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This report focuses on the following United Nations Sustainable Development Goals: goal 3 (good health and wellbeing); goal 12 (responsible consumption and production); goal 13 (climate action).

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Foreword

When I started as a university student, the Club of Rome had just released its famous report 'Limits to Growth'[1], suggesting that without major changes in resource use and environmental impact, an uncontrollable decline in population and industrial capacity was likely. I remember the impact it had on society, as well as on me personally. This impact was compounded by the fact this was a time of a global food crises, resulting in concerns about our ability to feed everyone on the planet. At that time, the world population was less than half what it is today. Remarkably, despite this doubling of the population, hunger on a global scale has decreased since then. However, food insecurity remains an important issue to solve.

In addition to this existing issue, new challenges associated with the negative impact of food production have come to the fore in recent decades. Think of biodiversity loss, land and water use, deforestation, and the greenhouse gas emissions associated with agriculture and livestock farming. Since meat production in particular has a large greenhouse gas footprint, increasing attention is being paid to possible *meat alternatives*. These include both plant-based substitutes as well as insect-based products, fermentation products, and cultivated meat.

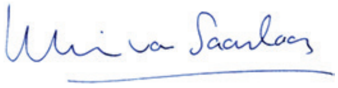
But what is the viability of such alternatives—what are the technical challenges of some of these? What are the prospects to scale up the production so that they really can provide a significant fraction of our food? What is the environmental footprint of some of the alternatives? Which alternatives really contribute to a healthy diet? What are the safety concerns? And to what extent will consumers' attitude affect the acceptance of new product alternatives?

This EASAC report aims to answer such important questions. It reviews the various meat alternatives and assesses the scientific, technological, societal, and regulatory developments of such products. The report shows that, indeed, several meat alternatives do potentially have a lower environmental footprint than conventional meat, particularly when compared with beef production. Distinguishing between the various alternatives, the study concludes that plant-based meat alternatives may in fact have the lowest land and water use requirements, that insects and microbial fermentation provide efficient protein sources with minimal environmental impact when using sustainable feedstocks, and that cultivated meat could potentially offer sustainability benefits. But in practice, as the report convincingly shows, when we weigh in other aspects, such as human health and nutrition impact, consumers' attitudes, technological and economic challenges and opportunities, as well as regulatory and policy aspects, the picture becomes much more nuanced.

This report is launched at a timely moment when the Danish presidency of the European Union is addressing an EU Action Plan for Plant-Based Foods and an EU Protein Strategy. Clearly, many of the issues addressed in this report are immediately relevant to the discussion about these initiatives.

EASAC's work relies on the input and contributions of Europe's leading scientists with a broad range of expertise and from many different disciplines; this also holds for the project that led to this report. The report is an evidence-based contribution to support European policy-makers and stakeholders—our hope is that it will help guide them in assessing and stimulating the most viable routes to meat alternatives, and in preparing for the necessary regulatory frameworks. To this aim, several clear recommendations are included.

I thank all the members of the Working Group who generously gave their time to make this project a success and to write such a comprehensive report. I also express my gratitude to COFRA Philanthropy for generously supporting the Meat Alternatives project with a donation, without any strings attached other than that we report on the outcome.



Wim van Saarloos
EASAC President

[1] https://www.clubofrome.org/publication/the-limits-to-growth/

Executive summary

This report aims to assess the scientific, technological, societal, and regulatory developments in meat alternatives defined as products (plant as well as non-plant-based) aiming at mimicking meat in terms of technical features (e.g. taste, texture, appearance) and sometimes nutritional properties. The report evaluates the following categories of meat alternatives as potential alternatives to conventional meat: plant-based alternatives, insect-based proteins, biomass fermentation products, precision fermentation products, and cultivated meat.

The report was prompted by earlier EASAC work calling for a better assessment of the scientific evidence around the potential benefits and challenges of innovative foods in the context of the current climate change crisis, and its implications for health (EASAC 2019).

Key objectives of the report are as follows:

- To assess the impacts of different meat alternatives (environmental impacts of production, human health impacts of consumption, ethical impacts) compared with conventional meat production.
- To understand consumers' attitudes and acceptance of meat alternatives.
- To identify technological and economic challenges and opportunities related to scalability, cost, and production methods.
- To review the existing regulatory frameworks and policy implications in the European Union (EU).
- To provide recommendations for improving transparency, sustainability, and responsible innovation in the sector.

While several aspects of this report may have implications for human diets, it does not focus on these aspects and does not aim to provide dietary guidance.

Key findings

The transition to meat alternatives presents significant opportunities and challenges. While some meat alternatives (and alternative proteins) may offer potential environmental, health, and ethical benefits, careful consideration is needed to ensure their sustainability, affordability, and accessibility.

1 Environmental impacts

- On the basis of current knowledge and estimations, some meat alternatives have a lower environmental footprint than conventional meat, particularly when compared with beef production.
- Plant-based meat alternatives may have the lowest land and water use requirements but this varies depending on their processing intensities.
- Insects and microbial fermentation provide efficient protein sources with minimal environmental impact when using sustainable feedstocks (e.g. waste streams and side-streams).
- Despite controversies, cultivated meat could potentially offer sustainability benefits, especially when compared with beef. Given that cultivated meat as well as precision fermentation may have high energy demands, the potential environmental benefits of these technologies would depend on the optimisation of renewable energy sources.

2 Human health and nutrition impacts

- Plant-based and microbial protein alternatives can have an adequate nutritional composition although the bioavailability of some micronutrients remains a concern. However, the impact of nutrient intakes depends on the overall diet rather than on the consumption of specific products.
- Some highly processed plant-based products may contain high levels of salt, saturated fat, and additives, raising concerns about their long-term health effects.
- Insect proteins are a rich source of high-quality protein (comparable to that of conventional meat), vitamins, and minerals and they provide highly bioavailable iron and zinc, but they pose potential allergenicity risks for some consumers.
- Products of biomass fermentation may have high protein content and beneficial micronutrients, but the contents are product-specific and due attention needs to be given to potential allergic reactions. Likewise, precision fermentation products can have tailored ingredients to enhance health benefits, including vitamins, antioxidants, and probiotics, but their safety and potential to induce adverse reaction, including allergic reactions, need to be considered.
- Cultivated meat could theoretically be engineered to have the same nutrient composition of conventional meat or even to create leaner meat (with reduced fat content and potentially healthier),

but long-term health impacts are still uncertain because of limited market exposure and limited knowledge for this technology.

3 Consumer attitudes

- Consumer acceptance of meat alternatives varies across demographics, with younger, urban, and environmentally conscious consumers and/or consumers concerned about animal welfare more open to meat alternatives and alternative proteins, with some variations across countries and other preferences.

- Naturalness is another key driver of consumer's acceptance of meat alternatives, which explains why some consumers are more likely to accept known products such as plant-based alternatives.

- Taste, texture, and price competitiveness remain major barriers to widespread adoption of meat alternatives, with safety being a prerequisite.

- Regulatory uncertainties, lack of trust in the food tech industry and labelling issues could influence the uptake of meat alternatives and consumer trust.

- Consumer awareness campaigns and transparent labelling are critical to fostering informed choices.

4 Technological and economic challenges and opportunities

- While the market for plant-based meat alternatives is well developed, the simulation of the features of animal meat (e.g. taste, texture) is particularly challenging and often involves the use of additives that give raise to potential health concerns. Hybrid products (blending plant and animal proteins) are emerging as a transitional approach to encourage adoption while maintaining the affordability and familiarity of the products as well as recreate some of the characteristics of meat.

- Insect-based proteins face challenges related to the digestibility of products and the need to remove or reduce chitin as well as limitations to achieve economies of scale by small companies without vertical integration.

- Precision fermentation and microbial proteins offer promising solutions but need sustainable feedstocks and improved waste management.

- Cultivated meat faces scalability hurdles, including high production costs, a specific business model, complex infrastructure requirements and question marks about waste management.

5 Regulatory and policy considerations

- The EU Novel Foods Regulation governs most meat alternatives (and alternative proteins), requiring sometimes lengthy and complex approval processes. The EU Food Information Regulation aims to ensure the provision of clear and accurate information about food products to consumers and applies to meat alternatives.

- Labelling restrictions and consumer transparency are key issues for all meat alternatives.

- Trade policies and international regulatory harmonisation will also shape the industry's future growth and competitiveness.

- Farmers and rural communities may face economic and social challenges as the meat alternatives industry evolves, highlighting the need for transition strategies and policy support.

Recommendations

Policy-makers, industry stakeholders, farmers, researchers, and consumers must collaborate to develop transparent regulations, invest in innovation and fair communication, and ensure consumers are empowered to make informed dietary choices. As new technologies and products emerge, continued research and proactive policy measures will be essential to shaping the future of sustainable protein production as well as the involvement of all key stakeholders.

Transparency and labelling standards

1. Increase transparency of all production processes and their assessment by independent third bodies.

2. Mandate clear nutritional labelling, including macronutrients, micronutrient content, and food processing levels.

3. Involve stakeholders to ensure that transparency and food labelling regulations include relevant information for consumers in an adequate way.

4. Implement standardised sustainability metrics (e.g. carbon footprint, water use, ingredient sourcing) and ensure transparency about the use of genetically modified organisms, animal-derived inputs, and ethical sourcing.

Health and nutrition guidelines

1. Regulatory frameworks should encourage manufacturers/producers to enhance the nutritional quality of meat alternatives.

2. Clear policies should guide the fortification of plant-based and microbial protein products to mitigate potential deficiencies.

3. Governments and health organisations should support longitudinal studies assessing the long-term health impacts of meat alternatives.

Environmental sustainability standards

1. Standardised, transparent, and updated life cycle assessment methodologies should be implemented to assess environmental impacts across production systems.

2. Meat alternative production facilities should be encouraged to use renewable energy sources to minimise their carbon footprint.

3. Comparison between products should be conducted when the same type of energy is used.

4. Side-streams from agriculture and food industries should be leveraged as feedstocks for microbial fermentation and insect farming.

5. Manufacturers of meat alternatives and livestock producers should assess the sustainability of their processes.

Consumer information and awareness

1. Governments and industry stakeholders should invest in initiatives to inform consumers to improve understanding of the benefits and trade-offs of different meat alternatives.

2. Nutrition authorities should provide evidence-based recommendations on integrating meat alternatives into balanced diets.

3. Public institutions should work to combat misinformation about meat alternatives as well as conventional meat production, so that scientific evidence drives consumer perceptions.

Regulatory frameworks and policy support

1. The EU should continue to streamline regulatory approvals for novel foods while maintaining high safety and sustainability standards.

2. Public funding should support research into cost-effective production methods, scalability, and improved nutritional quality of promising meat alternatives.

3. Policies should help livestock farmers adapt to changing markets for meat alternatives and alternative proteins when needed.

4. Concerns about meat alternatives should be raised in policy debates on the basis of sound science rather than opinions.

5. Food security and food diversification debates should include consideration of meat alternatives.

Ethical and societal considerations

1. Policies should recognise the varying dietary needs, culture, traditions, and economic conditions across different regions and their implications in the uptake and acceptance of meat alternatives and conventional meat among different groups of stakeholders.

2. While reducing reliance on conventional meat may benefit animal welfare, attention must also be given to ethical considerations in insect farming and ethical issues raised by cultivated meat relying on animal cells.

3. Governments should explore grants and other potential incentives to overcome some of the challenges of sustainable meat alternatives.

MEAT ALTERNATIVES

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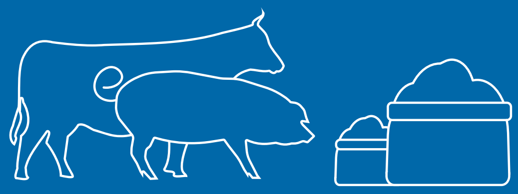
Main drivers for the EU to act:

>50% — **Carbon footprint of food consumption** due to livestock production

≈ 48% — **Environmental footprint of consumption** due to food consumption

>40% — **Biodiversity loss** due to food production

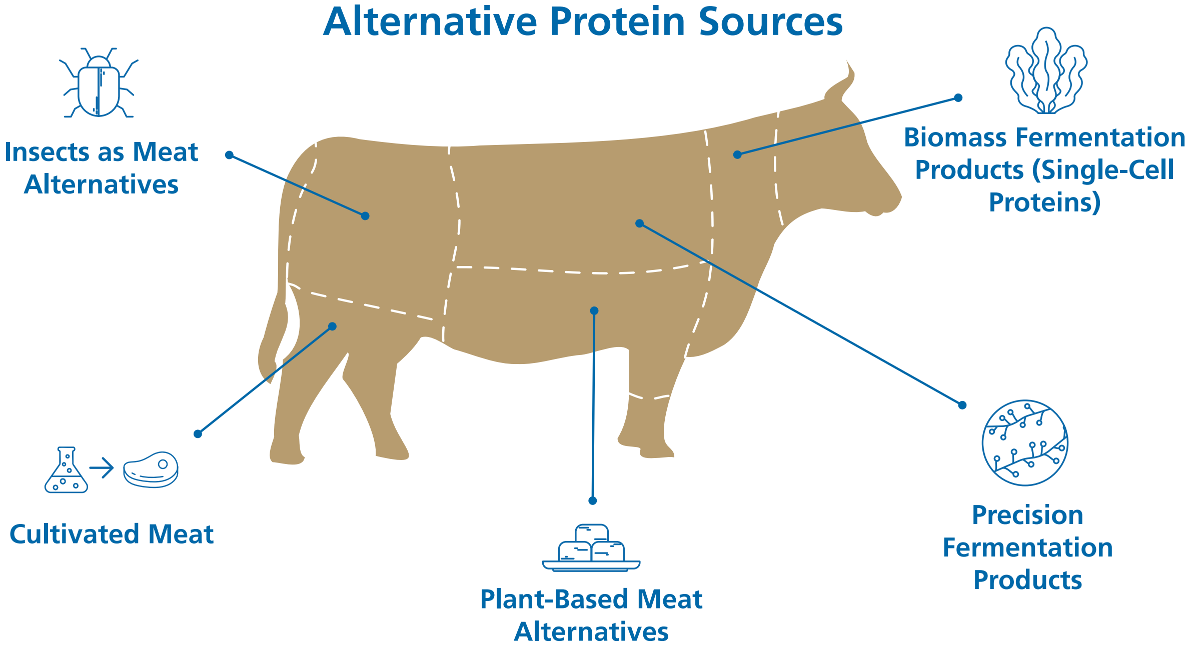


Total **annual consumption** of **feed protein** for livestock production in the EU (2023-2024):

72 million tonnes

¼ being imported

Alternative Protein Sources



Recommendations

1. Raise consumer awareness
2. Adopt health and nutrition guidelines
3. Introduce environmental sustainability standards
4. Create framework for innovation
5. Pay attention to ethical considerations
6. Increase transparency

1 Introduction

1.1 EASAC's involvement in meat alternatives

The EASAC report on Climate Change and Health (2019) suggested that, in answering questions about the benefit for the climate of reducing livestock production, there is a need for further work on innovative foods, noting that '… research and development opportunities for meat substitutes as innovative foods and other "future" foods (e.g. from insects, algae and seaweed) are worth pursuing, alongside clarification of the associated socio-political and regulatory challenges' (EASAC 2019).

A range of meat alternatives are currently being commercialised or developed in some countries with the expectation of contributing to reducing meat consumption, especially in the developed world. 'Meat alternatives' are sometimes broadly defined to encompass plant-based as well as non-plant-based alternatives (Van der Weele *et al*. 2019), and at other times defined as plant-based alternatives only (Thavamani *et al*. 2020). Definitions can also vary as to whether meat alternatives are only those produced by new technologies or also encompass new technologies as well as more traditional alternatives. However, it is often understood that meat alternatives are potential substitutes for animal-based products used for food and animal feed. At the European Union (EU) level, there is some overlapping with the more widely used term of 'alternative proteins' (EPRS 2024), but each term encompasses a different subset of products. This report uses 'meat alternatives' to encompass plant as well as non-plant products made with traditional or new methods, which are often processed with the purpose of mimicking meat in terms of technical features (e.g. taste, texture, appearance) and sometimes nutritional properties.

Reasons for the interest in and uptake of meat alternatives include claims that some of these alternatives may lead to environmental benefits, that they may bring health benefits, and concerns for animal welfare. This discussion is also important for broader issues such as the availability of food supply in light of available resources and growing demand (including future needs in the global south), regional and national food security concerns, and food source diversification to improve the resilience of food supply chains. While there may be other routes for the future, including revisiting current livestock production systems (EASAC 2022), this report focuses on the assessment of existing and emerging meat alternatives as defined above.

1.2 The food system, proteins, and conventional meat

With a growing world population estimated to reach 10.3 billion people in the mid-2080s,[2] challenges include feeding a growing world population as well as producing food (e.g. meat and other protein sources) in a more sustainable way. Although overall global food production could theoretically meet the current demand, issues such as lack of affordability, food waste, and logistic problems may result in further inequalities in food intake across countries and groups. Strategies to address these challenges are much broader than the scope of this report. More resilient food and agricultural systems are required to address both undernutrition and overnutrition, reduce food waste, allow a diversification of diets, and reduce the associated environmental damage of certain diets (EAT–*Lancet* Commission 2019).

This report focuses on a narrower set of challenges relating to protein production and consumption. These are crucial issues at global and EU levels. The protein intake levels in the EU are estimated to be 82 g per person per day. Of this, 49 g is from animal products and 33 g from plant products[3]. On average, according to the 2019 report of the Food and Agriculture Organization of the United Nations (FAO), an EU citizen consumed 22 kg per year of animal-based proteins and 16 kg per year of plant-based proteins (FAOSTAT 2018; Health Council of the Netherlands 2023). In addition to human consumption, proteins are an important component of animal feed; in the EU, the total annual consumption of feed protein for livestock production was 72 million tonnes in 2023–2024, which included proteins from plants and non-plant sources[4]. Despite the growing demand for food and proteins at the global level, it is also important to notice that in many developed countries the protein intake exceeds the protein requirements per kilogram of body weight (Joint FAO/WHO/UNU 2002).

To address some of these challenges, innovations to explore sources of alternative proteins are required, including meat alternatives that could have better health and environmental impacts while meeting food safety and quality standards.

[2] https://desapublications.un.org/publications/world-population-prospects-2024-summary-results
[3] Food balances (2010–). FAOSTAT https://www.fao.org/faostat/en/#data/FBS (2022).
[4] https://agriculture.ec.europa.eu/news/feed-protein-overview-eu-production-and-options-diversify-sources-2024-05-24_en

1.2.1 Meat and proteins

Access to adequate amounts of quality food is essential to maintain body composition and functions and to preserve health, and proteins are an essential element in a healthy diet. While there is a broad consensus about the importance of proteins in human diet as they perform critical functions for all living organisms, including humans, the optimal mix of proteins and other micronutrients that should be present in diets containing proteins from other sources beyond livestock meat is still being researched actively. There have been various attempts at global, EU, and national levels (Joint FAO/WHO/UNU 2002) to assess the impacts of protein intake[5] but these have not been exempted from criticism (Millward 2012). Box 1 provides an overview of some issues related to the estimation of optimal levels of protein consumption.

As a source of proteins, meat and animal-based products are high in protein and contain various essential nutrients for humans, including 'essential amino acids', those that cannot be synthesised by humans to meet their needs and thus need to be present in their diets, fatty acids (including the unhealthy saturated), polyunsaturated omega-3 fatty acids (especially eicosapentaenoic acid and docosahexaenoic acid in fish, and docosahexaenoic acid in eggs) and micronutrients (e.g. iron, zinc, selenium, iodine, calcium, folate, and vitamins B_{12} and D). Meat has also a high digestibility score (corrected amino acid score of 0.92) (FAO 2013).

In addition to being a good source of protein, meat consumption has been regarded as a contributor to human evolution and development (Van der Weele *et al*. 2019) and has played an important role from a cultural and social point of view in some regions of the world. This is, for instance, the case in Europe, where, despite the increasing popularity of plant-based sources of protein, meat and other animal products remain the main source of protein for most adults[7].

While globally most dietary protein comes from plants (57%) (mainly wheat, maize, and rice), in Europe, since the mid-1970s, animal sources have surpassed plants and it is estimated that around 55–60% of consumed proteins are of animal origin, with reported overconsumption of proteins in some parts of the world, including Europe (EPRS 2024; Joint FAO/WHO/UNU 2002). At the same time, consumers in Europe and worldwide are exploring alternatives and, in some cases, switching from meat to plant-based diets or other alternatives for various reasons (e.g. health, environment, and animal welfare concerns).

1.2.2 Environmental issues

Rearing livestock significantly contributes to climate change and environmental degradation. It is estimated that the release of greenhouse gases (GHG) throughout the livestock life cycle (including all processes from resource extraction up to waste management) accounts for a significant proportion of human-induced GHG emissions, ranging from 12% (see footnote[8]) to 14.5% (Gerber *et al*. 2013) or 19% (Xu *et al*. 2021). Greenhouse gas emissions from animal-based foods have been estimated to contribute 60% of the emissions from food systems at global level (Xu *et al*. 2021).

In the EU, food consumption has been estimated to contribute 48% to the total environmental footprint of consumption (Sanyé Mengual and Sala 2023), with

Box 1 Optimal protein consumption

- **EU-level references.** At EU level, the European Food Safety Authority (EFSA) developed a Scientific Opinion on Dietary Reference Values for protein, stating that 'an Average Requirement (AR) and a Population Reference Intake (PRI) for protein can be derived for adults, infants and children, and pregnant and lactating women' (EFSA Panel on Dietetic Products, Nutrition and Allergies 2012).
- **The population reference intake.** According to the EFSA, the Population Reference Intake for healthy adults of both sexes is 0.66 g protein per kilogram body weight per day on the basis of nitrogen balance data and the Population Reference Intake for adults of all ages is estimated to be 0.83 g protein per kilogram body weight per day (applicable both to high-quality protein and to protein in mixed diets). For children from 6 months onwards, age-dependent requirements for growth estimated from average daily rates of protein deposition and adjusted by a protein efficiency for growth of 58% were added to the requirement for maintenance of 0.66 g per kilogram body weight per day (EFSA Panel on Dietetic Products, Nutrition and Allergies 2012).
- **Health recommendations on protein intake** vary widely globally and across EU countries[6] as well as for specific groups such as athletes and those going through (peri)menopause (Simpson *et al*. 2022). For instance, protein requirements may increase slightly for those older than 65 years (0.9–1.2 g per kilogram of body weight per day) since muscle mass is harder to build and maintain (Hettiarachchi *et al*. 2024).
- **Countries translate requirements to national food-based dietary guidelines** and although most European countries implement EFSA nutrient requirements, the specifics of food-based dietary guidelines can differ, which will affect how much of each protein source people will consume.

[5] https://knowledge4policy.ec.europa.eu/health-promotion-knowledge-gateway/dietary-protein-health-effects-2_en
[6] https://knowledge4policy.ec.europa.eu/health-promotion-knowledge-gateway/food-based-dietary-guidelines-europe-table-8_en
[7] https://knowledge4policy.ec.europa.eu/health-promotion-knowledge-gateway/dietary-protein_en#nav_Tocch2
[8] https://foodandagricultureorganization.shinyapps.io/GLEAMV3_Public/

livestock products contributing approximately to more than 50% of carbon footprint even when they represent only about a quarter of total food consumed (Sanyé Mengual and Sala 2023). To reach the safe planetary boundary level designed by the Stockholm Resilience Centre[9] for climate change, it is estimated that the carbon footprint of food consumption in the EU would need to be reduced by 90%, or a target of carbon dioxide (CO_2) equivalent emission per citizen for food amounting to 350 kg (Sala *et al*. 2020).

Livestock rearing is also a major driver of environmental degradation, significantly contributing to deforestation, biodiversity loss, soil depletion, and water contamination. Agricultural expansion is responsible for nearly 90% of global deforestation, with livestock grazing accounting for approximately 39% of this deforestation[10]. The global food system is identified as the primary driver of biodiversity loss, with livestock production being a key factor, as it contributes to habitat destruction, overgrazing, and land degradation (Benton *et al*. 2021) and is estimated to contribute between 40% and 85% to the biodiversity footprint of consumption in the EU (Sanyé Mengual and Sala 2023). Among livestock products, beef, pork, and poultry are identified as the main contributors because of their high land requirements, deforestation impacts, and associated emissions. However, significant differences exist between the contribution of each product, with beef contributing much more than pork and poultry, and conveying the environmental impacts of livestock rearing remains a complex exercise (Manzano *et al*. 2023).

