practices are placing increasing strain on the earth’s biosphere and biodiversity. Livestock farming is facing particular scrutiny for its contribution to climate change through GHG emissions, and is one of the primary drivers of deforestation in many parts of the world, for pastoral land for raising animals, and arable land to grow crops for animal feed.

2.3.1 Greenhouse gas emissions

Approximately one third of all global GHG emissions are attributed to the food production system, with meat, eggs and dairy consumption contributing overall 18% of global emissions (Crippa et al., 2021). In Europe, 83% of food GHG emissions, (including on-farm, processing, distribution, and retail) are attributed to meat, eggs, and dairy as illustrated in Figure 4.

Livestock, cattle in particular, generate 7% of total global GHGs largely due to methane emissions, manure management, and land use changes associated with animal feed production. Moreover, climate change is itself threatening agricultural land and the global food and animal feed production capacity and nutritional content of crops, compounding decades of soil degradation caused by over-intensive food production systems based on chemical pesticides, fertilizers and monocrops (IPCC, 2019). Figure 5 presents a comparison of the GHG emissions of various traditional protein-rich foods, showing beef and lamb are the most significant contributors to climate change, followed by farmed shrimp and dairy (Poore & Nemecek, 2018; Poore & Richie, 2018). To illustrate the difference with plant-based proteins, beef production can have GHG emissions of almost 20 times that of tofu, or more than 100 times that of nuts (Tso & Forde, 2021). There is considerable variability depending on geographic location, feedstock, and intensity of farming, but nevertheless, the arguments for reducing livestock farming appear compelling on a carbon footprint basis. Plant-based proteins such as beans, peas and nuts can have negligible overall emissions, and even negative emissions in some situations where they sequester emissions or reduce the need for fertilizers. However, these figures for beans and peas are when treated as whole food – moving away from the whole bean towards more extensively processed ingredients such as protein isolates can increase GHG emissions substantially.

Figure 4 Carbon footprint of diets across the EU by food type and source

Source: Our World in Data – Ritchie (2018); Sandström et al. (2018)

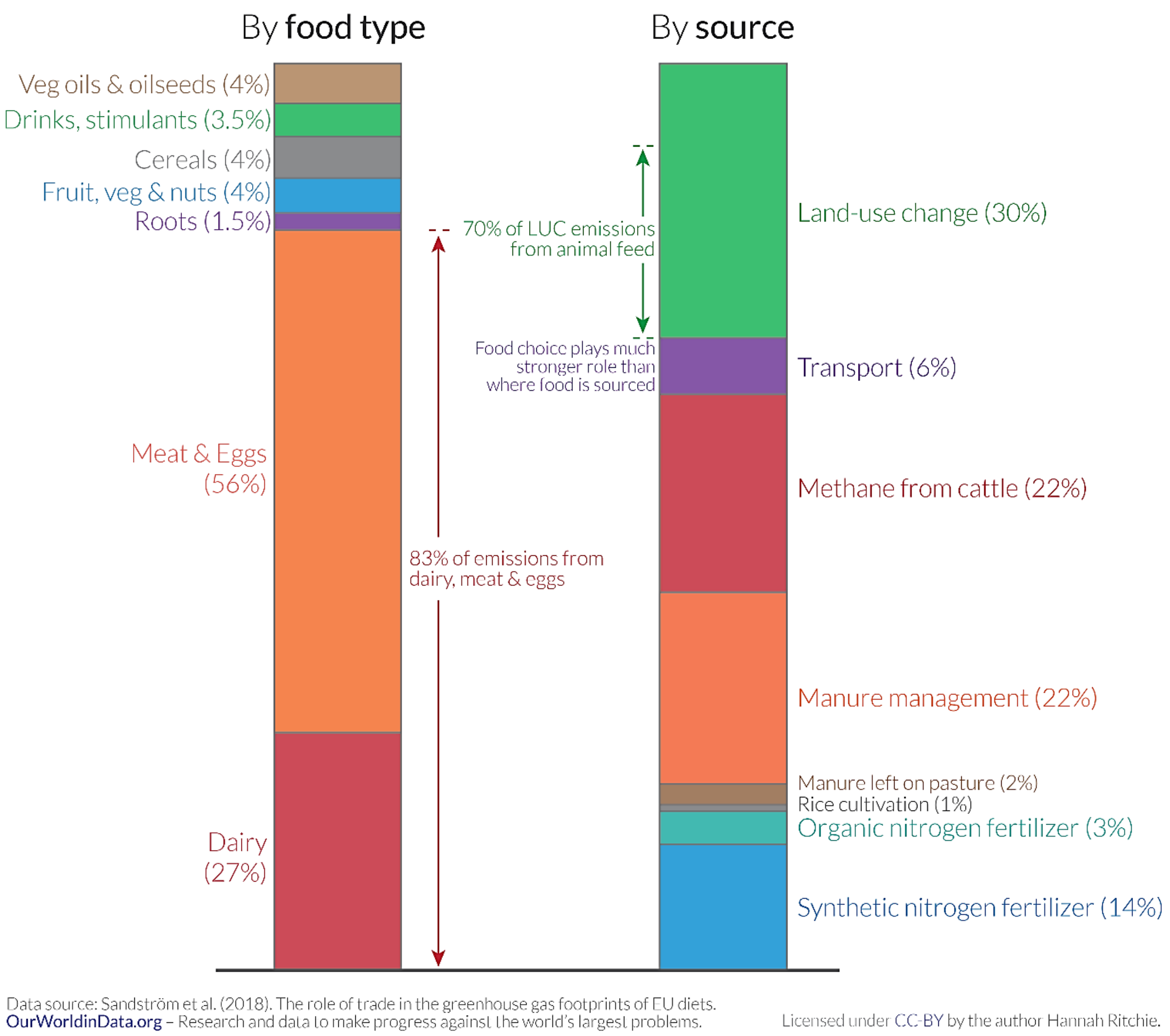
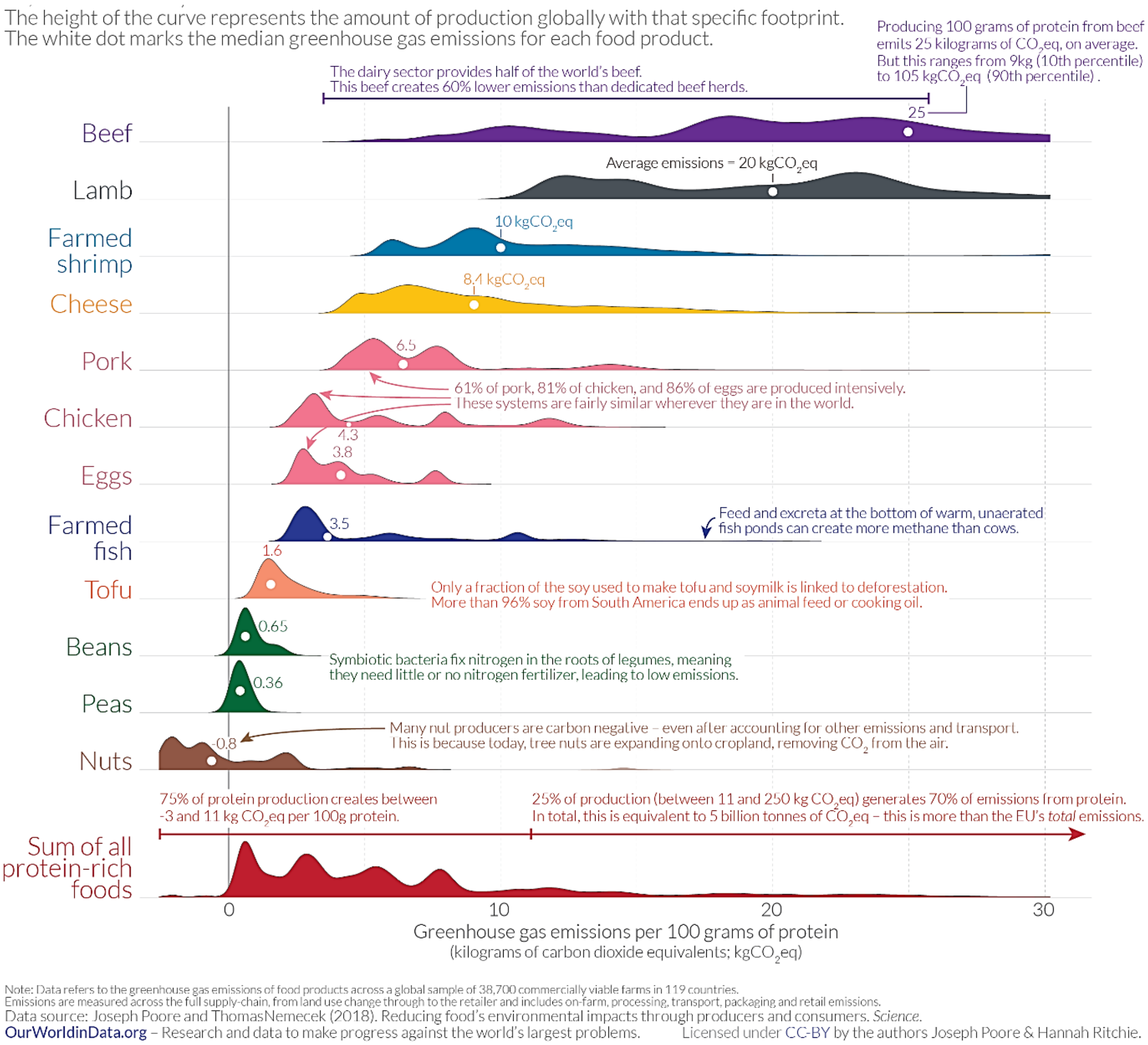


Figure 5 Comparison of carbon footprint of protein-rich foods

Source: Our World in Data – Poore & Nemecek (2018); Poore & Richie (2018)

Carbon footprint measured in $kgCO_2$ equivalent per 100 grams of protein



2.3.2 Land, freshwater, and eutrophication

A comprehensive sustainability assessment and comparison with alternative protein sources must also consider land use and deforestation/repurposing, freshwater use, and eutrophication from runoff of excess nutrients from fertilizers and manure which affect and pollute ecosystems. Key metrics are shown in Figure 6, and as illustrated, livestock particularly, has a high impact on most metrics. These figures illustrate that there can be conflicting priorities, so for example growing nuts in place of livestock, while reducing GHG emissions has a detrimental impact on water use. Moreover, available land and freshwater availability varies greatly by region and therefore region-specific constraints need to be considered in any assessment of the environmental impact. As such, simply switching food sources based on any single metric like GHG emissions can be problematic.

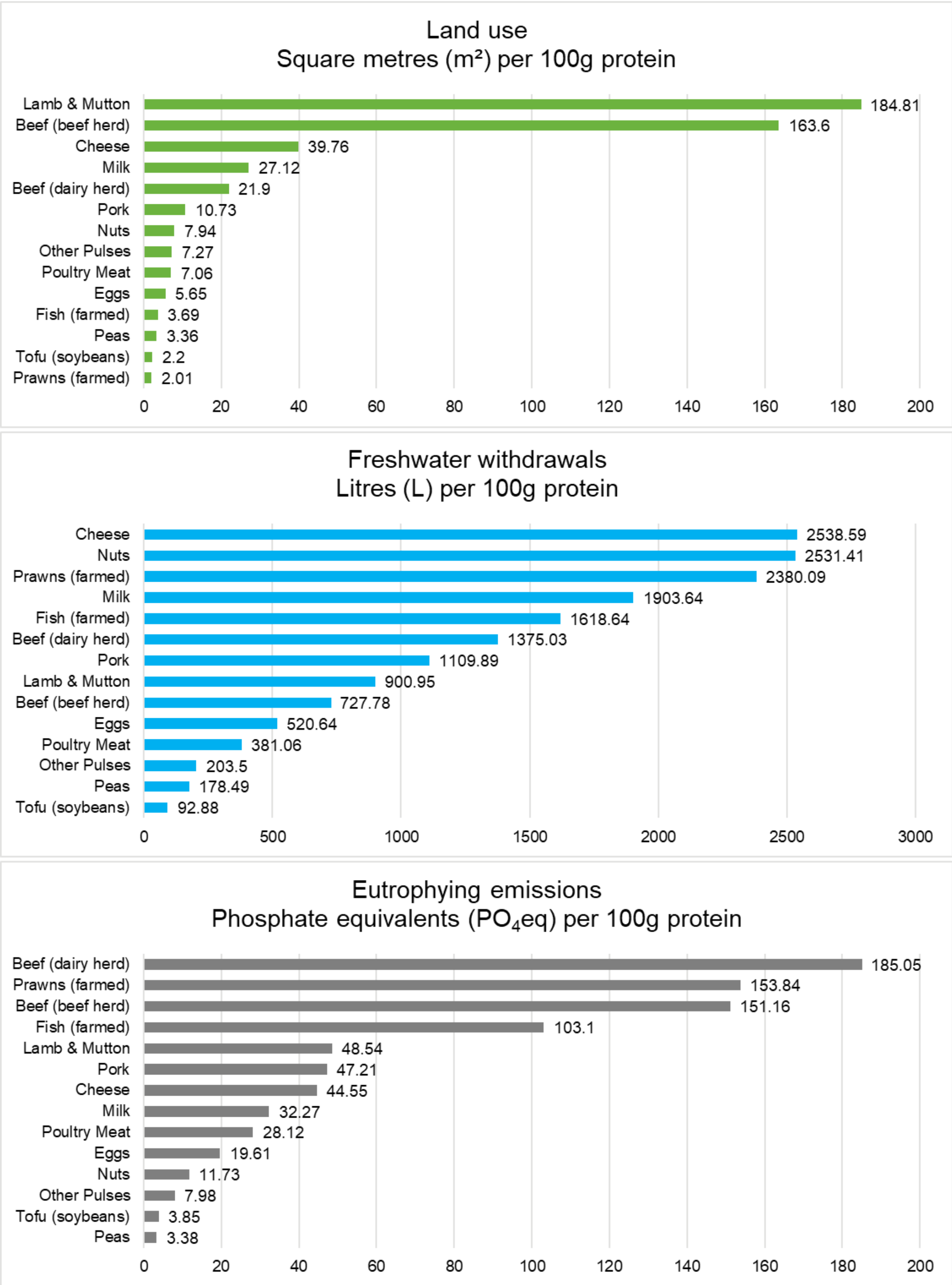
2.3.3 Impact of industrial processing

Environmental impacts of traditional wholefood, or minimally processed plant-based diets can be a fraction of their animal counterparts, as shown in Figure 5 and Figure 6. However, more heavily processed plant protein as used in the meat substitute sector, can generate significant additional energy and water use and GHG emissions depending on the number and complexity of processing steps in production, and whether renewable sources of energy are considered. Additionally, the complex extraction and processing of alternative protein sources may degrade the quality of the protein and other nutrients, representing a form of food waste.

It should be noted that LCA comparisons for food types and alternative proteins are complicated by the differing sources of energy and emissions (methane from cattle, CO_2 for electricity, etc), significant variations by geography and type of farming, and differing views on the relevant functional unit of analysis. Moreover, there is limited lifecycle inventory data for the novel processing techniques and novel biomaterials used in emerging products, and data that does exist is often based on prototype processes and so may not be representative of production at scale.

Figure 6 Environmental impacts of food production

Source: Our World in Data – Poore & Nemecek (2018); Poore & Richie (2018).



2.3.4 Food waste

The global food system is estimated to lose and waste an estimated 1.3 billion tonnes of produce per year, approximately 30% of all produce. The majority is lost through inefficiencies in production, handling and storage, and in retail and home consumption. Within this, fruit and vegetables make up the largest share, about 42% by weight, while in the protein categories, 4% is meat products, and 8% dairy. This reflects challenges of supply chain and product shelf life and safety. In terms of calories in each food group, 24% of all fish and seafood, 19% of all meat, and 18% of all dairy products are wasted across the value chain (Lipinski et al., 2013).

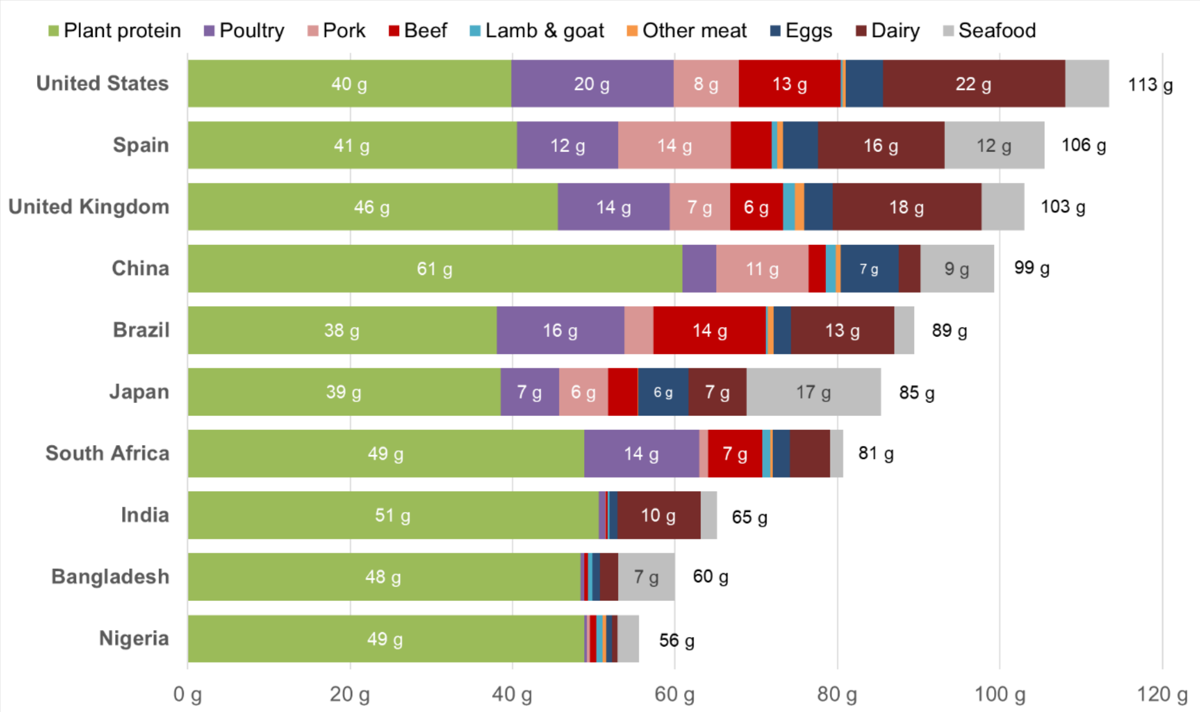
With growing demand for food and particularly for protein, and hard constraints on expanding the food system, there is an urgent need to address these inefficiencies in the global food system, and particularly to tackle the issue of waste, and introduce circular economy concepts to make better use of food industry by-products and waste streams.

2.3.5 Over-consumption

The overall role of animal-based proteins in the average daily diet as of 2017 is shown in Figure 7. These figures highlight a stark difference in levels of consumption and types of proteins consumed between nations, particularly between affluent developed nations such as the US and Western Europe, and developing nations in Africa and Asia (FAO, 2020a; Richie & Roser, 2021). Levels of consumption, particularly of meat and dairy in the developed world often exceed the daily needs of many, representing a waste of global nutritional resources. Moreover, over-consumption of protein may be related to general excessive consumption levels that are contributing to an obesity epidemic in the West, which has been linked to a rise in non-communicable diseases such as cardiovascular disease and diabetes. Addressing over-consumption needs to be an important part of tackling public health issues and sustainability challenges facing the food sector.

Figure 7 Average daily grams per capita sources of protein, 2017

Source: FAO (2020a); Richie & Roser (2021)



2.3.6 An environmentally sustainable food system

As illustrated in this section on sustainability, there is significant scope to reduce GHG emissions, land and water use, and eutrophication, simply through a shift in the type of animal proteins that are currently consumed globally. Specifically, a shift away from beef and dairy (predominantly consumed in the US, Europe, and Brazil, as illustrated in Figure 7), towards poultry, eggs, and fish that offer far better feed conversion ratios. Even simply shifting away from dedicated beef herds to dairy beef herds may offer notable benefit because a share of their GHG emissions is allocated to dairy protein, so the resulting beef can have a 60% lower GHG emissions profile. A shift to a predominately wholefood and minimally processed plant-based diet as is traditional in many parts of the world, such as India, or use of low-tech low-energy processing of plant proteins, such as traditional fermentation of tofu, offers further benefit.

2.4 A dynamic foodtech innovation sector

As of 2019 the global market for meat consumption was approximately $1.7 trillion and growing, as the world becomes wealthier. In contrast, the global market for alternative protein was estimated at just $2.2 billion (Bashi et al., 2019). The potential for alternative protein sources, subject to regulation and consumer acceptance, to capture even a small share of the existing meat market, or to grow as a parallel market, therefore represents a huge commercial opportunity for the entrepreneurs and innovators who successfully develop and secure the patents and production knowhow for these emerging technologies. Offering consumers novelty, improved taste and food experiences, and healthier options, combined with the promise of delivering environmental and public health benefits also makes a compelling case for the growing community of Environmental, Social and Governance (ESG) and impact investors.

Investment in the overall global foodtech ecosystem has expanded rapidly over the past few years, more than doubling between 2017 and 2020 from EUR 9 billion to EUR 22.3 billion (DigitalFoodLab, 2021b). Food sciences/next-generation food and drinks, which includes the alternative proteins sector is one of the fastest growing sectors in foodtech, with hundreds of new start-ups, that have raised approximately EUR 1 billion in the H1 2020 period globally, while competition from the large food corporations is also growing (ForwardFooding, 2020).

Figure 8 presents a breakdown of the investment in food sciences over the 2014-2020 period (DigitalFoodLab, 2021b), highlighting the marked rise in funding for alternative proteins in 2019 and 2020, driven by large funding rounds for companies including Oatly (www.oatly.com), Meatless Farms (www.meatlessfarm.com), Legendairy (www.legendairyfoods.de/) and Mosa Meat (www.mosameat.com). Further illustrating the rapid growth in the sector, Next Gen Foods (www.nextgenfoods.sg), a Singapore-based producer of plant-based chicken meat, has just secured the largest Series A investment in the plant-based meat sector to date (Poh, 2022).

Table 1 presents the Good Food Institute’s breakdown of the alternative protein segment, by three key areas of investment: plant-based proteins, fermentation, and cultured meat (GFI, 2021a). These figures include some large funding rounds for a handful of market leaders, but nonetheless indicate that funding is increasing across the spectrum of alternative proteins. Cultured meat and fermentation funding lags the more mature plant-based protein sector but is expanding at pace.