There may be ways to promote sustainability in the livestock sector, such as the use of side-streams from the food industry as feed and using manure as fertiliser of soils or as substrate for biogas production in anaerobic digesters, as well as a set of other regenerative agriculture practices (EASAC 2022). Additionally, animal feed innovations (e.g. alternatives such as insect-flour and others expanded on below) or other innovations (e.g. gene editing/animal breeding) may enable the tailoring of dietary components to ruminant physiology to reduce methane production (Smith *et al*. 2022). However, this report does not focus on these aspects.

From a societal point of view, there are signs of growing environmental awareness and a sense of urgency in the developed world where animal protein consumption is high. It has been estimated that halving consumption of animal-sourced food and choosing low-impact producers could lead to significant reductions of around 10 billion tonnes of CO_2 equivalent per year (Poore and Nemecek 2018). At the same time, newly emerging economies are expected to increase meat consumption as per past trends.

According to the EAT–*Lancet* Commission, a global transformation towards a healthier and more environmentally sound diet would require doubling the consumption of fruits, vegetables, nuts, and legumes and a reduction of foods such as red meat and sugar by more than 50% by 2050 (EAT–*Lancet* Commission 2019). Similar recommendations have been issued at national level in different countries within and outside the EU. For instance, in 2023, the Health Council of the Netherlands, as part of the protein transition, concluded that a shift towards a diet containing 40% animal and 60% plant-based proteins will not only benefit the health of most of the population, but also lead to environmental gains (Health Council of the Netherlands 2023). The UK's Climate Change Committee recommends a 20% reduction of meat and dairy products by 2030, with a further 15% reduction of meat products by 2050, emphasising the role of dietary changes and meat reduction in achieving net-zero emissions[11] and in line with the recommendations of the UK Climate Assembly of a 20–40% reduction in meat and dairy consumption by 2050.[12]

1.2.3 Health considerations

Metabolic and health benefits can be a strong motivation for consumers to reduce or replace meat consumption. Excessive consumption of red and processed meat has been associated with adverse health effects, for instance as a causative factor in colorectal cancer, or as contributor to obesity and cardiovascular disease because of high content of saturated fats and cholesterol (Qian *et al*. 2020; Papier *et al*. 2021; Health Council of the Netherlands 2023). Evidence is mixed, although there are clear associations between high meat consumption and disease risk, in particular for red and processed meats; there is also abundant evidence that more plant-based diets (such as the EAT–*Lancet* diet or vegetarian diets) tend to be higher in fruits, vegetables, and fibre, which are also protective against disease risk (Fogelholm *et al*. 2015).

On the other hand, research suggests that diets having lower environmental impacts (e.g. reducing animal protein intake) may increase the risk of inadequate iron, zinc, and vitamins B_{12}, A, and D (Beal 2024; Leonard, *et*

[9] https://www.stockholmresilience.org/research/planetary-boundaries.html
[10] https://unstats.un.org/sdgs/report/2024/Goal-15/
[11] https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf
[12] https://www.climateassembly.uk/report/read/final-report.pdf.

al. 2024); in particular, there is a risk of micronutrient deficiencies in vulnerable groups, such as women of fertile ages, children, and adolescents. However, most of the evidence is based on observational or modelled scenarios; and more studies will be needed to fully understand the health impacts of different diets in the long term.

Technically, the ability to synthesise meat and precisely engineer its composition opens the opportunity to adjust its composition, such as lowering saturated fats and cholesterol, and increasing certain micronutrients; however, several technical challenges remain (see section 6). Reduced livestock farming may also reduce the prevalence of animal pathogens and zoonoses and hence help to avoid excessive use of antibiotics in agriculture, a crucial issue for the One Health agenda to address concerns about rising antimicrobial resistance at EU and global levels. While excessive use of antibiotics in agriculture can also be addressed through changes in current livestock systems, this falls outside the scope of this report.

In addition, it has been proposed that reducing meat consumption can contribute to food security, especially for land-scarce countries. For instance, in Singapore the development of novel foods, including meat alternatives, has been stimulated by the government with the aim of improving food security (Stevens and Ruperti 2023).

1.2.4 Ethical and social considerations

Several ethical and social considerations need to be included in the assessment of conventional meat and meat alternatives. These include concerns about animal rights and welfare, justice, labour conditions in slaughterhouses, the (un)natural status of meat alternatives, the processing level of foods, the respect for autonomy, cultural appropriateness of food, and farmers' livelihoods and ways of life, among other issues. In addition, perspectives widely differ between countries and among the stakeholders involved in these discussions. To guide this complex discussion, this report uses an ethical matrix to map stakeholders and involved values (see section 7.2).

1.3 Regulatory and policy issues and relevance of this project in the EU

At EU level, the EFSA has a mandate on novel and traditional foods, conducting centralised scientific risk assessments on novel foods, with some meat alternatives falling under this framework. In addition, the EU Food Information Regulation EU/1169/2011 sets up rules on labelling that apply to all types of food, including meat alternatives (see section 7.4).

At EU level, the production and consumption of proteins raises issues of food security, environmental sustainability, energy costs, and social and economic impacts (Scarborough *et al*. 2023). Europe is a net importer of proteins, with estimates dating from 2021 that around 26% of proteins are imported, which raises issues of food insecurity. The European 'feed protein deficit' for animal feed adds another layer of complexity (Kim *et al*. 2019), and concerns have been increasing because of the war in Ukraine. There is also evidence of overconsumption of proteins in the EU (Mariotti and Gardner 2019; Joint FAO/WHO/UNU 2002) and most dietary proteins come from animal-based sources.

The need to stimulate the development and adoption of alternative proteins has been addressed in the EU Sustainable Food System legislative framework, the Farm to Fork Strategy, the circular economy principles in the Green Deal, and the revised EU Industrial Strategy, but while the European Parliament called the European Commission to present a EU Protein Strategy covering meat alternatives in 2023, no strategy has been presented so far, and the 2025 EU 'Vision for Agriculture and Food' does not indicate any planned work in this area[13].

Meat alternatives have been the object of wide debate, including at the European Parliament (ENVI Committee) in the context of EU funding to support projects related to cultivated meat. There has also been debate at the EU Council, and different Member States remain divided on these issues (see section 7.5).

The EU Research and Innovation Framework Programmes (Horizon 2020 and Horizon Europe) have supported projects looking at various technological, regulatory, and other aspects of different meat alternatives, and the EU's Farm-to-Fork Strategy recognises the need for research and innovation support for the development and uptake of alternative proteins (some of which fall under this report's definition of meat alternatives).

Summing up, there are reasons, including geopolitical, environmental, and ethical ones, to question the current means of production as well as levels of consumption of meat and proteins at global and EU levels. A different balance between plant and animal proteins and the use of alternative proteins, including meat alternatives, have been suggested as potential solutions to these issues. By looking into the available scientific evidence around meat alternatives to assess them compared

[13] https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/main-initiatives-strategic-dialogue-future-eu-agriculture_en

with conventional meat, this report does not necessarily argue in favour or against the use of meat alternatives compared with other available options.

1.4 Scope of this report

This report focuses on newer emerging technologies (e.g. cultivated meat, precision fermentation) as well as on some traditional meat alternatives (e.g. plant-based alternatives and products of fermentation), and alternatives that are not new to the world but may be new to the EU (e.g. insect-based proteins) to develop products mimicking meat in terms of taste, texture, and mouthfeel. The impacts of these meat alternatives are compared with conventional meat as defined in the EU (see definitions above). For the purposes of this report, meat alternatives include the following.

- **Plant-based meat alternatives**. While this category may include products such as tofu, which have been available in Europe for decades, as well as newer foods that incorporate other plant protein isolates (e.g. peas, lentils, rice), the focus of this report is on plant-based products mimicking meat.

- **Insect-based proteins**, including their direct consumption as well as the use of insect-flour for meat alternatives.

- **Biomass fermentation** 'leverages the fast growth and high protein content of many microorganisms to efficiently produce large quantities of protein'[14], such as mycoprotein (e.g. Quorn).

- **Precision fermentation** 'uses microbial hosts as "cell factories" for producing specific functional ingredients'[15]. For instance, microbes can be genetically modified to produce animal proteins, fats or collagen.

- **Cultivated meat**, also called cultured, cell-based, clean, or *in vitro* meat, is produced by cultivating animal cells in bioreactors, rather than by raising and slaughtering animals. We focus on cultivated meat products following the EU definition of meat, which excludes ratites and fish[16].

The use of technologies is not mutually exclusive, and while the above categories aim at helping a comparative assessment, there might be some overlap. For instance, ingredients made with fermentation or cultivated meat can help optimise plant-based meat products, precision fermentation can also help to produce nutrients and growth factors for cell culture media, and collagen or fibronectin produced through fermentation can also serve as animal-free components of scaffolding for more complex cultivated meat products.

There are also some indications of the interest in meat alternatives. The size of the market for global meat substitutes was valued at USD7.24 billion in 2024, and there are expectations that it will grow to USD16.13 billion by 2032, with a compound annual growth rate of 10.78% during this period. In 2024, Europe led the meat substitutes market with a market share of 42.27%.[17] Among the presumed reasons for this growth are the EU's progressive consumer preferences and strict food quality standards as well as the rising popularity of vegetarian and flexitarian diets. Countries such as Germany, the UK, and France have experienced significant declines in meat consumption, which makes them key markets for meat alternative products. In Germany, for example, meat consumption per person fell by around 4.2 kg from 2021 to 2022, to 52 kg.[18]

This report aims to help policy-makers understand the potential benefits and risks related to these products and the issues related with people choosing and being (un)aware of the impacts of meat alternatives, including the following:

- overall environmental impacts;

- human health impacts including nutritional aspects surrounding alternatives (e.g. calories or macro-nutrients, but also level of processing, bioavailability, and micronutrients);

- technological and production issues;

- regulatory and food safety issues, including labelling requirements and information given to the public;

- stakeholders' and especially consumers' perceptions of meat alternatives as well as other issues with impacts on the acceptability and potential uptake of meat alternatives;

- ethical and societal considerations as drivers of the switch to meat alternatives among consumers.

[14] https://gfi.org/science/the-science-of-fermentation/
[15] https://gfi.org/science/the-science-of-fermentation/
[16] While this report focuses on human consumption, meat alternatives are also considered for the purposes of animal feed, including for companion and pet animals.
[17] https://www.fortunebusinessinsights.com/industry-reports/meat-substitutes-market-100239
[18] https://www.ble.de/SharedDocs/Pressemitteilungen/DE/2023/230403_Fleischverzehr.html

While focusing on Europe, these issues are not unique to the region. There are other regions with significant growth, innovation intensity, and commercial production of these technologies (e.g. North America and the Asia–Pacific region) with many companies and startups already developing different meat alternatives. For instance, Singapore has played an important role as leader in the regulation and approval of some products such as cultivated meat (see Box 8).

The implications of this report may also be of interest to the wider scientific and policy community, given the relevance of the topic to climate change and biodiversity, food nutrition, and security. In addition, the possibility of reducing meat intake (including through flexitarian diets) raises key questions about these choices. While this report does not include the provision of dietary guidance for consumers, its conclusions can shed light on some of the questions about available meat alternatives and indicate knowledge gaps for further research and technological development.

Meat can also be replaced by foods that require no or limited processing, such as legumes and nuts; however, the focus of this report is on the assessment of meat alternatives as defined above.

2 Plant-based alternatives

Plant-based alternatives to meat and dairy products comprise a wide variety of products: from plants high in protein that are unprocessed or minimally processed, such as pulses, to processed products such as soy-based tofu and to highly processed plant-based products using biotechnology to mimic the taste and texture of meat and dairy products. This section focuses on plant-based meat alternatives based on plant protein extracts that are texturised to mimic meat (Figure 1), which means that they require some form of industrial processing. This definition and the products included in different studies can be very heterogenous and encompass a wide range of products, including some that are processed but incorporate the whole-plant product (bean burgers), some that are hybrid (such as meat balls with pulses used to reduce meat content), and some that contain some other animal proteins (e.g. eggs). This choice does not imply that other, less processed plant-based products may not have better health, environmental, or nutritional qualities; rather, it reflects the scope of this report and the adopted definition of meat alternatives. Some plant-based products produced with precision or other fermentation techniques (e.g. Impossible Burger umami taste) are included in the sections below.

Plant-based products such as tofu and tempeh were developed thousands of years ago; however, the plant-based meat industry in the USA flourished in the 20th century with several leading plant-based meat companies such as Morningstar Farms and Lightlife established in the 1970s–1990s, although Loma Linda Food Company, founded in 1933, started to produce meat analogue products prepared with soy and wheat earlier[19]. There was an acceleration from the 1990s, associated with technical and corporate consolidation in small market niches (during the 1990s–2000s), the presentation of alternative proteins as a 'solution' to climate change (2000-2013), and the acceleration of some market niches since 2013 (Mylan *et al*. 2023). Subsequently, the market expanded with new companies producing plant-based burgers and other products more closely resembling meat, such as the 2012 launch of Beyond Meat's chicken strips, and the 2016 launch of the Impossible Burger and the Beyond Burger[20].

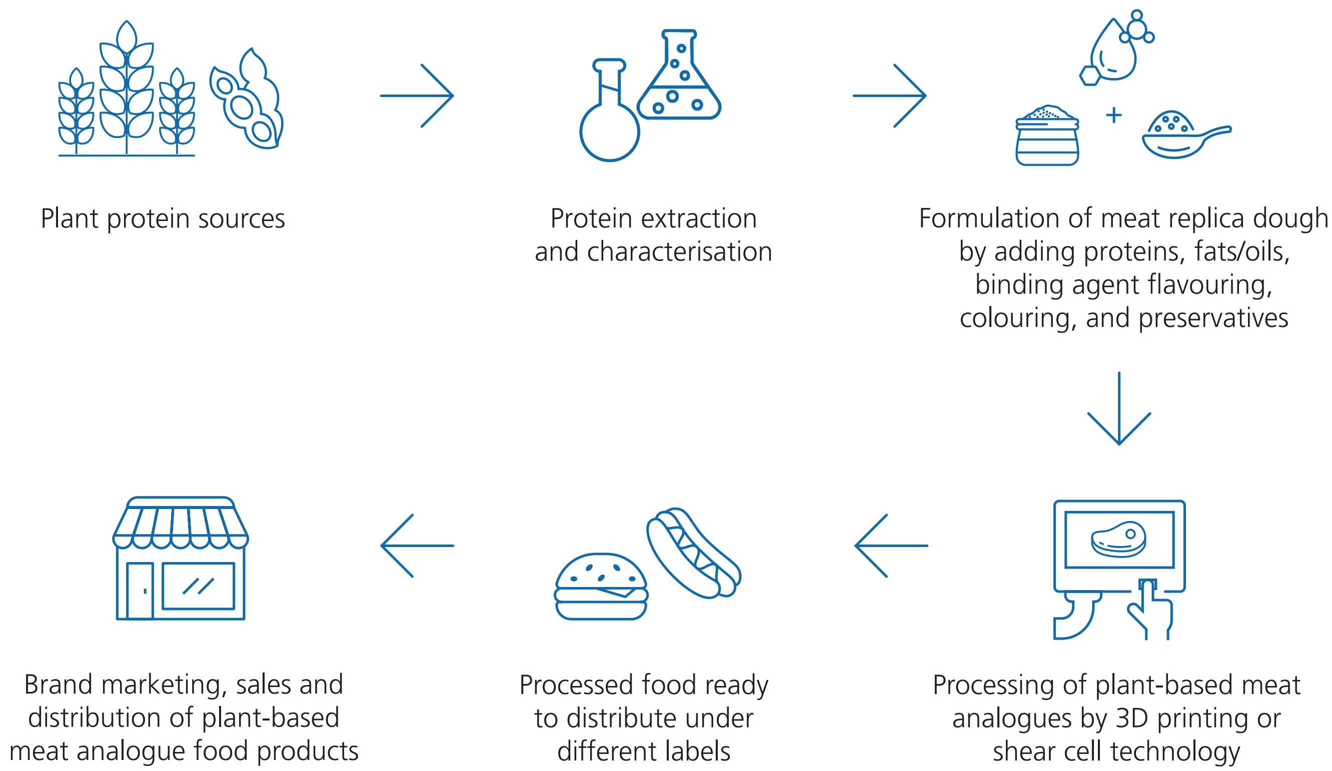


Figure 1 The production of plant-based meat alternatives.

[19] https://www.motherjones.com/environment/2013/12/history-fake-meat/
[20] https://gfi.org/plant-based/

Hence, today's meat alternatives differ from traditional whole food and fermented products such as tempeh in nutrient composition. While this may lead to issues, such as the potential accumulation of the anti-nutrient phytate with the consequent reduction in micronutrient bioavailability because of extraction of plant protein in today's products, depending on processing methods and fortification both traditional and modern products can have high bioavailability (Fredrikson *et al*. 2001). In addition, some studies have found that most commercialised plant-based products were classified as ultra-processed foods according to the NOVA system (Sultan *et al*. 2024) with some finding that products also contained higher amounts of salt (Rizzolo-Brime *et al*. 2023). However, the NOVA system has not been widely accepted as a suitable scale of food processing level (Braesco *et al*. 2022).

Most alternative proteins sources are currently plant-based, and it is expected that this trend will continue until 2030 (EPRS 2024). Box 2 provides a list of most plant proteins currently being explored/produced. However, it is worth mentioning the potential of breeding for new varieties optimised for protein production (Safdar *et al*. 2023). Plant varieties have been developed for other purposes, for example to produce oil or feed; and in the future, new varieties with lower contents of anti-nutrients and giving rise to less off-flavours could also be produced (see Figure 2).

2.1 Environmental impact and life cycle assessment

Despite some data gaps, evidence supports the environmental advantages of plant proteins, including plant-based meat alternatives over conventional meat, especially when compared with beef (Poore and Nemecek 2018; Smetana *et al*. 2023). Processing of plant-based meat substitutes and a longer list of ingredients, especially those of animal origin (e.g. eggs), generally increases the environmental impacts of the raw materials by 13–26% (Smetana *et al*. 2023). However, despite a significant increase with highly processed products, such as plant-based burgers, there are still environmental benefits to be accrued with the substitution of ground beef consumption (Goldstein *et al*. 2017).

Plant-based alternatives typically require less land and have lower carbon footprints, eutrophication, and acidification impacts than animal-based proteins (Poore and Nemecek 2018; Mazac *et al*. 2023). Nitrogen-fixing

Box 2 Plants used in plant-based meat alternative products

The following plant proteins are being explored[21]:

Pulses and legumes most widely used

- Faba bean: used in products such as Meatless Farm's Plant-Based Mince, which incorporates faba bean protein to mimic the texture of ground meat.
- Pea: prominently featured in Beyond Meat's Beyond Burger, where pea protein isolate serves as the primary protein source.
- Soy: used in products such as Tofurky's Plant-Based Deli Slices, offering a soy-based alternative to traditional deli meats.
- Lentils: incorporated into Amy's Kitchen's Veggie Burgers, which combine lentils with other vegetables and grains to create a hearty patty.
- Lupins: used in Lupii's Lupini Bean Bars, providing a protein-rich snack option derived from lupin beans.
- Chickpeas: found in Banza's Plant-Based Mac with Chickpea Pasta, offering a chickpea-based pasta paired with a plant-based cheese sauce.
- Mung beans: used in JUST Egg, a plant-based egg substitute that uses mung bean protein to replicate the texture and taste of scrambled eggs.

Underused legumes

- Mucuna, canavalia, winged bean, sword bean, velvet bean, jack bean: these legumes are currently under research for potential applications in plant-based products, although specific commercial products are limited at this time.

Proteins from oilseeds and other sources

- Canola (a variety of rapeseed): used in Puris Protein's Canola Protein Powder, which is incorporated into various plant-based meat products to enhance protein content.
- Pumpkin: featured in Superseedz Gourmet Pumpkin Seeds, offering a snackable source of pumpkin seed protein.
- Hemp: found in Tempt Hemp Tofu, providing a soy-free tofu alternative derived from hemp seeds.
- Sunflower: incorporated into Sunflower Family's Organic Sunflower Haché, a ground meat substitute made from sunflower protein.
- Potato: used in Lightlife's Plant-Based Burger, which combines pea and potato proteins to achieve a meat-like texture.
- Rice: used in Beyond Meat's Beyond Sausage, where rice protein is part of the blend used to replicate the taste and texture of pork sausage.

Proteins from grains:

- Oat: featured in Oatly's Oatgurt, a plant-based yogurt alternative made from oat protein.
- Gluten (wheat): used in Field Roast's Celebration Roast, which uses vital wheat gluten to create a firm, meat-like texture.

[21] Of those, faba bean, pea, soy, and proteins from grain are most important from a Nordic perspective, while proteins from rice are not considered as that crucial.

	Plant-based meat	Cultivated meat
Colour	Heat-stable fruit and vegetable extracts (e.g. apple extract, beet juice) or recombinant haem proteins (e.g. leghaemoglobin) are used as colour additives.	Colour can be regulated by supplementation of extracellular haem proteins (e.g. myoglobin) or by increasing intracellular expression levels.
Texture	Next-generation products include visible plant-based fats (e.g. coconut oil, cocoa butter) to emulate animal-based fat marbling.	Animal cell-based fat can be produced by culturing and differentiating fat cells (i.e. adipocytes). Skeletal muscle and adipose tissue could be grown together or combined post-harvest.
Structure	Fibrous structure of plant proteins can be generated by twin-screw extrusion or shear cell technology. Fungi-based products can have inherent fibrous structure.	Muscle fibre structure can be controlled by eliciting cell alignment during differentiation and employing aligned scaffolds.

Figure 2 Plant- and cell-based approaches to meat production. Based on Rubio et al. (2020).

legumes also provide environmental benefits indirectly as they help to reduce the nitrogen fertiliser inputs for the following crop in a crop rotation. On the other hand, for livestock, there may be some benefits to use lands such as natural pastures in the mountains in which no crops are possible, such as the conversion of natural grass into meat and milk (Mottet *et al*. 2017).

The water footprint of nuts can be higher than that of some livestock products, depending on the production region (Smetana *et al*. 2023; Poore and Nemecek 2018). Similarly, rice produced in flooded systems has a relatively high water footprint. For other, plant-based ingredients, such as legumes and grains, the water footprint varies depending on the type of crop, production system, and region. Again, the overall environmental impacts of plant-based meat alternatives depend on the different proportion of plant-based and other products used.

2.2 Impacts on human health

2.2.1 Health impacts of plant-based meat alternatives

Plant-based alternatives often vary in nutrient profiles compared with conventional animal products. When evaluating their nutrition and health implications, it is important to highlight the differences between whole-plant foods (e.g. pulses, tofu, tempeh) and highly processed meat analogues (e.g. plant burgers made from pulses or tofu with other ingredients).

Plant-based meat alternatives are generally produced by extracting protein from plants and texturising it to resemble meat. This means that, although plant-based diets tend to be lower in saturated fats and cholesterol, some plant-based processed foods such as meat analogues made from extracted and texturised plant proteins are classified as highly processed foods. While no epidemiological studies have assessed the long-term health of these highly processed meat analogues, concerns have been raised about their nutritional quality, with certain products exhibiting high levels of salt and saturated fat (Mayer Labba *et al*. 2022) and other consequences such as the by-products of the processing that could potentially affect micronutrient bioavailability. In addition, plant-based diets are not always associated with higher quality or affordable diets (Leydon *et al*. 2023).

Highly processed plant-based products may also have different health impacts depending on the processing methods used. For instance, during protein isolation, soluble compounds are reduced, while compounds with a high affinity for proteins (such as phytates and saponins) may become enriched, leading to differences between plant protein varieties (Subasi *et al*. 2024).

One concern with this process is that phytate, a potent mineral absorption inhibitor (i.e. an inhibitor of the absorption of iron and other minerals), accumulates in the protein fraction. Hence, the protein isolation process may affect both flavour as well as nutrient composition. Iron is a nutrient of particular concern since there are two factors in meat and fish that are beneficial for iron uptake: the content of haem-iron, which is easily absorbed and the so-called 'meat factor' which promotes the iron absorption from the entire meal (Hallberg and Hulthén 2000; Hurrell *et al*. 2006).

A study comparing vegan and vegetarian burgers found significant variations in nutritional parameters, depending on the ingredients and formulations used (Boukid and Castellari 2021). Additionally, a risk-ranking analysis of chemical hazards in plant-based burgers highlighted the influence of recipe formulations on potential health risks (van Asselt *et al*. 2024).

A study of 44 meat substitutes in Sweden found that 59% of the products contained at least 2.1 mg of iron per 100 g (not meeting the threshold for a nutritional claim as it is not available to the body), yet none had a phytate/iron (Phy/Fe) ratio below 1, meaning the iron was poorly bioavailable (Mayer Labba *et al*. 2022b). For reference, the EFSA allows a nutritional claim on iron to be included in a product (for iron when this contains more than 2.1mg per 100 g) if the nutrient for which the claim is made 'is in a form that is available to be used by the body' is fulfilled. This suggests a serious issue with highly processed plant-based meat analogues which needs to be addressed.

Fermentation, hydrothermal treatment, and other processing techniques that reduce phytate content could provide possible solutions to enhance iron bioavailability by reducing anti-nutritional factors such as phytates (Brune *et al*. 1992; Scheers *et al*. 2016; Parodi *et al*. 2018).

2.2.2 Evidence from studies on the health impacts of plant-based diets

Plants have been a major source of proteins for centuries in many populations throughout the world. Examples of these food sources include pulses (legumes, soy), tree nuts and peanuts (groundnuts), and grains. Plant-based diets have been defined in various ways, including vegetarian, vegan, lacto-ovo-vegetarian, and pesco-vegetarian diets and through a Plant-Based Dietary Index score (WHO 2021). More recently, the literature has been using the term 'planetary health diets' to describe more healthy sustainable diets that are plant-based but which may contain some animal-source foods including meat (EAT—*Lancet* Commission 2019). Systematic reviews have been conducted on (observational) prospective cohort studies about the associations between adherence to plant-based diet patterns and various disease outcomes. A summary of some of these studies is presented in Box 3.

While this section briefly examines some of the evidence about the health impact of plant-based diets, it should be highlighted that plant-based diets are whole diets, and may encompass different types, such as vegan, vegetarian, or even flexitarian diets. On the other hand, plant-based meat alternatives are products, and their overall health impacts depend on the effects of their plant components as well as on the impacts of the other ingredients (e.g. salt, fats) and by-products of their processing.

2.2.3 Evidence from studies on nutrients in plant-based diets

Dietary modelling research suggests different dietary ranges of plant-based protein intake that can meet nutrient requirements. A summary of studies assessing optimal plant-to-animal protein ratios is provided in Table 1. However, studies have not yet been performed to understand the clinical outcomes.

Among these studies, there are only a few controlled trials investigating the nutritional effects of replacing animal proteins with plant proteins. In Table 1, the only randomised controlled trial found that partial replacement of animal-source proteins with plant proteins led to decreases in vitamin B_{12} and iodine levels, while iron status remained unchanged, highlighting the need for those following vegetarian, vegan, or flexitarian diets to ensure adequate micronutrient intake (Pellinen *et al*. 2022). Since study participants were not allowed to use dietary supplements, and as the use of supplements can be crucial for these diets, the results call for clear dietary guidelines for consumers. Another randomised controlled trial found that a behavioural programme involving free meat substitutes could help to reduce meat intake (Bianchi *et al*. 2022).

Likewise, a recent study of 3099 adolescents using data from the Swedish dietary survey Riksmaten Adolescents 2016–2017 found that females with a more climate-friendly diet and lower intake of red meat/haem-iron had a higher prevalence of iron deficiency than females with a higher dietary climate impact (Hallström *et al*. 2025). Furthermore, the Iron Insight study performed in October 2023 of 475 high school students in Malmö found a higher prevalence of iron deficiency among Swedish teenage girls adhering to plant-based diets (Stubbendorff *et al*. 2025).

Some of the evidence above suggests that transitioning to plant-based diets requires careful planning to prevent nutritional deficiencies, particularly among populations with higher nutritional needs, such as women of reproductive age (especially pregnant women), children, adolescents, the elderly, and people with specific conditions or diseases.

Box 3 Summary of evidence of health impacts of plant-based diets

Plant-based diets

- Meta-analyses of cohort studies showed that increased adherence to plant-based diets was significantly associated with decreased all-cause mortality (Jafari *et al*. 2022). Significant inverse associations were also found with mortality from coronary heart disease but not with mortality from cardiovascular disease or other causes of death (Jafari *et al*. 2022). Meta-analyses of cohort studies showed a significant inverse association between plant-based diets and the risk of disease (incidence), of cardiovascular disease and coronary heart disease (Gan *et al*. 2021), type 2 diabetes (Qian *et al*. 2020), and gastrointestinal cancers (Zhao *et al*. 2022).
- Systematic reviews and meta-analyses of randomised controlled intervention trials on the effects of plant-based diets on intermediate outcomes suggest beneficial effects of plant-based diets on LDL-cholesterol levels, systolic and diastolic blood pressure, and body weight (Medawar *et al*. 2019; Gibbs *et al*. 2021; Remde *et al*. 2022). A meta-analysis on intervention studies with markers of bone health as an outcome found no differences between soybean protein and animal protein (Shams-White *et al*. 2018).

Vegetarian diets

- Meta-analyses found inverse associations with a combination of multiple health outcomes (Oussalah *et al*. 2020), mortality from cardiovascular disease and coronary heart disease, risk of diabetes, and risk of colorectal cancer (Huang *et al*. 2012; Dinu *et al*. 2017; Godos *et al*. 2017; Lee and Park 2017; Dybvik *et al*. 2023).

Vegan diets

- Meta-analyses about vegan diets found inverse associations with cancer incidence and positive associations with fracture risk (Selinger *et al*. 2023).

Flexitarian diets

- An increasing number of substitution studies have investigated the influence of decreased meat consumption with an accompanying increased consumption of other protein sources on mortality and disease risks. This has been done in cohort studies where the influence of replacing red and processed meat with other protein sources (poultry, eggs, fish, nuts, legumes, dairy foods) on cause-specific mortality was investigated using substitution models (Farvid *et al*. 2017; van den Brandt 2019). Meta-analyses of cohort studies investigating the substitution of red meat by nuts or legumes showed inverse associations with all-cause mortality and with risk of coronary heart disease (Hidayat *et al*. 2022). Replacing processed meat with nuts or legumes showed stronger inverse associations with all-cause mortality and with risk of coronary heart disease than for red meat substitution (Hidayat *et al*. 2022). There are also meta-analyses of randomised clinical trials and cohort studies on replacing animal protein with plant protein. In the randomised clinical trials, the effects of substitution on blood lipids, glycaemic markers, and blood pressure were studied. While the cohort studies reported associations with decreased risks of cardiovascular disease and type 2 diabetes in substitution models of animal protein with plant protein, the biological plausibility based on the randomised clinical trials was supported for cardiovascular disease alone with effects on total and LDL-cholesterol (Lamberg-Allardt *et al*. 2023).

Table 1 Optimal plant-to-animal protein rations (selected studies and key findings)

Study	Recommended percentage plant protein in diet	Key findings
Fouillet *et al*. (2023)	25–70%	A wide range of plant-based protein intake (25–70%) is compatible with nutrient adequacy, but exceeding about 80% leads to deficiencies in iodine, vitamin B_{12} (in males), bioavailable iron (in females), calcium, and omega-3 fatty acids.
Pellinen *et al*. (2022)	30–70%	Partial replacement of animal proteins with plant proteins had minimal impact on iron status, but led to deficiencies in the intake and status of vitamin B_{12} and iodine.
Seves *et al*. (2017)	30%	A 30% reduction in meat and dairy intake improved fibre intake and reduced saturated fat but had minimal impact on micronutrient adequacy. A 100% replacement led to intakes zinc, thiamine, vitamins A and B_{12}, and probably calcium below recommendations
Simon *et al*. (2023)	40%	A 40:60 animal-to-plant protein ratio was identified as optimal for balancing environmental sustainability and nutrient adequacy.

For instance, with regard to proteins, while both plant- and animal-based products contain proteins, the proportion of proteins and the amino acid compositions differ widely. Cereal proteins generally contain lower amounts of some amino acids such as lysine or taurine, whereas legume proteins have lower amounts of sulfur-containing amino acids. This means that combining legumes and grains in meals can help create a complementary amino acid profile and provide a good distribution of essential amino acids in plant-based diets; it also highlights the importance of careful dietary guidance, including towards diet variation.

Plant-based diets may have nutritional limitations due to low bioavailability of micronutrients (Beal 2024; Leonard *et al*. 2024), for instance the potential risk of iron and zinc deficiency, particularly among vulnerable groups such as women of reproductive age, children, and older adults (because of age-related anabolic resistance and thus higher risk of developing sarcopenia). However, apart from the type of products covered in the diet (e.g. vegan, vegetarian), the overall quality of the diet is a crucial but less studied factor to understand the different health impacts of each diet (Sotos-Prieto *et al*. 2024).

2.3 Technological and production issues

The market for plant-based meat alternatives is growing; however, there are still numerous technological challenges, and further technological expansion and innovation are needed. Especially challenging is the simulation of the sensory characteristics (texture, flavour, colour, etc.) of animal meat and/or meat products. The flavour of meat is well known as savoury (Flores 2018).

In addition to the main material, protein, used for developing plant-based meat alternatives, various other ingredients are also required. The latter are used to mimic the texture, appearance, flavour, and mouthfeel of meat and/or meat products. However, the inclusion of a variety of additives raises concerns about the nutrition, safety, clean label, cost, and consumer acceptance of plant-based meat alternatives (Kyriakopoulou *et al*. 2021; McClements and Grossmann 2021). Notwithstanding the significant progress in improving the characteristics of plant-based meat alternatives, the food industry is still seeking technologies and sustainable, nutritious, and clean-label ingredients for preparing plant-based meat alternatives (Boukid 2021).

When discussing the main ingredient, protein, theoretically all plant proteins are suitable for the preparation of meat analogues. However, the most popular ones are soy, pea, and wheat proteins (Sha and Xiong 2020). Additionally, to balance the amino acid profile of plant-based meat alternatives, main legume proteins are often combined with rice and mung bean proteins (Migala and Nied 2019). Also, wheat (Chiang *et al*. 2019), potato (Alting *et al*. 2011), mung bean (Yi-Shen *et al*. 2018), and rice (Amagliani *et al*. 2017; Wang *et al*. 2018) proteins are combined with soy or pea proteins to develop desirable textural parameters for plant-based meat alternatives. Another source of protein for preparing plant-based meat alternatives is protein-rich oilseeds, such as sunflower and rapeseed, and their by-products from oil production, which can be economically very attractive for valorisation.

However, there are some limitations in using these raw materials because of anti-nutritional factors, for instance glucosinolates in rapeseed (Fetzer *et al*. 2018). To reduce their negative impact on the nutritional and technological properties of proteins, additional technological steps should be applied, such as specific extraction protocols, fermentation, or crop breeding. It should also be pointed out that plant-based materials, in addition to meeting the demands for nutritional, technological, and functional characteristics, must be economically viable. For example, despite their huge potential, lupin-based ingredients are not competitive with other more popular crops because their cultivation in Europe remains insufficient to guarantee a steady supply (Lucas *et al*. 2015).

Pseudo-cereals, vegetables, their seeds, as well as nuts have also gained attention as possible protein sources for plant-based meat alternatives. However, research on these protein sources is still in its early stages.

In addition to the preparation of plant protein isolates and/or concentrates and the development of the main formulas for plant-based meat alternatives, specific processing methods should be used to achieve the desired meat-like textural properties of the plant proteins. Usually, intensive processing techniques such as thermos-extrusion, shear, spinning, and cross-linking are applied to form meat-like fibrous structures (Chajuss 2004).

Mixing, heating, and different extrusion technologies are still the most established methods for plant protein treatment with the aim of mimicking meat-like structures. Other technologies, such as shear cell technology, spinning, and 3D printing are also explored. For each product type (emulsion, minced, muscle-type meat alternatives), the structuring technology is optimised on the basis of the protein ingredients used. The texture changes are related to the interaction between proteins and carbohydrate polymers, as well as the transformation of protein native structures. Pre-treatment technologies for plant proteins used for mimicking meat-like texture have been described (Dekkers *et al*. 2018). Box 4 illustrates some of these technologies.

To mimic meat characteristics (nutritional, sensory, such as colour, aroma and texture), intensive processing techniques and additional non-protein ingredients are used. This is usually why plant-based meat analogues, in addition to protein, contain other, sometimes highly refined, ingredients, such as oil or fat, flavourings, binding, and colouring materials. Technologists are looking for more natural or less refined ingredients for the production of plant-based meat alternatives.

Fats used for the production of meat alternatives are typically obtained from soy, sunflower, rapeseed, canola, corn, palm, coconut, sesame oil, tropical fruits such as cocoa beans, avocado oil, etc. To produce low-fat meat analogues, fat substitutes are used, namely protein

Box 4 Examples of technologies to mimic the structure of meat in plant-based meat alternatives

- The basis of the wet spinning technique (patented by Boyer in 1954) is that a solution containing protein is extruded through a spinneret and subsequently immersed in a bath containing a non-solvent for the protein (Boyer 1954).
- The electrospinning technique also can be used to produce plant-based protein fibres (Nieuwland *et al.* 2014).
- Extrusion (both low- and high-moisture), although relatively energy-intensive, is the most commonly used technology to transform plant-based proteins into fibrous materials (Dekkers *et al.* 2018).
- Fibrous products can also be obtained by mixing plant protein with hydrocolloids that precipitate with multivalent cations (Kweldam 2011).
- In freeze structuring, an aqueous solution or slurry of proteins is frozen and heat removal from a well-mixed slurry leads to an isotropic structure (Middendorf *et al.* 1975; Lugay and Kim 1978; Consolacion and Jelen 1986).
- Well-defined shear flow deformation was applied to produce texturised products (Manski *et al.* 2007).
- Fibrous product texture can be obtained by mixing calcium caseinate with appropriate plant proteins (Dekkers *et al.* 2018).

particles (i.e. soy protein isolate), synthetic lipids (Olestra sucrose polyester), modified and resistant starches, dietary fibres, amorphous cellulose fibre (Z-trim), etc. (Giese 1996; Schmiele *et al.* 2015; Mao *et al.* 2018; dos Santos *et al.* 2020; López-Pedrouso *et al.* 2021). However, many meaty (savoury) compounds are fat-soluble flavour volatiles generated from animal fat (adipose and intramuscular fat), including hydrocarbons, alcohols, aldehydes, and sulfur compounds (Shahidi *et al.* 1986; Arshad *et al.* 2018), which are not generated in plant-based alternatives. On the other hand, plant oils are considered healthier than animal fat, because of the absence of cholesterol and their lower saturated fat content. Solid fat such as coconut oil is preferred in plant-based meat analogues to mimic the solid texture of animal fats (McClements and Grossmann 2021); however, the saturated fatty acid profile of vegetable solid fats such as coconut oil makes them less suitable nutritionally. Other plant-based oils such as canola oil are used, whose content of omega-3 fatty acids such as α-linolenic acid can have health benefits; however, unsaturated fatty acids in processed plant-based food may provide undesirable rancid flavours during processing (McClements and Grossmann 2021).

Another challenge is to mimic the colour of meat and/or meat products. The colour of cooked final products can be provided by using chemically synthesised or naturally derived heat-stable colourants. However, 'raw' meat alternatives require colour changes to be mimicked upon thermal treatment. To do this, betanin and beetroot extracts were proposed for the production of meat alternatives (Hamilton *et al.* 2000; Herbach *et al.* 2004; Kyed and Rusconi 2009). Additionally, for chromaticity issues, different reducing sugars are used in various combinations depending on the production technology used for the meat alternative (Hamilton and Ewing 2000; Rolan *et al.* 2008). Also, to ensure the stability of colourants, different acidulants are applied (Orcutt *et al.* 2008).

The selection of the flavour agents and aromatic profile modelling are also very important. Technologies such as defatting, deactivation of lipoxygenases, fermentation, etc. of the ingredients have been suggested to remove undesirable flavour characteristics Roland *et al* 2017; Kaczmarska *et al.* 2018; Duque-Estrada *et al.* 2020; Li and Li 2020).

Salt is also a very important ingredient in formulations of plant-based meat alternatives as it enhances flavour, improves texture, and acts as a preservative. It should be noted that, owing to the fractionation process, the protein isolates already contain some salt (Peng *et al.* 2020).

A recent trend is blended or hybrid products (Grasso *et al.* 2022; Miao *et al.* 2023). In hybrid products, plant-based ingredients are used in high and different proportions to replace the animal ingredients with the aim of meeting sustainable and nutritional claims; they are not used for technological purposes such as binders or extenders (van Dijk *et al.* 2023; Boukid *et al.* 2024). They are formulated to resemble familiar products to deliver the sensory properties and nutritional and sustainability benefits without altering consumers' diets (Grasso *et al.* 2022; Miao *et al.* 2023).

3 Insects as alternatives

Insects have been an important part of the diet of many cultures outside the Western world. More than 2000 species of insects are consumed at the global level, among which the most consumed orders are beetles (Coleoptera), caterpillars (Lepidoptera), bees, wasps, and ants (Hymenoptera), grasshoppers, locusts, and crickets (Orthoptera), cicadas, leafhoppers, planthoppers, scale insects, and true bugs (Hemiptera), termites (Isoptera), dragonflies (Odonata), flies (Diptera), and others (see Van Huis *et al*. 2013).

In recent years, edible insects have garnered attention as sustainable and nutritious alternatives to traditional meat sources, supported by advances in both conventional and modern processing techniques. Traditional methods such as blanching, boiling, drying, and milling are widely used to produce insect flours for integration into baked goods and other products, while emerging technologies aim to extract functional components such as proteins, lipids, polyphenols, and chitosan for the development of novel food analogues, including meat alternatives. These approaches not only enhance the nutritional value and shelf life of insect-based ingredients but also address safety and quality concerns by minimising solvent residues and controlling anti-nutritional factors (Kozlu *et al*. 2024).

Several features, such as high fecundity, high feed conversion efficiency, and rapid growth rates as well as their low environmental impacts have made insects attractive for some groups (e.g. farmers, policy-makers), which see them as a sustainable alternative or supplementary source of proteins for human food and animal feed, with subsequent research and commercial interest, and with insect farming activities increasing worldwide. The Food and Agriculture Organization of the United Nations (FAO) highlights that insects are rich in high-quality proteins, vitamins, and amino acids, and their farming emits significantly fewer greenhouse gases (GHG) compared with conventional livestock (Van Huis *et al*. 2013). The potential for insects to contribute to attaining several of the United Nations Sustainable Development Goals, starting from SDG2 'zero hunger', has been highlighted (Moruzzo *et al*. 2021). In addition, experts believe that hand collection of edible insects can be a potential source of income for rural populations, especially women, as it requires little capital[22].

The European Union has approved insects as a protein source for human consumption, turning them into a novel source of proteins with four species approved so far (*Tenebrio molitor* larva, the yellow mealworm; *Locusta migratoria*, the migratory locust; *Acheta domesticus*, the house cricket; and *Alphitobius diaperinus*, the lesser mealworm) and eight other safety assessments currently being carried by the European Food Safety Authority (EFSA)[23] (see Table 2 for an overview of the approved species and companies authorised to commercialise them).

Owing to safety reasons, only these species are approved. Insect-based proteins illustrate the difficulty of differentiating 'meat alternatives' and 'alternatives to meat', as some foods, such as insects, are not direct or obvious alternatives to meat, defined as those seeking to mimic conventional meat properties in the first case, or alternatives to the use of conventional meat in the second.

However, key challenges include legislative barriers, standardisation, and public acceptance[24] as well as scaling up production under sterile conditions. In addition, ethical concerns include animal welfare as insects are also animals and likely to be sentient

Table 2 Overview of approved insect species in the European Union

Company	Product	Species
Agronutris	Dried yellow mealworm	*Tenebrio molitor*
Fair Insects BV (Protix)	Frozen, dried powder form of migratory locust	*Locusta migratoria*
Fair Insects BV (Protix)	Frozen, dried and powder forms of yellow mealworm	*Tenebrio molitor*
Fair Insects BV (Protix)	Whole and ground forms of house cricket	*Acheta domesticus*
Cricket One	Partly defatted powder forms of house cricket	*Acheta domesticus*
Ynsect NL BV (formerly Proti-Farm Holding NV)	Frozen, paste, dried, powder form of lesser mealworm	*Alphitobius diaperinus* larvae
Nutri'Earth	Dried larvae and ultraviolet-treated powder from whole larvae of yellow mealworm	*Tenebrio molitor*

[22] https://news.un.org/en/story/2004/11/120332
[23] https://food.ec.europa.eu/safety/novel-food/authorisations/approval-insect-novel-food_en (last accessed 23 May 2024)
[24] https://sustainabledevelopment.un.org/content/documents/12867Policybrief_Insects.pdf

according to many scholars[25]. Advancements in farming techniques and regulatory approvals are essential to overcome these hurdles and fully realise the benefits of insect-based proteins.

3.1 Environmental impact and life cycle assessment

Insect production generally results in lower GHG emissions compared with conventional livestock. The carbon footprint of insect farming ranges from 0.3 to 3.0 kg of carbon dioxide (CO_2) equivalent per kilogram of insect biomass, which is lower than many conventional protein sources. Insects require significantly less land than traditional livestock because of their high feed conversion ratios and the ability to cultivate them vertically, which makes them a highly land-efficient source of protein (Smetana 2023).

The water footprint of insects has only been included in a few studies and with large ranges. As a result, while it is not expected that they will bring environmental gains in this area, the results of studies produced so far are limited or have been criticised (Smetana *et al*. 2023a).

Insects are highly efficient at converting feed into protein, often outperforming traditional livestock. Many insects can be fed organic waste, therefore reducing food waste and converting it into valuable protein. The use of by-products and waste streams as feed for insects lowers the production cost but also minimises the environmental footprint of their cultivation (Skrivervik 2020; Oonincx and Finke 2023). A substantial amount of food waste can be used for insect meal production, which could have considerable impacts on markets with GHG emissions being modestly affected (Elleby *et al*. 2021).

3.2 Impacts on human health

Insects are a rich source of high-quality protein, vitamins, and minerals. Studies have shown that the protein quality of insects is comparable to that of conventional meat, and they are particularly rich in micronutrients such as iron and zinc, whose bioavailability is high (Belluco *et al*. 2013). In addition, some insect species are rich in amino acids such as lysine, tryptophan, and threonine, which are often low in some cereals.

On the other hand, insects can induce allergic reactions in individuals who are sensitive to crustaceans and dust mites because of the presence of similar proteins, such as tropomyosin. This phenomenon, known as 'cross-reactivity', suggests that people with allergies to these groups might also react to insect proteins (Belluco *et al*. 2013). While insects can induce allergic reactions in consumers sensitive to crustaceans and dust mites through 'cross-sensitisation', it is unclear whether they can also directly trigger allergic reactions ('direct sensitisation'). The presence of chitin, a component of the insect exoskeleton, may affect the digestibility of insect proteins and potentially trigger allergies (Burton and Zaccone 2007), but the evidence of allergies through the consumption of insects is scarce (Van Huis et al. 2013; EFSA Scientific Committee 2015).

Depending on the potential application and use, certain health risks need to be visualised such as possible microbial contaminations, allergenicity, and toxicological factors while selecting particular insect species (see Schlüter *et al*. 2017). Some of the popular insect species consumed include caterpillars (Lepidoptera), grasshoppers and locusts (Orthoptera), flies (Diptera), beetles (Coleoptera), ants, bees, and wasps (Hymenoptera), bugs, aphids, and leafhoppers (Hemiptera), and termites (Isoptera) (Yi *et al*. 2013).

3.3 Technological and production issues

The insect farming sector is largely dominated by small companies with limited investment capacity, which hinders the automation and scaling up necessary to reduce production costs. This lack of vertical integration, where most companies focus solely on processing rather than the entire value chain, poses a barrier to growth (EPRS 2024), unlike, for instance, existing vertical integration in the field of cultivated meat (Reis *et al*. 2020).