Figure 8 The rise of alternative proteins – Investment in Europe

Source: DigitalFoodLab (2021b)

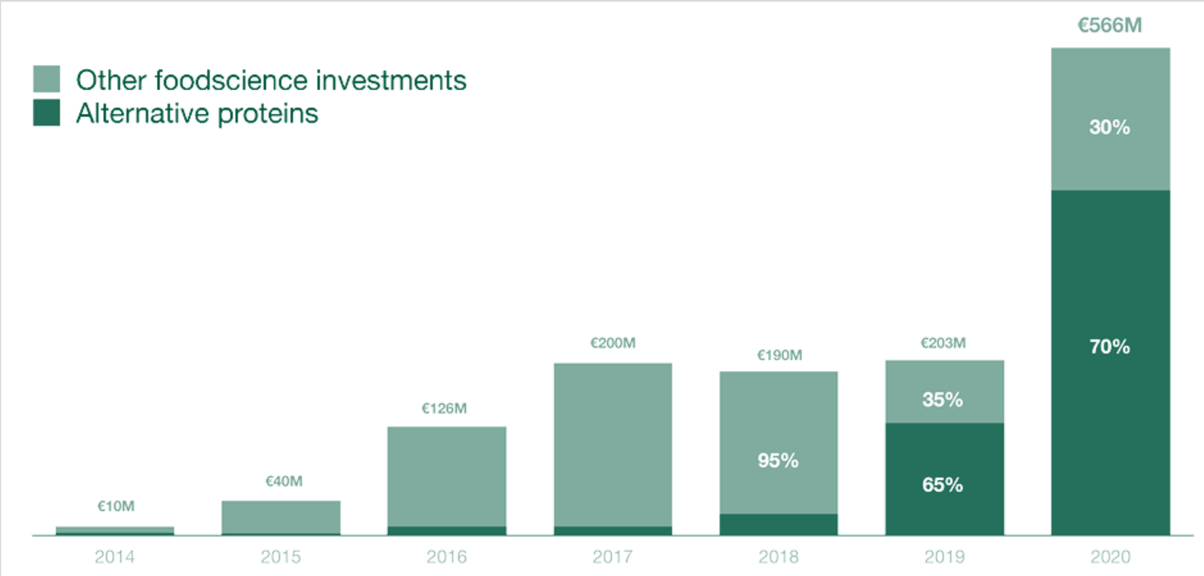


Table 1 Alternative protein investment summary, 2010-2020

Source: GFI (2021a)

Category	Total invested, 2010-2020	Invested capital, 2020	1-year growth	Largest funding round
Total alternative protein	$5.9 billion	$3.1 billion	3x	$500 million Impossible Foods, Series F
Plant-based	$4.4 billion	$2.1 billion	3x	$500 million Impossible Foods, Series F
Fermentation	$1 billion	$590 million	2x	$300 million Perfect Day, Series C
Cultured meat	$490 million	$360 million	6x	$186 million Memphis Meats, Series B

3. Innovation in alternative proteins

The agri-foodtech sector is responding to the above-mentioned drivers of change with a host of technological and business model innovations, and technology push is transforming the sector with the potential to unleash a flood of novel ingredients and food products on to the market.

In this chapter we introduce the categories of emerging proteins (section 3.1), discuss the technical/commercial maturity of each of these categories (section 0), the future growth forecasts for the sector (section 3.3), and finally, the challenges around consumer acceptance and achieving mass-market adoption (section 3.4).

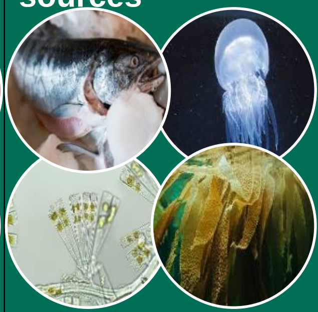
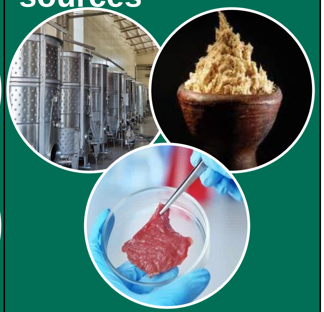
3.1 Categories of alternative proteins

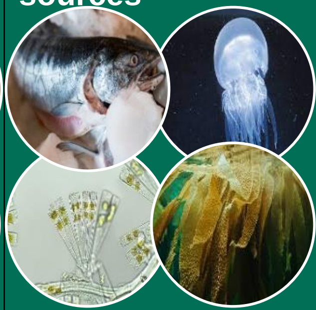
A range of innovations in alternative proteins are emerging aiming to displace traditional animal farming with more efficient solutions. Table 2 presents an overview of the primary sources of proteins: terrestrial agricultural land-based sources; aquatic “blue” sources; and laboratory/factory synthetic sources (based on Bashi et al., 2019; DigitalFoodLab, 2021b; ForwardFooding, 2020; GFI, 2021b). Identifying the proteins by their primary source offers a framework to explore how these novel proteins enter the food system and how they are used, and to consider the impact of changes on agriculture and farming practices, environmental impacts, and related topics such as communities and livelihoods associated with each system of food production.

Traditional plant-based and animal-based sources of proteins, generally consumed with relatively low levels of processing, are differentiated from the range of emerging alternative sources of protein that are sophisticated re-engineered, foodtech innovations or novel food types. Based on this definition, we exclude from this study products such as plant-based dairy alternatives that are often presented as alternative proteins in the media or industry, as they are quite conventional sources of protein. Innovation in animal farming, notably in animal feedstocks, aquaculture systems, and genetically modified (GM) animals and crops to improve yields are potentially significant for the future food system (Short et al., 2021), however we also exclude them from this study as they are not fundamentally alternatives to the current systems and will not greatly change existing value chains, consumption patterns, and health and sustainability outcomes.

Table 2 Alternative protein sources for human consumption

Source: Developed from Bashi et al. (2019); DigitalFoodLab (2021b); ForwardFooding (2020); GFI (2021b) and others

	Terrestrial protein sources 	Aquatic protein sources 	Laboratory protein sources 
Main protein groups	– Conventional animal meat – Dairy and eggs – Plant-based protein – Insect protein – GM animals & molecular farming	– Conventional fish and shellfish – Microalgae – Macroalgae – Jellyfish	– Biosynthesised proteins through precision & biomass fermentation – Cultured meat
New ingredients: – Processed ingredients – Concentrates – Protein isolates	– Plant protein concentrates and isolates – Insects as ingredients, concentrates and isolates	– Novel organisms as ingredients, concentrates and isolates	– Generation of protein molecule isolates

	Terrestrial protein sources 	**Aquatic protein sources** 	**Laboratory protein sources** 
New foods: – Whole foods – Processed foods – Ultra-processed foods	– Insects as foods – Re-engineered protein formulations to create meat analogues	– Novel organisms as foods – Novel organisms as inputs into ultra-processed foods	– Generation of protein biomass – Blended meat-like foods – Input into ultra-processed foods

For the purposes of this study, we focus on the key emerging ingredients/foods of interest in the alternative protein sector and categorise by four technology/market-orientated groupings of interest. This grouping, described below, and represented in Figure 9, reflects the existing literature and the categorisations generally adopted by the food industry:

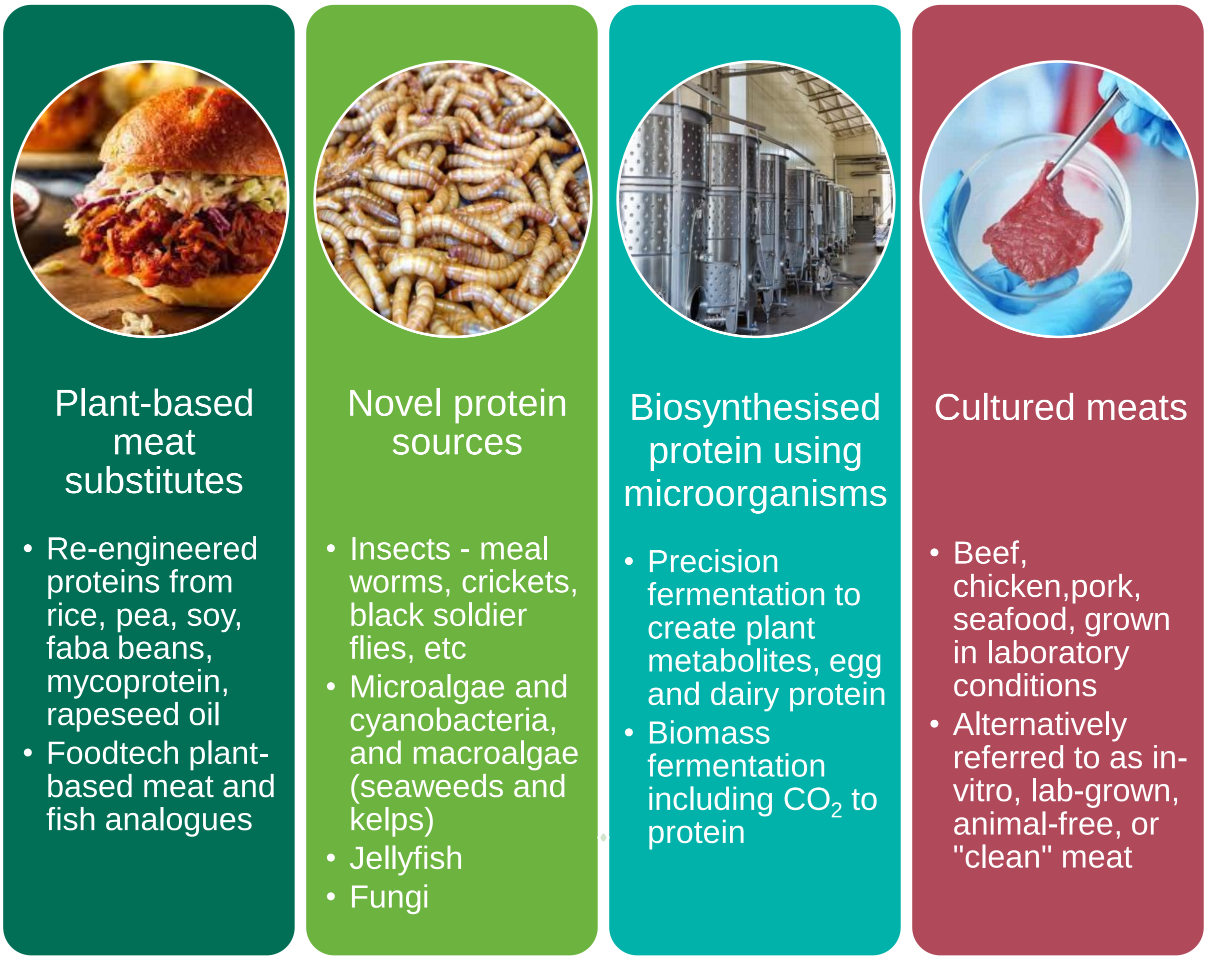
1. **Plant-based meat-substitutes** – Re-engineered food technology products based on protein extracts from plant material and complex processing to achieve convincing meat-like tastes and textures.
2. **Novel protein sources** – Non-traditional sources of protein such as insects, seaweeds, and microalgae. (These are novel foods to the UK, Europe, and US markets, although not novel to the world).
3. **Proteins biosynthesised by microorganisms** – Predominantly protein functional ingredients generated through precision fermentation and biomass fermentation processes using genetically modified yeasts, fungi, or microbes. (e.g., used to produce milk and egg proteins).

4. **Cultured meat protein** – Alternatively referred to as in-vitro, lab-grown, or synthetic meat, these are mainly animal-meat muscle cells grown in laboratory conditions.

The proposed categorisation involves some simplification, and the boundaries between the categories are not entirely distinct, for example, there is high potential for different protein sources to be combined to create new plant-meat-synthetic protein hybrid food products. Hybrid foods may be an important feature of the future food system, as a means to encourage a transition towards a more plant-based or alternative protein-based diet (while retaining characteristics of conventional meat), and as a means to allocate animal meat proteins more widely to address rising demand (Banovic et al., 2022; Grasso & Jaworska, 2020). However, for simplicity and the purpose of this report each of the categories is considered distinct.

In the longer-term, molecular farming, whereby crops are used to synthesise animal proteins may be an important alternative source, bridging between synthetic sources and terrestrial and perhaps aquatic sources. However, these technologies are at a very early stage of development and face considerable regulatory hurdles related to their genetically modified organism (GMO) status, so are considered unlikely to be significant within the 10-year time horizon of this study.

Figure 9 Categorisation of alternative protein sources for human consumption

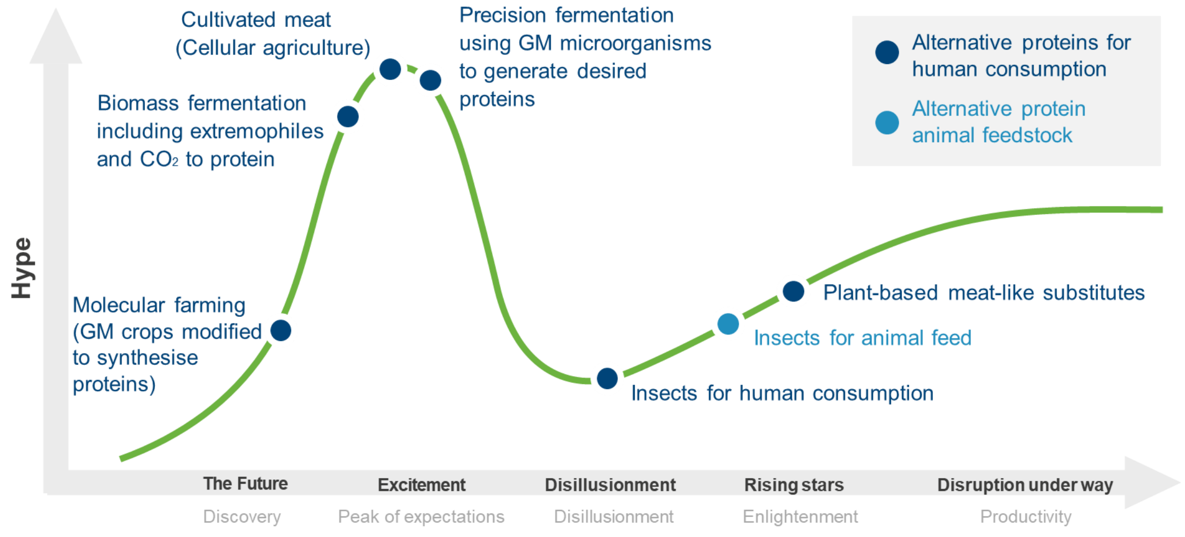


3.2 Maturity of the emerging alternative protein sources

The different segments of the alternative proteins market are at very different levels of maturity and have varying potential for mainstream adoption and impact on the food system. Figure 10 presents a Gartner curve of the agri-food technology sector, illustrating a qualitative assessment of the level of hype, versus the maturity of the technologies (DigitalFoodLab, 2021a). Positioning on the curve is relative to other technologies and is somewhat subjective, but understanding the position on the curve helps to distinguish between hype and reality and provides an indication of how long it might take these technologies to achieve mainstream adoption and high levels of productivity.

Figure 10 Disruptive food technologies (Europe) mapped on Gartner Hype Curve

Source: adapted from DigitalFoodLab (2021a)



As illustrated, among the alternative proteins, plant-based meat substitutes are the most mature and can now be found in many supermarkets and a number of global fast-food chains, although they remain somewhat niche, and challenges remain in reaching full productivity. Insects for human consumption have made progress against regulatory hurdles but have lost ground to the newer and more attractive plant-based alternatives and are currently struggling to gain acceptance with consumers in Western markets, remaining very much artisanal curiosities at present. Precision fermentation, cultivated meat (cellular agriculture), novel biomass fermentation, and molecular farming are still at very early stages in their evolution – more investor hype and speculation than commercial reality, still only in laboratory or pilot scale projects, and have yet to demonstrate technological or commercial viability (DigitalFoodLab, 2021a).

The positioning of biomass fermentation on the curve in Figure 10 represents emerging new technologies such as Nature's Fynd's (www.naturesfynd.com) extremophile ecosystem, and CO_2 to protein systems that are still several years from commercial reality. Some biomass fermentation products such as mycoprotein product, Quorn (www.quorn.co.uk), have been on the market for several decades, but have not yet become mass-market products.

The related sector of insects for animal feed is included in the figure to illustrate how this segment is evolving, and it is recognised that innovation and success in this segment may pave the way for broader adoption of insects for human consumption in the West. In some parts of Africa and Asia, where protein sources are limited and insects are already accepted as part of the culinary culture, this segment is already established and looks likely to expand strongly, albeit at a local level, rather than globally (Filou, 2022).

3.3 Future growth prospects

Although the sector has seen rapid growth over the past few years, recent earnings reports from the sector suggest a slowdown in the market in 2022, with Maple Leaf (www.mapleleaffoods.com), that owns the plant-based meat brand Lightlife (www.lightlife.com), explaining that "consumers viewed plant-based meat as an expensive novelty leading to high trial rates but low repeat purchases" (Terazono, 2022). This suggests significant challenges remain for the sector in achieving widespread consumer acceptance. Key determinants of the future success of alternative proteins will be development of new tastes and textures that adequately replicate traditional meats and dairy, affordability and accessibility for mass-market adoption, and potentially nutritional value.

There is considerable uncertainty over the future technological innovation and economies of scale that may be achievable. However, some estimates suggest plant-based proteins and microorganism-based proteins may reach price parity with meat by 2025, and cultured meat parity with animal meat by 2035 as illustrated in Figure 11. Alternative proteins may capture over 10% of the existing meat, eggs, and dairy protein market by 2035 in their base-case, with an upside potential of 22% market share by 2035 with supportive regulatory intervention such as carbon taxes or reallocation of subsidies away from animal farming (Witte et al., 2021).

Market development is anticipated to occur in three main waves of growth (as illustrated in Figure 12):

1. The initial wave, already underway is the plant-based meat-substitutes.
2. By mid-decade the second wave, made up of microorganism-based products produced through precision fermentation will gain momentum

3. By 2035 the third wave, in cultured meats, may be underway.

Figure 11 Alternative proteins: Price parity forecast

Source: Witte et al. (2021)

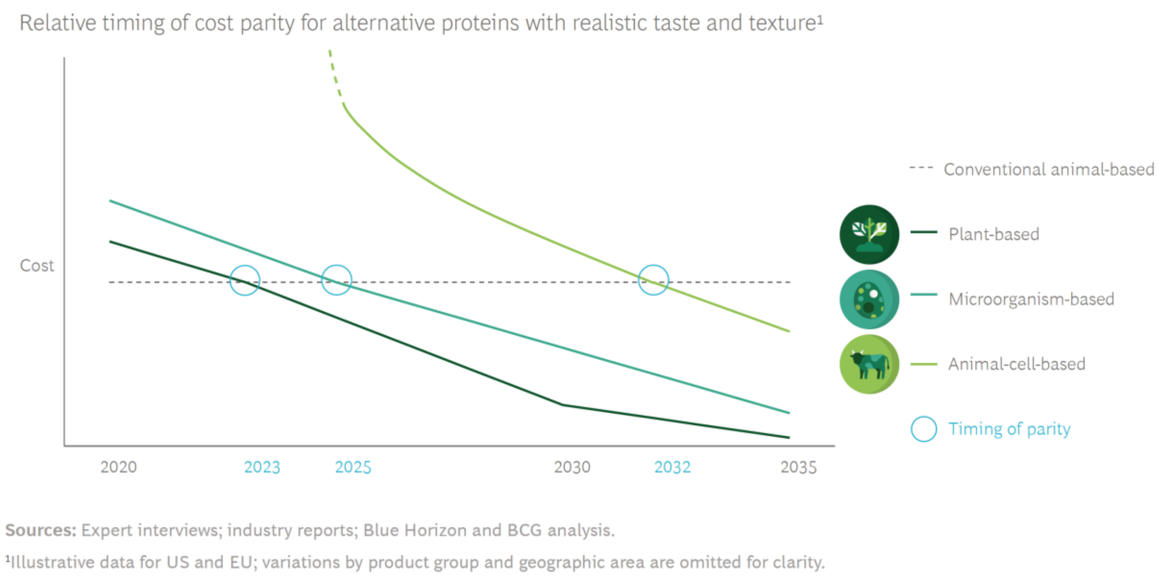
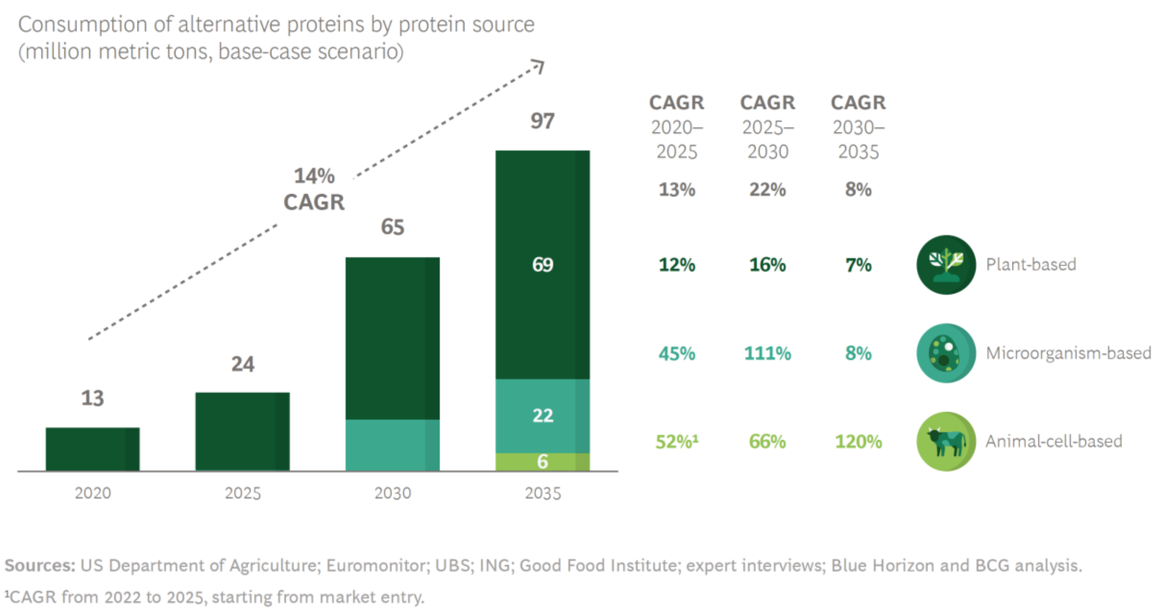


Figure 12 Alternative protein consumption: Three waves of growth

Source: Witte et al. (2021)



Within these categories, dairy alternatives are anticipated to dominate the market for at least the next decade and considerable disruption in dairy farming might be expected. Growth can be anticipated to be regionalised: the US is the most mature market at present and anticipated to grow strongly as educated consumers demand quality, novelty, and greater environmental performance. However, the Asia-Pacific region is anticipated to rapidly become the largest market with potentially two-thirds of the market for alternative proteins, driven by population growth and rapidly increasing affluence, and a younger population more open to experimentation and novelty. This has relevance to the UK as these regions will drive much of the innovation in the sector, lead the way with regulation, and may represent significant imports into the UK market. The forecasts above from Witte et al. (2021) do not include alternative proteins such as insects and algae in their study, and directly comparable data is unavailable, but subject to regulatory changes and consumer willingness, may be expected to gain momentum by mid-decade, but again is likely to regionalised, with perhaps limited market impact in the West in the near-term.

3.4 Achieving mass-market consumer adoption

The literature presents a range of views on which factors are of primary importance in determining consumer acceptance and willingness to try alternative sources of proteins. Evidence suggests that priorities vary by demographics (Weinrich, 2019) and by geographic region and cultural tradition (C. Bryant & Barnett, 2018), with younger, not neophobic demographics with no strong meat consumption habits likely to be the early adopters, with fastest growth anticipated in Asian markets.

A recent study published by the Good Food Institute found consumers choose alternative proteins, in order of preference, based on (Ignaszewski, 2022):

- Strong positive: Taste and sensory experience
- Moderate positive: Familiarity and tradition, and freshness
- Weak positive: Health and nutrition, and price
- Very weak positive: Specific nutritional claims, and altruistic benefits such as environmental and social benefits and animal welfare

According to a Mintel market study, among adults who do not currently consume meat alternatives, when asked why they don’t eat plant-based proteins, 66% stated they simply prefer meat, 20% point to high price as a barrier, and 18% feel there are not enough appetizing options (Ignaszewski, 2022). Weinrich (2019) confirms that consumers decide based on appearance and sensory aspects (taste, texture, smell) which are ultimately the crucial factors in achieving regular consumption. Contrary to the focus of much of the industry, Weinrich (2019) suggests that analogy/similarity/likeness to meat is not actually key, although there has been little research on this question.