There are many challenges towards accepting insects as a source of protein. The most important is cultural acceptance, as the majority of consumers worldwide do not consider insects as edible, leading to strong resistance as food (see section 7.1). Safety and public health are also other issues of concern (Van der Fels-Klerx *et al*. 2018; Belluco *et al*. 2023; Meijer *et al*. 2025). For example, although nutritionally versatile, insects can be carriers of microbial pathogens or allergens if they are not properly farmed or processed. Moreover, disease incidence in edible-insect rearing systems has also been reported (Maciel-Vergara *et al*. 2021). However, many countries (including the EU) consider insect-based foods as 'novel foods' and require extensive safety testing and bureaucratic approvals, which may lead to delays in marketing (Lotta 2019; Fuso *et al*. 2024; Lähteenmäki-Uutela *et al*. 2025).

Further, constraints related to procurement of an operating license for the mass production of insects might also face practical difficulties. Nevertheless, setting up insect farms on a pilot scale can also be a

[25] See the New York Declaration of animal consciousness, https://sites.google.com/nyu.edu/nydeclaration/declaration

labour-intensive process. There might also be high costs involved, as insect protein is often much more expensive than traditional animal or plant-based protein sources (Niyonsaba *et al*. 2021; Kozak and Jupowicz-Kozak 2025). Concurrently, limited demand from consumers in many countries for insect proteins can also be a major challenge for large-scale production.

In addition, consuming the entire insect as a source of protein may not be acceptable to consumers and processing into protein powder or protein isolate would be necessary, thus adding to the existing cost. There might also be challenges of producing new food products, as new formulations incorporating insect protein into popular food matrices (noodles, protein bars, pasta, burgers, etc.) require specialised equipment.

Finally, there will always be issues and concerns over the environment, animal ethics, GHG emissions, and waste management strategies adopted (Gjerris, *et al*. 2016; Ardoin and Prinyawiwatkul 2020; Delvendahl *et al*. 2022; Corona-Mariscal *et al*. 2024; Jafir *et al*. 2024; Rossi *et al*. 2024).

There are also technical obstacles to completely substituting conventional animal-based food and feed with insects. Concerning food, the digestibility of insect protein may be negatively affected by chitin. Therefore, processing methods that remove or reduce chitin are important to minimise these risks and preserve protein quality (Van Huis *et al*. 2013). In addition, complete substitution of animal feed such as soybean meal with insect meal may negatively affect animal growth.

4 Biomass fermentation products

Biomass fermentation or single-cell protein (SCP) production is an innovative approach in sustainable food technology, focused on generating protein from microorganisms rather than animals. This process harnesses various microorganisms, such as bacteria, algae, yeast, and fungi, to produce high-protein biomass through fermentation. SCP production is particularly valuable in the field of alternative protein sources because of its efficient use of resources and ability to be scaled up for large-scale food applications. The process typically involves growing microbial cells in controlled fermentation environments, where they metabolise inexpensive carbon sources (such as agricultural waste, methanol, or even carbon dioxide (CO_2)) to generate protein-rich biomass. As a result, SCP production not only provides a protein source but also contributes to environmental sustainability by minimising land, water, and energy requirements relative to conventional animal agriculture. Notable examples of SCP-based products include Quorn, made from the fungal species *Fusarium venenatum*, and Noblegen's euglena-based protein. Other companies are also pioneering SCP from bacteria using CO_2 and hydrogen as feedstocks, illustrating the potential to leverage atmospheric gases for food production. SCP's versatility in food formulation, coupled with its lower environmental impacts, emphasises its potential as a transformative component in the future of protein production.

SCP is used to obtain a protein-rich biomass, which may then be handled in similar ways as plant proteins to mimic meat's features such as structure and flavour. As a result, SCP proteins can be processed in a similar way as described in section 2.3 (Technological and production issues for plant-based products).

4.1 Environmental impact and life cycle assessment

Fermentation for producing food or feed proteins involves energy use, primarily for producing feedstocks and powering the fermentation process. The impact varies widely depending on the type of SCP produced, the production system, and the location. Nevertheless, the energy intensity of producing mycoprotein is frequently noted as higher than that needed for plant-based protein production (EPRS 2024). The production of hydrogen-oxidising bacteria has especially high energy use due to the electrolysis process that is needed to split water molecules to obtain a source of hydrogen (Järviö *et al*. 2021). However, the total energy requirements of microbial protein production are lower compared with beef production (Smetana *et al*. 2023).

The land use impact of microbial fermentation is largely dependent on the feedstocks used. While glucose from refined maize or sugar cane is commonly used, the overall land use for growing mycoprotein is lower compared with beef or chicken production (Mazac *et al*. 2023). Fermentation processes that rely on gases such as CO_2 result in minimal land use, highlighting the potential for further reducing land impacts by exploring alternative feedstocks (Järviö *et al*. 2021).

Microbial fermentation has the potential to reduce greenhouse gas (GHG) emissions compared with conventional animal proteins. Mycoproteins, in particular, offer lower GHG emissions than beef production, although emissions can be comparable to the most efficient poultry systems. Reducing GHG emissions is a major challenge for agriculture, and alternative proteins such as those produced through fermentation could play a significant role in mitigation efforts (Smetana *et al*. 2023).

Fermentation processes can have variable water use impacts, generally lower than beef production but potentially similar to poultry (Mazac *et al*. 2023). Improvements in water efficiency are possible, particularly through the use of alternative feedstocks and optimised production processes. It was found that the water scarcity impact of using hydrogen-oxidising bacteria is substantially lower than that of livestock products, but higher than that of most plant-based ingredients.

4.2 Impacts on human health

Fermentation products such as mycoproteins (Coelho *et al*. 2020) and other microbially fermented proteins can offer a balanced nutritional profile, including essential amino acids, vitamins, and minerals. The nutritional content can vary depending on the microorganisms used (bacteria, yeast, fungi, algae) and the fermentation process (Hooda *et al*. 2014).

Fermented products such as mycoprotein are known for their high protein content and beneficial micronutrients, which can contribute to better health outcomes (Smetana *et al*. 2023; Coelho *et al*. 2020). While the bioavailability of nutrients in fermented products can be high compared with traditional meat, this cannot be quantified in general but rather product by product and there are many unknowns. However, specific treatments to reduce nucleic acid content in microbial proteins can have an environmental cost and affect overall nutrient bioavailability (Järviö *et al*. 2021; Graham and Ledesma-Amaro 2023).

Fermented products must be carefully regulated to ensure safety. The production processes need to adhere to strict standards to prevent contamination and ensure the final product is safe for consumption (Hadi and Brightwell 2021). Consumer information and clear labelling are crucial to mitigate any allergic reactions (Mazac *et al*. 2023).

Despite controversies after launch in the 2000s (e.g. claims of mis-advertising, rare allergenic adverse reaction, use of eggs), these products are now widely available in Europe (Jacobson and DePorter 2018).

4.3 Technological and production issues

A significant bottleneck in the microbial fermentation sector is the lack of sufficient food-grade industrial capacity and infrastructure to scale up commercial production. Many existing fermentation facilities were originally designed for purposes other than food production, leading to challenges in adapting them for large-scale food protein production. Investments have been increasing to address this gap, but many new facilities are being planned outside Europe, particularly in North America and the Middle East (EPRS 2024).

Scaling up microbial fermentation processes requires overcoming several technical obstacles, including optimising the fermentation process itself and developing downstream processing methods. This includes refining feedstocks such as moving from refined sugars to lower-footprint alternatives such as agricultural residues or waste streams. There is also a need to develop new bioreactor facilities and other infrastructure to support the scale-up, which is critical for reducing production costs and achieving commercial viability (EPRS 2024).

Fermentation processes rely heavily on feedstocks, which can have significant environmental impacts. Transitioning to sustainable feedstocks such as residues from agriculture of food industry side-streams, or gases such as CO_2 and methane (CH_4) could reduce land and resource use (Grossmann 2024). For example, companies such as Cargill and Novozymes are exploring ways to use agricultural by-products, such as corn stover or wheat bran, in fermentation processes for producing SCP beside other bioproducts. By using these materials, they reduce the need for primary agricultural crops, lowering the environmental impact associated with land and water use.

For SCP production, CO_2 can be used as a feedstock in gas fermentation processes. Recently, companies such as LanzaTech and Carbon Clean Solutions have been pioneering carbon capture and utilisation technologies that convert captured CO_2 into useful products, including proteins, chemicals, and biofuels. Microorganisms such as acetogens can metabolise CO_2 into valuable products such as proteins or organic acids. Another example is Deep Branch Biotechnology, a company that produces SCP using CO_2 and hydrogen as feedstocks, which uses methanotrophic bacteria that consume CO_2 and methane to produce protein-rich biomass suitable for animal feed. This approach uses emissions from industries such as steel manufacturing, turning waste gases into a valuable protein source. Finally, agricultural and industrial side-streams can be used to reduce waste and promote circular economies by incorporating them into biomass fermentation processes (Kobayashi *et al*. 2023).

However, managing water use remains a challenge, as it could undermine the sector's environmental ambitions if not addressed properly. Typically, bioprocesses rely on high water use for cultivation, cooling and downstream processing, and wastewater generation, where the last of which might contain high concentrations of organic matter, salts, and other chemicals, requiring significant treatment infrastructure to avoid contamination or environmental harm.

To address water management challenges in SCP and precision fermentation facilities, several strategies can be adopted. Recycling and reuse systems, such as Nestlé's water-reuse technologies or Novo Nordisk's effluent purification for cooling, help reduce water consumption. Advanced wastewater treatments such as Cargill's use of anaerobic digestion or membrane bioreactors in breweries effectively minimise environmental harm. Process optimisations, including high cell-density cultures by Unibio and water-efficient filtration methods common in pharmaceuticals, enhance resource efficiency. Cooling systems can be improved by adopting air-cooling, as seen in biotech facilities in arid regions, or by optimising cooling towers with GE Water's treatment solutions. Real-time monitoring, such as Siemens' MindSphere platform, ensures precise water management and reduces waste. Collaboration with local ecosystems, such as water-sharing agreements or using constructed wetlands, further promotes sustainability. Ensuring regulatory compliance, conducting life cycle assessments, and engaging stakeholders are also essential to align operations with environmental goals while driving innovation in water conservation.

It is also worth noticing that after their production, SCP products must be processed in a similar way as plant-based products. This is because SCP products are a biomass, but if the purpose is to mimic the structure of meat they need to be processed. In addition, companies such as MeaTech 3D in partnership with the food company Enough, are combining biomass fermentation with cultivated meat and 3D technologies to develop hybrid products.

5 Precision fermentation products

Precision fermentation 'uses microbial hosts as "cell factories" for producing specific functional ingredients'[26]. It is a sophisticated biotechnological process used in food production that leverages microorganisms such as yeast, bacteria, or fungi to produce specific functional ingredients or food components. Unlike traditional fermentation, which typically results in a range of metabolic by-products, precision fermentation uses genetic engineering to fine-tune these microorganisms to produce specific molecules with high yield and purity.

In the context of food, precision fermentation is primarily used to create proteins, enzymes, vitamins, and other bioactive compounds that can enhance the nutritional profile, flavour, texture, and shelf life of food products. The process involves several key steps: (1) microorganism selection and engineering; (2) cultivation; (3) fermentation; and (4) purification.

Examples of precision fermentation is the production by engineered yeasts or bacteria of the following.

(1) Dairy proteins, such as casein for use in dairy-like products such as ice cream, cheese, and yogurt, offering the texture and functionality of dairy without animal inputs.

(2) Egg proteins, such as egg albumin. By replicating the properties of traditional egg whites, these proteins provide a versatile, animal-free alternative suitable for baking and other food applications.

(3) Haem: the most prominent example has been production of soy leghaemoglobin by Impossible Foods. This haem-containing molecule produced by a genetically modified yeast gives plant-based meats a meat-like flavour and aroma and is used in providing beef-like taste profile in plant-based burgers.

(4) Vitamin and enzymes: bioidentical proteins, vitamins, and enzymes that enhance functional properties or nutritional profiles in food products.

5.1 Environmental impact and life cycle assessment

Precision fermented ovalbumin has been estimated to require approximately 85% less land and reduce greenhouse gas emission by 56% compared with egg white production (Järviö *et al*. 2021). The water scarcity footprint of precision-fermented ovalbumin was 87% lower than chicken egg white production in Germany, but higher when compared with chicken egg white production in Poland. Behm *et al*. (2022) found that the carbon footprint and water scarcity footprint of precision-fermented milk protein (whey) varies highly depending on the source of glucose and energy and the production location. Only some of the precision-fermented milk protein production scenarios had lower carbon and water footprints compared with dairy milk. Some studies suggest that innovations in feedstock technology could further reduce this.

Effective waste management strategies are necessary to address by-products such as microbial biomass and wastewater. The challenge of disposing of genetically modified microbial biomass in regions such as the European Union is notable, and finding sustainable solutions for waste is critical for minimising environmental impacts (EFSA Panel on Genetically Modified Organisms 2011).

A study found that the total energy consumption of precision-fermented ovalbumin and chicken egg white were at the same level (Järviö *et al*. 2021b). However, precision fermentation processes may require more electricity compared with livestock production. Process improvements and the use of renewable energy sources are crucial for enhancing the sustainability of these technologies.

The sustainability of fermentation products is influenced by the choice of feedstocks, energy sources, and waste management practices. While current production methods are energy intensive, there is considerable potential for improving the environmental footprint through technological advancements and the adoption of more sustainable practices, such as the use of low carbon energy sources (Järviö *et al*. 2021b).

5.2 Impacts on human health

Precision fermentation allows the production of functional ingredients that can be tailored to enhance health benefits. These include vitamins, antioxidants, and probiotics, which can contribute to overall health and well-being (Tzachor *et al*. 2022). However, the safety of microbial-based foods and their ingredients is under consideration. The presence of contamination products or those causing allergic or adverse reactions

[26] https://gfi.org/science/the-science-of-fermentation/

is of concern (Graham and Ledesma-Amaro 2023); however, as explained below, the US Food and Drug Administration has indicated that some products are safe for consumption.

5.3 Technological and production issues

Different considerations should be made about the production of functional ingredients by precision fermentation. The stoichiometry, thermodynamics, and kinetics of the fermentation process are essential criteria together with the economic part. The complexity of managing the production in bioreactors is a challenge to scale up production processes. Environmental concerns include the power optimisation, and a recent focus has been directed to develop mechanistic models for large-scale aerobic precision fermentation processes (Jahanian *et al*. 2024).

In the case of the production of proteins by biotechnological processes, they can be used in the production of processed foods such as cheese and meat products as they can replicate animal foods (cellular agriculture) (Kühl *et al*. 2024). These proteins may be indistinguishable from their animal counterparts and sustainable. However, economic barriers remain significant, as production must be cost competitive in the market. Scaling up requires substantial investment in new manufacturing infrastructures, from fermentation tanks to bioreactors, and downstream processing, which involves separating, purifying, and preparing the desired product for use, is often more complex and costly than the upstream fermentation process itself. Additionally, factors such as consumer perception of unnaturalness, regulatory hurdles, and proper labelling about the origin of these proteins remain key concerns.

Another challenge is the optimisation of the feedstock and process efficiency to reduce costs and enhance sustainability. Recent advancements suggest the use of alternative feedstocks, such as agricultural side-streams and more energy-efficient microbial strains, could play a role in making production more viable on a commercial scale (Graham and Ledesma-Amaro 2023). Additionally, while microbial-based proteins hold promise, issues related to metabolic by-products, residual DNA content, and allergenic potential need further assessment (Jahanian *et al*. 2024).

There are also risks about the incorporation of microbes in foods, particularly concerning potential contamination, allergenicity, and unintended health effects (Graham and Ledesma-Amaro 2023). Regulatory agencies such as the US Food and Drug Administration have taken steps to evaluate the safety of precision fermentation-derived ingredients, with some being classified as Generally Recognized as Safe (GRAS)[27]. However, the approval process for novel foods remains complex and varies across different regulatory bodies.

Investments in microbial fermentation, particularly in precision fermentation, have significantly increased, reflecting growing interest and potential in the sector (Graham and Ledesma-Amaro 2023). However, financial viability depends on achieving economies of scale and reducing production costs, the use of advanced fermentation technologies, and engineered microbes to achieve high yields. Recent data from 2024 indicate the presence of many different start-ups in North America, Europe, and Israel mainly focused on alternative protein production although based on different technologies including precision fermentation (Lurie-Luke 2024).

[27] See https://www.foodnavigator-usa.com/Article/2024/01/17/imagindairy-receives-gras-nod-from-fda-acquires-industrial-scale-precision-fermentation-lines and https://www.fda.gov/media/157970/download

6 Cultivated meat

Cultivated or cell-based meat is a new way to produce meat alternatives involving *in vitro* meat production using animal cells. The production of cultivated meat involves three different but related processes: (1) cell sourcing (cells are taken from living animals or alternatively an immortalised cell line can be used), (2) cell cultivation (cells are cultivated or cultivated in a controlled environment so that they can proliferate and differentiate), and (3) tissue formation (cells mature or 'differentiate' to form muscle tissues that resemble meat, or are used together with other techniques for tissue formulation).

Although cultivated meat products have yet to be authorised in the European Union, they have been authorised for consumption in Singapore since 2020 (cultivated chicken produced by Eat Just[28]), in the USA since 2023 (cultivated chicken and quail produced by Eat Just and Vow respectively[29]), and in Israel since 2024 with the first regulatory approval of cultivated beef by Aleph Farms[30]. An application for pet food was also recently approved in the UK (cultivated chicken by Meatly)[31]. While early applications of cultivated meat methods focused on beef, many recent commercial applications have focused on chicken. Yet, only a few products have been authorised worldwide, and they are expensive because of the complexity of the production processes (see Figure 3), the need for additional cellular growth factors, and the small scale of production.

While cultivated meat is a timely topic, its scientific evaluation is difficult because the required information and data needed for its thorough assessment are mostly proprietary information produced by private actors in this area. This leads to questions such as whether we have sufficient evidence to gauge its impacts, whether there is a reliable regulatory framework, including for life cycle assessments (LCAs) as well as other technological, quality-related issues (e.g. nutritional value and health claims or food-safety issues), as well

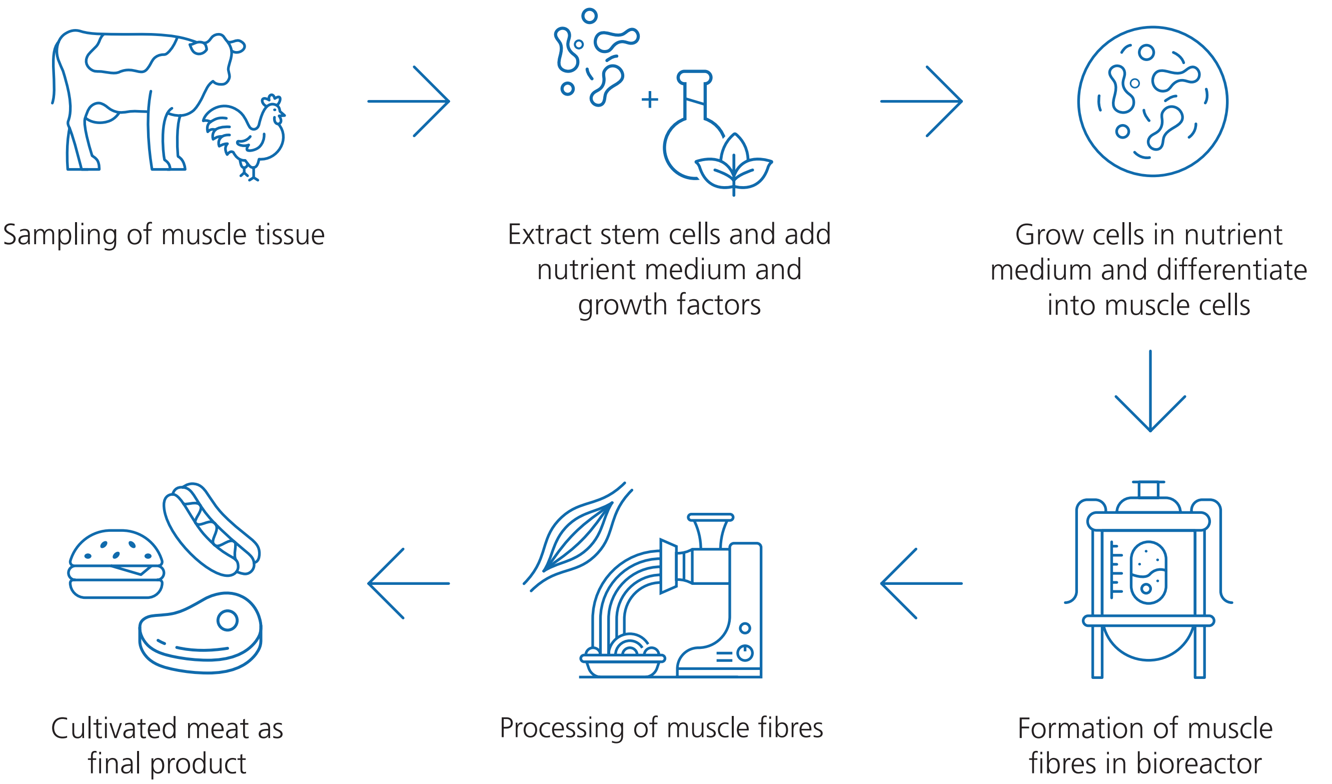


Figure 3 The production process for cultivated meat.

[28] https://gfieurope.org/blog/worlds-first-regulatory-approval-for-cultivated-meat-begins-new-space-race-for-the-future-of-food/
[29] https://gfieurope.org/blog/us-approval-cultivated-meat-europe-falling-behind/
[30] https://aleph-farms.com/journals/aleph-farms-granted-worlds-first-regulatory-approval-for-cultivated-beef/
[31] https://meatly.pet/meatly-approval/

as how sustainable this technology is, and what its potential human health benefits or risks are. More generally, there is a lack of transparency since most cultivated meat is produced mainly by private actors, although there are also many research institutes and universities developing cultivated meat now (e.g. Tuft University, Aarhus University, Nofima, Tokyo Women's Medical University).

6.1 Environmental impacts and life cycle assessment

Current estimates of its environmental impacts show that cultivated meat production is expected to emit levels of greenhouse gases (GHG) similar to those of conventional chicken production, although potentially lower than those of beef (Tuomisto *et al*. 2022; Sinke *et al*. 2023). However, the impacts vary depending on the type of the end product and the production processes. The efficiency of cultivated meat production might be improved with technological advancements, which could further reduce emissions (Tuomisto *et al*. 2022; Smetana *et al*. 2023).

Only a few LCAs of cultivated meat have been published so far (Tuomisto and Teixeira de Mattos 2011; Mattick *et al*. 2015; Smetana *et al*. 2015; Tuomisto *et al*. 2022; Kim *et al*. 2022; Sinke *et al*. 2023; Risner *et al*. 2024). A review looking at LCAs suggested that several steps in the production process had been excluded from the system's boundaries and hence that the GHG emissions may have been underestimated (Rodríguez Escobar *et al*. 2021). However, several studies done after 2021 have addressed some of these identified gaps.

A LCA of cultivated meat performed in 2022 found that culture media production provided the highest contribution to the environmental impact of cultivated meat, with the highest reduction in environmental impact being achieved by improving cellular metabolism and yield (Tuomisto *et al*. 2022). The study showed that cultivated meat had less environmental impact than conventional beef production although the impacts were higher than or similar to chicken, and suggested that impacts could be further reduced by improving cell culture yields, increasing efficiency, and using renewable energy sources. The estimates show that the electricity consumption of cultivated meat production is higher than that of livestock meat. However, as cultivated meat production requires less land, some of the land released from livestock production could be used for production of renewable energy. While this study was performed in hollow fibre bioreactors, many cultivated meat production sites use stir tank reactors (see Table 4). Similarly, a 2023 study found that cultivated meat had a potentially lower environmental impact for most indicators, such as land use, air pollution, and nitrogen-related emissions, with its carbon footprint being substantially lower than that of beef. However, compared with chicken and pork, its environmental impacts depend on the energy mixes used. The study suggested that as cultivated meat production and its upstream supply chain are energy intensive, the use of renewable energy would help it become a sustainable alternative to conventional meat (Sinke *et al*. 2023).

Producing undifferentiated cells used for processed meat products (e.g. sausages or chicken nuggets) rather than aiming at whole-meat texture using (differentiated) muscle cells leads to lower overall environmental impacts (around 60% less if a 7-day differentiation period is skipped in the model used in Tuomisto *et al*. (2022)) because of the shorter cultivation time. As undifferentiated cells are generally mixed with plant-based ingredients, the total environmental impact of the final product depends on the type of other ingredients used.

Land use requirements for cultivated meat depend on the sources of feedstock used to provide nutrients for the cells. If production systems use high-yielding sources, such as cyanobacteria for amino acids and carbon sources, the land use requirements could be lower compared with those for conventional beef and chicken. However, if traditional feed inputs such as soy and corn are used, the land use requirements would be lower than those for beef, but not necessarily chicken (Tuomisto *et al*. 2014). The development of new nutrient sources from side-streams of the food industry and from grass crops continues.

Estimations about the impact of livestock on land use also need to consider that herbivores convert grass and forages (non-edible feed) into meat and milk and at the global level. On the basis of the proportions of unfrozen land surface (13.2 billion hectares) corresponding to non-agricultural land (cities, deserts, forests) and agricultural land, it is estimated that of the 2.5 billion hectares used for livestock production, more than half (1.3 billion) are non-arable land. This means that around 57% of the land used for feed production cannot be converted to food production and can only be used by livestock, in particular herbivores, which have the capacity to convert the grass and forages from these areas into protein-rich foodstuffs (dairy and meat products) directly used by humans (Mottet *et al*. 2017). However, alternative proteins require substantially less land than ruminant production, so some of the pasture lands could be converted back to natural habitats.

Cultivated meat is also likely to use significantly less water than beef production and potentially comparable amounts to poultry production if the water is recycled in the production system (Tuomisto *et al*. 2022). In terms of waste management, cultivated meat production is considered more manageable and recyclable compared with traditional meat production, which involves significant organic by-products and wastewater.

The environmental impacts of cultivated meat depend on the details of the system design. Each cultivated meat production system has different environmental impacts. As only few studies have estimated the environmental impacts of cultivated meat production, it is not possible to know all of the possible ranges that the impacts can have. Further LCAs of cultivated meat are needed to understand the full impacts of using different types of cells, bioreactors, and medium ingredients and to better guide policy decisions. Box 5 illustrates some issues related to LCA studies used in policy discussions.

Table 3 shows the carbon footprint and land use of cultivated meat found in studies of LCA published in peer-reviewed journals and Figure 4 shows the relative differences in the environmental impacts of cultivated meat when compared with livestock meat, plants, and other cell-cultivated food ingredients

Box 5 Life cycle assessment studies: controversies and limitations

The studies cited in the paper by Italy and other EU Member States for discussion in the EU Council[32] calling for the European Commission to launch a comprehensive public consultation and impact assessment on laboratory-grown meat received some criticisms:

- The study by Risner *et al*. (preprint)[33] had not been through peer review at the time although it was later published (Risner *et al*. 2024). The study estimated the climate impact of cultivated meat production when pharmaceutical-grade ingredients were used for cultivated meat production. The purification process of the ingredients is energy intensive, so this study found a carbon footprint for cultivated meat that was many times higher than those in published papers on LCA. However, several studies (Yamanaka *et al*. 2023) as well as industrial practices[34] consider that pharmaceutical-level purity is not needed for the ingredients used in cultivated meat production, but food- or feed-grade ingredients are sufficient. Therefore, the findings of the paper by Risner *et al*. may not be relevant for cultivated meat.
- Lynch and Pierrehumbert (2019) compared the climate impact of cultivated meat and beef when using a 1000-year time frame and estimating the actual climate impact instead of the commonly used global warming potential during a 100-year (GWP100) time frame. As the lifetime of methane in the atmosphere is only around 12 years, these two methods give different weights for methane. Whereas the GWP100 showed higher climate impact for all beef production systems than cultivated meat, when the warming impact for 1000 years was studied, the worst-performing cultivated meat system started to have a higher climate impact than beef after around 150 years. Because of the urgency of mitigating climate change, instead of using the GWP100 impact factors it might even make more sense to use GWP20 impact factors that give even higher weight for methane.

Table 3 Carbon footprint and land use of cultivated meat LCA studies published in peer-reviewed journals

	Carbon footprint (kg CO_2-eq/kg cultivated meat)	Land use (m^2/kg cultivated meat)	Details
Tuomisto and Teixeira de Mattos (2011)	1.9–2.2	0.2	Cyanobacteria as a main source of nutrients in the culture medium, stir-tank bioreactor
Smetana *et al.* (2015)	23.9–24.6	0.4–0.8	Data mainly from Tuomisto and Teixeira de Mattos (2011), but cyanobacteria produced in bioreactors instead of open ponds
Mattick *et al.* (2015)	3.0–25.5	1.5–9.5	Chinese hamster ovarian cells, standard serum-free culture medium, stir-tank bioreactors
Tuomisto *et al.* (2022)	4.9–25.2	1.8–6.9	C2C12 cells, standard culture medium with and without fetal bovine serum, hollow fibre bioreactors
Sinke *et al.* (2023)	2.9–14.3	2.5	Aggregated data from companies (several cell types and culture medium ingredients)
Kim *et al.* (2022)	15.4	0.08	Burger patty made of primary bovine cells, standard culture medium, data from a company
Risner *et al.* (2024)	12-1508		Used data from techno economic assessments. The worse-case scenarios include energy intensive purification steps for the medium ingredients.

[32] https://data.consilium.europa.eu/doc/document/ST-5469-2024-INIT/en/pdf
[33] https://www.biorxiv.org/content/10.1101/2023.04.21.537778v1
[34] https://gfi.org/wp-content/uploads/2024/02/Letter-to-UC-Davis-CM-LCAs.pdf

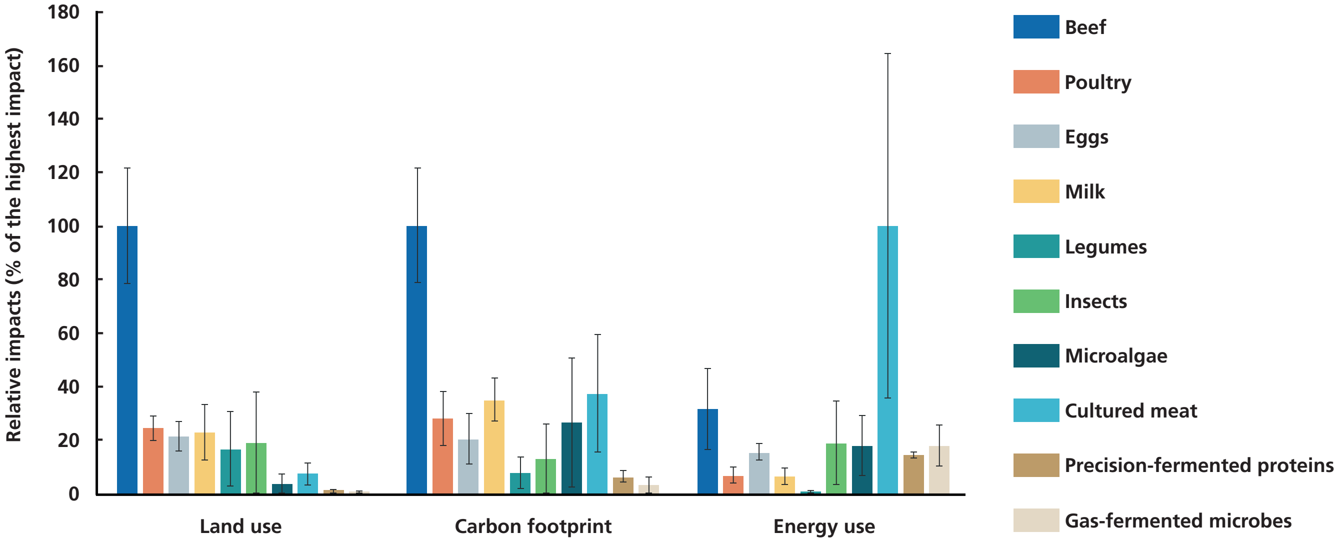


Figure 4 Relative environmental impacts and resource use of different ingredients used for meat alternatives per unit of protein on the basis of published LCA studies (source of data: Tuomisto 2022; Smetana et al. 2023). The error bars represent the range of results found in the literature.

6.2 Impacts on human health

Cultivated meat has the potential to replicate the nutritional content of conventional meat, including protein, fat, and micronutrient levels. Cultivated meat opens up the potential for new modifications that are not possible with traditional meat. For instance, the levels of cholesterol, haem-iron, and types of fat, such as saturated and unsaturated fats, can be controlled during the production process (e.g. when fat is added, or when fat cells are co-cultivated with muscle cells and it is possible decide what type of fat and how much is added). Given this, cultivated meat could have lower cholesterol levels and alter the fat content to increase healthier fats such as omega-3 fatty acids (Mazac *et al*. 2023), with potentially beneficial health impacts. However, the literature on these specific issues is limited.

Food safety aspects are central to the uptake of cultivated meat (FAO and WHO 2023). Cultivated meat could offer improved food safety compared with conventional meat. Since there are no digestive organs involved, the risk of contamination with pathogens such as *Escherichia coli*, *Salmonella*, or *Campylobacter*, which can occur with conventional livestock at slaughter, is significantly reduced. Additionally, the need for antibiotics and vaccines could be greatly reduced or even eliminated, potentially lowering the risk of antimicrobial resistance. While antibiotics are used as a standard practice in research, it is expected that this will not be needed[35] in cultivated meat production (McNamara and Bomkamp 2022).

The composition of the growth media is particularly important. Growth factors are generally used, but some companies say that they do not need them. Essential amino acids are certainly needed, as the cells cannot grow without them. The question is more about what source of amino acids is used (e.g. whether they are synthetic amino acids or extracted from plants or algae). A study demonstrated that by adjusting insulin levels in the culture medium, researchers could control the deposition of fat in muscle tissues. Elevated insulin concentrations led to increased lipid accumulation, resulting in cultivated meat with higher fat content, which is associated with enhanced flavour and juiciness. Conversely, lower insulin levels produced leaner meat with reduced fat content, potentially affecting taste and mouthfeel as well as having a different nutritional profile (Ma *et al*. 2024), which could potentially contribute to reducing the risks of some chronic diseases.

Furthermore, insulin is essential for muscle cell growth and maturation. Appropriate insulin concentrations promote the development of muscle fibres, contributing to the desired texture and structural integrity of the meat. Insufficient insulin may impair muscle formation, leading to a less desirable texture in the final product.

6.3 Technological and production issues

6.3.1 Inputs, processes, and scalability

Cultivated meat production involves complex biotechnological processes, including cell sourcing, cultivation, and tissue formation to replicate conventional meat's texture and nutritional profile. The inputs, such as growth media and scaffolding

[35] https://gfi.org/blog/cultivating-a-future-where-antibiotics-still-work/

materials, are critical as they influence the cost and feasibility of the production. The growth media, often expensive owing to the requirement for specific nutrients to support cell growth, remain a significant part of continuing research to reduce costs and improve efficiency (Mazac *et al*. 2023).

Scaling up cultivated meat production to commercial levels poses significant challenges, primarily because of the need for large-scale bioreactor facilities and the associated infrastructure. While pilot projects have been successful, transitioning to larger production scales requires substantial investments in both technology and facility development. In addition, engineering strategies are focused on the enhancement of the cell proliferation and differentiation in a cost-effective manner (Park *et al*. 2024). The scalability challenges are compounded by the need for stringent quality control to maintain safety and growth and ensure the cell harvest. Other factors such as the presence of different cell types in the production process may be taken into consideration to meet industry requirements (Santos *et al*. 2023).

Many developers are now focusing on how to scale-up processes for cost effectiveness to be able to initiate meat cultures from embryonic or induced pluripotent stem cells, or other genetic editing or modification to remove the need to repeatedly harvest cells from livestock muscle, and to develop low-cost, high-quality culture media to feed the cells. The scaling strategy is also a major discussion: scale-up (larger sales) or scale-out (parallel medium scale cultivations). For instance, there is currently a wide discussion about scaling out in the Netherlands with production in the lower cubic metre level for parallel bioreactors such as those used in farm-sized factories (Kurt et al. 2022)[36].

An industry survey from 2023 found that the availability and cost of growth factors (or alternatives) are among the most limiting factors for scalability along with the available human talent and affordable bioreactors[37].

Table 4 Bioreactors used in cultivated meat

Bioreactor type	Definition	Examples of companies/products
Stirred-tank bioreactors	Vessels where an impeller mixes the culture medium, ensuring uniform nutrient distribution and oxygenation	Mosa Meat uses a unique stirred-tank bioreactor system[38] Upside Foods
Air-lift bioreactors	Uses rising air bubbles to circulate and mix the culture medium, reducing mechanical shear stress and enhancing energy efficiency	Ark Biotech[39]
Hollow-fibre bioreactors	Use porous fibres to supply nutrients and remove waste, mimicking natural tissue structures and achieving high cell densities	Memphis Meats (now Upside Foods) uses specialised hollow fibre bioreactors to cultivate meat[40]
Packed-bed bioreactors	Use a solid matrix for cells to grow on, reducing shear stress and supporting scaffold-based tissue engineering	Ever After Foods' edible packed-bed system[41]
Rocking bed bioreactors	Uses a rocking motion to gently mix cells[42]	Cell-Tainer (in collaboration with Mosa Meat)[43]

[36] https://sentientmedia.org/lab-grown-meat-netherlands/
[37] https://gfi.org/wp-content/uploads/2024/04/Trends-in-cultivated-meat-scale-up-and-bioprocessing.pdf
[38] https://cmr.berkeley.edu/2023/07/disrupting-the-plate-cultivated-meat-technology/
[39] https://www.freethink.com/science/bioreactor-cultivated-meat
[40] https://cmr.berkeley.edu/2023/07/disrupting-the-plate-cultivated-meat-technology/
[41] https://www.foodnavigator-usa.com/Article/2025/04/01/ever-after-foods-and-buhler-aim-to-lower-cultivated-meat-costs/
[42] https://www.bdspublishing.com/_webedit/uploaded-files/All%20Files/Open%20Access/9781801469333_web.pdf
[43] https://celltainer.com/cell-tainer-single-use-rocking-bioreactor-applied-for-cultivated-meat/

7 Cross-cutting issues with meat alternatives

This section provides an overview of cross-cutting impacts, including attitudes towards meat alternatives, ethical issues, and regulatory and policy issues. Different meat alternatives have so far been examined by the literature to different extents; for instance, more studies and surveys have tackled the attitudes towards cultivated meat or cellular agriculture or the ethical and regulatory issues around these novel meat alternatives.

7.1 Perceptions and attitudes towards meat alternatives

Many studies have focused on the attitudes of consumers to cultivated meat or issues around cellular agriculture (which comprises cultivated meat but also biomass and precision fermentation). The asymmetry in the number of available studies and information, which is reflected in this sub-section, follows the attention and controversy generated by the 'more novel' meat alternatives, rather than being a value judgment on the relative importance of any meat alternative.

The term 'perception' covers stakeholders' perspectives to meat alternatives (e.g. views, imageries, attitudes, beliefs, motivations, etc.) and perceptions of stakeholders tend to be fluid and change if novel information is introduced. The perceptions of future alternative products are based on abstract impressions and concepts people have or distil from the various media outlets and social interactions. Key stakeholder groups include those at the start and the end of the current food value chains: consumers or citizens, scientists, and livestock farmers. Although the 'middle players' of the food value chain such as food processing companies are increasingly interested in cellular agriculture, product development takes place mainly in small-scale start-up companies.

The most studied stakeholders are consumers or citizens. Consumers' food perceptions, preferences, and choices are complex and involve a multitude of cultural, societal, social, and individual motives. Studying attitudes towards future or very novel foods adds another layer of complication; as people have not seen or tasted the products, the research is not about the products but rather the impressions of a potential product. And social science research settings tend to affect results considering speculative food products; for instance, presentation style and content of relevant information conveyed to respondents is seldom similar (Bryant and Barnett 2018). Hence, consumers' evaluation of potential future foods is often based on imageries drawn from extant food and popular cultures, social media sources, or influencers. Social norms and expectations of close others also affect ways in which potential novel foods are perceived (Heiskanen and Ryynänen 2024).

7.1.1 Consumers' attitudes towards meat alternatives

According to the Eurobarometer on Food Safety in the European Union (EU) (EFSA 2022), the main factors that European consumers value in food purchases are cost (54%) followed by taste (51%), food safety (46%), origin of the food (46%), and nutrient content (41%). The impact on the environment and climate (16%) and ethics and beliefs (15%) rank lowest in importance (EFSA 2022; Liu *et al*. 2023). Therefore, the uptake of meat alternative products seems to depend on these value judgements. However, caution should be applied when generalising observations from current food systems and foods to alternative categories and novel food items.

Studies point out that people tend to prefer meat to meat alternatives and have shown, on average, quite a low acceptance of meat alternatives (Hartmann and Siegrist 2017; Onwezen *et al*. 2021). Among the relevant drivers for acceptance of all meat alternatives are taste and sensory attributes, perceived health benefits, environmental concerns, familiarity, food neophobia, disgust, social/cultural norms, and trust in food safety and production methods. Box 6 presents a non-exhaustive summary of studies on these drivers and their main findings.

Consumers' attitudes to meat alternatives vary across demographic groups. Studies have found that individuals who are younger, highly educated, urban dwellers, not politically conservative, or already vegetarian/vegan are generally more open to some alternative proteins (Onwezen *et al*. 2021; Gousset *et al*. 2022). Individuals who are younger, highly educated, urban citizens and are less familiar with the livestock or the meat sectors may also be more generally open to cultivated meat (Hocquette *et al*. 2022), while insects tend to be more accepted by men and plant-based alternatives by women (Onwezen *et al*. 2021; Bryant and Sanctorum 2021). Cross-cultural studies suggest that consumer openness to alternative proteins depends on regional dietary habits and exposure to plant-based or novel protein sources (van Dijk *et al*. 2023).

7.1.2 Consumers' attitudes towards plant-based alternatives

As explained above, several studies on the drivers for accepting meat alternatives show that plant-based alternatives are, overall, more acceptable than other meat alternatives. A review of the literature on

Box 6 Evidence from selected studies on the drivers for the acceptance of meat alternatives

- **Taste and sensory attributes, perceived health benefits, environmental concerns, familiarity, food neophobia, disgust, and social/cultural norms** are key drivers (Hartmann and Siegrist 2017; Onwezen *et al.* 2021; Siddiqui *et al.* 2022).
- **Trust in food safety and production methods** are especially important for highly processed alternatives such as cultivated meat and hybrid meat products (Miao *et al.* 2023).
- **Ability to mimic conventional meat sensory properties such as taste and texture.** Early products had low sensory acceptance among meat eaters as they were mostly designed for vegans and vegetarians (He *et al.* 2020) while new products have focused on flexitarians and meat eaters, with improvements in sensory appeal (Grasso *et al.* 2022). Developing plant-based or hybrid alternatives with desirable taste and texture often requires multiple additives and processing methods, which may lead to scepticism due to unfamiliar ingredients and concerns about over-processing (Siddiqui *et al.* 2022; Grasso 2024).
- **Environmental concerns.** These are a key determinant explaining why some consumers are more willing to reduce their meat intake and/or replace it with alternatives (Gulliksen 2022). However, there is relatively low awareness of the environmental impact of conventional meat production (Hartmann and Siegrist 2017). Studies suggest that consumers, particularly younger and more sustainability-conscious groups who are more knowledgeable about the environmental benefits of alternative proteins tend to show higher acceptance (Onwezen *et al.* 2021; Miao *et al.* 2023). On the other hand, some groups have criticised the food technology industry for allegedly exaggerating the environmental impacts of conventional meat.[44]
- **Health, taste, and convenience.** Plant-based alternatives may be perceived as either healthier or less healthy than meat, depending on the composition of ingredients and the processing methods (Onwezen *et al.* 2021; Grasso *et al.* 2022). Convenience is often cited as a barrier to choosing plant-based alternatives, particularly when cooking methods or availability differ from conventional meat products (Onwezen *et al.* 2021).
- **Familiarity and food neophobia.** These issues significantly affect acceptability (Hartmann and Siegrist 2017). For example, using plant-based ingredients in familiar food formats, such as nuggets or burgers, has been shown to increase consumer willingness to try them, and cooking ability and habits are also important for consumers to prefer some products (Onwezen *et al.* 2021).
- **Perceived naturalness.** This may explain why people are generally more accepting of plant-based alternatives than cultivated meat (Onwezen *et al.* 2021). Research also indicates that consumers are more likely to accept hybrid meat products, which blend plant-based proteins with conventional meat, as they are perceived as a more gradual transition rather than a complete shift away from animal-based foods (van Dijk *et al.* 2023; Grasso 2024).

consumers' attitudes towards meat alternatives found higher acceptance for plant-based than other meat alternatives; key drivers included taste and health, familiarity, attitudes, food neophobia, and social norms, with health motivations being particularly relevant for this category (Onwezen *et al.* 2021). A study of consumers' attitudes in the USA and Asia found that higher familiarity and lower food neophobia predicted higher acceptance of plant-based meat alternatives (Bryant *et al.* 2019).

In terms of socio-demographic differences, plant-based alternatives were more appealing to women and those with vegetarian diets, and both cultivated meat and plant-based meat were more appealing to younger consumers and those in the northern, predominantly Dutch-speaking region of Flanders (Bryant and Sanctorum 2021). Similarly, a hypothetical choice experiment found that, in line with previous studies, younger and more educated consumers were more likely to consume plant-based meat alternatives. Outside the demographics, two of the strongest predictors of cultivated meat consumption were the importance consumers place on the environment and their beliefs about the environmental impact of livestock production. This suggests that the market for meat alternatives could be expanded by increasing either environmental consciousness or consumers' awareness of the environmental impact of livestock production (Slade 2018).

A cross-sectional survey of consumers in Belgium found that in 2002 around 51% said existing plant-based meat alternatives met their needs, an increase from 44% in 2019 (Bryant and Sanctorum 2021). However, the degree of processing seems to be an important factor in plant-based meat alternatives. A study in Sweden compared different plant-based products, including plant-based meat alternatives mimicking meat and less processed products. The study found that plant-based meat alternatives were perceived as more modern, artificial, and expensive compared with pulses, and these latter were perceived as healthier and a better climate choice than the former. Also, meat eaters in the study gave more importance to taste, perceived protein content, satiety, and domestic origin (from Sweden), whereas omnivores gave more weigh to taste, ease of cooking, health, climate change, and the link between food and climate (Spendrup and Hovmalm 2022).

7.1.3 Consumers' attitudes towards insect-based proteins

From a consumer standpoint, insects are often perceived as a protein alternative rather than a direct meat substitute. This distinction is crucial, as the term 'meat' is closely associated with traditional animal sources. While insect protein extracts can be incorporated as ingredients in various food products, their acceptance as 'meat' remains low (Mancini *et al.* 2022) and most consumers worldwide do not consider insects as edible,

[44] https://leszhomnivores.fr/wp-content/uploads/2024/12/EGE_RAPPORT_MERCURIE_2024_WEB_light.pdf

leading to strong resistance. This may be due to a lack of exposure to the culinary traditions of consuming insects, psychological barriers, or practising vegan diets/dietary habits (Hartmann *et al*. 2015; Tan and House 2018; Wilkinson *et al*. 2018; Bazoche and Poret 2021; Wendin and Nyberg 2021).

In many parts of the EU, cultural norms and food traditions pose significant barriers to the acceptance of insects as meat alternatives. However, there is growing openness to using insect proteins in processed food forms, such as protein bars, flour-based snacks, and high-protein supplements. These applications may help overcome the disgust factor by reducing the visibility of whole insects in food products (Mancini *et al*. 2022).

Interesting details on consumerism and acceptance of insect-based food products in Western societies and consumers' psychological and socio-cultural perspectives have been reviewed (Tan and House 2018; Kröger *et al*. 2022). Greater consumer awareness about the nutritional benefits and safety of insect-based proteins could improve acceptance, particularly if allergenicity concerns are addressed and clear labelling is provided.