While consumers are aware of health, environment, and animal welfare issues, and these can influence or persuade consumers to try these products, studies suggest these arguments are not critical or decisive, and only a minority are motivated by these concerns (C. Bryant & Barnett, 2018; Weinrich, 2019). A recent review of consumer studies found that only 13 – 26% of consumers were willing to significantly reduce or stop their meat consumption for environmental reasons, and even among consumers who prioritise health and the environment this often does not translate into positive food choices (Tso & Forde, 2021).

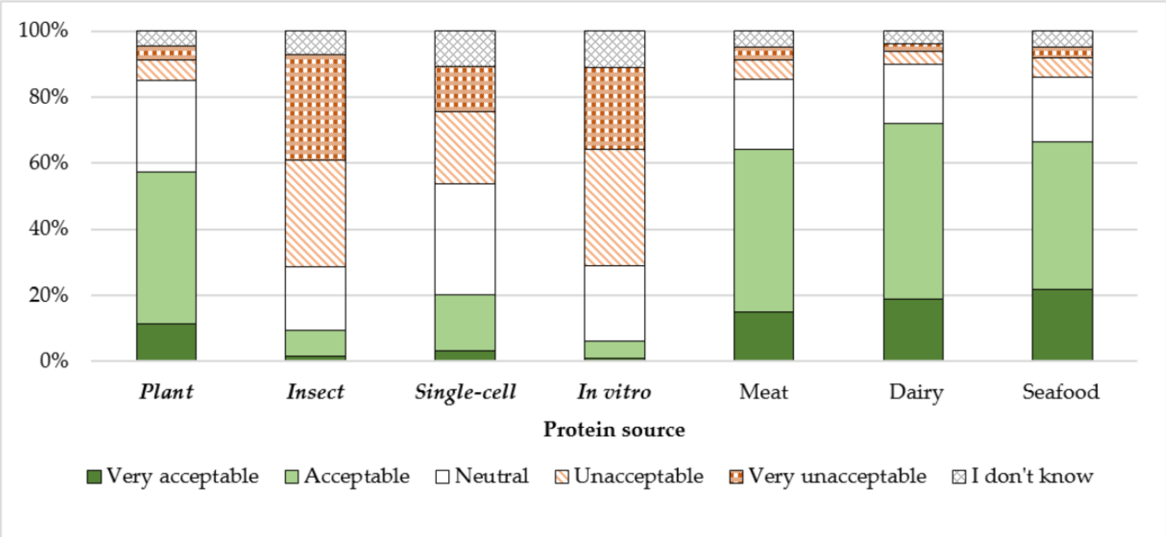
Beyond the above factors, consumers may have cultural aversions to trying certain food types or have preconceived perceptions over food safety. For example, in many cultures there is strong attachment to meat-centric social constructs (Grasso & Jaworska, 2020); in the West insects are typically viewed with disgust, as dirty and carriers of disease and allergens (Circus & Robison, 2019; Tso et al., 2021); and, cultured meats and biosynthesised proteins may be perceived as unnatural, synthetic and dangerous to one's health and society (Filcak et al., 2020). An additional challenge for the alternative proteins sector is the growing consumer demand for natural products and ingredients, which may be perceived to be at odds with synthetic biology and the highly processed nature of most alternative protein sources (Hocquette, 2016).

Grasso et al. (2019) explored the level of acceptance of various alternative protein sources against meat, seafood, and dairy, illustrating an openness to plant-based proteins, but significant consumer resistance to insects, single-cell protein (e.g., mycoprotein, microalgae) and in-vitro (cultured or "clean" meat), as shown in Figure 13. The study was among adults aged 65 years and over, so does not represent the entire population, and acceptance is expected to be higher for younger demographics, but nevertheless, the study is informative, and overcoming these barriers will be a key challenge for the alternative protein industry.

Figure 13 Level of acceptance to eat food containing alternative proteins

Source: Grasso et al. (2019)

Data for adults aged 65 years and older in five EU countries



4. Plant-based meat substitutes

The leading segment of the alternative protein market is currently plant-based meat-like substitutes. This chapter provides a detailed overview of the topic of plant-based meat substitutes. Firstly, section 4.1 introduces this alternative protein source; then section 4.2 discusses the technical and commercial challenges and viability; section 4.3 discusses consumer acceptance; section 4.4 explores health and food safety; section 4.5 looks at sustainability implications; and finally section 4.6 discusses emerging regulatory issues.

4.1 Introduction to plant-based meat substitutes

Plant-based meat substitutes are blended products made from plant materials to have comparable protein content, appearance, taste and textures of conventional meat and seafood products. Early entrants typically used soybeans as a primary input, but the range of protein sources has expanded in recent years to include peas, lupins, and a variety of other plant protein sources. Additives are used to enhance appearance and taste, and sophisticated production processing, including 3D printing, are employed to create muscle-like fibres and textures. Figure 14 shows examples of the inputs, production processes, and outputs of these plant-based meat substitutes.

Figure 14 Plant-based proteins production process and outputs

Source: developed from Leonardo Paradisi (2021)

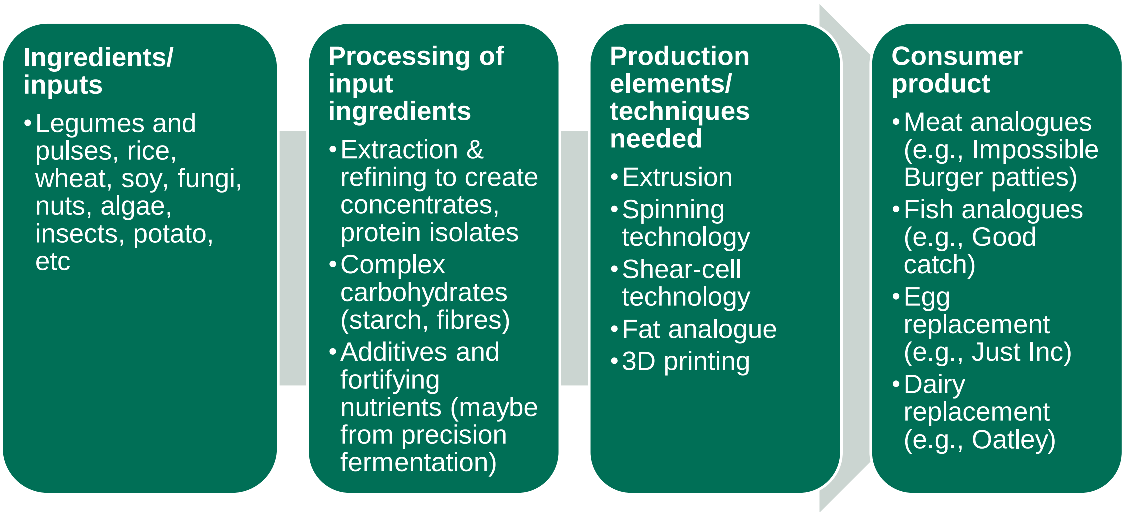


Table 3 and Table 4 present examples of some of the major brands of plant-based burger and seafood substitutes and their protein sources, gluten, and potential allergens (soy, wheat) and some of the more controversial additives and ingredients employed.

Table 3 Ingredients of a sample of brands of plant-based meat substitutes

Source: Santo et al. (2020)

Company name	"Burger" product	Primary protein source(s) (>2% by weight)	Other relevant ingredients
Amy's Kitchen (www.amys.com)	All American Veggie Burger	• Textured soy protein	None
Beyond Meat (www.beyondmeat.com)	Beyond Burger	• Pea protein • Rice protein • Mung bean protein	Coconut oil

Company name	"Burger" product	Primary protein source(s) (>2% by weight)	Other relevant ingredients
Boca (www.bocaburger.com)	All American Veggie Burger (XL)	• Soy protein concentrate	None
Dr. Praeger's (www.drpraegers.com)	Perfect Burger	• Hydrated pea protein	None
Field Roast (www.fieldroast.com)	Field Burger	• Vital wheat gluten	Palm fruit oil, carrageenan
Gardein (www.gardein.com)	Ultimate Beefless Burger	• Textured wheat protein • Vital wheat gluten • Soy protein concentrate • Soy protein isolate • Pea protein	None
Impossible Foods (www.impossiblefoods.com)	Impossible Burger	• Soy protein concentrate	Soy leghemoglobin (heme protein), coconut oil
Lightlife (www.lightlife.com)	Plant-Based Burger	• Pea protein	Coconut oil
Morningstar Farms (www.morningstarfarms.com)	Meat Lovers Vegan Burgers	• Wheat gluten • Soy protein isolate • Soy flour	None
Quorn (www.quorn.co.uk)	Meatless Gourmet Burgers	• Mycoprotein • Egg whites • Milk protein concentrate	Palm oil
Tofurky (www.tofurky.com)	Plant Based Burgers	• Soy protein concentrate • Soy protein isolate • Wheat gluten	Coconut oil

Table 4 Ingredients of a sample of brands of plant-based seafood substitutes

Source: Santo et al. (2020)

Company name	Product name	Primary protein source(s) (>2% by weight)	Other relevant ingredients
Gardein (www.gardein.com)	Mini Crispy Crabless Cakes	• Textured wheat protein • Soy protein isolate • Vital wheat gluten • Chickpea flour	None

Company name	Product name	Primary protein source(s) (>2% by weight)	Other relevant ingredients
Gardein (www.gardein.com)	Golden Fishless Filet	• Soy protein concentrate • Soy protein isolate • Vital wheat gluten • Pea protein	None
Good Catch (www.goodcatchfoods.com)	Fish-Free Tuna	• Good Catch™ Protein Blend (Pea Protein Isolate, Soy Protein Concentrate, Chickpea Flour, Lentil Protein, Faba Protein, Navy Bean Flour)	None
Heritage Health Food (www.heritagehealthfood.com)	Vege-Scallops	• Wheat gluten • Soy protein isolate	None
Loma Linda (www.atlanticnaturalfoods.com)	TUNO	• Non-GMO textured soy protein	No
Quorn (www.quorn.co.uk)	Fishless Sticks	• Mycoprotein	Palm oil, Coconut oil
Sophie's Kitchen (www.sophieskitchen.com)	Breaded Vegan Fish Fillets	• Textured vegetable protein (non-GMO isolated soy protein, pea protein)	No
Sophie's Kitchen (www.sophieskitchen.	Black Pepper Vegan Toona	• Pea protein	No
Vbites (www.vbites.com)	Fish-free smoked salmon slices	• Soy protein	Carrageenan
Vegetarian Butcher (www.thevegetarianbutcher.co.uk)	Vegetarian NoTuna	• Soy protein • Wheat protein • Whey protein	None

4.2 Plant-based proteins: technical and commercial viability

The market for plant-based meat alternatives is already well developed with products now available in many supermarkets, but they remain a niche segment at present and pricing remains above that of conventional animal meats and fish. Market leading products such as Beyond Meat's and Impossible Foods' plant-based burgers, that most closely resemble the experience of consuming meat are estimated to be about twice the price of conventional meat at present, although some forecasts suggest costs may reach parity with conventional meats within the next 2-3 years (Witte et al., 2021). Premium pricing is a barrier to widespread adoption, and the challenge facing producers is finding commercially viable trade-offs between improving textures and flavours further to resemble more natural meat products, driven mainly by technology and investor push which can be very R&D intensive and costly, and offering affordable products. Achieving price, taste and texture at parity with conventional meat products requires further innovation in several key areas (Witte et al., 2021):

- Optimising the source protein crops to deliver higher protein content and reducing the variability in taste and colour will reduce the extraction costs. Key protein sources at present are soybeans and peas, but neither crop is optimised for human consumption.
- Protein extraction processes and the separation and drying steps still need to evolve to deliver greater performance at scale, reduce costs and improve the quality of the extracts. Improved processing may also reduce the need for chemical additives currently required to mask colour and flavours.
- Reducing the use of artificial additives is an important objective for the sector to meet consumer demands for natural, animal-free products. Key ingredients such as methylcellulose, a binding agent, need to be replaced with plant-based extracts.
- Novel technologies for texturizing proteins are still needed to reduce costs and improve final products, and operation at scale is needed to realise the growth potential of the sector. Innovative approaches using 3D printing, electro-spinning and shear cells are in development and promise to create realistic meat-like fibres and textures (Pereira et al., 2021; Singh et al., 2021).

4.3 Plant-based proteins: consumer acceptance

Consumer acceptance of plant-based proteins is increasing as they look to replace meat-based products with comparable plant-based products in taste and sensory profile (Circus & Robison, 2019; Grasso et al., 2019). In the UK, while meat consumption appears to be declining, sales of meat-free foods increased by 40% from 2014 to 2019 (Tso et al., 2021). The UK National diet and nutrition survey 2008-2019 based on longitudinal dietary data observed a reduction in meat consumption from 99g/capita/day in 2008 to 85g/capita/day in 2019, and an increase in plant-based alternative foods from 6.7% of the diet in 2008-2011 to 13.1% in 2017-2019.

Among these products, substitutes for red meat seem to be the most popular, with products mimicking fish and poultry found to be less popular in a recent study in Australia (Estell et al., 2021). Common complaints over plant-based alternatives to date relate to uniform taste, dryness, compactness and softness (Weinrich, 2019), but a number of companies have shown success in creating compelling meat analogues, although cost and complex production processes and reliance on additives remain a challenge for consumer acceptance. Grasso & Jaworska (2020) suggest that a bridge between existing meat-centric diets, and meat-free products could be hybrid products in which a proportion of meat has been replaced with plant-based proteins.

In the UK there is currently a 32% price premium for plant-based burger patties, which compares favourably with many other markets e.g., US 65% premium, Italy 187% premium, Australia 233% premium, and Japan 335% premium, but nevertheless the price premium acts as a barrier to mass-market uptake.

4.4 Plant-based proteins: food safety and public health

Plant-based proteins are traditionally an important part of most diets, and on the face of it, plant-based meat substitutes may appear to be the most natural and hence healthiest of the alternative protein sources covered in this report. However, the striving to transform plant products into meat-like substitutes may require extensive processing and the use of additives, which may be cause for concern.

4.4.1 Food safety

Allergens: Most plant-based substitutes contain at least one major food allergen, such as soy or wheat/gluten as their primary ingredients. Additionally, mycoprotein, or fermented mycoprotein is sometimes used in plant-based substitutes to give meat-like texture or flavours and may also cause intolerance in some people. There may also be intolerance to certain gums and food additives, such as carrageenan from seaweed, that are widely used in these products (Santo et al., 2020).

Additives: Much of the innovation to create realistic meat analogues uses novel additives, such as soy leghemoglobin (heme protein) used in Impossible Foods burger patties, for which there is currently little food safety data and the long-term effects of regular consumption are unknown (for example, implications for type two diabetes).

Highly processed ingredient streams: Another general safety aspect of plant-based meat alternatives is their often highly processed nature due to the combination of different processed ingredient input streams. This introduces the risk of contamination and the creation of metabolites that could be of health concern.

Mislabelling, traceability, and authenticity: For all processed foods there is the potential for food fraud risks, particularly mislabelling. Plant-based meat substitutes should not necessarily present greater risk than any other processed food types, but as they are often marketed as healthier alternatives, there may be a need for closer scrutiny of labelling and presentation of ingredient lists and health claims. Traceability of ingredients, particularly protein isolates and other functional ingredients extracted from novel sources such as food waste-steams may need consideration.

4.4.2 Nutrition and health

Nutritional content: Harnack et al. (2021) conducted a study of 37 of the major brands of plant-based ground-beef alternatives in the US, and concluded they have nutritional strengths as well as some shortcomings compared to ground-beef. They are generally a good source of nutrients like folate, fibre, and iron, and are lower in fats and saturated fats, but are also often substantially lower in protein content, zinc and B12, while notably higher in sodium. Alessandrini et al. (2021) undertook a cross-sectional survey of plant-based meat products available in the UK and concluded that nearly 75% of them did not meet UK sodium targets. These products can also be lower energy density and low in calcium, potassium, and magnesium

(Tso & Forde, 2021). Fortification with additional nutrients such as B12 is possible, but few products are to date, and therefore the nutrition spectrum of these products can often be more akin to traditional fast food-style meals, rather than a whole-food based vegetarian diet they are often associated with in advertisements, and may in some cases be less healthy than their animal-meat counterparts (Tso & Forde, 2021).

By presenting these plant-based alternatives as healthy options, the industry may in fact be encouraging consumers to make poor nutritional choices leading to over-consumption of certain nutrients, while not providing the same nutritional density they are used to and making them believe they are eating healthily.

Processing transfiguration: Processing can damage the biological value and nutritional value of the proteins. A key aspect of the processing required to make plant-based meat substitutes is the extraction, disassembly, and reassembly of specific structural elements of the ingredients to achieve the desired physicochemical properties to resemble/mimic animal products. These multi-stage processes typically require aggressive treatments for isolation, purification, and texturization of ingredients, using chemicals, centrifuges, high pressure, and mechanical processing such as extrusion and shearing for forming, all of which can impact nutritional value (McClements & Grossmann, 2021).

4.5 Plant-based proteins: sustainability

Input sources: Many of the alternative protein sources covered in this report rely on traditional plant crops as input streams, contributing to some environmental degradation, but as discussed in Section 2.1, this can be much less than that required for most conventional animal meat farming due to the high conversion ratios of crop calories to meat calories (Santo et al., 2020). A shift to plant-based proteins therefore brings potential environmental benefits in terms of land use, freshwater use, reduced eutrophication, and reduced GHG emissions compared with traditional agricultural animal husbandry.

There are also some considerable benefits associated with high protein crops such as soy, pea, and legumes that are often used as primary sources of protein in plant-based meat alternatives, in that they help to fix nitrogen and can reduce dependency on fertilizers, which in turn supports soil diversity and above-ground invertebrate biodiversity (Santo et al., 2020). Crop rotation using alternative crops such as lupins could further support soil health and agrobiodiversity. Conversely, many plant-based meat substitutes use coconut or palm oil, the latter of which has been implicated in deforestation in tropical regions such as Indonesia and Malaysia, which may be comparable to deforestation for animal farming in the Amazon.

Processing intensity: A cradle-to-distribution LCA of Beyond Meat's Beyond Burger found that it generates 10% of the greenhouse gas emissions, requires 54% of the non-renewable energy, 7% of the land use, and less than 1% of the water use, compared to a typical U.S. beef burger, as shown in Figure 15 (Heller & Keoleian, 2018). Nevertheless, while these products clearly seem to be better for the environment than beef, energy use can be high and the environmental gains uncertain due to the processing associated with highly purified ingredients such as protein concentrates (mixture of protein with little residual water) and protein isolates (single pure protein), and post-processing to deliver meat-like textures (Alexander et al., 2017; van der Weele et al., 2019). As illustrated in Figure 16, the incremental impact on GHG emissions from post-processing varies by crop type but can be significant. Santo et al (2020) found that due to processing, the production of plant-based meat substitutes generates on average 1.6 times more GHG than tofu, 4.6 times more than pulses, and 7 times more than peas, illustrating the benefits of a traditional plant-based whole-food diet over these sophisticated alternatives.

Figure 15 Relative comparison of environmental impacts between beef and Beyond Burger's plant-based alternative

Source: Heller & Keoleian (2018)

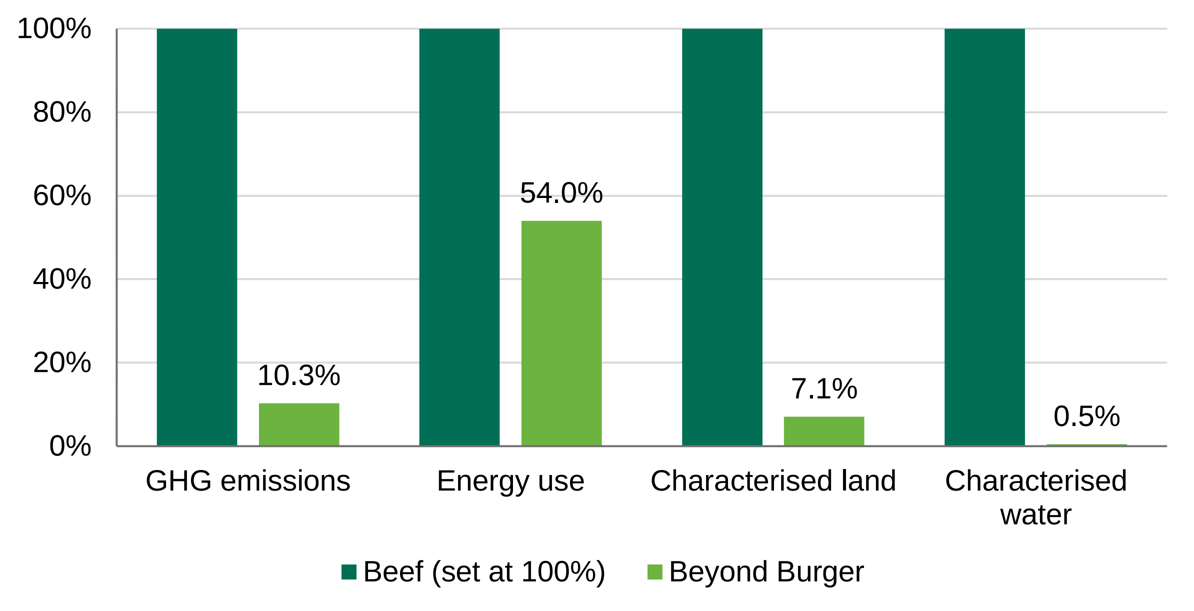
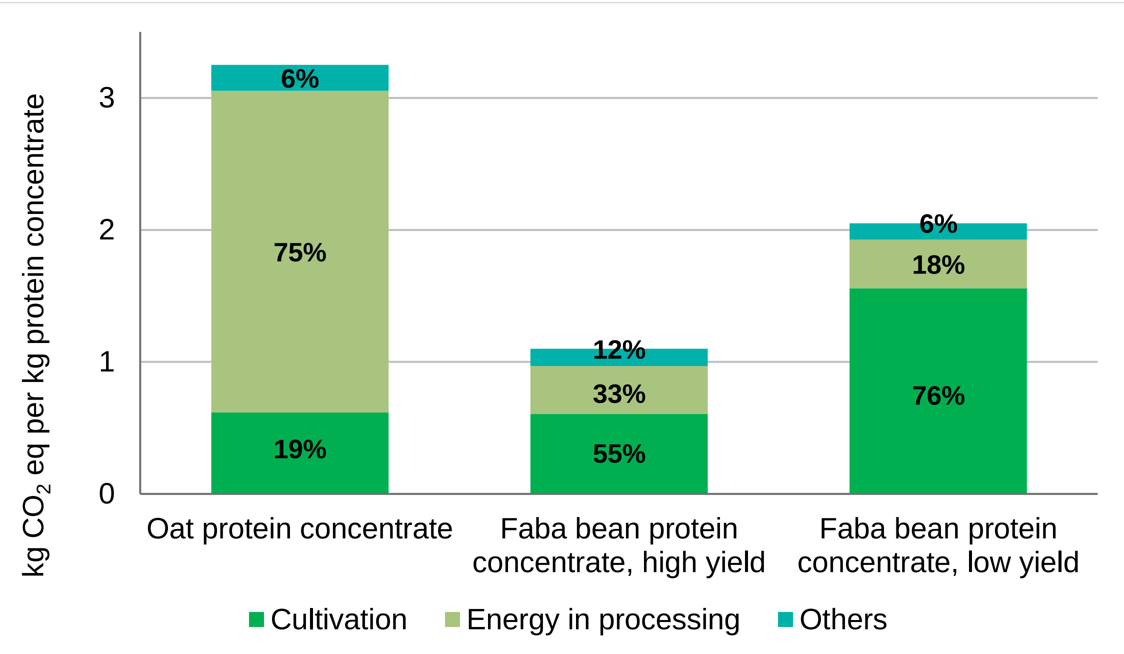


Figure 16 Carbon-footprint of cradle-to-processing of protein concentrates

Source: Heusala et al. (2020)



Use of industrial food processing waste as input source: An emerging topic of interest in this field is the use of non-conventional sources of plant-proteins, such as extraction of food-grade proteins from rape seed oil production waste (e.g., Kozlowska, 2022), which delivers proteins of high nutritional value and technological characteristics (e.g., readily soluble, creates foams and emulsifies). There may be other opportunities for extraction of proteins from waste/by-product streams of the agriculture and food processing sectors presenting opportunities to enhance environmental performance and reduce waste in the food system (Short et al., 2021).