7.1.4 Consumers' perceptions of biomass and precision fermentation

Although some studies focusing on cellular agriculture cover the three categories, there are far fewer focusing on biomass and precision fermentation than cultivated meat. An exception is a study on the preferences and attitudes of consumers towards fermentation, including 7812 people surveyed across nine European countries, which found high overall willingness to try products of traditional, biomass, and precision fermentation. The study also found similar levels of acceptance for biomass (around 49%) and precision fermentation (around 52%); however, these levels were lower than acceptance of traditional fermentation (around 61%), and around 23% of respondents were unwilling to try either option. In addition, respondents who identified themselves as vegetarian or vegan tended to favour biomass over precision fermentation while omnivores had lower willingness to try products prepared through all types of fermentation (Perez-Cueto *et al*. 2024).

A major issue for precision fermentation is consumer perception of genetically modified foods, because regulations in some regions mandate that precision fermentation products must be labelled as genetically modified organisms, which might negatively affect their uptake. This labelling requirement may affect market acceptance, particularly in Europe, where consumers' attitudes to genetically modified organisms are generally negative (Kühl *et al*. 2024).

7.1.5 Consumers' perceptions of cultivated meat

Studies across various countries indicate that a significant and variable proportion of consumers express interest in trying cultivated meat but their willingness to consume it regularly is much lower (Kombolo *et al*. 2023; Liu *et al*. 2023b). Food neophobia (Siegrist and Hartmann 2020; Boereboom *et al*. 2022; Rombach *et al*. 2022) and experienced naturalness (Siegrist and Hartmann 2020) affect the attitudes towards cultivated meat. Familiarity with cultivated proteins is also ambiguous as it tends to both increase (Bryant *et al*. 2019; Mancini and Antonioli 2019) and decrease (Zhang *et al*. 2020; Dupont *et al*. 2022) consumers' willingness to taste and use cultivated proteins. A selected summary of studies on consumers' attitudes is shown in Box 7.

Consumers highlight the following potential beneficiaries from novel products of cellular agriculture such as cultivated meat: the environment, farmed animals (in terms of welfare), and human health or more generally resolution of global food challenges (Wilks and Phillips 2017; Circus and Robison 2019;

Box 7 Selected summary of studies on consumers' attitudes towards cultivated meat

Consumers' attitudes towards cultivated meat tend to be very uncertain:

- **Willingness to taste cultivated meat** ranges from 40% to 72% (Verbeke *et al*. 2015; Wilks and Phillips 2017; Bryant and Dillard 2019; Bryant *et al*. 2019; Mancini and Antonioli 2019; Weinrich *et al*. 2020; Chriki *et al*. 2021; Francеković *et al*. 2021; Liu *et al*. 2021, 2023; Dupont *et al*. 2022; Heiskanen and Ryynänen 2024; Jacobs *et al*. 2024)
- **Willingness for regular consumption** fluctuates between 30% and 57% (Wilks and Phillips 2017; Bryant and Dillard 2019; Weinrich *et al*. 2020; Heiskanen and Ryynänen 2024; Jacobs *et al*. 2024).
- **Willingness to pay** ranges from 5% to 47% more for cultivated meat (Wilks and Phillips 2017; Mancini and Antonioli 2019; Bryant and Sanctorum 2021; Chriki *et al*. 2021; Asioli *et al*. 2022), but willingness to pay more than 50% extra compared with meat is rare (Bryant and Sanctorum 2021; Kombolo *et al*. 2023; Liu *et al*. 2023b).
- **Young people and educated consumers are willing to pay the most** for cultivated meat (Mancini and Antonioli 2019; Jacobs *et al*. 2024) as are people trying to voluntarily cut meat consumption (Mancini and Antonioli 2019).
- **Lower prices increase consumers' interest to buy** (Mancini and Antonioli 2019; Carlsson *et al*. 2022).
- **There is some evidence that people with higher education** (Jacobs *et al*. 2024), higher income (Wilks *et al*. 2019), who are **younger** (Jacobs *et al*. 2024), **men** (Jacobs *et al*. 2024), and **politically left-leaning** (Wilks and Phillips 2017; Slade 2018; Bryant *et al*. 2019) tend to be more positive towards cultivated meat, while having a higher income may also have the opposite effect and refer to conservative attitudes (Wilks and Phillips 2017).

Weinrich *et al*. 2020; Bryant and Sanctorum 2021; Heiskanen and Ryynänen 2024). When asked about potential disadvantages, consumers emphasise issues such as anticipated low taste, high price, perceived unnaturalness, perceived low healthiness, lack of trust, and the ability of cultivated meat to resolve the challenges of meat production (Hocquette *et al*. 2015; Wilks and Phillips 2017; Circus and Robison 2019; Weinrich *et al*. 2020; Ahsan *et al*. 2021; Bryant and Sanctorum 2021).

Although consumers' attitudes to cultivated proteins are uncertain, there seems to be a very positive consumer segment that does not need persuasion as well as a counter-weighting segment that tends to hold very negative attitudes. People belonging to this latter segment are probably not the early adopters of cultivated proteins and are difficult to convince about positive sides of the novel foods. The middle segment, populated by acceptors or moderates, may be the most favourable people to be potential consumers of the novel foods. However, uncertain or negative news and setbacks in development may also swing them to the conservative or sceptical segment.

7.1.6 Livestock farmers' perceptions of meat alternatives

Despite increasing academic interest and political discussions, the perceptions of livestock farmers on meat alternatives have been scarcely studied. Most studies so far have focused on cellular agriculture, especially on cultivated meat. The development of meat alternatives may have potential consequences for the work and livelihoods of livestock farmers as well as on rural areas and food systems in general (Saavoss 2019; Gerhardt *et al*. 2020; Chiles *et al*. 2021). Studies anticipate that technological development of cellular agriculture will potentially change the food systems and affect primary producers, especially livestock farmers (Gerhardt *et al*. 2020; Bryant and van der Weele 2021).

Farmers and farming sectors constitute a heterogeneous group (e.g. intensive farming, open-air livestock farming) with very different environmental, heritage, and rural implications. It could be expected that some agricultural or primary production sectors such as vegetable or crop production are potentially untouched by the developments of cellular agriculture, that some innovative farmers could benefit from cellular agriculture, and that, for livestock farmers, cellular agriculture could negatively affect their livelihoods. However, further research is needed about the impacts of meat alternatives on the different segments of livestock types of production.

A multi-stakeholder study conducted in the USA found that farmers and people working with the primary production of food could benefit from food security improvements, novel employment opportunities, and potential health benefits, while identified threats included barriers to enter or switch to cellular agriculture production, the diminishing income of livestock farmers, and the potential dictation power of a few large companies as the novel production demands high-technology and massive investments (Newton and Blaustein-Rejto 2021). A similar dependency between the anticipated dominant market position of cellular agriculture companies and the diminishing potential for farmers' livelihoods has been reported in a study considering precision-fermented cheese production in Germany (Kühl *et al*. 2024).

Cellular agriculture may open some opportunities for livestock farmers who could still practise farm animal husbandry as well as take cell biopsies for cultivated meat, switch production sector, and produce ingredients or input materials for growth media (Newton and Blaustein-Rejto 2021). Nevertheless, a qualitative study of their perceptions of cellular agriculture conducted in Finland showed uneasiness among the farmers. Although the livestock farmers did not perceive cellular agriculture meeting or exceeding the volumes of conventional livestock production and competing with subsidised production any time soon, they wondered what would happen to livestock and anticipated the potential impacts for rural areas and the kind of support they would need in the future (Räty *et al*. 2023). Lack of support was also a key theme in a study considering farmers' perceptions of alternative proteins in the UK (Crawshaw and Piazza 2023) and on a study considering cultivated meat perceptions in the UK (Manning *et al*. 2023). These findings highlight the importance of dialogue and collaboration across sectors (i.e. traditional farmers and the cultivated meat industry) (MacMillan *et al*. 2024).

Livestock farming is a major livelihood provider in rural areas and, while discussed in several studies (e.g. Chiles *et al*. 2021; Newton and Blaustein-Rejto 2021; Manning *et al*. 2023; Räty *et al*. 2023), it has been discussed to a far lesser extent in the media (Helliwell and Burton 2021). Focusing on cultivated meat, a study also found that the rural population worries more about the potential adverse impacts of cellular agriculture on food production and farming than the urban population (Shaw and Mac Con Iomaire 2019).

7.2 Ethical considerations with meat alternatives

The transition to meat alternatives involves a complex web of ethical and social considerations affecting various stakeholders, including traditional farmers, meat alternative producers, consumers, and animals. Ethical considerations should also extend to meat consumption itself, as it remains the dominant source of protein globally. These considerations can be systematically analysed through an ethical matrix focusing on three core values: well-being, autonomy, and fairness. Well-being pertains to impacts on livelihoods, health, and environmental sustainability. Autonomy involves the freedom of choice and participation in decision-making processes. Fairness addresses equitable access, affordability, and the distribution of benefits and risks.

While each of the ethical considerations is important in its own right, in policy discussions the different considerations often need to be balanced against each other. For some, this would be done in a utilitarian ethical framework, which focuses on the outcomes (consequences) of each choice and proposes that the most ethical choice is the one that leads to the greatest good for the greatest number. For others, different ethical considerations should be considered in their appropriate context, and moral decisions should adhere to certain *a priori* principles: there may be rights that cannot be overridden by other interests. This means, for instance, that while it is important to take farmers' livelihoods into account, the problems associated with livestock production may be so grave as to overrule their interests. Similar arguments could be made about other risks or benefits. Also, while value conflicts will remain between different groups, this does not mean that ethics is just a matter of individual preferences, but that good arguments need to be given for different positions. Table 5 provides an overview of some of these considerations based on the previous sections and on discussions held by the Working Group.

7.2.1 Meat consumption

Meat consumption nowadays presents a range of ethical concerns, particularly about animal welfare, environmental impact, and human health. Industrial livestock production raises questions about the treatment of animals in intensive farming systems, including confinement, genetic modification, (global) transportation of living animals, and slaughtering practices (Croney and Swanson 2023). Ethical debates also extend to whether animals should be raised and killed for food at all, particularly when alternative protein sources are becoming available. Recent research in (cognitive) ethology, linguistics, and primatology, among others, shows that animals have more complex inner lives than has traditionally been assumed. This means that the focus on animal welfare science and animal ethics has shifted from an emphasis on the absence of negative welfare states to the importance of guaranteeing positive welfare for animals. It means that minimum standards in codes of welfare for animals need updated (Mellor 2016). However, this would be difficult to realise in the current conditions of many farming systems.

The environmental impact of meat production is another major ethical concern. Animal agriculture is a significant contributor to greenhouse gas emissions, land degradation, and water use. The meat industry is responsible for about 12% (see footnote [45]) according

Table 5 Ethical matrix for meat alternatives

Stakeholder	Well-being	Autonomy	Fairness
Traditional farmers	Economic impact due to declining meat demand and competition from new industries. As they are under pressure to reduce greenhouse gas emissions, meat alternatives could also provide farmers with new income opportunities.	Ability to maintain traditional farming practices or transition to alternative protein sectors.	Risk of marginalisation if policies favour high-tech food production.
Producers of meat alternatives	Opportunities for market expansion contingent on consumer acceptance.	Navigating regulatory frameworks and technological constraints in production methods.	Concerns about corporate control and equitable access to emerging markets.
Consumers	Health implications of new products; environmental impact of food choices and in the long term, a variety of potentially healthy and sufficient food for the growing world population.	Freedom to choose alternatives, influenced by factors such as price and information availability.	Accessibility and affordability of meat alternatives for diverse socio-economic groups and across countries and regions.
Farmed animals	Potential reduction in livestock farming, leading to fewer animals bred for consumption and better well-being for animals.	Lack of autonomy; ethical considerations vary across species, including insects.	Ethical distinctions between farmed animals and insects in alternative protein production.

[45] https://foodandagricultureorganization.shinyapps.io/GLEAMV3_Public/

to data from the FAO (2022), 14.5% (Gerber *et al.* 2013), or, according to some calculations (Xu *et al.* 2021), around 19% of greenhouse gas (GHG) emissions, with cattle farming being a major driver of deforestation (FAO 2023). The large range of these estimations is due to several issues such as the year in which the estimate was made, the included sources of GHG emissions, and the methods used to convert emissions of different GHG into single metrics[46]. Regardless of the exact figure, this raises ethical questions about the responsibility of governments, corporations, and individuals in reducing meat consumption (Van der Weele *et al.* 2019) or in revisiting livestock farming systems to mitigate climate change[47]. Moreover, environmental and animal welfare concerns may conflict; while from an environmental perspective (on the basis of GHG emissions only) it is deemed more sustainable to consume poultry than beef, from an animal welfare perspective this is not the case.

Health considerations further complicate the ethics of meat consumption. While meat is a valuable source of essential nutrients, excessive consumption – particularly of red and processed meat – has been linked to increased risks of cardiovascular disease, cancer, and metabolic disorders (Mason-D'Croz *et al.* 2022). This raises concerns about public health policies and the role of education in promoting balanced diets. In addition, increased meat production to meet the demand of consumers is associated with increased use of antibiotics and therefore higher risks of antibiotic resistance as well as higher risks of zoonoses.

There are also equity concerns about meat consumption patterns across different socio-economic groups. In high-income countries, reducing meat intake is often framed as an ethical or environmental choice, whereas in low-income regions meat remains an important and sometimes scarce source of nutrition. Encouraging global reductions in meat consumption without considering disparities in food access may reinforce inequalities (Mahoney 2022). Furthermore, there are justice concerns relating to the labour conditions and of slaughterhouse workers and the emotional toll of this work.

7.2.2 Plant-based meat alternatives

Plant-based meat alternatives offer potential environmental benefits, such as reducing GHG emissions from the food system by decreasing the number of animals needed for meat production (Mason-D'Croz *et al.* 2022). However, ethical concerns arise about their highly processed nature and nutritional content. Some dietitians argue that these products are not necessarily healthier than meat because of their processing and sodium content (Van der Weele *et al.* 2019).

The affordability and accessibility of plant-based alternatives also raise ethical questions. These products remain more expensive than conventional meat in many markets, potentially exacerbating dietary inequalities (Mahoney 2022).

7.2.3 Insect-based proteins

While a small group of consumers in Western countries are willing to sample insects out of curiosity, routine consumption tends to lag behind and is dependent on many factors, including convenience, price, taste, presentation (whether the insects are visible or processed), status, and cultural appropriateness. Insects can contribute to the sustainability of the food system by providing high-protein ingredients for various food products. Insect farming also has the potential to reduce food waste, as many species can be fed on organic waste materials, contributing to a more circular economy. However, the use of insects as animal feed is debated. While feeding insects to livestock could replace less sustainable feed sources, it involves additional ethical concerns about the treatment of insects and overall animal welfare (FAO 2023). Moreover, insects as feed could provide the means to further facilitate the growth of the livestock sector.

Insect-based proteins also introduce distinct ethical considerations, particularly about the moral status of insects. Some vegetarians and ethical consumers reject insect consumption because of concerns about their capacity to experience suffering (Elorinne *et al.* 2019). While there is no scientific consensus yet about the ability of insects to consciously experience pain and pleasure, evidence seems to be accruing for a realistic possibility of consciousness (see New York Declaration on Animal Consciousness[48]).

7.2.4 Precision fermentation

Precision fermentation involves genetically modifying microorganisms to produce target proteins, offering a way to reduce reliance on animal agriculture. However, as some organisations or individuals are concerned about the use of genetically modified organisms, this technology may raise similar ethical concerns or issues, including public scepticism and debates over naturalness, for those groups (Van der Weele *et al.* 2019). This calls for public deliberation about the desirability of using this technology and clear dissemination of information about potential risks.

[46] https://thebreakthrough.org/issues/food-agriculture-environment/livestock-dont-contribute-14-5-of-global-greenhouse-gas-emissions#fn-1
[47] Dublin Declaration of Scientists on the Societal Role of Livestock, https://academic.oup.com/af/article/13/2/10/7123469
[48] https://sites.google.com/nyu.edu/nydeclaration/declaration

Some of these concerns relate to corporate control over food production. If precision fermentation technologies are dominated by a few large corporations, access and affordability could be restricted, leading to new forms of food system inequality (Mahoney 2022).

7.2.5 Cultivated meat

Cultivated meat presents complex ethical questions. In Europe, animal welfare is a key driver for its development, whereas in other regions sustainability and life cycle assessments are more central. A significant ethical issue is the perception of cultivated meat as 'unnatural', exacerbated by negative narratives, including pejorative terms such as 'lab-grown tumours'. Such portrayals reflect deep-seated cultural and ethical concerns about the acceptability of laboratory-produced food (Croney and Swanson 2023). Similarly to conventional meat and other meat alternatives, the consumer acceptance of cultivated meat will therefore be influenced by the way it is framed in public communications.

The use of fetal bovine serum in the cultivation process also raises ethical concerns. Because fetal bovine serum is derived from animal sources, its use could undermine the welfare benefits associated with cultivated meat (Mahoney 2022). Ethical concerns also extend to the economic and social implications of cultivated meat. If production is centralised in high-tech facilities controlled by large corporations, traditional farmers may face economic displacement, and access to these products could be limited, reinforcing existing inequalities in the food system (Mahoney 2022).

Keeping only a few farm animals to make repeated biopsies on them to collect enough cells to be cultivated for the production of cell-based food might be also an issue. While making one biopsy on one animal is not an issue, repeated and frequent muscle biopsies on the same animals might be considered an issue in terms of animal welfare (Chriki *et al*. 2022).

Another ethical question is the way the products are presented to consumers. Some authors claim that naming this product 'meat' may be misleading and may introduce ambiguities that are favourable to proponents of cultivated meat (Chriki *et al*. 2022). Other organisations such as the FAO suggest calling this product cell-based food, which has the advantage of inducing less ambiguity and not misleading consumers as to the true nature of the product.

7.3 Technological readiness of meat alternatives

The meat alternatives assessed in this report are also different in terms of their potential to complement or substitute meat-based diets in the near future. Technology Readiness Level (TRL) and Commercial Readiness Index (CRI) are used to assess the maturity and market readiness of a technology or product. The TRL system assesses how close a technology is to being ready for its use, by means of a scale from 1 to 9 that measures the developmental progress of a technology. The CRI assesses how close or far a product is from commercialisation. The CRI considers factors such as regulatory approvals, market demand, and production scalability, and there are different scales available.

The commercial landscape for fermentation products is dynamic, with a steady increase since 2013 in the number of companies involved in biomass and precision fermentation (Lurie-Luke 2024). However, achieving higher technology readiness levels (TRL) and commercial readiness indices (CRI) remains a challenge. Insects, plant-based alternatives, mycoproteins, and other microbial fermentation products have reached advanced TRL and CRI levels (TRL 8–9, CRI 3–4), indicating they are ahead in terms of technology and commercial readiness levels, and that their potential is higher as they have well-established production and processing methods, and multiple market applications. Insects have a higher commercial readiness as a feed rather than as a food, while products of fermentation still need to become more widely available on the market (CRI 2).

Precision fermentation and cultivated meat have generally reached lower levels of technology and commercial readiness (TRL 3–7 and CRI 1–2), with higher TRL for cultivated chicken than other species. While cultivated meat is not yet authorised on the EU market (CRI 1), it has been approved in the Singapore, Israel, the USA, and more recently in the UK for pet food (CRI 2).

Summary of technological readiness across alternatives

Meat alternative	TRL	CRI	Market readiness and challenges
Cultivated meat	3–7	1–2	High cost, regulatory barriers, scalability issues, issues about consumer acceptance
Plant-based meat alternatives	8–9	3–4	Well-established, with continuing innovations in texture and nutrition
Insects	8–9	3–4	Accepted in some regions, but cultural barriers limit adoption
Biomass fermentation	8–9	3–4	Commercialised, but high energy costs and limited production capacity
Precision fermentation	3–7	1–2	Emerging, with cost and regulatory challenges

7.4 Regulatory issues

The regulation of meat alternatives involves a complex and evolving landscape that varies significantly across jurisdictions. Regulatory frameworks affect market access, food safety, labelling, and consumer acceptance. Despite progress, the regulatory landscape for alternative proteins remains fragmented, creating uncertainty for producers and investors. Key regulatory issues include approval pathways, food safety concerns, labelling restrictions, and market accessibility. These challenges differ on the basis of the type of meat alternative, as outlined below.

In the EU, plant-based alternatives, cultivated meat, and insect-based proteins are subject to distinct legal requirements, primarily under the Novel Foods Regulation (EU Regulation 2015/2283), which mandates scientific evaluation and pre-market approval before commercialisation (Lähteenmäki-Uutela *et al.* 2025). This Regulation applies to foods not widely consumed in the EU before May 1997, traditional foods from other countries, new food ingredients, and food from new sources such as algae and microorganisms. In contrast, other regions, such as Singapore and the USA, have developed more defined pathways for the approval of certain meat alternatives (Stevens and Ruperti 2023). A significant challenge in regulating meat alternatives is determining how they fit within these existing food law categories. While plant-based alternatives are generally covered under conventional food regulations, novel proteins such as cultivated meat, precision fermentation, and insect-based products face additional regulatory scrutiny due to their classification as 'novel foods' (Van der Weele *et al.* 2019).

Labelling is another contentious regulatory issue, particularly concerning whether alternative proteins can be marketed using traditional meat-related terms. The EU Food Information Regulation EU/1169/2011 contains labelling rules that apply to all food. According to the Regulation, under certain circumstances foods that contain genetically modified organisms must be labelled; however, it is still not clear whether other labelling will need to be introduced, for instance for cultivated meat products. In addition, some countries, such as France and South Africa, have introduced restrictions on the use of words such as 'burger' and 'sausage' for plant-based and cultivated meat products, arguing that such terms could mislead consumers. In contrast, other jurisdictions, such as the USA, emphasise transparency rather than terminology restrictions (Mahoney 2022).

The European Food Safety Authority (EFSA) has a mandate on novel and traditional foods, conducting centralised scientific risk assessments on novel foods on the basis of EU legislation and the regulatory framework for novel foods while product authorisation is granted by the European Commission, which recently revised its guidance on novel foods, introducing state-of-the-art provisions for the safety and nutritional assessment of meat alternatives covered by this report (cultivated meat, fermentation, insects)[49]. The EFSA has also focused on ingredients and sourcing[50], while its remit focuses on compositional, nutritional, toxicological, and allergenic properties of foods, not on the environmental impact or embodiment of products. However, in addition to developing nutritional and safety criteria for cultivated meat, the EFSA could be the appropriate regulatory body to cover the additional elements of environmental impact and transparency, provided it has access to the required additional expertise (and with potential input from the European Environment Agency). A potential risk would be that the EFSA loses focus by starting new activities beyond its mission and core areas of expertise. The European Environment Agency or another body could, alternatively, exercise this function, not to influence approval but to guide labelling and eventually other interventions (e.g. green taxes).

The European Environment Agency and EIONet concluded in 2020 that it was still difficult to assess the environmental impacts of cultivated meat[51]. In the same brief, the European Environment Agency suggested the need for more systemic assessments, based on LCA and monitoring. Although a few LCAs of cultivated meat (Tuomisto *et al.* 2022; Kim *et al.* 2022; Sinke *et al.* 2023) have been published since the Agency's report, more assessments are still needed to understand the environmental impacts of different types of cultivated meat production (this is also applicable to other meat alternatives covered by this report).

Trade policies also complicate regulation. Diverging national approaches to alternative protein regulation create trade barriers and hinder market access, affecting global expansion and cross-border product standardisation (Mason-D'Croz *et al.* 2022).

7.4.1 Regulatory issues with plant-based meat alternatives

Plant-based meat alternatives face fewer safety-related regulatory barriers compared with cultivated meat, but labelling and marketing remain significant challenges.

[49] https://efsa.onlinelibrary.wiley.com/doi/full/10.2903/j.efsa.2024.8961
[50] See the EFSA's public consultation (January 2022) for the development of a model for EU-wide front-of-pack nutrient-profiling labelling, and the arrangements for EFSA implementation of the EC Transparency Regulation.
[51] https://www.eea.europa.eu/publications/artificial-meat-and-the-environment

In the EU, debates continue about whether plant-based products can use terms traditionally associated with meat, such as 'burger' or 'steak'. However, the European Parliament rejected a 2020 proposal to ban such terminology, allowing companies to continue using these descriptors (Van der Weele *et al*. 2019).