Supply-chain requirements: Most of the plant-based meat substitutes to date, like their meat counterparts, require polymer-based packaging and refrigeration or freezing to maintain freshness (e.g., refrigerated and consumed within 14 days of manufacture, and within 3 days of opening), raising potentially significant energy demands, single-use plastics waste, cold-chain requirements, and potential for spoilage and food waste. Heller & Keoleian (2018) in their LCA study of Beyond Burger's plant-based burger, observed that packaging represents a hotspot in the lifecycle, representing 11% of GHG emissions, 21% of energy use, and 14% of water. Cold storage, excluding household refrigeration, is estimated at 2% of GHG emissions.

While packaging and cold storage requirements are also similarly an issue for animal meat products, the potential to manufacture these products in close proximity to consumer markets such as on the periphery of urban centres, rather than the often-significant distances that meat is transported could present some environmental benefits.

4.6 Plant-based proteins: regulation

Alternative proteins from traditional culinary sources such as soybean and peas do not require additional regulatory approval for marketing and sales (Witte et al., 2021). Similarly, there is a consensus that if an additive compound/molecule is already included in the list of authorised compounds, it can be used in plant-based meat substitutes. However, where new production processes are involved in the extraction and use of food molecules, or where novel additives are introduced, or specific protein isolates are used in an unusually high concentration there may be a requirement for new evaluation to ensure their food safety (Faustino et al., 2019).

When considering regulation of plant-based proteins the following factors related to processing intensity need to be taken into consideration: energy use (as true carbon footprint may be much higher than claimed, at least while the energy system is not fully based on renewables); nutritional value of end products particularly when it comes to labelling for consumer information; use of additives and ingredients with unclear longitudinal understanding of allergenic and health profiles.

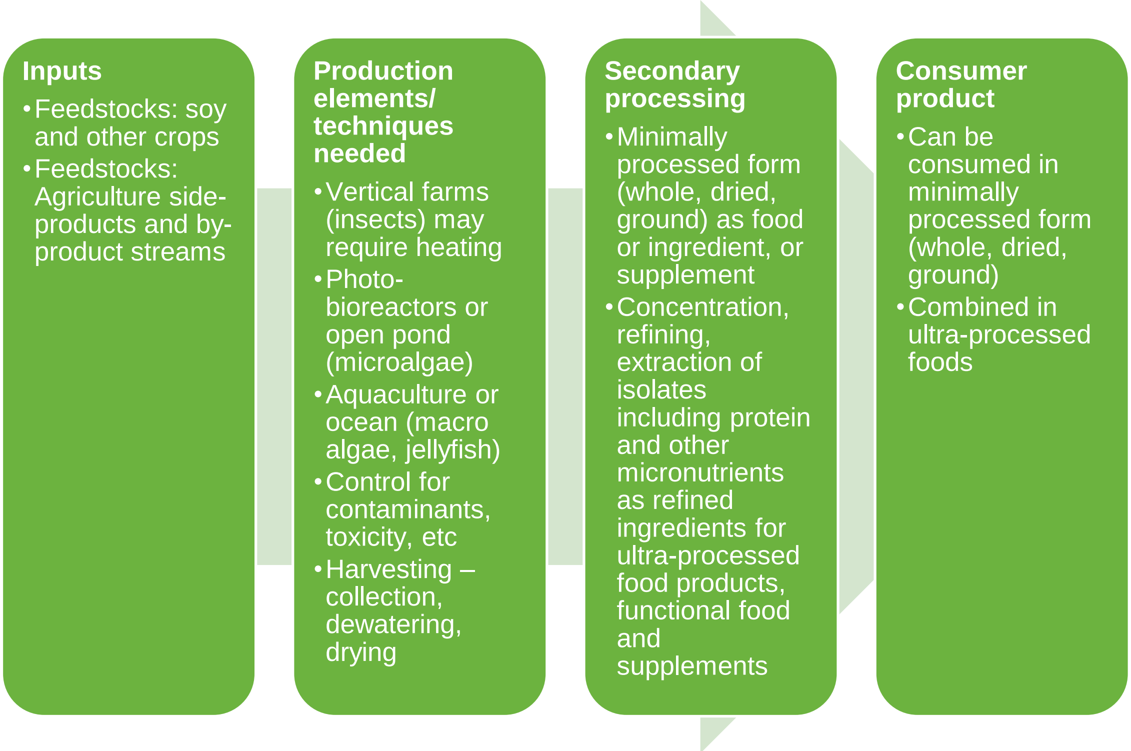
5. Novel sources of protein

In this chapter we discuss novel sources of protein, including edible insects, microalgae and cyanobacteria, macroalgae (kelps and seaweeds), edible jellyfish, and fungi. Firstly, section 5.1 gives an overview of the main organisms within this category; section 5.2 discusses the technical and commercial challenges; section 5.3, consumer acceptance; section 5.4, health and food safety; section 5.5, sustainability implications; and finally section 5.6, emerging regulatory issues.

5.1 Introduction to novel sources of protein

These sources offer high-protein content alternatives to traditional animal proteins. For much of the developed world some of these sources of proteins are considered novel food types, but they are not new to humanity, and have long been part of the diet in many cultures. However, the production of source organisms at industrial scale often involves novel production technologies and exposure of these organisms to manmade environments and novel feed sources.

Figure 17 Novel sources of proteins production process and outputs



5.1.1 Edible insects

Entomophagy is the practice of eating insects by humans and is common practice in many tropical regions, with over 2,000 species of insects being consumed by humans (Van Huis, 2016). For commercial production in Western markets, crickets, black soldier fly, grasshoppers, and mealworms are currently the main insects of interest, and all have high nutritional value, are high in fats and proteins, and are also a good source of vitamins and amino acids. Scientific literature on their exact nutritional content is a growing field in nutritional sciences (e.g. (Soares De Castro et al., 2018). The primary market for insects and the other novel proteins discussed below will probably be as ingredients in the food value chain, with market categories for insects including processed whole insects, animal and pet feed products, processed insect powder, insect protein bars and protein shakes, insect baked products and snacks, insect confectionaries, and insect beverages (Allied Market Research, 2019; Bug Burger, 2021).

A by-product of insect processing is chitin, and chitin-containing leftover substrates can be used as fertiliser to promote plant health (van Huis, 2020). Moreover, insects have the largest anti-microbial peptide reservoir of all animals, so other beneficial secondary by-products may emerge (Moruzzo et al., 2021).

5.1.2 Microalgae and cyanobacteria

Microalgae have been explored as a possible food source since the 1950s, as they are high in essential amino acids, fatty acids, B vitamins, and other nutrients, are well suited for incorporation into other food products (Caporgno & Mathys, 2018; Mok et al., 2020; Wang et al., 2021), and can produce proteins more efficiently than terrestrial plants. Cyanobacteria protein content can be as high as 46–63% (dry matter), with good digestibility making it a good substitute for soy or animal meat, but many algae require processing to make them digestible by humans (Pereira, 2021). They can be cultivated in marine and freshwater as well as waste water, in open pond systems or photobioreactors, using phototrophic production where the primary inputs are sunlight (or LED lighting) for photosynthesis, CO_2, and nutrients (Ullmann & Grimm, 2021). Algae can also be cultivated through heterotrophic production in fermenters using a carbon rich feedstock, which is discussed in the next chapter. Currently microalgae are sold, primarily in Asia, in the form of dried algae, as sources of proteins and carbohydrates as ingredients for manufacturers and as food supplements.

5.1.3 Macroalgae

Macroalgae such as seaweeds and kelps are also a good source of protein (up to 50% protein by dry weight) and other important nutritional and functional food supplements (binding agents and gels) for human consumption, and can also contribute to the food system and natural ecosystem health as chemical-free fertilizers and pesticides (Bourgougnon et al., 2021). Macroalgae have the benefit of being easy to cultivate as they can be grown in freshwater and saltwater environments (Doubleday & Connell, 2018). This is a well-established industry in Asia, with annual production of 32 million tonnes of aquatic algae (almost all from aquaculture, and mostly seaweed) in 2018 (FAO, 2020b).

5.1.4 Edible jellyfish

Jellyfish have potential as food, feed, and as a source of bioactive compounds for pharmaceutical and other biotechnological applications. They are primarily harvested in wild fisheries at present, although large-scale aquaculture operations started in the 1980’s and are expanding (Duarte et al., 2022). Jellyfish are typically processed through a multi-phase drying process, using mixtures of salt and alum (Bleve et al., 2019), into a semi-dried and/or salt preserved product to be used as ingredients or as snacks. Protein content by dried weight can be as high as 50% for some species, with minimal fat content (Khong et al., 2016). Global production was estimated at around 10,000–17,000 tonnes/year between 2011 and 2015. Currently, they are mainly marketed and consumed in China, Japan and South Korea, but, like insects and algae, are considered a novel food in Europe with no established regulatory framework for handling and processing, nor industrial infrastructure, and as of yet there has been little research into potential jellyfish aquaculture or consideration of sustainable fishery practices in Western locations (Duarte et al., 2022; Edelist et al., 2021).

5.1.5 Fungi

Fungi are another alternative protein source that is gaining increasing attention as a low-calorie source of protein, with a texture suitable for meat and seafood substitutes. Fungi tend to require less land, energy and water to produce than most plants (Anatürk, 2021). Fungi are not novel in Western markets, but they will increasingly be used not only as a source of protein biomass, but also through genetic modification technologies such as gene editing, as cellular production organisms for specific non-fungal proteins, such as bovine albumin or casein (Edelist et al., 2021; Wikandari et al., 2022).

5.2 Novel proteins: technical and commercial viability

Technological innovation in these emerging novel protein sources goes well beyond traditional harvesting and preparation of these products, aiming to introduce industrial-scale farming and complex processing to extract proteins and other nutrients as valuable inputs into other parts of the food sector. There is significant opportunity for these emerging protein sources to be combined with plant-based proteins to create novel hybrid alternative meat-substitutes.

Insects are currently of high interest with many hundreds of start-up companies globally investing in research and productisation of various types of insects, particularly crickets and black solder flies (Bug Burger, 2021). However, in Western markets regulatory barriers, uncertainty over health and safety, and low consumer appetite for insects have so far held back growth of this sector. Currently, the primary market of the industry is aquaculture and fish feedstocks and some pet foods, while products for human consumption are limited to artisan offerings of curiosity products. Nonetheless, market leaders in insect feed for animals such as Ynsect in France are well positioned to advance the food sector.

Although the alternative protein industry in this category, particularly insects, represent an opportunity to disrupt the existing food system (Payne et al., 2016), current solutions are still small scale. Challenges facing the industry include:

- Technological improvements are required to industrialise production at scale and reduce operating costs. A typical insect vertical factory might produce 10 tonnes per day, but to contribute meaningfully to the global food/feed system requires factories producing thousands of tonnes per day, and it is currently still a labour-intensive industry. Similar challenges are seen in algae production, also often undertaken in vertical factories using photobioreactors and LED lighting, and for macroalgae where there are challenges in harvesting at scale in marine environments.
- There are specific challenges in processing insects due to chitin-protein interactions, and the need to separate potential allergens. For algae such as seaweed, the complex polysaccharide matrix of the cell walls is a barrier to protein extraction, and improvements in extractability and digestibility are required (Samarathunga et al., 2022). For microalgae, contamination is a particular concern requiring tight process controls, and harvesting/dewatering is particularly energy intensive (Kratzer & Murkovic, 2021).
- Insect and algae operations can be fed on waste biomass and wastewater, but nonetheless are highly dependent on economically viable feedstuffs (DiGiacomo & Leury, 2019). Capturing regionally-scalable and economically viable organic waste streams of a reasonable quality will be essential for the

expansion of the sector (Lundy & Parrella, 2015). The sector may have to compete for these resources to some extent with existing animal farming.

- Edible insects and algae are more likely to be accepted by consumers if processed into non-recognisable forms (Liceaga, 2021), and therefore, as with plant-based proteins, extraction, and separation and drying steps need to evolve to create flours, isolate desired proteins, oil and lipids, and other molecules, and deliver performance at scale without compromising techno-functional, nutritional and sensory properties.
- Further development is needed on food formulation prototypes using these novel sources of protein as ingredients to engage consumers.

The greatest challenges facing the sector though are likely to be consumer acceptance and perhaps regulatory hurdles as discussed below.

5.3 Novel proteins: consumer acceptance

Consumer acceptance of novel alternative sources of proteins such as insects as a human food stuff is rising (van Huis, 2020), but there are still significant barriers to wide-spread adoption and scale-up of the technologies. In Western markets insects are often perceived as disgusting and unsafe due to concerns over disease and allergens, and algal proteins raise concerns over exposure to marine heavy metals and contaminants (Circus & Robison, 2019; Tso et al., 2021). Van Huis (2020) suggests that insects need to be processed into ingredients (e.g., baked and ground into a protein 'flour') that can be applied for safe and appetising products; and use in processed products seems far more likely than consumption of whole insects. Innovative means of using insects as food might include 3D food printing (Motoki et al., 2022; Payne et al., 2016). However, Hartmann & Siegrist (2017) in a systematic review of the literature on consumer attitudes to insects find that the question remains whether insect proteins actually have the potential to gain a permanent position in the western diet, and whether they would actually be consumed as a substitute to traditional animal proteins. On the other hand, interest in industrially farmed insects is rising rapidly in some parts of the world such as Africa (Filou, 2022), driven in part by positive support by the World Bank (e.g., Verner et al., 2021).

For macroalgae, there is already a market as condiments or supplemental products, so adoption is perhaps more feasible in the West, and when used in such applications the quantities are unlikely to raise concerns over adverse effects. However, as little is known about the implications of consuming algal proteins in greater quantities consumer resistance may be anticipated.

Among the novel proteins identified here, fungi are perhaps the most acceptable to western consumers as they have long been part of the culinary tradition and therefore introducing new varieties and species is likely to face less resistance. Mycoproteins, proteins from fungi, are also quite well established under the brand Quorn, so innovation in this area is also likely to be broadly acceptable (Grasso et al., 2019).

Marketing and branding to present these novel proteins in an attractive manner to address consumers’ perceptions will be essential for success (Mancini et al., 2022). Regulation may help by addressing some of the above-mentioned concerns regarding cleanliness and process and production conditions.

5.4 Novel proteins: food safety, nutrition, and public health

Most of these novel proteins from source organisms are part of traditional diets elsewhere in the world. Moreover, seaweed has been available in the UK for some time as a whole food, functional food, or supplement. Therefore, the health and food safety risks are likely to be relatively low and well understood. However, the emerging nature of this sector means there is limited experience and insight into the nutritional and health effects and the long-term implications of intensive human consumption of these novel proteins when produced in novel industrial production processes with novel feedstocks. Further research is also required on the treatment and processing methods and on microbial and hygienic safety and toxicology (Hartmann & Siegrist, 2017).

5.4.1 Food safety

Allergenicity: This is a concern with these novel proteins as UK consumers have no history of long-term exposure at the population level to allow an assessment of how prevalent allergic responses to these kinds of proteins could be. Allergen response can be dependent on dietary habits, food preparation, and age of first exposure, as well as ethnic background, meaning that consumption in western markets may create new allergen issues once wider uptake is seen (Verhoeckx et al., 2016). For example, chitin contamination in insect protein products has implications for allergen testing and there is potential for cross-reactivity with allergens in house dust mites or crustaceans; although currently rare, this might be more common once more chitin is consumed on a regular basis (Burton & Zaccone, 2007; FAO, 2021). Fungal mycoprotein products, such as Quorn, can also cause gastrointestinal reactions and sometimes life-threatening allergies (Hashempour-Baltork et al., 2020).

Toxicology: The effects of using organic waste-derived substrates as feedstocks for insects, microalgae and fungi cultivation require further investigation to understand the implications on nutrition, taste, and toxicology (e.g., FAO, 2021). In the case of marine algae there are potential health concerns over high iodine levels, or accumulation of arsenic, marine heavy metals and contaminants, which although not a great problem when algae are consumed at low levels as condiments, could present a health risk if eaten in greater quantities (Bouga & Combet, 2015; Tso et al., 2021). The type of seaweed, season, harvest and cultivation environment, water quality, geography, and postprocessing are all factors in ensuring safety (Samarathunga et al., 2022). Certain types of organisms can also create high levels of mycotoxins during protein production, and this needs to be carefully monitored during production (Hashempour-Baltork et al., 2020). Lastly, insects may have the potential to transmit pathogens to humans. In their study of central European production, Gałęcki & Sokół (2019) detected parasites in 81% of examined farms, and parasites potentially pathogenic for humans in 30% of the farms.

Mislabelling, traceability, and authenticity: Currently production of these sources of protein is almost entirely outside of the UK, and they will enter the UK food system primarily as ingredients for inclusion in processed foods, or as food supplements. This creates potential issues around traceability, and, as with any processed food category, there is potential for food fraud and potential mislabelling. This may be particularly so for sources of protein such as insects where there is expected to be considerable consumer aversion and hence perhaps an incentive to misrepresent the ingredients.

5.4.2 Nutrition and health

Nutritional content: Insects, algae, and fungi are all high in protein (see Table 5), low in fat, and excellent sources of micronutrients including amino acids, antioxidants, omega-3 fatty acids, vitamins, and minerals including iron and zinc that can be difficult to obtain directly from a plant-based diet, a source of anti-inflammatories and anti-microbial agents in some types, and a source of fibre to assist in digestion (Van Huis, 2013; Wang et al., 2021). The bioavailability, amino acid profile and digestibility of these novel sources of protein can reach levels as high as those of animal sources.

Health impact: Some novel proteins, such as seaweed and fungi are associated with significant positive health benefits e.g. seaweed consumption can linked to reduced incidences of cancers, hyperlipidaemia, coronary heart disease (CHD), metabolic syndrome, increased digestive tract and bone health as well as antiviral properties (Bouga & Combet, 2015; Moussavou et al., 2014). Fungi (mycoproteins) have been demonstrated to be capable of reducing cholesterol, and contributing to satiety and appetite regulation (Hashempour-Baltork et al., 2020; Souza Filho et al., 2019).

One specific nutritional concern with jellyfish is the high sodium content that results from the drying processes. Conversely, seaweed can be a good substitute for salt contributing to a healthy diet and can be a valuable functional food to reduce iodine deficiency in the UK population, although excess levels of iodine can cause toxicology and adverse effects (Bouga & Combet, 2015; Tso et al., 2021).

Table 5 Examples of alternative protein sources and their protein content

Source: based on Fasolin et al. (2019)

Source	Name	Protein content (%, *w*/w)
Vegetable	Amaranth (Amaranthus spp.)	12.5–17.6
Vegetable	Lupin (Lupinus spp.)	38–55
Vegetable	Navy bean (Phaseolus vulgaris)	26.0
Vegetable	Quinoa (Chenopodium quinoa Willd)	12–23
Algae	Aphanothece microscopica	42
Algae	Arthrospira platensis (Spirulina platensis)	53.5
Algae	Chlorella vulgaris	12.7–53.0
Algae	Dunaliella salina	51.2–82.2
Algae	Haematococcus pluvialis	30–51.7
Algae	Tetraselmis sp	36
Fungi	Aspergillus niger	10.3–61.2
Fungi	Fusarium venenatum	41.8–46.4
Fungi	Saccharomyces cerevisiae	15.3–49.3
Fungi	Torula utilis (Candida utilis)	28.4–48.9
Fungi	Yarrowia lipolytica	45–55
Fungi	Methylococcus capsulatus	53
Bacteria	Rhodopseudomonas sp.	54–92
Bacteria	Rhodopseudomonas faecalis	50–51.5
Insect	Cricket (Gryllodes sigillatus)	56.8*
Insect	Grasshopper (Schistocerca gregaria)	76.0
Insect	Honeybee brood (Apis mellifera)	22.1
Insect	Mealworm (Tenebrio molitor)	51.0*
Fish	Catfish	22.5
Fish	Lobster	18
Fish	Shrimp	20
Meat	Chicken breast	31
Meat	Pork loin	25
Meat	Beef	22.5

* Protein conversion factor of 6.25

5.5 Novel proteins: sustainability

The above-mentioned novel sources of protein have a high feed to edible protein conversion ratio, short life cycles and high reproduction rates compared to conventional animal farming, particularly livestock, and so offer several sustainability benefits.

Feed conversion ratio: Feed conversion efficiency varies depending on feed stock and cultivation conditions. For insects it is on average about 2.1 kg of feed per kg edible weight, compared to 4.5 for poultry, 9.1 for pork, and 25 for beef (Van Huis, 2013). Most research indicates these efficiencies translate into a reduction of GHG emissions, agricultural land, and water use in the production of animal feed. Microalgae offer many of the nutritional benefits of insects, and cultivated using efficient photosynthesis and CO_2 as a primary feedstock have the lowest arable footprint of any crops (Pereira, 2021; Wang et al., 2021).

Land use and other factors: Insects, algae and fungi can be grown in vertical factories (e.g., bioreactors for microalgae) and can be placed on brown-field sites or in urban areas so requiring far less agricultural land than livestock, and potentially be positioned close to food processing centres and consumer markets reducing transportation requirements. They also require substantially less water, their GHG and ammonia emissions are lower than livestock, and potential eutrophication from waste is negligible, making them a significantly more sustainable option than animal farming on key metrics.

Energy use: Industrialized production of these organisms can require large energy inputs for heating, automation of feeding and harvesting, artificial lighting in the case of microalgae bioreactors, and harvesting in marine environments. Moreover, although traditionally these novel proteins have often been consumed with relatively little processing, there may be a requirement for more extensive processing to avoid nutritional risks related to food toxicology and allergens or for incorporation into sophisticated processed food products.

Use of waste as feed sources: One of the main potential benefits from an environmental sustainability perspective is that these novel sources can be fed on a wide range of foods including organic waste and wastewater, and so offer a way of transforming low-value food waste and by-product biomasses/streams from the food and agriculture sector (even low-grade wastes such as animal manure could be used for algae cultivation), into valuable feed materials and high-value ingredients for human consumption (Fasolin et al., 2019; Salter & Lopez-Viso, 2021).

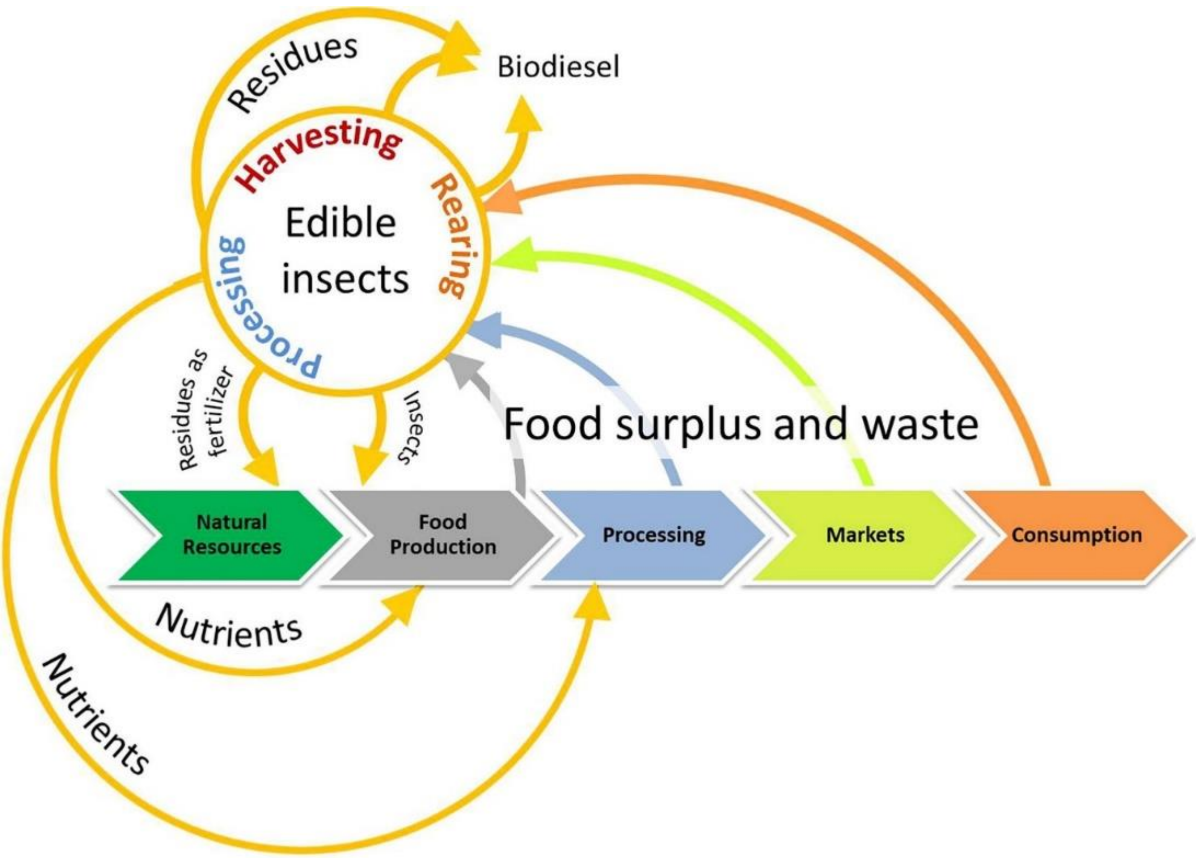
In doing so these production systems could make a valuable contribution to circular economy objectives and tackle the significant problem of global food waste (Mancini et al., 2022; Moruzzo et al., 2021). See Figure 18 for an illustration of the application of circular economy in insect production (Ojha et al., 2020), and similar systems can be applied to microalgae, macroalgae, and fungi (Moruzzo et al., 2021).

Organic waste streams are already used in production systems, but restrictions due to concerns over human health currently constrain broader application and hence limit the economic viability of their use in novel protein farming. Moreover, the quality of the organic waste greatly influences feed conversion ratios and the health of the organisms – for example, Lundy & Parrella (2015) found that insects fed on minimally processed municipal waste experienced >99% mortality before reaching harvestable size. Successful expansion of the sector and realisation of the full sustainability benefits will require significant innovation and regulatory change, supported by research on the safety of some of the non-intentional components that may be present in a fully circular food-system and their accumulation to gain a better understanding of use of suitable waste streams.

Environmental regeneration benefits: Microalgae and macroalgae can also offer broader environmental sustainability benefits by contributing to bioremediation and cleaning wastewater streams. Seaweeds, for example, can be used as biofilters to assist in tackling coastal eutrophication, reducing nutrient load, and improving water quality and oxygen levels. Additional benefits of seaweeds are the creation of new habitats and food sources for marine life, dampening wave energy and providing protection against coastal erosion, and mitigation of ocean acidification through carbon sequestration (Bourgougnon et al., 2021). Through these benefits seaweed can also symbiotically contribute to improved efficiency and productivity in the aquaculture sector supporting fishing economies and the food system.

Figure 18 Circular economy-based insect production and processing system

Source: Ojha et al. (2020)



5.6 Novel proteins: regulation

EU and UK legislation already authorises the use of proteins from seven insect species – Black Soldier Fly, Common Housefly, Yellow Mealworm, Lesser Mealworm, House Cricket, Banded Cricket, and Field Cricket – and the allowed substrates to rear insects for feed for aquaculture animals (Adopted by the European Commission on 24 May 2017). As of May 2021, EU regulators have approved mealworms for human consumption.

For human consumption, insects and algae fall within the Novel Foods legislation in the UK so regulatory approval is required for their use. As algae and insects have long been eaten in certain parts of the world the regulatory process is expected to face only moderate challenges (van der Weele et al., 2019). Regulation is anticipated to play an important role in addressing public concerns over health and safety and increasing consumer acceptance. The speed of implementing new legislation is expected to have a significant influence on the development of the sector (Payne et al., 2016).

Legislation will be required for the raw material inputs and feedstocks for insects, algae, and fungi for human consumption and particularly the use of organic waste to ensure safe operation of these facilities to meet food safety standards. There is currently a lack of evidence to support the safe use of organic waste, and EU regulations currently prohibit the use of animal manure, catering waste and former foodstuff (meat and fish) as substrate for insect growth for both animal feed and human consumption (Mancini et al., 2022; van Huis, 2020). Addressing this issue will be key to achieving cost effectiveness and realising the sustainability potential of the sector, and regulators (probably DEFRA) will need to balance the calls for tightly controlled use of organic waste streams and production systems with the commercial needs of the industry to support growth of the sector.

Regulation will also need to be developed for the operation of production facilities to ensure contamination, disease, toxins and pathogens are controlled, and possibly there will be concerns over sentience of insects and animal welfare that need to be addressed (De Goede et al., 2013; Lambert et al., 2021).

For jellyfish and macroalgae new legislation may be required to support development of the sector and control operations in marine environments, and specifically to control for potential pollution and contamination in marine waters.

FSA will also need to look at the inclusion of these alternative proteins as functional ingredients in processed foods as well as related labelling issues, and, as with plant-based proteins, possible regulation around health and sustainability claims.

6. Proteins biosynthesised using fermentation

Plants and animals provide a plethora of high value compounds for food and medicinal applications, but their production demands arable land and water, and is subject to seasonality and climate variability, and often long generation periods. Synthetic biology, alternatively referred to as cellular agriculture, offers an efficient alternative to generating these compounds, through use of single-cell organisms, cell culture technologies, and bioreactors for the industrial production of food ingredients in place of traditional agriculture and animal husbandry (Ercili-Cura & Barth, 2021).

In this chapter we look at biosynthesised proteins produced by using genetically modified microorganisms. Section 6.1 gives an overview of this emerging source of protein, and discusses two types: precision fermentation and biomass fermentation; section 6.2 discusses the technical and commercial challenges; section 6.3, consumer acceptance; section 6.4, health and food safety; section 6.5, sustainability implications; and finally section 6.6, emerging regulatory issues.

6.1 Introduction to cell-based biosynthesis of proteins

Cellular agriculture relies on one of three mechanisms:

1. The capability of single-cell organisms to convert organic or inorganic carbon atoms into biomass, proteins, carbohydrates (sugars), lipids (fats) and other nutrients.
2. Fermentation of biologically engineered (using GM and genome editing (GE) technologies) microorganisms to produce high-value macromolecules extracted via biochemical methods from the fermentation culture.
3. Lab based, or In-vitro production of multi-cellular aggregates of plant or animal origin.

The latter of these, production of multi-cellular aggregates, is covered separately in the next chapter on cultured meat.

The first of these mechanisms enables the creation of food molecules industrially from air and sunlight, and input nutrients. Renewable solar power can be used to split water to generate hydrogen, which when combined via chemical reactions with carbon dioxide from the air together with nutrients and vitamins as a feedstock for hydrogenotrophic bacteria, produce biomass by proliferation (e.g., Solar Foods (www.solarfoods.fi, Finland), Deep Branch (www.deepbranch.com, UK), and Air Protein (www.airprotein.com, US)). These can then be blended with other nutrients to create more complex food ingredients.

In the second mechanism, which is the primary focus of the industry at present, fermentation processes using a microorganism, often a type of yeast, or certain bacteria, fungi, or single-cell algae, are fed with plant-derived feedstocks to generate the desired metabolites. GM and GE technologies are used to insert the gene for the desired protein/molecule into bacteria or yeast, which then produce the protein. For example, yeasts have successfully been modified to create plant metabolites such as cannabinoids, opioids, and cocoa butter compounds (Goold et al., 2018), as well as animal proteins, such as egg and milk proteins. Microorganisms can also play an important role in improving the taste and texture to better emulate animal-based alternatives (e.g., Impossible Foods' soy leghemoglobin heme protein to mimic meat taste and "bleeding" effect).

Beyond traditional fermentation processes, two areas of innovation are emerging: biomass fermentation and precision fermentation.

6.1.1 Biomass fermentation

Microorganisms, usually filamentous fungi, are grown in a solid-state culture, and the resulting biomass is harvested in its entirety. These are protein-rich, and their molecular fibrous composition can make them convincing substitutes for animal-based proteins after processing into a texturized food product. This technique has been used for several decades now to produce mycoprotein products such as "Quorn", but emerging technologies may greatly expand the range of products, tastes and textures that can be created, such as start-up Meati’s aim to create credible alternatives to beef steaks.

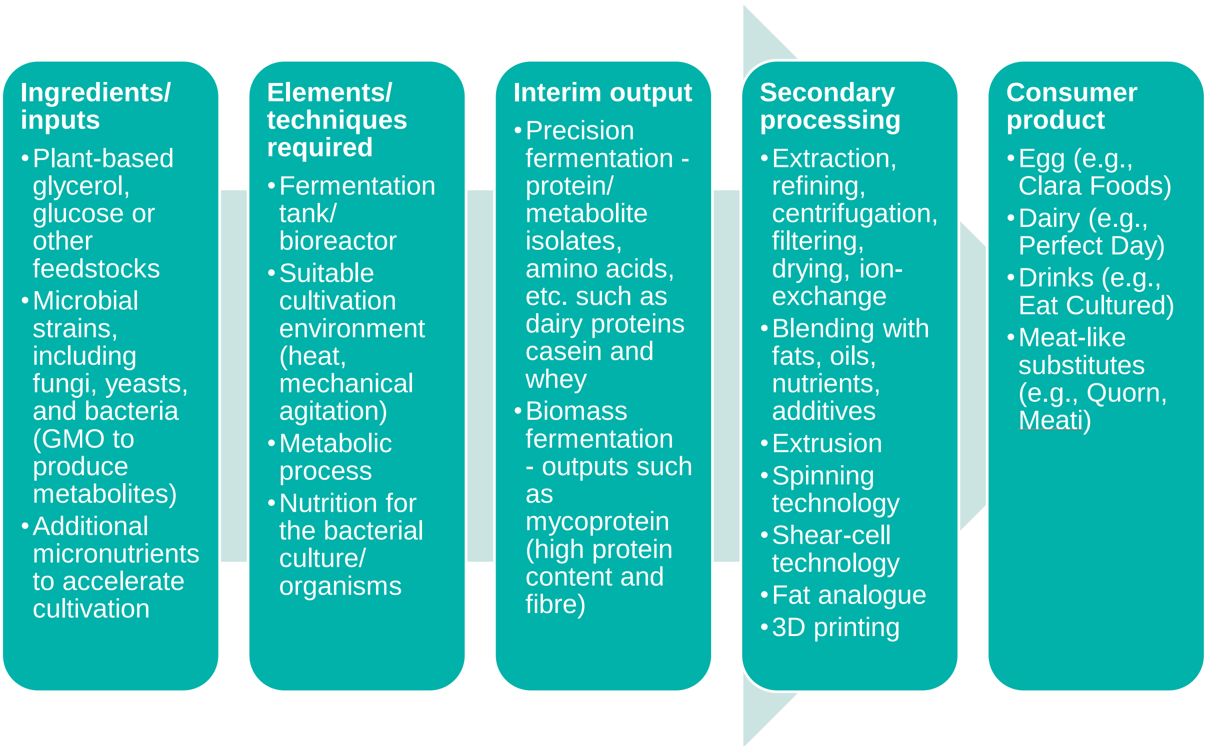
6.1.2 Precision Fermentation

Microorganisms are grown in a liquid suspension culture, and the desired protein/metabolite is subsequently extracted and purified biochemically from the bacterial/yeast culture. Applications in this field have become standard in large production segments such as dairy using lab-produced enzymes for yoghurt/cheese making, and are used for egg and milk proteins, e.g., The Every Company (www.theeverycompany.com, formerly Clara foods) egg white protein, and Perfect Day’s (www.perfectday.com) whey protein. These can then be further processed into food ingredients by adding nutrients, plant-based starches, and fats to create a similar texture to conventional products.

The general fermentation process for both precision and biomass fermentation, with examples of inputs and outputs is shown in Figure 19.

Figure 19 Examples of protein production by fermentation processes and outputs

Source: developed from Leonardo Paradisi (2021)



6.2 Biosynthesised proteins: technical and commercial viability

At present the cost of microorganism-based proteins is still two or three times that of conventional meat protein, and significant innovation is still required to achieve parity on cost, taste, and textures. Innovations are required to:

- Increase the metabolic conversion efficiency of feedstock to desired protein.
- Lower costs of feedstocks. Glycerol and glucose are the primary feedstocks used at present, but they are expensive.
- Optimise the harvesting, extraction, separation, and drying processes for microorganism-based proteins.
- Reduce cost and complexity of additives to deliver acceptable taste and textures for microorganism-based proteins.
- Develop production processes for large-scale, reliable texturizing of protein products.
- Enable transition from the current expensive pharmaceutical-grade processes to less demanding, food-grade standards and volumes to achieve economies of scale.

Some of these challenges can be addressed through genetic modification and selection of the best strains of microorganisms and adjusting the bioreactor conditions to optimise growth through heat, aeration and stirring, and input of additional nutrients to accelerate the process. In addition to faster processing and reduced costs, improved metabolic efficiency can also improve tastes and nutritional value by reducing the creation of unwanted outputs. Experimentation with alternative feedstocks and by-products from other industrial processes are also underway to reduce costs.

Techniques such as centrifugation, filtration and drying are expensive and inefficient, so the industry is experimenting with technologies such as membrane-filtration, but more needs to be done to lower costs. One of the most commonly used processes for protein extraction and concentration is industrial scale ion-exchange chromatography (using ion exchange resins), which involves the use of acids and other harsh chemicals. Such chemical extraction processes (of whatever source) present a challenge for preserving "protein functionality" and "nutritional value". The former means the protein is in its natural state and can still perform its biochemical function, which is only possible by more expensive "gentler" extraction and purification technologies. Nutritional value can be affected by the choice of these technologies, as they damage proteins to different degrees and may modify their bioavailability and digestibility. In the dairy sector microfiltration has become common to produce better quality whey proteins, to address such issues (France et al., 2021).

6.3 Biosynthesised proteins: consumer acceptance

Traditional fermentation, and even biomass and precision fermentation processes are established and accepted practices in the food industry, albeit biomass and precision fermentation are only used for a handful of foods for human consumption at present. Moreover, their plant-based feedstock from soy and other crops may prove acceptable, in particular for vegans, vegetarians, and flexitarians (Teng et al., 2021). Studies to date show a general consumer willingness to try these new sources of protein; Zollman Thomas & Bryant (2021) surveyed individuals across Brazil, Germany, India, the UK and the US, and determined substantial levels of acceptance for dairy products derived from precision fermentation, with 78.8% definitely or likely to try such a product, and 70.5% likely to buy.

Potentially consumers could reject these new proteins on the basis that they are considered “unnatural”, and the use of GMOs designed to secrete specific proteins may raise safety concerns. In addition, there might be unexpected taste and texture experiences of these proteins once they are processed into foods, despite the fact they are chemically identical with the proteins found in natural products. Key to consumer adoption will therefore be education on the benefits of the technology, addressing potentially wrong perceptions over food safety, and developing the taste and textures of the final blended products.

6.4 Biosynthesised proteins: food safety, nutrition, and public health

6.4.1 Food safety

Contamination and toxins: Fermentation processes are a natural way to preserve food and contribute to food safety because the process typically excludes spoilage microbes and creates an inhibitive environment preventing the growth of pathogens (e.g., through release of alcohol, acetic acid, or lactic acid). Nevertheless, contamination and spoilage can occur in unhygienic conditions, and there can be a risk of proliferation of undesirable or even pathogenic microorganisms and toxins (Teng et al., 2021). Safety risks may arise from (Williams, 2021):

- The starting microorganisms (particularly from novel or genetically engineered microorganisms with no long-term human use profile)
- Contamination of the fermentation tanks and the growth medium
- Waste disposal
- Handling and downstream processing after fermentation

Quality assurance processes to continuously monitor, identify and halt proliferation of undesirable microbes are essential, and various technologies are emerging to meet this need, such as metagenomics that enables accurate monitoring of microbial communities (Teng et al., 2021). There is a need for further assessment of the long-term health effects relating to toxicity and allergenicity of consuming microbial proteins. For example, microbial biomass can have high nucleic acid content that needs to be removed prior to human consumption to avoid negative health effects (Pereira, 2021).

Mislabelling, traceability, and authenticity: As biosynthesis technologies evolve and costs reduce the potential for food fraud will increase. Biosynthesised molecules (particularly milk and egg protein) are likely to form ingredients for a wide array of dairy and processed food products, but it may be impossible to differentiate them from their animal-based equivalents. Authenticity of regional cheeses created with biosynthesised protein is just one example of the many issues that may arise.

Allergens: An additional concern relates to the fact that intolerances to conventional dairy may also apply to synthesised dairy proteins.

6.4.2 Nutrition and health

Fermentation using microorganisms has the potential to deliver proteins that are biologically and nutritionally identical to existing animal proteins such as dairy and egg proteins. However, their use generally requires significant post-processing, such as extraction and refining and processing into food products. Furthermore, their nutritional value when digested may differ from that of proteins from traditional sources, which are usually complex mixtures of proteins (e.g., milk or yoghurt). Further research is needed to better understand this emerging technology and the implications for nutrition and long-term impact on human health.

6.5 Biosynthesised proteins: sustainability

Fermentation processes offer a rapid and efficient means of production with feed conversion ratios of possibly 40%-80%. Compared to other alternative proteins, fermentation can be more efficient as it can use a wide variety of nutrients and feedstocks (Teng et al., 2021). The environmental impact of fermentation primarily depends on three aspects:

1. Nutrient sources for feedstock
2. Energy use for fermentation processes
3. Processing into final products

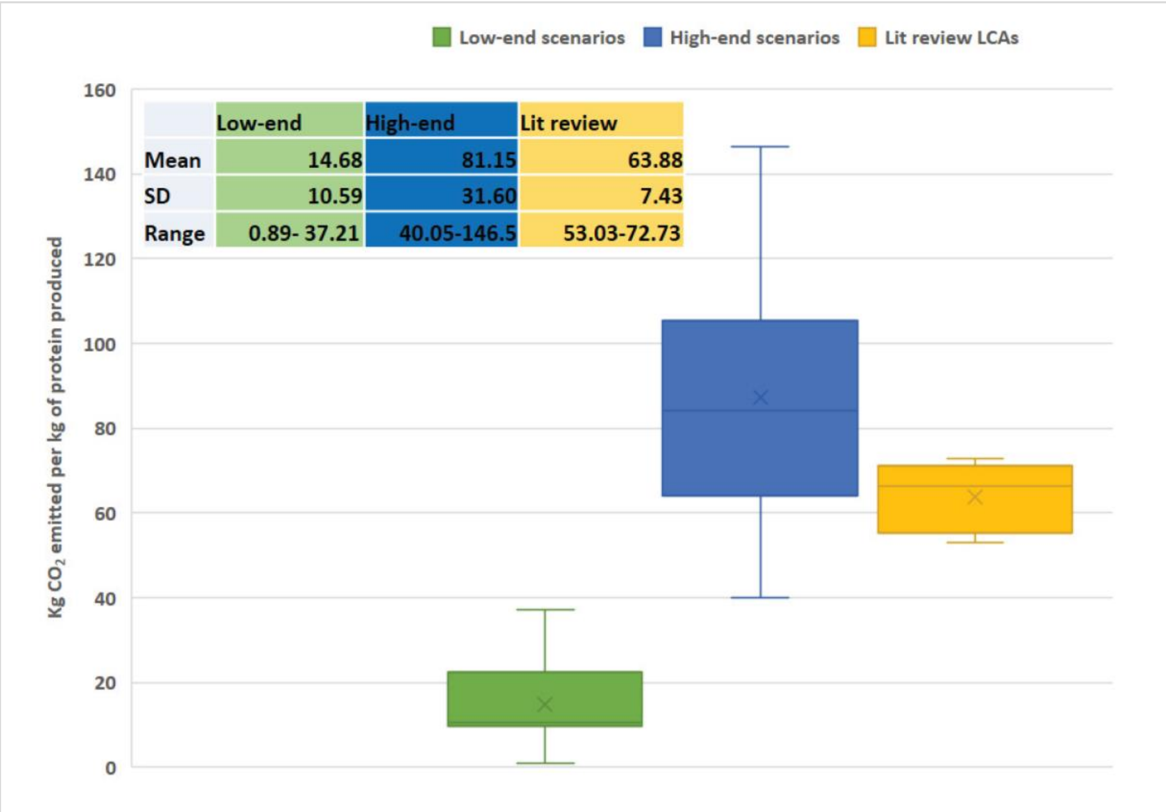
Feedstocks: Usual feedstocks are soy or cereals, but given the ability of many microorganisms to metabolise any substrates, there is the possibility, as with the novel proteins discussed in the previous chapter, of using low-value by-products of the agri-food industry as input streams into fermentation processes (e.g., molasses from sugar production, pulp from starch production, and processing waters from breweries) creating high value proteins for food ingredients (Ercili-Cura & Barth, 2021).

Energy use and GHG emissions: The fermentation process and the post cultivation extraction, and in the case of precision fermentation the purifying and postprocessing to achieve desired taste and textures, are energy intensive and so contribute to GHGs unless using fully renewable energy sources. Precision and biomass fermentation are an emerging field of research and development, with ongoing experimentation with a wide variety of microbes and substrates, and at present there is limited verified data on environmental life-cycle impacts and GHG emissions (Souza Filho et al., 2019). However, Tso & Forde (2021), in their review of the literature, found that the mycoprotein product 'Quorn', produced through biomass fermentation, contributes approximately 3 kg CO_2 equivalent per kg, while other mycoproteins can be up to 6 kg CO_2 equivalent per kg, which is about the same as poultry production. Bhandari et al. (2021), modelling GHG emissions for precision fermentation of milk protein, casein, calculate that fermentation may offer significant benefit over traditional milk protein. However, due to the energy input required for fermentation, if the energy generation system is not low-carbon, the process may generate significantly higher emissions than traditional animal-based milk protein as shown in Figure 20.

Figure 20 GHG emissions for cultured proteins vs traditional milk protein

Source: Bhandari et al. (2021)

Lit review LCAs are for conventional milk protein production



	Low-end	High-end	Lit review
Mean	14.68	81.15	63.88
SD	10.59	31.60	7.43
Range	0.89- 37.21	40.05-146.5	53.03-72.73

Food system security: Looking at the bigger picture, the use of fermentation bioreactors able to use a wide variety of input feedstocks to generate desired output food molecules offers the potential benefit of shielding the food system from some of the vagaries of seasonality, weather, disease, and other economic and political factors and therefore can enhance food system stability and food security (Tubb & Seba, 2019). Production volumes can also be controlled to better meet fluctuations in demand avoiding the levels of waste often seen for example in the dairy sector.

Broader economic and social implications: Williams (2021) suggests that additional environmental and social benefits may arise from the potential for production facilities to be co-located adjacent to by-product feedstock sources, and, or consumer markets. The possibility of micro-bioreactors could result in a more distributed, localised food-production system that is more resilient and less dependent on transportation and expensive cold-chains. Smaller production facilities could contribute to local economic development and encourage the growth of specialist niche providers. However, the industry could equally move toward highly centralised, large-scale production facilities controlled by large multinationals that benefit from economies of scale, with potentially huge disruption for the dairy and egg sectors and exclusion of many rural economies and smaller players from the market.