In other regions labelling rules vary, with some countries enforcing stricter regulations on the terminology used for plant-based products to differentiate them from conventional meat (Mahoney 2022). This regulatory uncertainty complicates branding and marketing efforts for plant-based meat producers.

The growth in popularity of plant-based meat alternatives has caused pushback from the meat industry about how these 'meat' products should be labelled (Gallelli 2024). Another key regulatory issue relates to nutritional standards and disclosure of ingredients. Ensuring transparency in ingredient sourcing, processing methods, and nutritional content is crucial for maintaining consumer confidence and compliance with food labelling regulations (Zhang *et al*. 2020). Because of the high number of combinations of animal and non-meat protein ingredients, there is no clear definition or regulation about their quality and properties (Boukid *et al*. 2024); and because these products generally use source materials that have been used before, they may evade regulatory assessments.

7.4.2 Regulatory issues with insect-based proteins

Insect-based proteins are regulated differently across jurisdictions, reflecting varying levels of acceptance and historical consumption patterns. In the EU, edible insects are classified as novel foods, requiring EFSA approval before entering the market. This process involves evaluating potential allergenicity, microbial contamination, and nutritional composition (Lähteenmäki-Uutela *et al*. 2025). Regulatory challenges, including navigating some uncertainties around the interpretation of the novel food authorisations in the EU[52], would need to be overcome to expand the presence of insect-derived products in the market (Van der Spiegel *et al*. 2013). The EU's novel food regulations can limit commercial exploitation to specific applicants for up to 5 years, hindering technology replicability and market entry. Additionally, regulatory approval for new insect species as novel foods is still pending for some species.

The production and marketing of insects as food in the EU is governed by 'novel foods legislation' (Regulation (EU) No 2015/2283). So far, four species of insect have been approved (*Tenebrio molitor* larva, the yellow mealworm; *Locusta migratoria*, the migratory locust; *Acheta domesticus*, the house cricket; and *Alphitobius diaperinus*, the lesser mealworm), eight safety assessments are currently being carried by the EFSA[53], and details on safety have also been updated[54].

The allergenic potential of insects is a significant consideration in their regulatory approval as novel foods. Understanding and managing these allergenic risks are key to the broader acceptance and safe consumption of insect-based foods (European Commission, Novel Food Catalogue). Because of the potential for allergic reactions, EU regulations require clear labelling of food products containing insect proteins, especially noting the presence of known allergens such as tropomyosin. This labelling is crucial to inform consumers about possible allergens and help them make safe dietary choices (EU Commission Implementing Regulation 2023/58).

Despite these strict requirements, many species of insect have been consumed globally for centuries (see section 3) and are generally recognised as a sustainable protein source. However, European regulatory agencies remain cautious, requiring extensive safety assessments before approving new insect species for human consumption (FAO 2023).

7.4.3 Regulatory issues with biomass and precision fermentation

The regulatory landscape for microbially fermented foods in the EU is also complex and evolving. These products are often considered novel foods under Regulation (EU) 2015/2283; in addition, if the product involves the use of genetically modified organisms, it will need an authorisation under Regulation (EC) No 1829/2003. Additionally, existing restrictions in labelling and marketing, such as reserved terms for dairy products, present challenges for some microbial fermentation products (EPRS 2024). Streamlined regulatory processes and faster responses from authorities such as EFSA are needed to support sector growth.

One of the barriers to commercialisation of microbial foods is the lengthy and expensive processes associated with obtaining the necessary regulatory and safety approvals. The use of new or engineered species may also require stricter rules, and in specific cases the design will need to address specific cultural or religious requirements (e.g. kosher, halal) (Graham and Ledesma-Amaro 2023).

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52 https://ipiff.org/insects-eu-legislation-general/
53 https://food.ec.europa.eu/safety/novel-food/authorisations/approval-insect-novel-food_en (last accessed 1 June 2025)
54 https://food.ec.europa.eu/document/download/6479a80a-92f3-42b2-b8a9-1dd63a9baf50_en?filename=animal-feed_marketing_concept-paper_insects_201703.pdf

Precision fermentation, which involves genetically modifying microorganisms to produce target proteins, faces unique regulatory challenges. In the EU, precision fermentation-derived products fall under the Novel Foods Regulation, which requires extensive pre-market authorisation and scientific evaluation (Lähteenmäki-Uutela *et al*. 2025). However, if the product contains genetically modified organisms, or their residues, it will fall under the scope of Regulation (EC) No 1829/2003 on genetically modified food and feed. Following this, the product must also be clearly labelled as such, and this labelling requirement extends to precision fermentation-derived products if they contain or are produced from genetically modified microorganisms. With the somewhat negative consumer perception of genetically modified organisms in the EU, this is a critical issue for fermentation products.

7.4.4 Regulatory issues with cultivated meat

Cultivated meat faces significant regulatory hurdles, as it represents an entirely new category of food that does not neatly fit into existing frameworks. The regulatory landscape for meat is still evolving, with significant differences across regions (see Box 8). In the EU, cultivated meat is regulated as a novel food under the EFSA's approval process, requiring extensive safety assessments, including evaluations of microbiological risks, genetic stability of cell lines, and potential allergens (Lanzoni *et al*. 2024). This process may be lengthy and can create uncertainties for companies seeking approval, potentially slowing down market entry.

Currently, no cultivated meat products have been approved for the market in the EU, and only one has been approved for pet consumption in the UK. In contrast, the USA[55], Singapore (Box 8), and Israel have begun granting regulatory approvals, highlighting the regional variability in regulatory frameworks. At least two applications have now also been submitted to the EFSA[56].

One of the main regulatory concerns for cultivated meat is food safety, particularly about potential risks such as microbiological contamination, chemical residues from culture media, and structural modifications during

Box 8 Regulatory and policy framework for cultivated meat in Singapore

Singapore is considered an attractive market for launching novel foods because of its robust biotech infrastructure, skilled workforce, and supportive regulatory environment. The 'Singapore Food Story'[57] is the food strategy aiming for an ambitious '30 by 30' (30% self-sufficiency by 2030) in a land-scarce country, supported by the Singapore Food Story R&D Programme instituted to fund specific themes[58]. The Singapore Government has actively invested in the agri-food tech ecosystem with SGD144 million in grants allocated under the R&D Programme to drive innovation in sustainable urban food solutions, advanced biotech-based protein production, and food safety science in 2020. Temasek, the state wealth fund, has made significant investments in several companies working on cultivated meat and plant-based meat alternatives since 2013. Food security has been identified as a top national strategic priority, heightened during the COVID pandemic, which exposed the fragility of food chains and the country's reliance on imports.

In December 2020, Singapore became the first country to approve the sale of cultivated meat, with GOOD Meat (a division of Eat Just) launching its cultivated chicken at the high-end restaurant 1880,[59] in the world's first commercial sale of cultivated meat. Singaporean regulations required that the product be clearly identified as cultivated meat, although specific nutritional labelling was not mandatory in restaurant settings. Since then, GOOD Meat has expanded its presence, and in 2024 it introduced GOOD Meat 3, a hybrid product containing 3% cultivated chicken, now available at Huber's Butchery in Singapore.[60]

Regulatory issues: the Singapore Food Agency established a clear framework for the safety assessment of novel foods, requiring companies to obtain pre-market approval by conducting and submitting safety assessments to ensure consumer safety[61]. Its regulatory framework aims to provide clarity and transparency to the industry about the definition, scope, and assessment criteria for novel foods, supporting Singapore's vision to be a leading food and nutrition hub with a strengthened ecosystem for food innovation and research and development[62].

Consumer demand: a survey found that Singaporeans exhibit higher acceptance of cultivated meat than Americans, largely because of stronger social image motivations, such as the cultural trait of kiasuism (fear of missing out), which drives them to embrace novel foods to project a progressive image. Additionally, the study found that celebrity versus expert social media influencers had no significant impact on consumer acceptance in either country, suggesting that marketing strategies should instead focus on highlighting 'firsts' and technological breakthroughs to attract socially conscious consumers (Chong *et al*. 2022).

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[55] https://www.fda.gov/food/cfsan-constituent-updates/fda-completes-first-pre-market-consultation-human-food-made-using-animal-cell-culture-technology

[56] https://www.eitfood.eu/news/gourmey-files-the-first-eu-novel-food-submission-for-cultivated-meat and https://mosameat.com/blog/submitting-our-first-eu-market-authorisation-request

[57] https://www.sfa.gov.sg/fromsgtosg/our-sg-food-story

[58] https://www.sfa.gov.sg/recognition-programmes-grants/grants/singapore-food-story-rd-grant-call

[59] https://www.businesswire.com/news/home/20201220005063/en/Eat-Just-Makes-History-Again-with-Restaurant-Debut-of-Cultivated-Meat

[60] https://www.goodmeat.co/all-news/good-meat-begins-the-worlds-first-retail-sales-of-cultivated-chicken

[61] https://www.sfa.gov.sg/regulatory-standards-frameworks-guidelines/novel-food-framework/guidelines-on-novel-food

[62] https://www.sfa.gov.sg/food-for-thought/article/detail/balancing-innovation-with-safety-novel-food

cell proliferation and differentiation. To address these concerns, a study suggested implementing principles of hazard analysis and critical control points (HACCP) to systematically manage safety risks throughout production (Lanzoni *et al*. 2024).

Another regulatory challenge involves the use of animal-derived inputs, such as fetal bovine serum, in cultivated meat production. The continued reliance on fetal bovine serum (cultivated meat commercialised in Singapore being produced with this) raises ethical, economic, and regulatory questions, particularly in regions with stringent rules on animal-derived ingredients (Mahoney 2022).

Additionally, consumer trust in cultivated meat may depend on clear communication from regulatory agencies about food safety, transparency in production processes, and potential health benefits (Tsvakirai *et al*. 2024). Regulatory clarity and consumer information are essential in addressing concerns about the perceived unnaturalness of cultivated meat and its alignment with traditional food standards (Lanzoni *et al*. 2024).

Discussions are continuing in some EU Member States about how cultivated meat can be labelled and marketed. There are considerations around whether cultivated meat should be allowed to use designations traditionally associated with conventional meat products. Such regulatory considerations could significantly influence how cultivated meat is perceived and accepted in the market (Boukid *et al*. 2024).

There is a need for greater transparency about the environmental and health data of cultivated meat. Many claims about its benefits rely on theoretical models and assumptions due to the novelty of the industry. Transparent and publicly accessible data are essential to validate these claims and build consumer trust. Ensuring more robust, peer-reviewed LCAs and health impact studies will be critical as the industry matures (Tuomisto 2022).

7.5 Policy issues

The production and consumption of proteins raises issues of food security, environmental sustainability, energy costs, and social and economic impacts (Scarborough *et al*. 2023). This is even more important because for the EU most dietary proteins have come from animal-based sources since the 1970s. Europe is a net importer of proteins, with 2021 estimates that around 26% of proteins are imported, which raises issues of food insecurity. The European ‘feed protein deficit’ for animal feed adds another layer of complexity, and concerns have been increasing because of the war in Ukraine (Kim *et al*. 2019).

There is also evidence of overconsumption of proteins in the EU of around one-third more than the recommended dietary allowance, and of overconsumption of proteins even among children (Mariotti and Gardner 2019), in line with overconsumption in other developed countries (Joint FAO/WHO/UNU 2002).

EU strategies such as the Green Deal, the Farm-to-Fork Strategy, the Bioeconomy Strategy, and the Biodiversity Strategy all identify alternative proteins as contributors to achieving sustainability, climate neutrality, and food system resilience. The EU’s Farm-to-Fork Strategy also points towards research and innovation as a key driver for accelerating dietary transitions, fostering the uptake of alternative protein sources, and creating new business models for farmers, industry, and consumers. Other important EU frameworks include the Sustainable Food System legislative framework, the circular economy principles in the Green Deal, and the revised EU Industrial Strategy, which focused on reducing the EU’s dependence in several strategic sectors.

In 2023, the European Parliament called the European Commission, to ‘urgently present a comprehensive and ambitious EU protein strategy covering the sustainable production and consumption of all types of protein in the EU, especially plant- and animal-based protein, and introducing effective measures to boost open European protein autonomy in the short, medium and long term’. This statement highlighted the need to prioritise protein crops and plant-based protein. Although a European Protein Strategy was initially expected in early 2024, it was subsequently delayed because of the EU elections[63] and its future remains uncertain[64].

In 2024, the report of the Strategic Dialogue on the Future of EU Agriculture[65], a consultative process with different stakeholders, called for the creation of an EU action plan for plant-based foods in 2026 (see footnote [66]). However, the ‘Vision for Agriculture and Food’, a non-legislative document published in early 2025, did not include any indication that initiatives on plant-based foods will be incorporated[67], which points to a shift in the current position of the EU Commission (2024–2029) to include meat alternatives or alternative proteins.

[63] https://sciencebusiness.net/news/agrifood/eu-novel-food-start-ups-call-more-clarity-approval-process
[64] https://www.euronews.com/health/2024/11/19/animal-or-plant-eu-countries-at-odds-over-protein-strategy
[65] https://agriculture.ec.europa.eu/document/download/171329ff-0f50-4fa5-946f-aea11032172e_en
[66] https://www.beuc.eu/sites/default/files/publications/BEUC-X-2025-004_Joint_call_EU_Action_Plan_for_Plant-Based_Foods.pdf
[67] https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/main-initiatives-strategic-dialogue-future-eu-agriculture_en

In the past, the European Parliament (ENVI Committee) has debated meat alternatives, with a few Members of the European Parliament objecting to EC funding of projects supporting 'synthetic meat' (cultivated meat) production, through for instance a €2 million COVID-recovery grant[68].

Nonetheless, several projects related to meat alternatives and alternative proteins have received EU funds from the Research and Innovation Framework Programme (Horizon Europe and its predecessor, Horizon 2020), including some focusing on the potential of cultivated meat. The EU Food 2030 initiative, which was launched in 2016 to steer research and innovation policy to transform food systems for them to deliver multiple benefits simultaneously, includes alternative proteins (e.g. plant-based, microbial, insect, algae-based, and cultivated meat).

The EU's Food 2030 initiative supports the development of alternative proteins as part of its broader goal to transform food systems towards sustainability, health, and climate resilience, and the exploration and scale-up of alternative protein sources such as plant-based proteins, microbial proteins, fungi, insects, algae, and cultivated meat. The initiative recognises alternative proteins as a key pathway to reduce GHG emissions, lower resource use, and enable healthier, more sustainable diets. Examples of funded projects are provided in Table 6 (Bizzo *et al*. 2023).

The Food 2030 initiative also supports overcoming regulatory, technological, consumer acceptance, and market barriers in the development of alternative proteins through its research and innovation funding actions and multi-stakeholder projects rather than through direct regulatory reforms. For instance, it funds projects aiming to develop processing techniques, improve sustainability, and scale up production for various alternative protein sources (e.g. plants, fungi, insects, microbial proteins, cultured meat). On consumer acceptance, several projects (e.g. NextGenProteins, Smart Protein, GIANT LEAPS, LIKE-A-PRO) specifically target increasing consumer trust, investigating nutritional adequacy, safety, allergenicity, and preferences to support market uptake, and the LIKE-A-PRO project aims to create 11 living laboratories engaging actors along the alternative protein value chain and directly involve citizens to co-design new products.

The EU's Farm-to-Fork Strategy explicitly named research and innovation as a key driver for accelerating dietary transitions, fostering the uptake of alternative protein sources, and creating new business models for farmers, industry, and consumers.

Table 6 Examples of EU-funded projects related to alternative proteins (EU Food 2030 initiative)

Project name	Alternative protein source	Technological focus	Funding programme and budget	Timeline
NEXTGENPROTEINS https://nextgenproteins.eu/	Microalgae, single-cell proteins, insects	Bioconversion technologies to turn underused biomass into protein ingredients; processing and safety optimisation	Horizon 2020, €8 million	2019–2023
SUSINCHAIN https://susinchain.eu/	Insects	Optimising insect farming and processing technologies; improving environmental and economic sustainability	Horizon 2020, €8 million	2020–2023
SMART PROTEIN https://smartproteinproject.eu/	Plants, fungi, microbial proteins	Processing of fungi (mycoproteins), plant proteins, microbial fermentation; using food industry side-streams	Horizon 2020, €8.2 million	2020–2024
GIANT LEAPS https://giant-leaps.eu/what-we-do/alternative-proteins	Multiple (plant, microbial, precision fermentation)	Generating safety, nutritional, and sustainability data for industrial processing scale-up	Horizon Europe, €10.3 million	2022–2026
LIKE-A-PRO https://www.like-a-pro.eu/	Mainstreaming alternative proteins by co-design and development of 16 new products across food environments		Horizon Europe, €12 million	2022–2026

[68] See https://www.europarl.europa.eu/doceo/document/E-9-2021-005095_EN.html and https://www.europarl.europa.eu/doceo/document/P-9-2021-004930_EN.html

Meat alternatives have also been debated at the level of EU Member States. The Italian Government unsuccessfully attempted to ban the use of cultivated meat[69], and brought this discussion in the EU Council (27 Member States) following a note raising issues about cultivated meat that was endorsed by Italy, Austria, and France[70]. A proposal to ban the manufacturing of cultivated meat was also introduced by the French 'Les Republicains' party at the National Assembly[71] and by Hungary[72]. Nonetheless, in November 2024, another group of countries (Denmark and Germany, supported by Czechia, Estonia, Ireland, Luxembourg), called on the European Commission to deliver its European Protein Strategy, including ways to foster green proteins (plant-based or alternative protein sources)[73].

These debates are reflected in the new EU long-term vision for Agriculture presented by the European Commission in 2025:

'Innovative technologies have emerged, including in the field of food technology, biotechnology and biomanufacturing. Keeping Europe's innovation edge in such new technologies is paramount for the sector to remain competitive and for the EU to remain a world leader in food innovation. At the same time, certain food innovation is sometimes seen as a threat to the traditions and culture across Europe. This calls for an enhanced dialogue on this matter and better knowledge, to make sure that these innovations can be assessed in an inclusive way that also considers social, ethical, economic, environmental and cultural aspects of food innovation'[74].

The affordability of meat alternatives is also an important consideration, as pricing affects consumer adoption and market expansion, although it is unlikely to be addressed directly through policy interventions. Despite technological advancements, cultivated meat remains significantly more expensive than conventional meat, with estimated production costs still considerably higher than traditional beef.

A study of Norwegian consumers found that price remains one of the most important factors influencing willingness to try cultivated meat, with those prioritising low costs being more likely to consider it as a viable option (Muiruri and Rickertsen 2024). For alternative proteins to become competitive, policy frameworks should consider strategies such as research funding, production incentives, and fair competition policies to reduce costs and enhance affordability.

Additionally, corporate control over some meat alternatives, for instance precision fermentation technologies, raises concerns about accessibility and affordability. If large corporations dominate the industry, smaller companies and lower-income consumers may face barriers to access, reinforcing food system inequities (Mahoney 2022).

[69] https://gfieurope.org/blog/is-italys-cultivated-meat-ban-unenforceable-european-commission-ends-tris-review-as-law-did-not-comply-with-procedures-rules/
[70] https://data.consilium.europa.eu/doc/document/ST-5469-2024-INIT/en/pdf
[71] https://www.assemblee-nationale.fr/dyn/16/textes/l16b2172_proposition-loi
[72] https://technical-regulation-information-system.ec.europa.eu/en/notification/26066
[73] https://data.consilium.europa.eu/doc/document/ST-15468-2024-INIT/en/pdf
[74] European Commission (2025). A Vision for Agriculture and Food: Shaping together an attractive farming and agri-food sector for future generations, Communication from The Commission to The European Parliament, The Council, The European Economic and Social Committee and The Committee of the Regions, COM(2025) 75 final.

8 Conclusions and recommendations

New technologies in the field of meat alternatives are being developed at different paces, and their full impacts on different sectors and stakeholders are still being studied and understood. The development of meat alternatives represents a significant shift in global food systems, offering potential benefits for sustainability, nutrition, and animal welfare. However, meat alternatives also present diverse challenges.

In the coming years, technological innovations, with implications for the characteristics and costs of different meat alternatives, will have an impact on their uptake and on the final effects that these products will have on society, the environment, and different groups. This will give rise to new opportunities for European Union (EU) developers and EU consumers to have a variety of choices in addition to conventional meat. While it is likely that meat consumption in the EU will decrease because of environmental concerns, global meat consumption is expected to grow in low- and middle-income countries. In light of this, providing support to other countries (e.g. low-and-middle income countries), including technology transfer to facilitate the shift towards meat alternatives, should also be explored by the EU as a potentially beneficial activity at the EU and global levels.

After exploring some of these meat alternatives, the key conclusions from this report are presented for each of the alternatives and for each of the impacts. Table 7 provides an overview of key findings for each of the alternatives.

8.1 Conclusions by meat alternative

Table 7 Overview of key findings for meat alternatives

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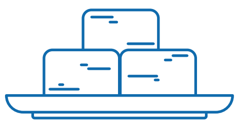
<td>
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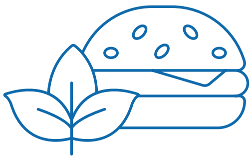
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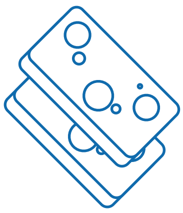
Tempeh</td>
<td>Plant-based meat alternatives
• The plant-based meat sector has expanded significantly, and commercially viable products are widely available. This category comprises a large range of products, including those that are highly processed, which present specific challenges.
• Compared with conventional meat, environmental impacts are lower in terms of emissions expressed per kilogram of product. However, processing intensity varies, and some highly processed products require additional energy inputs.
• There are some concerns about micronutrients (composition and bioavailability). Furthermore, high levels of salt, fat, and additives used in some highly processed products raise concerns about their long-term health effects.
• Consumer acceptance is relatively high compared with other meat alternatives although taste, texture, and price competitiveness remain key factors influencing or limiting market growth.
• Further technological advancements focus on enhancing texture, improving protein quality and bioavailability.
• Technological readiness: Technology Readiness Level (TRL) 8–9, Commercial Readiness Index (CRI) 3–4 (well-developed and widely commercialised, with continuing innovations in texture and nutrition).</td>
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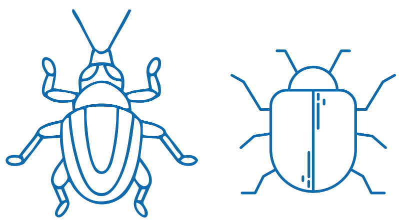
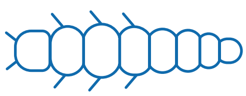
<tr>
<td>Insects as meat alternatives
• Insects offer a highly efficient and sustainable protein source, with minimal land and water requirements when by-products from agriculture or the food industry are used as feed. The ability to valorise side-streams areas feed makes them an attractive option for circular economy applications.
• Nutritionally, insects provide high-quality protein, iron, and zinc, with high bioavailability. However, concerns exist over allergenic potential and digestibility.
• Large-scale production faces technological hurdles, including automation, cost efficiency, and regulatory clarity, particularly in the EU's novel food framework.
• Consumer acceptance in Europe and North America remains low, largely because of food neophobia and cultural perceptions. However, market entry could be easier for processed forms (e.g. insect flour in protein bars).
• There are also some ethical challenges, including animal welfare implications with the use of insects.
• Technological readiness: TRL 8–9, CRI 3–4 (commercially available but not yet widely adopted in Western markets).</td>
<td>
Beetles and bugs

Mealworm</td>
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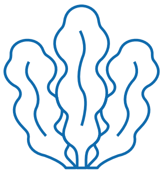
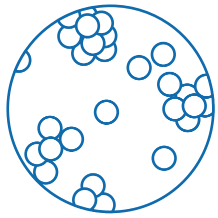
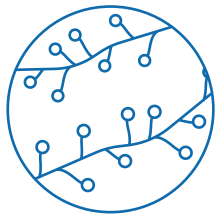
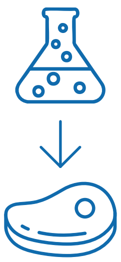
Table 7 Overview of key findings for meat alternatives (continued)

 Algae  Bacteria	**Biomass fermentation products (single-cell proteins)** • Biomass fermentation, particularly for mycoprotein-based products such as Quorn, has been commercially successful, but newer microbial protein sources are still scaling up. • Compared with conventional livestock, fermentation-based proteins have lower land and water use, but energy demands vary depending on feedstock (e.g. carbohydrate based versus gas fermentation based). • Nutritionally, microbial proteins are complete sources of amino acids, and technological processes may help with issues such as nucleic acid content management and bioavailability of certain micronutrients. • Scaling up remains a challenge because of high costs, limited food-grade fermentation capacity, and regulatory requirements. Further advancements in sustainable feedstocks (e.g. agricultural residues, carbon dioxide (CO_2)-fed microbes) could improve viability. • Technological readiness: TRL 8–9, CRI 3–4 (mature technology, but further developments needed for cost and scale improvements).
Precision fermentation products • Precision fermentation allows the targeted production of specific proteins, such as dairy (casein, whey), egg proteins, and haem for plant-based burgers. • Environmental benefits depend on the feedstocks used, with precision fermentation offering significant land use reductions but potentially high energy demands. • Nutritionally, these proteins can be bioidentical to animal-derived proteins, making them a functional replacement in processed food applications. • Scaling up remains a key barrier, with production still being expensive and feedstock optimisation (e.g. non-sugar inputs) is necessary to improve cost-effectiveness. • Regulatory approvals and consumer perception of the use of genetically modified organisms may affect adoption, particularly in regions such as Europe, where genetically modified organisms face greater scrutiny. • Technological readiness: TRL 3–7, CRI 1–2 (commercially emerging with increasing investment in scalable production).	 Yeast  Fungi
 Cultivated meat	**Cultivated meat** • A few life cycle assessments have estimated the environmental impacts of cultivated meat, but those studies have uncertainties surrounding several aspects of large-scale production processes. Studies suggest that cultivated meat could have lower emissions than traditional beef production, but that impacts are comparable to poultry if energy sources are not optimised. They also suggest that it could lead to potential environmental benefits due to lower land use and deforestation but may require high energy inputs, depending on the production process. • Health benefits and risks remain uncertain because of limited market exposure; it will not be possible to fully assess them until large scale consumption is achieved, and more research is conducted on product composition and digestibility. Although there are no early warnings in the USA, Singapore, and Israel, assessing overall health impacts may take time. However, customisation of nutrient profiles for products should be possible through bioengineering. • Production is still expensive, and scalability and cost (as well as affordability for consumers) remain important hurdles. • While approved in Singapore, the USA, and Israel, regulatory approval of products in the European Union is still pending (with at least two requests request made to the European Food Safety Authority in 2024). • Technological readiness: TRL 5–7, CRI 1–2 (not yet widely available, but progressing towards commercialisation in some markets).