Tubb & Seba (2019) suggest that the mass market adoption of dairy and egg proteins derived through fermentation will be a first decisive blow to the conventional animal farming sector. These synthesized proteins seem reasonably likely to gain market acceptance, and once established may rapidly undermine the existing dairy and egg industries, and in turn, the viability of much of the cattle and poultry industry. This will push up the costs for animal meat, opening the market up further to meat alternatives including cultured meat. This future scenario is highly uncertain, but if realised would have far reaching implications for the agriculture sector and local economies.

6.6 Biosynthesised proteins: regulation

The as of yet untested effects on human health of these biosynthesised proteins present a significant challenge for regulators around the world (van der Weele et al., 2019). Under the EU/UK Novel Foods regulation they will require safety testing and certification, but there will be considerable pressure from the industry to by-pass potential longitudinal studies on health on the basis that the new proteins are chemically identical to existing dairy or egg protein. The FSA may have to consider new approval processes, perhaps more akin to medicine for these proteins, particularly as the industry evolves and a broader array of molecules enter the market.

There is currently uncertainty over the GMO status for precision fermentation because although the microorganisms themselves may be GMO, designed to generate specific proteins or molecules, the resulting output secreted by the microorganisms may be indistinguishable from proteins of conventional animal sources. If categorised as GMO the sector may face considerable barriers given the uncertainties over the technologies and existing regulatory resistance to GMO in Europe. Biomass fermentation using GMO is likely to prove more problematic for approval as the genetically modified organisms themselves form part of the final product. There are also questions over whether the end products can be labelled using the terms dairy, milk, or egg.

Contamination of the fermentation process with potential toxins or pathogens and extraction processes will also need to be tightly controlled, and new regulation may be required for the industrial processes to ensure high levels of sanitation and quality control at all stages of production.

As fermentation techniques evolve and become more complex, and novel microorganisms are discovered or developed, rapid innovation in unpredictable directions is likely. The potential for distributed small-scale bioreactor operations across the world creating novel proteins/molecules will further complicate the FSA’s oversight role. As these proteins will likely become ingredients in food products produced elsewhere in the world there will be a need for the FSA to stay abreast of developments in the sector, determine how best to approve these products for consumption in the UK, and how to monitor and control imports.

7. Cultured meat

A further application of synthetic biology is the production of cultured foods including meat and seafood, also called *in-vitro* production, *cultivated* or *clean* meat. In this chapter, in section 7.1, we present an overview of this emerging technology; section 7.2 discusses the technical and commercial challenges; section 7.3, consumer acceptance; section 7.4, health and food safety; section 7.5, sustainability implications; and finally section 7.6, emerging regulatory issues.

7.1 Introduction to cultured meat

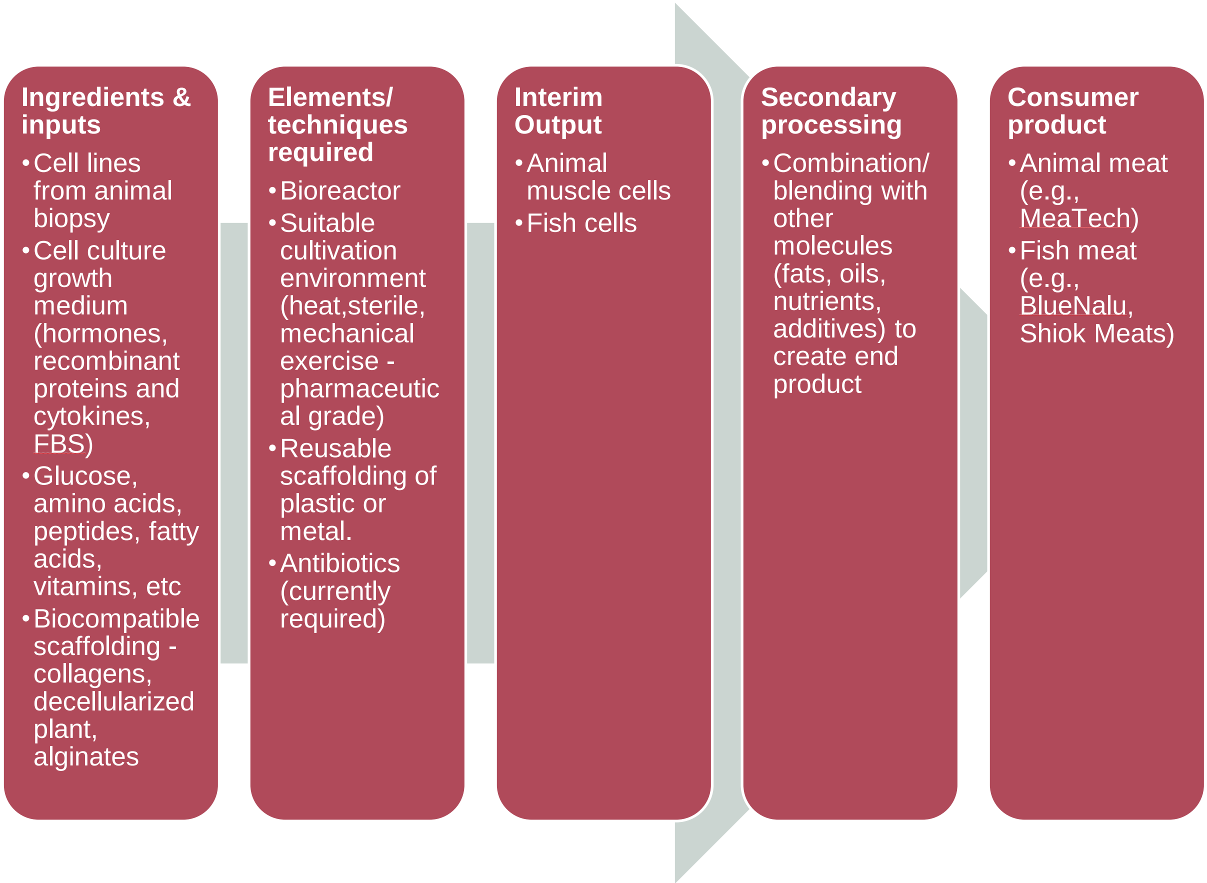
Cultured meat is produced by taking animal cells through a biopsy from a living animal and cultivating these cells outside the bodies of animals with the aim of creating meat that looks, tastes, and cooks just like conventional meat. Proponents of the technology suggest it has the potential to transform the food industry, and significantly impact or displace traditional animal farming and processing, and ultimately offer a superior product to conventional meat (Tubb & Seba, 2019).

Production requires a tank of nutrient-rich growth medium, or specific growth substrates under laboratory conditions using laboratory technologies, and the addition of bioactive molecules, such as hormones and growth factors, salts, sugars and amino acids, to induce cells to divide and produce new muscle cells (Choudhury et al., 2020). Fat and other components of meat need to be produced in separate cellular production processes and are then blended. Some cultivated meats are grown on a scaffold of food-grade material that mechanically “exercises” the muscle fibres and support development of the desired texture. These fibres can then be processed to create a ‘meat-like product’, which could be sold alongside a conventional steak or similar meat product.

Figure 21 shows some examples of the production process and outputs. Products are beginning to appear on the market, such as SuperMeat’s (www.supermeat.com) cultured chicken, and numerous start-ups are actively developing beef (e.g., MeaTech, www.meatech3d.com, combining cultured meat with 3D printing technology), poultry, pork, and seafood products (e.g., Blue Nalu, www.bluenalu.com).

Figure 21 Cultured meat production process and outputs examples

Source: developed from Leonardo Paradisi (2021)



7.2 Cultured meat: technical and commercial viability

Dolgin (2019) observes numerous start-ups and significant venture capital investment in the sector, but a lack of academic funding is holding back development of the needed scientific and engineering expertise to bring the products into the mainstream. Furthermore, without independent and rigorous academic scientific studies there is a lack of independent verification of methods and processes used by start-ups, which will have direct implications on the FSA’s ability to verify their products.

Products are still generally in the laboratory phase, with no viable commercial products on the market to date. Aside from a few niche examples such as Singapore's Eat Just lab-grown chicken (Steffen, 2021), meaningful commercialisation may still be 5 years or more away (DigitalFoodLab, 2021a; Witte et al., 2021). Costs and production at scale are still significant barriers to broader adoption, but costs have fallen dramatically in just a few years, and are anticipated to reach cost parity with conventional meat by the early 2030's. Nonetheless, many challenges remain to be addressed before there can be real certainty over commercial viability:

- The technology is still at an early stage of development, requires complex processing infrastructure, is expensive, and production at scale is still unproven. Scale-up from current pharmaceutical-grade laboratory or pilot-scale operations to full industrial operations while maintaining the necessary sterile conditions to avoid contamination and food safety risks presents a significant challenge.
- The industry needs to increase the metabolic efficiency to accelerate the culturing process. Developing better cell lines and optimising the growth medium and the growing conditions is required.
- The cost of the growth medium needs to reduce significantly to achieve commercial viability. Fetal bovine serum (FBS), extracted from the blood of bovine foetus when a pregnant cow is slaughtered, is used in most R&D programmes, but it presents ethical concerns and is too expensive for commercial operations (GFI, 2020). The price issue may be alleviated by recycling the medium, while use of animal-derived material in production remains an issue.
- A further key challenge for the industry is inducing the cells to generate more realistic fibrous quality and meat-like fat. The creation of edible structures (scaffolds) or removable scaffolds, is a key area of experimentation to help shape cultured cells into tissue, possibly made from plant-based alginate or starches or microorganisms, or animal-products like collagen, that become part of the final product (Dolgin, 2019; Tuomisto, 2019). This will, however, make the composition of lab grown meat very different from natural animal-based meat and will need to be addressed in regulation and labelling.

- Further development of processing technologies to blend muscle cells with fat cells is required to achieve realistic meat-like characteristics for cooking and consumption.

7.3 Cultured meat: consumer acceptance

The technical challenges identified above are significant, but the greater challenge facing cultured meat is likely to be consumer acceptance. Price and availability is currently a significant barrier, but even if production is achieved at scale and costs fall to parity with traditional animal meats, recent surveys present conflicting views on consumer openness to this emerging technology, with significant regional variations (e.g., Bryant et al., 2019; Weinrich et al., 2020).

Some consumers will reject the products on the basis that they are unnatural or unethical; others because the products cannot be called vegetarian or vegan (because they use animal stem cells and currently FBS); while others may reject them on the basis of taste and texture deficiencies (Choudhury et al., 2020). Controversy similar to that around genetically modified organisms seems likely to occur, with consumer concerns over food safety and long-term health implications (Bryant & Barnett, 2020; Filcak et al., 2020; Hocquette, 2016). There is however recognition of the potential benefits of its consumption to meet growing global demand for meat by consumers who do not want to consume cultured meat themselves (Circus & Robison, 2019).

The industry and other stakeholders will need to focus on increasing the acceptance of cultured meat and need to find a way to address safety concerns. It has been suggested that presenting cultured meat in a non-technical manner that emphasises the product characteristics and potential benefits (e.g., lower saturated fat content, lower antibiotic content, reduced risk of animal-borne infection), rather than the novel production processes can help with consumer perception (Siegrist et al., 2018). Another suggestion in the literature is to use alternative language such as ‘clean meat’ or ‘animal free meat’ rather than ‘cultured’, ‘synthetic’ or ‘lab-grown’ to help with consumer perceptions and acceptance (Bryant & Barnett, 2019). Although these approaches may help industry in spreading acceptance of their products among consumers, such language is unhelpful when it comes to labelling these products.

7.4 Cultured meat: food safety, nutrition, and public health

Given the early stage of development of the cultured meat industry much of the literature on food safety and nutrition is still somewhat speculative, and the potential risks and benefits of cultured meats may change as the technology advances.

7.4.1 Food safety

Contamination: As the process is undertaken in sterile conditions, it theoretically offers much lower risk of pathogens, allergens and toxins, eliminating the risks in conventional farming of contamination such as with E.coli, salmonella, and other chemical or physical hazards. However, cultured meat has yet to be achieved at scale outside pharmaceutical grade conditions, and there are concerns over potential pathogen contamination or allergenicity associated with industrialised production processes (Williams, 2021). Risks may arise with the starting cell cultures, contamination of the growth medium and during the growth phase, waste disposal, and in the handling of products after production.

One of the proposed benefits of lab-grown meat is the potential to avoid the use of antibiotics which are used extensively in most animal farming operations; however, at present, small quantities of antibiotics are used in the cultivation process, and the risk of contamination in industrial-scale processes without antibiotics is high. In addition, growing muscle cells under laboratory conditions involves the use of highly bioactive molecules, such as hormones and growth factors, and it is currently not well understood to what extent these can be removed in further processing steps. Given that lab-grown meat producers aim to offer rare- and medium-rare cooking options, one needs to consider that any bioactive molecules from the cell culture stage might still be present.

Mislabelling, traceability, and authenticity: These are significant problems in some parts of the existing meat industry. The source materials for cultured meat may be more easily traceable than in conventional animal meat farming, but this is far from certain at present. If cultured meat ultimately becomes cheaper than conventional animal products there may be a strong incentive for manufacturers to try to pass them off as ‘premium’ real animal products. Or, equally, if cultured meat becomes accepted as the more sustainability and healthier, premium option, there may be a temptation to pass off animal products as cultured meats. Traceability of imported cultured meats, perhaps in the form of processed meats or meat-plant hybrid products, may potentially present a significant monitoring and regulatory challenge for FSA.

7.4.2 Nutrition and health

The industry claims that cultured meat could potentially deliver a product that is nutritionally equivalent in every way to existing animal flesh, and even exceed animal proteins through tailoring to be for example, lower in saturated fats making it a more healthy option (Shapiro, 2018). However, cultured meat still has a long way to go to achieve these ambitions, and currently has less nutritional content than farmed meat, such as no vitamin B12, and the health implications if eaten instead of conventional meat need further investigation. A case by case risk assessment may be required due to difference in final cell composition (FSA, 2020). In addition, current research trends in this sector are testing new experimental approaches to improve taste and texture. Taste may be improved by the addition of a mixture of certain fats, and it needs to be seen which these are, and to what extent these will be healthier than animal fats. Texture improvement is currently attempted in various ways by providing structured scaffolding material to the cell culture growth phase, and these sources need to be safe and add to nutritional value rather than being anti-nutrients.

7.5 Cultured meat: sustainability

The industry claims cultured meat offers significant sustainability benefits in terms of arable land use, water consumption, and GHG emissions compared with conventional animal farming. Indeed, the nutrients that an animal consumes are used simply to grow and sustain its life while transforming them into a complete anatomy, of which only some parts are directly consumed as meat products, whereas in cultivated meat all the nutrients go into the final product.

The environmental impact of cultured meat primarily depends on three aspects (Santo et al., 2020):

1. Nutrient sources, currently still needing animal/cattle proteins, growth supporting hormones, and other inputs
2. Energy use for *in-vitro* production
3. Processing into final products

Growth medium: Lab-grown cell-based proteins rely on a culture medium for growth, often a sophisticated synthetic product produced from multiple sources both plant and animal based. This means essentially cultured meat is still dependant on conventional agriculture with the added use of energy, water, and other resources to transform source materials into the culture medium used in the process.

Energy and GHG emissions: The in-vitro processes and post-processing are energy intensive (significant heat energy is required to support the growing process), and a more critical analysis of the environmental footprint of large-scale food growing laboratory facilities gives a less optimistic view on realistic prospects of the technology (e.g. Muraille, 2019), and its potential environmental benefits (Escobar et al., 2021; Filcak et al., 2020). To date, studies on GHG emissions and environmental LCAs for the sector are subject to huge uncertainty, based on many hypothetical assumptions, and direct comparison with other protein sources is complicated by differing views on the appropriate functional unit of analysis (Escobar et al., 2021; Smetana et al., 2015). Moreover, the GHG emissions of in-vitro production vary greatly depending on assumptions on the scale of production, cell density, and cell proliferation rates (Santo et al., 2020).

An anticipatory LCA undertaken in 2011 suggested that cultured meat could use 7-45% lower energy than livestock production in the EU (of animals, only poultry production was lower), 78-96% lower GHG emissions (assuming renewable electricity generation), 99% lower land use, and 82-96% lower water use (Tuomisto & Teixeira De Mattos, 2011). More recent studies confirm GHG emissions would be lower than for livestock but suggest GHG emissions could be 1.1 to 6.1 times higher than animal products such as poultry and pork, and 4.8 times higher than tofu, 13.5 times higher than pulses, and 20.6 times higher than peas. Lynch & Pierrehumbert (2019) suggest that while fossil fuels remain a significant part of the energy mix the GHG emissions of cultured meat could even be higher than cattle production.

Water and land use: Estimates for water use reduction and land-use are similarly subject to significant uncertainty (Santo et al., 2020), and land-use reduction figures do not consider land-use change implications – livestock perform some useful ecosystem services and can make use of otherwise unusable non-arable land, so the land use benefits may be overstated. Some studies suggest that on a protein-basis land use for feedstock associated with cultivated meat is approximately equivalent to poultry production, while other studies suggest a significant reduction, e.g., Swartz (2021) suggests a 63% reduction.

Broader system implications: Taking a broader system perspective on sustainability, the potential system-level risks and benefits of cultured meat are similar to those discussed in the previous chapter on biosynthesised protein. Widespread uptake of cultured meat could deliver benefits in terms of localised production close to consumer markets, reducing transportation, cold chains, and waste, but also significantly disrupt existing agricultural systems, undermining livestock farming and agriculture-based economies and employment around the world. Among other things, this could exacerbate the rural-urban migration trend creating a range of other sustainability issues. As all of the development and the hi-tech skills-base needed to support the emerging industry (chemists, cell biologists, engineers, etc) are in the wealthy developed world, the technology is likely to further shift the balance of power away from developing nations, and will be particularly profound for smaller producers and low skilled agricultural workers (Filcak et al., 2020; Jairath et al., 2021; Santo et al., 2020).

Secondary industrial impacts: A significant shift away from animal farming would have knock-on effects on related industry sectors, both for the industries that supply the animal farming sector, such as feed, pharmaceuticals and chemicals, and those industries that currently use the extensive range and properties of non-edible animal by-products. While we should not dismiss the benefits of such a technological change, the implications of such a large societal and industrial transition certainly require further consideration. To date, none of the LCA studies have considered the environmental implications associated with replacing the current stream of useful non-edible animal by-products such as leather and other textiles, pet food, animal feed, industrial lubricants, cosmetics, and medicine and many others that would have to be synthesized elsewhere.

7.6 Cultured meat: regulation

Cultured meat currently falls under the EU/UK Novel Foods regulation which require safety testing and certification, and there are uncertainties over regulation at present, or whether it can be labelled as meat, or beef for example. Cultured meat may face considerable regulatory barriers given the uncertainties over the technologies, risk of contamination, and as of yet untested effects on human health (van der Weele et al., 2019). In this context, the Singapore Food Agency's approval of Eat Just's cultured chicken for commercial production is an important milestone for the industry (Steffen, 2021; Witte et al., 2021). In most countries there are also no existing frameworks for regulation on the harvesting of stem cells from livestock and growing of cells as food (Choudhury et al., 2020). There is also a need to decide who is the responsible regulator for certification and monitoring of the production processes, traceability in case of disease outbreak, and food fraud issues.

The starting cells used in production are currently sourced through biopsies from genetically unmodified cattle, chicken, sheep etc, so the resulting cultured meat is not GM. However, future innovations may include genetic modifications either in the source animals, or in the laboratory to enhance efficiency or for example to produce fats or taste enhancing molecules, which will have additional implications for regulation and for labelling.

8. Key findings

In this chapter we present a synthesis and discussion of key findings from the study. Section 8.1 presents findings for each of the four technologies; section 8.2 then discusses five key findings common across all categories of alternative proteins; and section 8.3 presents six broader macro-level observations from a systems perspective on alternative proteins. The chapter concludes with section 8.4

presenting a summary of the four categories of alternative proteins from a sustainable food system perspective.

8.1 Key findings for each alternative protein source

8.1.1 Plant-based meat substitutes are not equivalent to a traditional plant-based diet

Plant-based meat substitutes are presented as a healthy, environmentally friendly alternative to animal meat, and while they can offer nutritious alternatives and are sometimes fortified with additional nutrients, they may not be as nutritionally dense and environmentally sustainable as the industry might want consumers to believe. Generally, they are extensively processed foods more akin to fast-food offerings than the traditional wholefood vegetarian fare with which they are often associated, often with high levels of salt. Regulation of marketing, labelling and health and sustainability claims may be needed to ensure consumers are not mistakenly undermining their health through regular consumption.

8.1.2 Novel sources of protein will have differing uptake and local impact potential

In some parts of Asia and Africa, insects and other organisms are established parts of the traditional cuisine and offer a relatively low-impact source of protein – comparable to, or better than chicken on most environmental metrics. They have good protein content and good nutritional value and can be produced using relatively low-technology solutions, can potentially make use of organic waste streams as feedstock, and can be consumed with relatively little processing. This makes them potentially a good option for human health and environmental sustainability. However, consumer acceptance in the west is a significant barrier to adoption, and there are concerns over quality of feedstocks, microbial and hygienic safety, toxicity and allergenicity, and limited understanding of the effects of intensive human consumption. For these reasons, the potential for meaningful impact in Western markets seems quite limited. However, they could prove essential to increasing protein supply in developing nations, particularly those that already have a culinary culture around these products, and indeed expansion of the sector is already underway in parts of Africa and Asia.

8.2.3 Fermentation offers the most significant potential for disruption

Fermentation, particularly precision fermentation to produce dairy and egg protein, may prove to be the most disruptive segment over the coming decade. Challenges remain to achieve commercial viability and to operate at scale, and consumer and regulatory acceptance is far from certain, particularly due to uncertainties regarding GMO status, and the unknown health implications of long-term consumption. However, if these barriers can be overcome these technologies have the potential to upend the conventional dairy and egg industries, and this will have knock-on effects on the viability of the meat and poultry sector, with implications for the entire food eco-system and value-chain and may accelerate the transition to animal-free alternative proteins.

8.1.4 Cultured meat is still far from being a mature commercially viable technology

Cultured meat is one of the most controversial sources of protein and offers the most radical potential for disruption of conventional animal farming and animal-meat consumption. However, it is far from certain to prove technically or commercially viable, or to gain real acceptance with consumers. Currently, nutritional content is inferior to animal meat, there is no understanding of the long-term health implications of consumption, and there are significant technical and cost challenges, including the need to replace existing animal serum-based growth medium with more affordable alternatives, and the challenge of operating without antibiotics. Although there are likely to be important environmental benefits when compared to beef in terms of methane emissions, land-use, and eutrophication, at least until the energy system is decarbonised, conventionally farmed chicken, pork, fish, and novel sources such as insects and algae seem to be better for humans and the planet.

8.2 Key findings across the alternative protein sector

8.2.1 A wave of new ingredients/foods entering food system

A range of emerging technologies and novel food sources are on the horizon, offering the potential to dramatically reshape the way food is produced, to optimise formulations, enhance taste, supplement nutrition, and possibly deliver environmental benefits, cost savings and waste reduction. The advent of synthetic biology particularly could transform much of the food system. Combining artificial intelligence and machine learning and other emerging technologies such as 3D printing, with the ability to synthesise a wide array of bespoke metabolites, could lead to a an entirely new food production system, in which any desired molecule or food could be synthesised from any feedstock input.

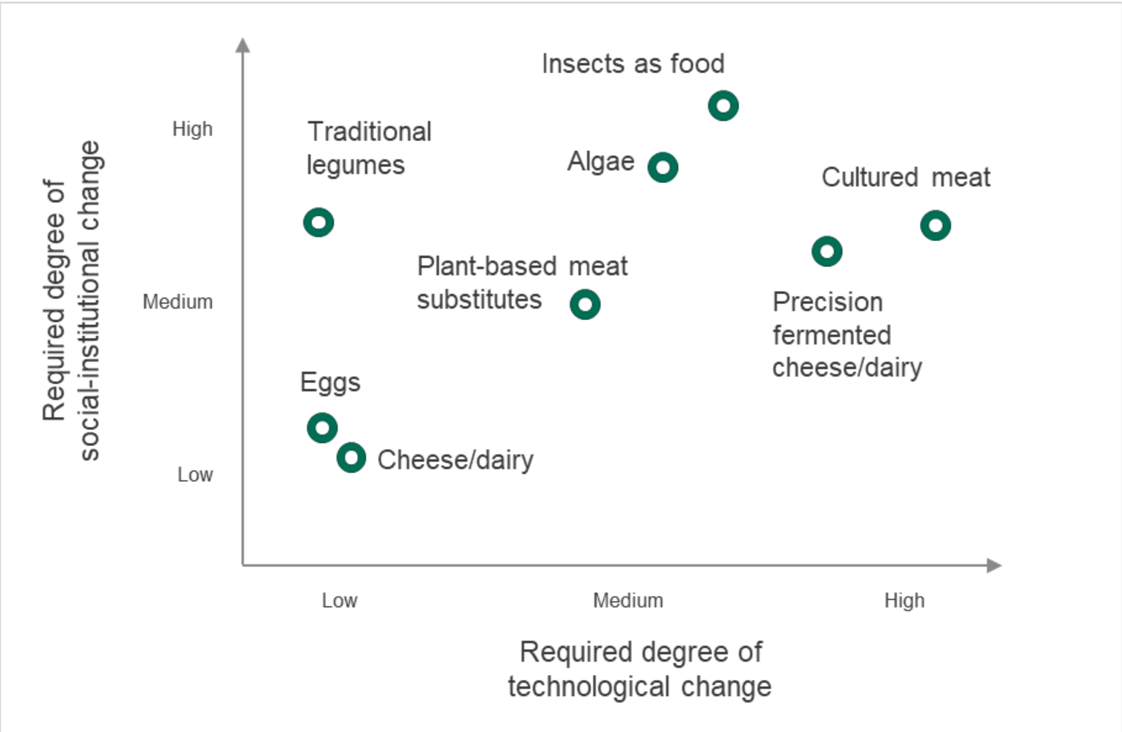
This has the potential to profoundly change the types of food we consume in the future, and the way most of our food is produced, potentially shifting to multipurpose, locally located, micro-bioreactors, with short, traceable supply chains, and fundamental redesign of rural economies, in place of the large food production factories of today. This may bring considerable benefits for food system resilience and food security, and at the same time help to reduce food waste. This potential future scenario is however far from certain at present and only one of many possible scenarios. Nevertheless, what is clear is that the current food system and stakeholders, consumers, and the regulatory framework are not set up or ready for this type of change.

8.2.2 Barriers to consumer acceptance of alternative protein sources

Consumer acceptance and willingness to try alternative proteins does not appear to be well aligned with the needs to address climate change, environmental sustainability, food security, food system resilience, and health. The dominant factor in food choices in affluent societies such as the UK seems to be the taste and sensory experience of the food, and although consumers do seem willing to try new products, and recognise the need for change, the industry is struggling to generate repeat business due to high prices and disappointing experiences. Although Western consumers often acknowledge the potential benefit of sources such as insects and cultured meat to feed the growing global need for protein, they generally perceive these as sources for others, and have little interest in reducing animal meat consumption themselves. Moreover, highly processed, and synthetic foods that characterise how most of these alternative proteins will be used, seem at odds with the current trend for whole-foods and minimally refined foods seen in many affluent societies today (Hocquette, 2016).

Figure 22 Social-institutional and technological change for meat-alternatives

Source: based on van der Weele et al. (2019)



Introduction and mass-adoption of alternative proteins will require a combination of social-institutional and technological change as illustrated in Figure 22 (van der Weele et al., 2019). In this figure, shifting a Western society like the UK towards a more traditional plant-based diet of legumes and other wholefood sources of protein, or a diet based more on eggs and dairy rather than animal meat, are compared to novel sources of protein. The higher the degree of social-institutional change required the more challenging it will be to implement adoption. Van der Weele et al. (2019) argue that reverting to a more wholefood plant-based diet in a society with a strong cultural tradition of meat consumption represents a significant challenge, compounded by the fact that there are no strong commercial or political lobbies for such a diet, so few resources (investment, research and development, etc) are dedicated to challenging the current system. Conversely, fermentation and cultured meat, while representing major technological change, theoretically might simply replace current animal-based consumption practices with minimal need for social-institutional change at the consumer-level, while supported by powerful commercial interests.

8.2.3 Most alternative proteins will need to be extensively processed

High levels of processing are required for most of the emerging alternative proteins either to purify them, or to reach the complexity of food structures demanded by consumers. Processes include extraction, purification, blending, fortification with additional minerals, use of artificial additives and colourings, and an array of sophisticated texturizing processes to achieve meat-like tastes and characteristics. This creates issues around nutritional properties, concerns over high levels of sodium, sugar and saturated fats, and among other things, significant energy consumption and GHG emissions in production, limiting the potential sustainability benefits (van der Weele et al., 2019). Processing in general also raises the potential for food contamination and creates food fraud risk around mislabelling, authenticity and traceability. For example, if these alternative protein sources become cheaper than conventional animal products there may be an incentive for manufacturers to pass them off as ‘premium’ real animal products, or vice versa.

The nature of these alternative proteins and novel production processes also makes it increasingly difficult for the consumer to make informed decisions on what they eat. Labelling and consumer education will be increasingly important, but this can only be beneficial if the information presented is meaningful to the average consumer. Attempts to include carbon footprints and “traffic-light” nutrition on labels have had only limited success to date with consumers, and although ingredient lists are mandatory, the average consumer has little understanding of the difference between for example wholefood flour, versus protein concentrate, versus protein isolate.

8.2.4 Limited understanding of long-term health implications

There is much hype in the sector, but whether these alternative proteins will be safe or beneficial for health is almost impossible to say with certainty at present because there are no longitudinal studies on the long-term implications of intensive consumption. Previous longitudinal health studies have not even investigated intensive consumption of plant proteins such as soy, and it may require 20 years of further studies before the health implications of these emerging sources of protein can be fully understood. Moreover, animal proteins generated through fermentation and cultured meats may well create some of the same health issues as their existing animal-based counterparts, undermining the potential health benefits of a transition. There are also concerns over allergens, pathogens, and potential toxicity for many of these alternative proteins.

8.2.5 The environmental case for alternative proteins is not yet fully defined

Environmental sustainability is a key claim of the sector, yet LCA-based sustainability claims are difficult to validate, making quantitative comparison of the different protein offerings unreliable, and there appear to be mixed views on the potential benefits. Much of the data presented to date is subject to significant uncertainty, in part because processes and input ingredients are commercially confidential making independent assessment difficult, in part because the processes are still in the prototype stage and life-cycle inventory data simply does not yet exist, and because the industry and the technologies are evolving rapidly meaning that studies today may not be representative of future production systems. Moreover, assumptions about the energy-mix and water use across different regions can present a distorted view of the relative benefits of alternative technologies.

Notwithstanding the above, some preliminary comparisons have been presented in the literature, for example, Rubio et al. (2020) as shown in Figure 23, and Tuomisto (2019), as shown in Figure 24. There seems to be consensus over the relative ranking between different protein sources. Plant-based meat-like substitutes, precision fermentation and cultured meat may deliver environmental benefits over beef and sheep. However, the case for these alternative proteins is significantly less compelling against other traditional forms of protein such as eggs, poultry, and pulses and legumes, and emerging sources such as insects and algae.

As discussed earlier in this report, energy use for cultivation and processing is a significant factor for plant-based meat alternatives, fermentation, and cultured meat, and GHG emissions calculations for these often assume that renewable energy sources will be used. These benefits will only be realised with a fully decarbonised energy system. Figure 25 presents the results of a recent study looking at six alternative proteins and their GHG emissions potential with a fully decarbonised energy system.

Figure 23 Comparison of the environmental impact of meat and meat analogues

Source: Rubio et al. (2020)

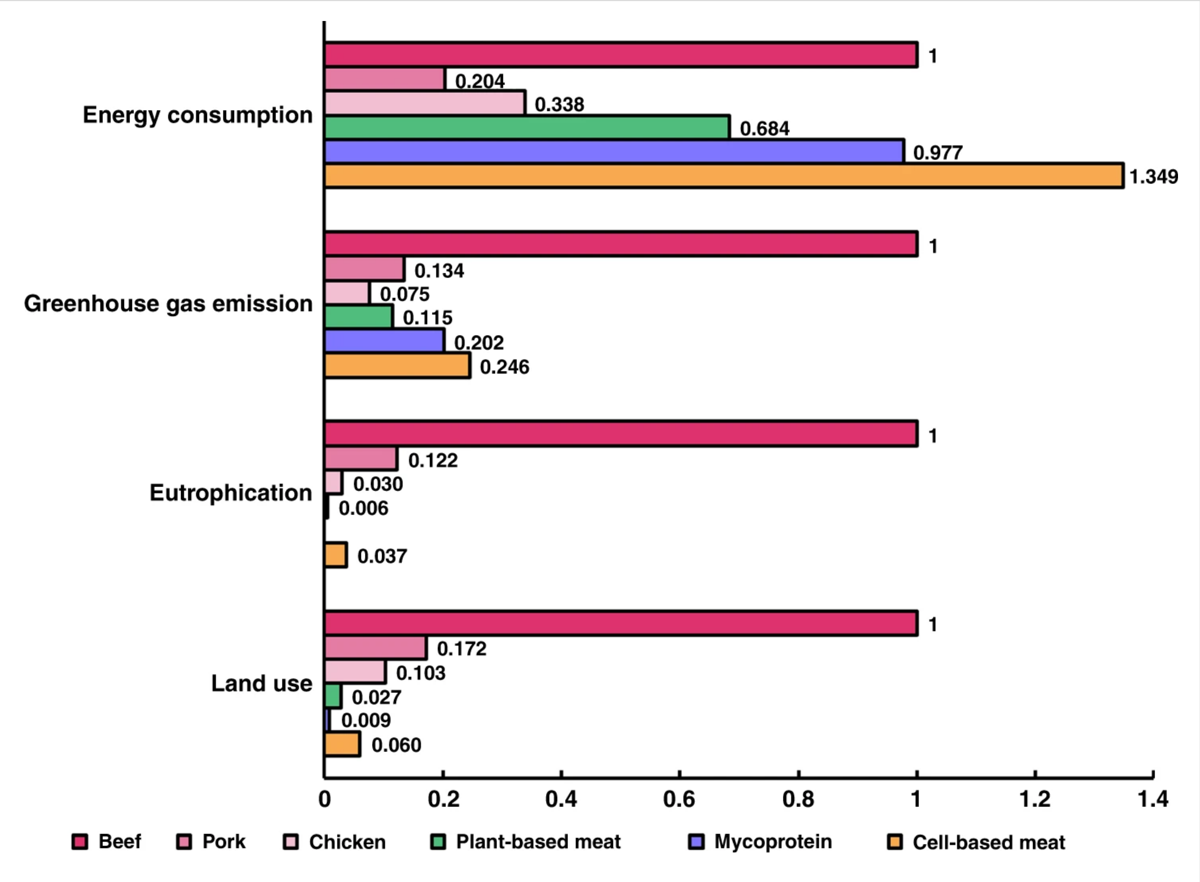


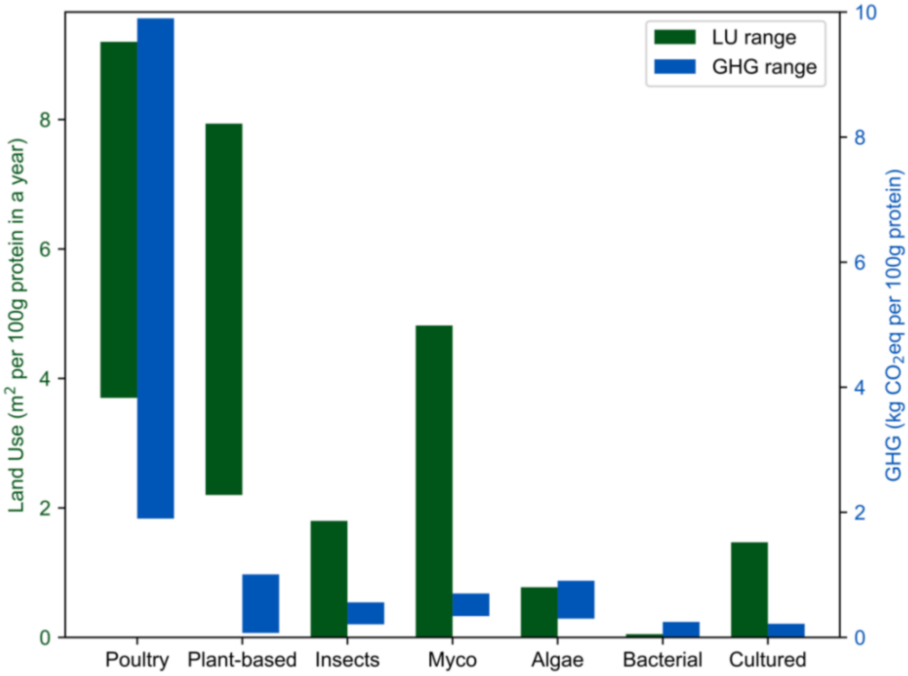
Figure 24 Environmental impacts of different protein sources

Source: Tuomisto (2019)

Figure 25 Land use and GHG emissions comparing six alternative proteins

Source: Collett et al. (2021)

Figures assume renewable energy sources, or net-zero energy generation. Poultry is shown for reference.



8.3 Macro-level perspective on alternative proteins

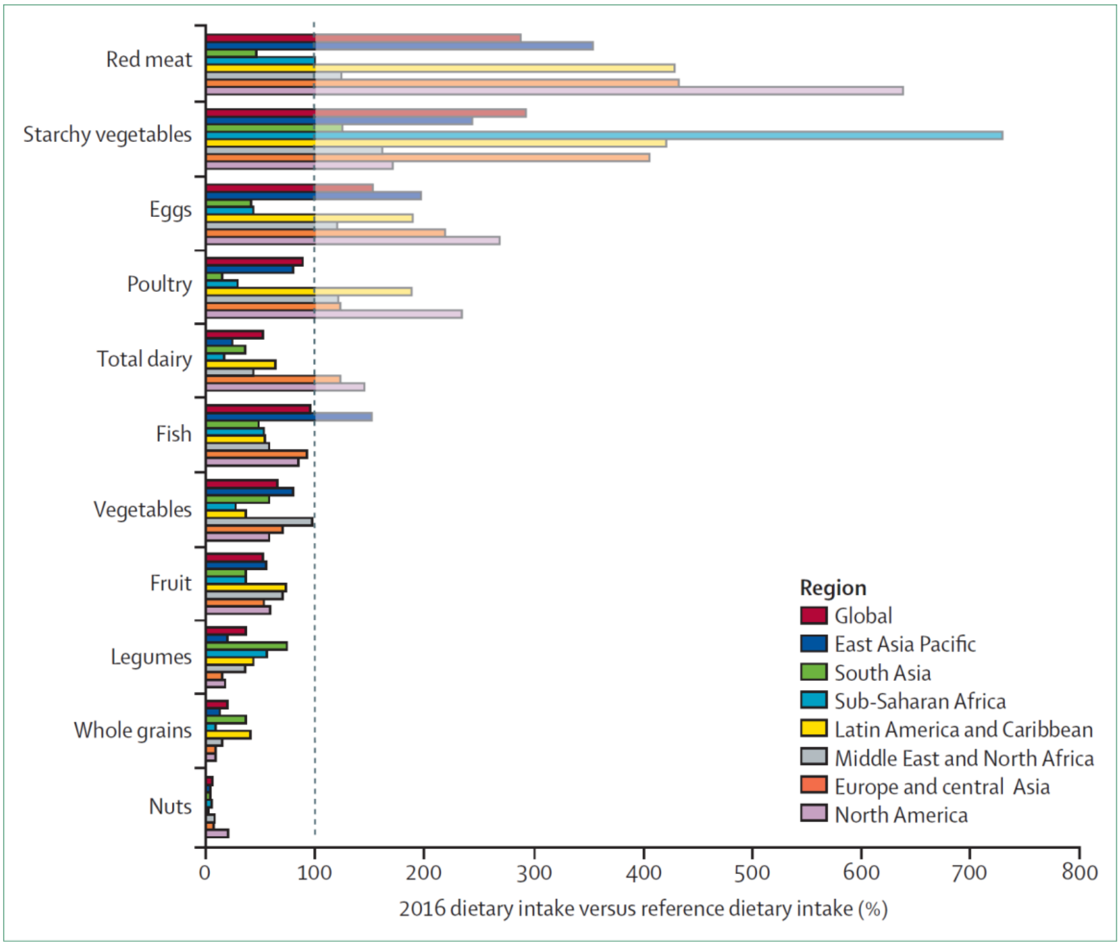
8.3.1 A need to moderate consumption versus expanding production

Demand management in the protein sector is rarely mentioned but may be at least as important as the development of new alternative sources of protein for the future. The current diet in much of the West is viewed as excessive for many, regularly over-consuming calories and protein, with resultant public health implications such as obesity and other diseases. Figure 26 illustrates the potential diet gap between current patterns of consumption and the reference diet intakes of food required for a sustainable food system, as recommended by the Eat-Lancet report (Willett et al., 2019). The report is not universally endorsed, but nonetheless it provides an indication of how far out of step modern consumption patterns in the West, particularly in the US may be. Moderation of consumption, not just shifting to alternative protein sources could be beneficial.

Figure 26 Diet gap between dietary patterns in 2016 and reference diet intakes

Source: Willett et al. (2019)

Data on 2016 intakes are from the Global Burden of Disease database.130 The dotted line represents intakes in reference diet for sustainable global food system.



Moreover, the introduction of alternative sources of protein raises the very real risk of rebound effects whereby consumers give themselves licence to consume more believing it is healthier and better for the environment. Also, as has happened with previous agricultural revolutions, populations may expand to absorb any surplus in the food supply. Going forward, industry and policymakers may need to consider how best to encourage industry and consumers to moderate consumption. Various strategies have been identified to enable the food industry to facilitate a 'sufficiency approach' to consumption (e.g., Bocken et al., 2020). Policy interventions include 'nudge' strategies, curtailing advertising (as has already been implemented for certain food types to limit promotion of junk-foods to children), or taxes/subsidies on specific foods to shift consumer buying habits and/or the industry formulations for food products (such as the soft drinks industry levy introduced in the UK in 2018). Other options need to be explored.

8.3.2 Low-tech solutions already exist and may be better, more sustainable solutions

High-technology alternative protein sources are presented as a revolutionary improvement in the food system, supported by considerable investor and entrepreneurial hype. However, sustainability and food security does not necessarily have to rely on high-technology solutions (McMahon, 2022), and for the reasons discussed above, they may not even be the best option for health and sustainability.

Plant-based whole foods and minimally processed foods, such as traditional legumes and pulses are better for the environment and their impacts on human health are very well understood, they can be produced through simple and low-cost production systems and require minimal packaging and cold chains for distribution (van der Weele et al., 2019). Additionally, aquatic 'blue' food sources, although over-exploited in some areas, still offer much untapped potential for high quality protein (UN, 2021). Relatively low-tech insect and algae farming, a traditional food source in many parts of the world, also has great potential for expansion in regions with poor access to other forms of quality protein (Filou, 2022). Encouraging a shift towards more traditional, largely plant-based diets, careful expansion of aquaculture and particularly macroalgae such as seaweeds and kelp that offer many additional environmental remediation benefits, and local initiatives sensitive to regional context may be the better solution. These might prioritise simplicity and durability and traditional techniques, align with and foster traditional culinary history, and support local communities and economies.

8.3.3 Need to reduce food waste across the value chain and foster circularity in the food system

The global food system is estimated to lose or waste almost 30% of all supply, and approximately 20% of all meat, dairy, and fish. Focusing on reducing these losses, much of which occurs at the household consumer level would make a significant impact on food availability and GHG emissions and other environmental impacts (Tso & Forde, 2021). Initiatives include consumer education and changes in retail such as reducing instore promotions, reassessing portion sizes, perhaps shifting back from ultra-convenience short shelf-life foods to which we have become accustomed, towards more home-preparation of foods. Focusing on development of solutions to better monitor and control food spoilage through the value chain, improving efficiency in agricultural systems, and regulatory change to enable more extensive reuse of side-streams and waste streams could be effective areas for technology innovation and regulatory intervention to address limits on food security and supply (Short et al., 2021).

8.3.4 Alternative proteins seem to have limited potential to address global challenges

A large part of the world currently obtains significant protein from plants, chicken, eggs, and fish. For example, 3.3 billion people rely on fish for almost 20 percent of their daily intake of animal protein, and aquatic food farming supports livelihoods for 10-12% of the world's population (UN, 2021). For these populations the environmental and health benefits of shifting to a sophisticated alternative protein diet may be far less significant than for beef and dairy consumers (primarily in the affluent West). Feed conversion ratios for the emerging technologies don't offer significant benefit, at least at present, over many of these conventional sources. Moreover, expensive novel technological solutions dependent on highly skilled biochemists, engineers, and other skillsets, and intellectual property will not easily be deployed in poorer developing nations. The prospect of undermining both the rural agricultural communities, and the major multinationals in conventional animal farming is also likely to generate major socio-political barriers to uptake. Consequently, many of the emerging alternative proteins may offer only limited potential to address global food security and environmental sustainability concerns.

8.3.5 Need for balancing technological push with societal needs

If these emerging technologies reach the scale that their advocates foresee, they will be highly disruptive for the food industry, and particularly for the rural economies and low-skilled workers across the world currently employed in animal farming. Industries that supply the agricultural sector, and those that use the in-edible by-products of animal farming such as the leather industry, cosmetics, pharmaceuticals, etc will also be hugely disrupted. Creating alternative industries to source or biosynthesise these useful materials elsewhere, possibly from petroleum, may even undermine much of the benefit of shifting away from animal farming. Animal husbandry, particularly ruminants, also currently plays an important role in use of marginal land that is unsuitable for productive crops and converting otherwise inedible biomass and side-streams from the agriculture and food processing industry into usable high-quality food for humans – replacement solutions may only partially match these benefits.

The potential environmental and socioeconomic impacts of such a transition are poorly understood to date. None of the LCA studies have taken such a broad system perspective on the implications for replacement of the animal by-products industry sectors for example. There may be significant benefits from such a transition, but if not managed carefully, the negative societal effects of such upheaval at least in the short-term, may greatly overshadow the benefits. This will require a systems-based approach to policy on an unprecedented scale to ensure a smooth transition and protection of employment and livelihoods.

8.3.6 Shift the narrative from ‘alternative protein’ to ‘protein diversification’

The dominant narrative in the protein sector is currently focused on alternative proteins. However, as observed in this report there are many benefits from re-adopting more traditional forms of plant proteins in a more whole form, and simply adjusting the mix of animal and seafood proteins that are consumed. Rather than focusing attention solely on the development of alternative proteins, consideration of the full spectrum of proteins, both existing and emerging may be beneficial. This means, not necessarily striving for the best alternative protein source, and not simply replacing certain proteins, but recognition that protein diversity may have the most beneficial impact for human health and biodiversity (e.g., Salomé et al., 2020).

8.4 Summary of implications of alternative proteins

Summarising the details of the emerging alternative proteins, Table 6 lists the key issues and implications of each of the alternative sources of protein and their potential contribution to a sustainable food system.

Table 6 Food safety and sustainability summary

Food safety & sustainability dimensions	Plant-based meat substitutes	Novel sources of protein	Biosynthesised protein from microorganisms	Cultured meat protein
Economic aspects Profit, jobs, investment, industry dynamics	– Growing sector – Significant investment – Multiple start-ups – Large firms emerging – Growth slowed in 2021 – Currently niche market	– Can be cultivated in low-tech applications – Regional economic development potential – Aquaculture in synergy with fish industry	– Emerging segment – Significant investment – Technical challenges – Potential to disrupt dairy and egg sectors – Distributed production & economic development	– Significant investment – Still prototype stage – Technical challenges – Significant uncertainty over viability Could be huge market if can perfect processes
Nutrition and health Calories and nutrients, knowledge and beliefs, food safety and fraud	– Ultra-processed food – High salt, fat, sugar – Fortified nutrition – Health implications not well understood – Allergens and gluten intolerance	– Good nutrition profiles – Use as supplements, ingredients, and food – Implications of intensive consumption unknown – Allergenicity, toxicity, pathogens	– Indistinguishable from animal protein – Ultra-processed food – No studies of long-term health implications – Risks of food fraud, contamination, GMO, dairy intolerance	– Lacks nutrition of animal meat – Ultra-processed food – No studies of long-term health implications – Hormones, antibiotics, food safety and fraud

Food safety & sustainability dimensions	Plant-based meat substitutes	Novel sources of protein	Biosynthesised protein from microorganisms	Cultured meat protein
Environmental aspects GHGs, land, water, waste, biodiversity,	– Benefits over beef and dairy farming – Energy intensive – Source crops good for soil health & biodiversity	– Benefits over most animal farming – Can be energy intensive – Organic waste as feed – Bioremediation (algae)	– Benefits over dairy – Similar environmental impact to chicken – Energy intensive – Uncertainty over waste	– Benefits over beef – Very energy intensive – Similar impact to chicken production – Growth medium (FBS).
Social aspects Consumer acceptance, cultural traditions, animal welfare, community	– Willingness to try for perceived health benefit – Repeat sales limited due to price and experience – Good for animal welfare	– Unattractive to Western consumers – Good acceptance where part of cultural tradition – Animal welfare better, but potential issues	– Uncertainty over consumer acceptance – Disruptive for rural communities, and traditional sectors – Some animal welfare benefit	– Customer acceptance highly uncertain – Could fit into traditional meat-centric cultures – Concerns over FBS as growth medium – Animal welfare benefits
Food security Food utilisation, access to food, availability of food, long-term system stability	– Premium-priced niche – Unlikely to be relevant in many parts of the world – Require cold chain for distribution and storage	– Mostly limited to animal and fish feed in West – Relevant in parts of Asia and Africa to address protein deficiency – Localised production	– Wide implications for food system – Synthesise any output from any feedstock – Transform production, reduce waste, enhance resilience	– Could be major disruptor – May increase meat consumption – Potential to deliver greater food security

9. Conclusion

This report has presented a comprehensive overview of the emerging alternative protein sector based on the existent academic and industrial literature. The key drivers of change in the industry are food security, health, environmental sustainability concerns, and a dynamic agritech sector that is both responding to these drivers and pushing new technologies at pace on to the market. These innovations could create a flood of new ingredients and foods into the market over the coming decade. Four main categories of alternative proteins are identified as being of particular significance. These are plant-based meat substitutes, novel sources of protein, fermentation-based biosynthesized protein, and cultured meat. For each of these categories a detailed assessment was undertaken to understand the technical challenges and the commercial viability within the coming decade, the consumer response to these technologies, food safety and public health issues, their impact on environmental sustainability contrasting that with current practices in farming and animal husbandry, and the potential areas needing a regulatory response.

In this final chapter, implications and recommendations for policymakers are discussed in section 9.1, and the FSA priority areas for the short, medium, and long-term are suggested in section 9.2. Limitations of the study are discussed in section 9.3, and finally in section 9.4, a series of recommendations for future research are offered to address the significant evidence gaps that remain in this field.

9.1 Implications and recommendations for the FSA

Before discussion and suggestions on regulatory interventions, it is useful to better define alternative proteins within novel foods from a regulatory perspective. The current UK Novel Food regulation is still based on the EU regulation. As part of the withdrawal agreement from the EU, the FSA took the oversight of the Novel Food regulation. In order to create a seamless transition, the FSA has not changed the application criteria and evaluation standards and they remain the same as the EC & EFSA from the EU law Regulation 2017/2469. This means the definition of a novel food remains the same as in the EU; namely, a novel food based on regulation (EU) 2015/2283 is defined as a food which had negligible or no human consumption in the European Union prior to 15th May 1997, the date when the first Novel Food regulation came into force with Regulation (EC) 258/97. The sources of novel foods include plants, animals, microorganisms, cell cultures, minerals, and other natural and synthetic sources. These include ingredients and products that are the result of modified or new production processes and new technologies and industry practices leading to new or modified molecular structures, use novel feed sources, genetic engineering interventions, introduction of nanomaterials, etc. Furthermore, novel foods cover a range of plant and animal products that are already consumed in other parts of the world but are new to EU markets.

Therefore, the majority of the protein sources discussed in this report in one way or another fall under Novel Food regulation, from jelly fish which are consumed elsewhere in the world but new to the UK, to protein ingredients and products resulting from novel processes and innovations from laboratories in the UK and worldwide. Technological advances combined with the pressure for more sustainable sources of protein have led to an acceleration of innovation and product development and the introduction of a plethora of new alternative protein ingredients and products to the market. Hence the need for development of a cohesive regulatory framework that can accommodate the novelty of these foods as well as the rapid pace of their market entry.

Apart from the novelty factor of the foods/proteins entering the market, regulation and policy design might need to consider the wider factors that will impact the context and function of these novel foods in the future and hence their regulation. The global food system is facing many challenges, from threat of climate change to the need to absorb and adapt to new technologies and innovations within the legacy infrastructure, supply chains and millennia of human eating habits. As food systems are the foundation of keeping the planet habitable for humans, preparing, and adapting agriculture and any other related industries towards building a resilient food system while minimising its impact on the environment has become a key challenge for governments and businesses alike.

Furthermore, one of the major challenges to any technological change is its adoption by consumers/users. The research carried out shows that this remains one of the most immediate challenges for novel protein sources, at least in western societies with a strong tradition of animal husbandry and meat and dairy based diets.

In this complex setting regulation has a strong and vital role to play. It is also important to emphasise that increasingly the role of regulation particularly in the food industry is moving from that of a watchdog for industry conduct, to that of a facilitator within a multi-stakeholder, complex, and rapidly changing environment, with the responsibility to safeguard the interests of consumers/end-users.

9.1.1 Overall Strategic Considerations

- **Mid- and long-term health impact on the population**: For some of the novel proteins, in particular biosynthesised proteins and potentially cultured meat, the mid- and long-term effects on human health remains an unanswered question. This means regulation may need to go beyond determining toxicity and hygiene and address the wider effects of these highly refined molecules in food compositions on human health. In the case of cultured meat too, although the source of the meat produced is a known and widely accessible animal tissue, e.g., beef, the processes, conditions and added chemicals, natural or synthetic, means that the end product is far from the natural cells that were the starting point.

  This may lead to the requirement for a more sophisticated regulatory approval system resembling pharmaceuticals regulation. However, such a process will increase time to market for novel synthetic proteins, lead to higher prices and reduce their competitive commercial position. Balancing the industry demand for faster/easier approval processes with potential long-term consumer and population health interests represents one of the dilemmas the FSA will face going forward.

- **Nutritional value and bioavailability**: These are other topics that may benefit from more clarity and where regulation may be able to help. In the case of plant-based meat substitutes, the processes that render grains or legumes into a highly texturized meat replacement imitating the sensory profile of meat ends with an extensively processed product containing numerous other ingredients also modified from their original state. Often the chemical processes used strip the original nutritional profile and qualities of the plant food. Functional ingredients, which may also be the result of synthetic biology mentioned above, may be added to replace those missing nutritional elements but may not be easily digestible and absorbable by the human digestive system. Once again, these novel foods require a deeper engagement of regulators with the details of food production beyond safety and hygiene.

- **Sustainability impact claims**: As discussed extensively in this report, establishing a clear sustainability credential for the novel proteins entering the market is not a straightforward task. This is due to a number of challenges including availability of necessary data, variation in frameworks for calculating environmental footprints and lack of industry willingness to engage in a transparent debate on sustainability credentials of these ingredients and products. Initiatives underway in the EU to introduce new sustainability labelling regulations might be expected to influence similar development in the UK food system. The FSA may face a considerable challenge in finding the right balance between enabling new innovations to market while protecting longer-term interests of the consumers and the wider society. This is further complicated by broader issues that may require regulatory consideration, such as the protection of current food sources and food production systems.

- **Bringing clarity to the debate**: As with any multi-stakeholder debate, the use of language can have a considerable impact on the outcome of a debate. By developing a clear language and messaging and avoiding the hype language coined by the industry PR, using a more direct, specific, and factual language when addressing the industry and the public can bring clarity to internal discussions as well as external negotiations required for building a functional regulatory framework.

- **Collaboration with regulators of other industries**: The interconnected nature of supply chains and industries means that the FSA will be required to work closely with regulators of other industries with direct or indirect impact on food supply chains. Sustainability issues in the food industry require consideration from the perspective of other industries that have an impact on the food industry or are impacted themselves by changes within the food industry. As discussed previously, a wholesale shift from animal husbandry to synthetic proteins and cultured meat will not only have a huge impact on the labour force that are currently employed in the agricultural sector and their livelihoods, but also will have a dramatic effect on industries that use by-products of meat production such as leather, and various natural animal-based ingredients for the cosmetics and chemicals industries, etc.

9.1.2 More detailed considerations

- **Food approval process**: given that the food approval process is one of the earliest steps where the producer seriously engages with the FSA it is the relevant starting point for the FSA to gather data or identify relevance and availability of data. While this is already part of the FSA processes, expansion of the FSA's remit, and the complexity of emerging food types may raise other legitimate factors that become increasingly important and therefore may need to carry greater weight in the FSA recommendations for approval decisions. These might include greater consideration of:
    - Details of manufacturing processes
    - Chemicals and other materials used in the process
    - Nutritional value and bioavailability of the products in question.
    - Any available data on mid- and long-term health risks of novel products particularly molecules from novel production processes or combination of molecules.
    - Sustainability claims data

Such engagement and the resulting data will help inform the requirements for design of robust approval processes that look beyond food safety, hygiene, and authenticity, and inform how to better integrate sustainability issues, nutritional value and long-term public health considerations into the food approval process. Furthermore, such a framework will also help support the regulation of food produced elsewhere in the world that may enter the UK food system either as food products or ingredients. This will enable the FSA to balance the industry push for rapid and easier access to market for their products vs. public health and sustainability considerations.

- **Data gathering standards**: Establishing standardised data requirements for different processes and novel foods will be crucial for developing regulatory and monitoring processes such as the novel food approval or certification processes. Furthermore, this will give the industry clear guidelines on what factors they need to take into consideration when they are preparing for launching new food products based on novel proteins, potentially leading to more transparency on nutritional and sustainability data from the industry.

- **Certification, monitoring, and audit of novel processes**: Building the framework and considering the requirements from a knowledge and skills perspective for the FSA to be able to carry out certification and audit of novel processes is another step which will require engagement with the industry and establishing requirements for data provision and transparency. This will open different possibilities:

    - Considering waste food or waste raw material from other parts of the industry as feed/substrate for fermentation processes, feed for insect production and other possible uses to increase circularity in the industry.

    - Defining metrics and evaluation methods for sustainability and criteria for data collection by the industry. LCAs across complex supply-chains are time-consuming and expensive to undertake, therefore the FSA and DEFRA will need to ensure a balanced approach to measurement, focusing on materiality, to ensure adequate depth of data for meaningful decision-making, without burdening the industry with unduly excessive reporting requirements.

- Potential for creating differential regulation for different novel proteins based on available data and details of the production process.

- **Framework for labelling**: Standardisation of labelling requirements for novel proteins will help both the industry in better preparing for approval processes, as well as hugely help the consumers to make informed choices both on the relative merits of these alternative processed food options and sustainability impact of the food in question. Such clear labelling standards will also make it easier to manage and moderate marketing and promotion of such products and health and sustainability claims. This may also impact consumer trust and adoption of the novel foods.

- **Managing consumption**: Consideration of levers such as taxation and/or subsidies as well as potential other levers to encourage increased consumption of whole foods in the UK based on plants, or a shift further away from red meat and dairy towards lower impact meats. This can be combined with consumer education and labelling standards.

- **Reduction of food waste at consumer level**: Managing food waste at the consumer level in every kitchen and household is a challenge but offers significant potential to contribute to a sustainable food system. Taxation and higher prices are probably not enough to shift entrenched habits, so retailers may need to be incentivised with positive regulation or regulation demanding change to engage with consumers and help push for behavioural change at the household level.

9.2 FSA priorities for the short, medium, and long-term

New regulation will be required to facilitate safe uptake of some of these emerging technologies, to encourage investment, and provide consumer confidence for widespread acceptance and adoption in tandem with sustainability considerations.

As mentioned previously the interconnected nature of supply chains and industries means that the FSA would benefit from working with multiple stakeholders including regulators in other industries with direct or indirect impact on food supply chains. This means preparing the organisation to potentially go beyond the current defined boundaries of responsibility for food safety, authenticity and hygiene and take on a wider challenge of understanding and regulating novel foods resulting from rapid advances in technology with potential ramifications for human health as well as environmental and societal impact. There is also some urgency in bringing the required changes to the regulatory framework both from the perspective of the industry as well as the consumer where their interests may not necessarily be fully aligned. There are also other stakeholders' interests to consider such as the incumbent animal products producers, the historic scorecard of impact of processed foods on population health, the need for building more secure and resilient food supply systems, and environmental and sustainability considerations for food products entering the market in comparison with legacy items.

Furthermore, due to rapid advances in technology, not only the flow of new ingredients and products to the market will increase, but also the processes and technologies used to make these products will also continue to improve and change. This means regulation will likely need to be a dynamic and proactive process, where the FSA interacts continuously with the industry to design regulation that is fit for purpose, both recognising and enabling innovation in the industry, while protecting long-term interests of consumers in terms of health and sustainability of food systems.

Below we present suggested priorities for the FSA. Although not all these recommendations sit within the FSA remit, the FSA can play a role in supporting wider government, including the Department of Health and Social Care, and DEFRA, on these issues.

9.2.1 Short-term FSA priorities (within 3 years)

1. Considering the systemic nature of the challenges the food system faces:
    a. Food safety – Immediate impact of novel foods on health. Including allergies and intolerances; loss of nutritional value in extensively processed alternative protein sources.

   b. Food authenticity – Engagement with the industry to establish access and data sources.

2. Building further knowledge and expertise to address the emerging complexity of food production and supply:
   a. In-house expertise
   b. Expert networks
   c. Industry networks
   d. Access to ways of crowd sourcing of expert knowledge
   e. Direct relationship with consumers to understand their needs

3. Initiating the design and testing of new approval frameworks and processes for novel foods.

4. Building connections with regulatory bodies in other relevant industries.

9.2.2 Medium-term FSA priorities (3 to 5 years)

1. Understanding actual environmental and climate impact of novel protein sources – Establish measurement metrics.

2. Food authenticity – Ingredient traceability.

3. Continuous adaptation of testing and new approval frameworks for emerging novel foods.

4. Continuous relationship with regulatory bodies in other relevant industries:
   a. Lifecycle assessment of technologies used in food production
   b. Understanding the vulnerabilities of underlying technologies to system failure
   c. Managing impact of changes in food production patterns on other industries that use animal by-products

5. Managing industry expectations and lobbies in favour of a systems approach to regulation.

6. Considerations for creating a regulatory framework for demand management to reduce consumption of high calorie foods which will include animal proteins as well as highly processed foods.

7. Creating a framework for food security and supply resilience in an interconnected world.

9.2.3 Long-term FSA priorities (5 to 10+ years)

1. Understand impact of novel foods on health:
    a. Issues such as interference with metabolism leading to chronic illness
    b. Different types of tolerance and response in different individuals or sub-populations

2. Safeguarding industrialised food systems from system failure – In a scenario where over 50% of food is produced in industrial settings highly dependent on myriad external factors from energy to functioning artificial intelligence-controlled systems and dependence on specific ingredients, any shortage or failure in the system may lead to large-scale system failure.

3. Finding a balance between continuation of traditional agriculture and wholesale industrialisation of the food system. Traditional agriculture, although vulnerable to disease and weather conditions has up to now had high evolutionary adaptability.

4. Continuous adaptation and updating of regulatory framework for demand management to reduce consumption of high calorie foods which will include animal proteins as well as highly processed foods:

    a. Educating consumers, helping them to discern and find a balance between nutritional intake that is beneficial to health while minimising impact on the planet
    b. Limiting or removing advertising for certain food products that do not fulfil these criteria
    c. Imposing calorie taxes, both on the industry and possibly on the consumer

9.3 Limitations of study

Alternative sources of proteins are an emerging sector of the food system, developing rapidly within a dynamic innovation ecosystem of food technologies and services. This report is believed to have captured the most salient categories of protein sources immediately relevant to the UK food system and to the FSA. The findings reflect expert opinions on the risks and opportunities, and the implications for mass-market deployment, consumer acceptance, food safety and public health, sustainability, and regulation. However, there may be other technologies, and risks and opportunities, as of yet unrecognised. There are also still diverging opinions amongst experts, as the technological feasibility is often perceived differently depending on the awareness of the technology. Moreover, this report focused specifically on emerging trends, whereas a holistic assessment of protein diversity by placing alternative proteins within the full spectrum of existing proteins might also be beneficial.

Quantitative and qualitative assessment of the relative merits of the alternative sources has been presented based on the available literature, but this is an emerging field of research, and detailed quantitative data such as LCAs and their boundary definitions, and comparable data across all categories of proteins are limited to date. Moreover, the proprietary nature of many of the emerging products will continue to make accurate comparisons somewhat difficult even as the field evolves. This report has attempted to prioritise the emerging alternative protein sources based on the available information, but this should be viewed as guidance only. More in-depth study is needed to more precisely determine the profiles these alternative sources of protein represent, and to develop detailed regulatory responses to ensure safe introduction across industry and society.

9.4 Recommendations for future research and analysis

The emerging field of alternative proteins is broad and the understanding of nutrition and health implications, environmental sustainability, and potential impact on food systems are currently at an early stage. As discussed in this report there are significant gaps in the available data, and further research is urgently required to expand the evidence base to enable informed decision-making. Suggested areas of research presented here summarise and build on comprehensive recommendations previously identified by Santo et al., (2020).

9.4.1 Food safety and public health

- Epidemiological studies examining how consumption of the alternative proteins, in various patterns, impacts diet quality, chronic disease biomarkers and the gut microbiome, in comparison with farmed animal meats and minimally processed/whole foods.
- Whether and how the nutrient profiles (including macro and micronutrients, fatty acid profiles, inflammatory compounds, allergens, etc.) of alternative protein products might differ from those of conventional animal protein.
- Detailed assessment of potential food safety risks and food fraud related to authenticity and traceability arising from novel production processes that are yet to enter the UK market, and identification of potential mitigating strategies such as new quality control procedures, use of biomarkers, sensors and novel detection technologies, and new monitoring regimes. Although this is part of the Novel Foods approvals process it may be beneficial for the FSA to initiate assessment in advance of formal applications to be better prepared.
- Geographic tracking of the production and processing locations for alternative proteins as ingredients and food products, and international trade and distribution to understand the potential impact and risks of overseas innovations and how and where they may enter the UK food system.

9.4.2 Environmental sustainability

- Comprehensive, multi-product life-cycle assessments comparing the different alternative proteins to reduce cross-study methodological inconsistencies. This should include development of a sustainability data presentation framework, specific functional units of analysis, and detailed breakdown of environmental footprint by energy use, emissions type, land and water use, eutrophication, biodiversity impact, deforestation, pesticides use, etc.

- Identify current metrics and standards in use in other parts of the world by regulators or industry (if they are) to inform development of UK framework for the development of standards to support regulation for sustainability.
- Sensitivity analysis to explore how environmental impacts may vary depending on the choice of feedstocks and production inputs, sources of energy, operational scale, geographical location, post-processing requirements, composition of final food products, and other factors that may materially affect sustainability performance.
- Ongoing LCA activities and dynamic modelling to stay abreast of technological developments and scaling of operations to generate and maintain up-to-date life-cycle inventory data (at present much of the modelling is based on hypothetical, or prototype-scale data only). Policymakers will need to explore how best to access and share such data and appropriate levels of reporting disclosure given that much of the needed information resides within companies' proprietary processes.
- Research on the safety of a fully circular food-system and the potential implications of non-intentional components that may be present and their accumulation to gain a better understanding of use of suitable waste streams.

9.4.3 Economic factors

- In-depth economic analysis of the cost of alternative protein sources, affordability, and implications for accessibility, and how these may change over time due to scaling of operations, availability of feedstocks and ingredients, production location, and other factors.
- Assessment of the role of alternative proteins as drivers of any observed shifts in meat consumption and animal farming (are they substitutive or do they lead to additional overall protein intake), and further assessment of the factors that might affect consumer willingness to make a permanent shift to these alternatives.
- The socioeconomic and employment implications of a significant decrease in industrial livestock production on agricultural/rural communities, animal processing, and related industries that use and depend on non-edible animal by-

product streams, such as pharmaceutical, cosmetics, leather goods, wool and clothing, pet food, and other areas of agriculture.

- Exploration of ways in which small and mid-sized producers could participate in the transition towards novel protein sources, biosynthesis of proteins, and cultured meat production, including the potential for distributed mini/micro-scale bioreactors.

9.4.4 Sociocultural factors

- Exploration of the potential role for proactive consumption demand-management strategies to partially address the forecast challenges in meeting demand for protein over the coming decades (to address currently high levels of consumption in many western countries). Also, assessment of the potential for rebound effects, whereby availability of alternative proteins gives consumers license to consume more and drives additional excess consumption.
- Further exploration of the disparity between consumers' willingness to try alternative proteins (and concerns over health and the environment), versus actual adoption of healthier/more environmentally friendly alternatives as a regular part of their diets.
- Understanding of the impact of different technological solutions and their affordability, and potential for creating dietary and societal inequities.
- Consumer perceptions of and knowledge of alternative proteins and their attributes, and reactions to labelling, marketing, and counter-marketing messages.

9.4.5 Policy and regulation

- Ongoing monitoring of technological innovations and evolving regulation and food agency approvals for emerging alternative protein sources around the world to understand and predict the potential future implications for the UK market.
- Examination of the emerging market dynamics in the food sector, the rise of well-funded start-ups, control of proprietary data and knowhow and the potential for monopolistic practices, and the anticipated response of vested interests in the current agricultural system. Exploring how best to regulate this emerging

market to ensure a competitive marketplace that serves the interests of consumers and public health, and society, not just the interests of big business.

- Exploration of whether and how to support or restrain the broader adoption of the various alternative proteins in the UK market (to align with public health, net-zero, and other environmental and social objectives), and identify priority areas for intervention through legislation, taxation (including carbon tax), subsidies, industry directives, and public education and awareness raising.
- Analysis of how the net-zero transition objectives and different GHG reduction policies such as carbon tax could impact the pricing, availability, and consumption of farmed animal meats and their alternatives.
- Analysis of the potential shape and scale of the societal transition that a shift away from livestock farming may entail, and how best to manage the transition from a policy perspective. Research might explore lessons learned from previous agricultural transitions to inform the development of policies to support farming, meat processing, and related sectors in transitioning to other livelihoods. There may be parallels with the ongoing digital transition that may also be informative for policymakers.

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