8.2 Conclusions by impact or issue

8.2.1 Environmental impacts of meat alternatives

The high environmental impact of conventional meat production needs greater attention.

Although outside the scope of this report, it is important to notice that meat can also be replaced by foods that require no or limited processing, such as legumes and nuts, which have even lower negative impacts on the environment.

Using the current calculations and assessments of environmental impacts, the negative environmental impacts described in this report (greenhouse gases, land use, water use) of meat alternatives are often lower than livestock meat (especially when compared with beef meat). However, the variation in the environmental impacts of different meat alternatives is high and the impacts also depend on the level of processing. Cultivated meat, microbial proteins, and precision-fermented proteins may have higher energy-use requirements than poultry. However, the impact on climate also depends on the source of energy: if low emission energy sources are used, the impact of any type of food production, including cell-cultivated foods, can be reduced.

The land use of meat alternatives is generally lower compared with livestock meat. The low land-use requirements can provide indirect climate benefits by reducing the need to clear forests for agricultural land. Recent studies highlight that microbial protein and mycoprotein production have a significantly lower land footprint than both livestock and some conventional plant-based alternatives, making them a promising sustainable option (Smetana *et al*. 2023). Yet, it is also important to notice that livestock can also convert grass in pastures that are not suitable for crops. The land use of cell-cultivated foods and insects can be reduced by using side-streams from agriculture and food industry as feedstock.

Because of their low land-use requirements, meat alternatives require less green water (i.e. rainwater) for production. However, blue water (i.e. tap water extracted from groundwater and surface water) consumption can be higher compared with some livestock products. This is the case if the plant products require irrigation or if water is not recycled efficiently in cell-cultivated food production facilities. Water use is also a concern in precision fermentation and microbial protein production, particularly in cooling systems and bioreactor cleaning processes. Recent research suggests that integrating closed-loop water recycling could significantly improve the water efficiency of fermentation-based food systems (Tuomisto *et al*. 2022).

The low land-use requirements of meat alternatives also cause fewer nutrient emissions to waterways and therefore lower eutrophication impacts compared with livestock meat. However, some precision fermentation and microbial protein systems could contribute to eutrophication if waste streams from nutrient-rich feedstocks are not properly managed.

The biodiversity impacts of meat alternatives depend on the type and production location of the ingredients. For instance, plant-based foods produced in tropical areas on deforested land cause high biodiversity loss, whereas in some cases extensive livestock grazing systems can provide benefits to biodiversity. New research highlights the importance of sourcing plant-based ingredients sustainably, as certain crops such as soy and palm oil continue to contribute to deforestation and habitat loss, and some studies suggest alternative protein sources, such as seaweed and microbial fermentation, as promising solutions with minimal negative biodiversity impacts (EPRS 2024).

To conclude, meat alternatives generally have lower negative environmental impacts compared with livestock meat, but the impacts depend on the type of products and the production processes, and on the type of environmental outcome. Recent research emphasises that a transition to renewable energy sources in production facilities will be key to ensuring that any type of food production (conventional livestock production, or energy-intensive alternatives such as cultivated meat) will be sustainable in the long-term (Sinke *et al*. 2023).

The highest environmental benefits can be achieved when (1) energy-intensive processing steps are avoided; (2) low-emission energy sources are used for the production processes; (3) side-streams from agriculture and the food industry are used as feedstock when possible; (4) sourcing of plant-based ingredients prioritises biodiversity conservation, avoiding deforestation-linked commodities where possible; and (5) water is recycled in the production processes.

The full environmental impacts of many alternatives, especially those based on emerging technologies such as cultivated meat, are still hard to assess. Although there are many life cycle assessment studies of cultivated meat from scientific groups and data seem to be reported transparently, a main issue is the uncertainties about how large-scale production processes would look. As the technologies are still under development, we do not yet know the details of fully optimised large-scale production systems. This leads to questions such as whether we have sufficient knowledge, and whether the current regulatory framework is fit for current goals. For instance, while at the EU level the mandate of the European Food Safety Authority focuses on ensuring safety, other issues including environmental and social impacts as well as technological matters, health risks and benefits, and quality-related issues (e.g. nutritional value and health claims or food-safety issues) are not addressed. Companies may currently be able, but not required, to report on their environmental footprint.

8.2.2 Health impacts and nutrition issues

The nutritional and health implications of meat alternatives vary significantly depending on their source, processing methods, and composition. While some alternatives provide complete protein and essential micronutrients, others may have bioavailability challenges, require fortification, or involve potential safety concerns. Substituting conventional meat with alternatives may have both benefits and risks, calling for a careful evaluation of their dietary role. However, robust scientific data on the long-term health effects of these products are still limited, with few randomised controlled trials and a lack of large-scale human consumption studies.

Traditional meat is a key source of bioavailable haem-iron, and other micronutrients such as vitamin B_{12}, while meat alternatives differ in protein quality, digestibility, and micronutrient content. For instance, while plant-based products and microbial proteins can provide essential nutrients, the bioavailability of these remains a concern, particularly for micronutrients such as iron, zinc, and vitamin B_{12}. This is not an issue if nutrient requirements can be met by the rest of the dietary components, but it calls for clear dietary guidelines for consumers substituting conventional meat with plant-based products, including advice on the use of supplements, which, if properly introduced in diets, could ensure the nutritional requirements of people consuming plant-based diets. Insect proteins and mycoproteins contain bioavailable iron and other nutrients. Cultivated meat offers potential nutritional benefits but remains largely untested in large-scale human consumption, especially for bioavailability.

Some meat alternatives, particularly plant-based and hybrid products, are highly processed and may contain additives, preservatives, and emulsifiers. The long-term health effects of consuming ultra-processed meat alternatives remain uncertain, as no large-scale, long-term randomised controlled trials have assessed their impact on chronic diseases. While studies indicate that whole-food plant proteins (e.g. lentils, tofu) are associated with health benefits, the implications of high consumption of highly processed alternatives require further investigation and call for labelling and transparency obligations to consumers on the potential impacts of these products.

Diets rich in plant-based proteins and mycoproteins have been associated with lower cholesterol levels, reduced cardiovascular risk, and better weight management. However, these associations are largely derived from epidemiological studies rather than controlled trials. Some plant-based alternatives (e.g. those highly processed) may contain high levels of saturated fats (e.g. coconut oil) and sodium, which may counteract potential benefits. Cultivated meat could be engineered to optimise fat composition, but its real-world health effects remain speculative for different reasons, including the lack of digestibility studies.

Some meat alternatives pose allergy risks. Mycoproteins and insect proteins can trigger allergic reactions in sensitive individuals, particularly those with existing allergies to fungi or shellfish. Precision fermentation products require regulatory oversight to ensure purity and absence of unintended allergens. Cultivated meat may reduce risks of bacterial contamination and antibiotic resistance compared with conventional meat, but its long-term safety profile requires further study to assess some specificities of this process (such as for instance any issue related to genetic drift or contamination by culture medium).

Despite the growing market for meat alternatives, significant gaps remain in our understanding of their long-term health effects:

- Most evidence on the health impacts of meat alternatives comes from epidemiological or observational studies, which cannot establish causality. Few randomised controlled trials have compared the long-term effects of meat alternatives versus traditional meat in controlled dietary interventions.
- While meat alternatives can match conventional meat in macronutrient composition, the bioavailability of key micronutrients (iron, zinc, vitamin B_{12}) remains a major concern. More studies are needed to assess whether fortification strategies effectively prevent deficiencies in populations that rely heavily on meat alternatives.
- Highly processed plant-based products differ nutritionally from whole-food plant proteins. However, their long-term metabolic and health impacts are not well understood, particularly in relation to obesity, cardiovascular health, and metabolic disorders.
- Cultivated meat, precision fermentation proteins, and microbial proteins are emerging technologies, and their long-term effects on human health and the gut microbiome remain unstudied. Regulatory agencies require rigorous safety assessments, but post-market surveillance will be crucial to detect any unforeseen effects.
- Research is needed to assess the suitability of meat alternatives for vulnerable populations (e.g. pregnant women, children, older adults) with higher micronutrient requirements in the context of the development of personalised nutrition and preventive medicine. The extent to which a diet including these products can meet dietary needs without supplementation remains unclear.

Meat alternatives can contribute to a balanced diet, but this depends on their source, formulation, and processing methods. While they offer potential health benefits, challenges remain about micronutrient contents and bioavailability, allergenicity, and the unknown long-term health effects of some products. Given the rapid development of these technologies, further research, including well-designed randomised controlled trials and long-term dietary studies, is needed to provide clearer guidance on their health implications. Transparent labelling, fortification strategies, and consumer information will be crucial in ensuring that meat alternatives support nutritionally adequate and sustainable diets.

8.2.3 Attitudes of different stakeholders to meat alternatives

Consumer acceptance is still being studied. The willingness of consumers to adopt meat alternatives varies across demographics, with younger, urban consumers not familiar with livestock and/or meat production and environmentally conscious consumers showing greater openness. Sensory characteristics (taste, texture, and aroma) as well as price/affordability remain critical barriers to widespread adoption. There is significant variation in the acceptance of different alternatives, with plant-based products being more accepted than insects and cultivated meat because of perceived naturalness. On the basis of European research, we know that some consumers will buy particular products and others most probably not. Furthermore, even though some people are interested in tasting a new meat alternative, they may not be interested in using these products systematically (significant differences were found between people's willingness to try and their willingness to buy).

The transition to meat alternatives and alternative proteins could have economic consequences for livestock farmers, requiring proactive policies to support adaptation and diversification. Farmers could play a role in producing inputs for meat alternatives, such as growing ingredients for plant-based proteins or supplying feedstock for microbial fermentation or cultivated meat (MacMillan *et al*. 2024). Farmers will also be needed to produce inputs for agriculture, including for plant-based and other meat alternatives. Policies must attempt to balance environmental goals with economic resilience for farmers and rural communities.

The timelines for the development of some of these technologies and the transition towards them are long; hence, it is difficult to predict their mid- to long-term impacts. However, understanding the impacts for farmers and how to involve them in a transition is a key priority for the EU. For instance, there might be few or no impacts on farmers producing crops, whereas livestock farmers could be directly affected. This has already created some opposition from some farmers' groups. For the future, it will be important to address sustainability issues with an active involvement of farmers while avoiding increasing polarisation between different groups.

8.2.4 Technological aspects

Scaling up production remains a challenge for many meat alternatives (particularly for cultivated meat and precision fermentation) because of high costs, immaturity of technology, and infrastructure requirements. Precision fermentation and microbial proteins hold promise but require sustainable feedstock and improved waste management solutions. Insects as an alternative protein source present economic and technological challenges, including large-scale production and consumer reluctance. Hybrid products (blending plant and animal proteins) could serve as a transitional approach, offering environmental and health benefits while maintaining consumer familiarity.

8.2.5 Regulatory landscape

The regulatory environment for meat alternatives is fragmented across jurisdictions, creating some uncertainties for producers and investors. Novel products, including precision fermentation, new insect species introduced in the EU, and cultivated meat, face stringent approval processes in the EU, while for cultivated meat, Singapore, Israel, and the USA have taken a more proactive regulatory approach with several products already approved, and the UK has also made progress[75]. The EU Genetically Modified Organisms Regulation, especially about labelling requirements, imposes additional issues, as the views of consumers may not be favourable to products containing genetically modified organisms.

Standardised guidelines for environmental impact assessments, nutritional labelling, and consumer education will be important to ensure transparency and informed decision-making for all involved actors. Sandboxes, which are regulatory tools that usually allow businesses, academia, and regulators to test and experiment with innovative products, services, or businesses under supervision of a regulator for a limited period of time, could also be explored, on the basis of the experience in the UK[76].

8.3 Recommendations for policy-makers

Increase transparency and labelling standards

1. **Increase transparency of all production processes and their assessment by**

[75] https://www.bbc.com/news/articles/cwy12ejz0mwo
[76] https://www.food.gov.uk/news-alerts/news/groundbreaking-sandbox-programme-for-cell-cultivated-products-announced

independent third bodies. Transparency is crucial for consumer awareness, and to build trust it should be applied to nutritional values (calories or macro-nutrients such as carbohydrate/fat/protein but also composition and bioavailability of micronutrients) as well as to other important aspects such as the level of processing.

2. **Mandate clear nutritional labelling, including macronutrients, micronutrient content and bioavailability, and food processing levels.** This will also require the development of an accepted scale of food processing level overcoming the issues identified with the NOVA system. Although this report does not focus on dietary recommendations, its conclusions point out the need for consumers to understand the impacts of adding meat alternatives to their diets. For these purposes, key information should be uniformly declared by manufacturers and easily understood by the public. The nutrient composition should be incorporated into existing food composition databases for population- or individual-level dietary assessment, and monitoring and this should apply uniformly to meat alternatives as well as to other products with similar issues (e.g. highly processed products).

3. **Involve stakeholders to ensure that transparency and food labelling regulations include relevant information for consumers in an adequate way.** More work and consensus are needed between different stakeholders (producers, consumers, policy-makers). EU policy-makers should consider these issues when issuing requirements about printed labels, electronic information, type of information included in labels, how the information should be presented, and other related aspects. Institutions in charge of building consumer awareness as well as consumers themselves should also be involved to ensure that the type of information and its presentation are adequate for consumers to be meaningfully informed. Labels should be clear, standardised, and accessible, ensuring consumers can make informed choices; information should also indicate ethical practices and address religious sensitivity. Useful information should also be included in electronic media and online websites to complement rather than replace the printed information available for products in a way that reaches all segments of the population and avoids creating inequalities in access to it. Most of this information cannot be included on the label but should be available to consumers on the producers' websites. For many meat products a QR code can provide significant amounts of information about the product (e.g. how it was reared, slaughtered, processed), and a similar mechanism could be useful for meat alternatives.

4. **Implement standardised sustainability metrics (e.g. carbon footprint, water use, ingredient sourcing) and ensure transparency about the use of genetically modified organisms, animal-derived inputs, and ethical sourcing.** We recommend the stipulation of an obligation on manufacturers for appropriate analyses and labelling on the following.

   - Meat alternatives as well as livestock meat products should be required to disclose their carbon footprint, water use, energy intensity, and ingredient sourcing. Regulatory criteria and standard of evidence need to be defined for these purposes, and this should include information on the sustainability of the production chain based on life cycle assessment (e.g. total carbon footprint from extraction of natural resources to waste management). This would require consensus building and involvement of all different stakeholders, including farmers, to avoid a backlash[77].

   - Nutritional information should highlight not only precise composition but also macronutrients and micronutrient content and bioavailability, especially for iron, zinc, and vitamin B_{12}. Information should go beyond macronutrients, for example protein isolates, essential amino acids, types of fat, fibre, and bioavailability of micronutrients, avoiding the inclusion of substances that are not bioavailable and indicating information about allergens, additives, and anti-nutrients.

   - Information about processes (e.g. how products were made), sourcing, and components should be included: some methods are animal-free, others are not (e.g. muscle cells in culture, fetal bovine serum in culture medium). Among other issues, ingredient sourcing should indicate whether products contain genetically modified organisms, are organic, or sourced from sustainable farms.

Health and nutrition guidelines

1. Regulatory frameworks should encourage manufacturers/producers to enhance the nutritional quality of meat alternatives, including by making their nutritional components similar

[77] https://www.thegrocer.co.uk/news/red-tractor-axes-greener-farms-commitment-after-furious-farmer-backlash/689587.article

to those of conventional meat (e.g. ensuring that products contain essential amino acids, bioavailable micronutrients, and balanced nutrient profiles).

2. Clear policies should guide the fortification of plant-based and microbial protein products to mitigate potential deficiencies.

3. Governments and health organisations should support longitudinal studies assessing the long-term health impacts of meat alternatives, particularly their role in nutrient adequacy and chronic disease prevention.

Environmental sustainability standards

1. Standardised, transparent, and updated life cycle assessment methodologies should be implemented to assess environmental impacts across production systems.

2. Meat alternative production facilities should be encouraged to use renewable energy sources to minimise their carbon footprint.

3. Comparison between products should be conducted when the same type of energy is used.

4. Side-streams from agriculture and food industries should be leveraged as feedstocks for microbial fermentation and insect farming.

5. Manufacturers should assess the sustainability of their processes, and a similar requirement should be applied to livestock producers as well as to producers of meat alternatives.

Consumer information and awareness

1. Governments and industry stakeholders should invest in initiatives to inform consumers to improve understanding of the benefits and trade-offs of different meat alternatives (e.g. that shifting to plant-based diets is positive/beneficial for the environment but also that it needs to be carefully designed to ensure micronutrients).

2. Nutrition authorities should provide evidence-based recommendations on integrating meat alternatives into balanced diets without compromising health and essential nutrient intake.

3. Public institutions should work to combat misinformation about meat alternatives as well as conventional meat production, ensuring that scientific evidence drives consumer perceptions.

Regulatory frameworks and policy support

1. The EU should continue to streamline regulatory approvals for novel foods while maintaining high safety and sustainability standards.

2. Public funding should support research into cost-effective production methods, scalability, and improved nutritional quality of promising meat alternatives.

3. Policies should help livestock farmers adapt to changing markets for meat alternatives and for alternative proteins when needed, including incentives for plant-based farming, feedstock production, and alternative protein integration.

4. Concerns about meat alternatives should be raised in policy debates on the basis of sound science rather than opinions. While the uptake of meat alternatives is a controversial issue at EU level (e.g. Member States are divided in their approach to cultivated meat), the European Food Safety Authority has strong procedures to ensure the safety of products and, once the EU approves novel foods, these will be available in all the single market.

5. Food security and food diversification debates should include consideration of meat alternatives.

Ethical considerations

1. Policies should recognise the varying dietary needs, cultures, traditions, and economic conditions across different regions and their implications in the uptake and acceptance of meat alternatives and conventional meat among different groups of stakeholders.

2. While reducing reliance on conventional meat may benefit animal welfare, attention must also be given to ethical considerations in insect farming as well as to the ethical issues raised by cultivated meat still relying on animal cells at some point; for instance, some products derive from animal egg cells which is ethically unacceptable to many seeking meat alternatives.

3. Governments should explore grants and other potential incentives to overcome some of the challenges of sustainable meat alternatives (e.g. costs, acceptance). These initiatives should meaningfully involve and consider the needs and preferences of key stakeholders such as livestock farmers and consumers.

Glossary of terms

Alternative proteins: there is no definition at European Union level, but it is generally understood that alternative proteins aim to replace or supplement conventional animal-based proteins and include plant-based proteins, cultivated meat, and proteins derived from fermentation, insects, and algae.

Biomass fermentation: a process using microorganisms (e.g. bacteria, fungi) to break down organic matter into products, including food. In this process, the microorganisms are themselves the ingredients for the products.

Cellular agriculture: the use of cell-cultivation technologies to produce alternatives to agricultural products by cells of animals, plants, fungi, or microorganisms. The term is used to refer to production methods to make acellular products (those made of organic molecules such as proteins and fats which contain no cellular or living material in the final product), for instance through precision fermentation, as well as those to make cellular products made of living or once-living cells by growing cells from a particular animal species (i.e. cultivated meat[78]). Cellular agriculture, hence, encompasses cultivated meat, biomass, and precision fermentation.

Cultivated meat: refers to cultured, cell-based, clean, or *in vitro* meat produced by cultivating animal cells in bioreactors, rather than by raising and slaughtering animals. Clean meat is real animal cell/tissue grown outside the animal. Rather than a substitute or analogue, it is actual meat (or components of meat such as muscle, fat, and connective tissue) produced without traditional animal farming.

Conventional proteins: proteins derived from traditional and widely used dietary sources. These include protein-rich foods that have been historically consumed and recognised as primary sources of protein in human diets, such as animal or plant-based proteins.

Fake meat: general term for plant-based or synthetic products designed to imitate meat. It does not necessarily imply technical processes or perfection in mimicking meat, and it may be used interchangeably with terms such as **mock meat** or **imitation meat.**

Highly and ultra-processed food products: industrially manufactured foods that have been significantly altered from their original form. These typically contain multiple ingredients, including additives such as flavourings, colourings, emulsifiers, preservatives, or artificial sweeteners.

Imitation meat: food products that are specifically designed to imitate the taste, composition, and appearance of traditional meat. While it is similar to meat analogues, the term 'imitation meat' often implies a stronger focus on resembling animal meat in every aspect, including flavour, colour, and texture. These products can be made from plant-based ingredients, fungi, or synthetic materials.

Life cycle assessment (LCA): the process of evaluating the environmental impact of a product over the entire period of its life cycle from extraction of natural resources to waste management[79].

Meat: all edible parts of animals including blood, and including the following animal species: domestic ungulates, in particular domestic bovine (cattle), porcine (pigs), ovine (sheep), and caprine (goats) animals, domestic solipeds (horses), poultry, lagomorphs such as rabbits, hares, and rodents as well as wild and farmed game. The definition excludes ratites and fish (EC Regulation 853/2004) (Lautenschlaeger and Upmann 2017).

Meat alternatives: plant as well as non-plant products made with traditional or new methods, which are often processed with the purpose of mimicking meat in terms of technical features (e.g. taste, texture, appearance) and sometimes nutritional properties.

Meat analogues: food products designed to replicate the structure, texture, flavour, and appearance of meat. They are typically made from plant-based proteins, fungi, or other non-animal sources. The goal is to mimic real meat as closely as possible both in sensory characteristics and in functionality, namely the physical structure and texture.

Mock meat: any food product that simulates the taste, texture, and appearance of meat, but is made from non-animal ingredients. It is a more casual or non-technical term for plant or fungal-based meat alternatives. Examples are tofu, tempeh, or seitan used in various forms (such as mock chicken or beef), which are traditional plant-based foods prepared to mimic meat.

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[78] https://knowledge4policy.ec.europa.eu/glossary-item/cellular-agriculture_en
[79] https://www.eea.europa.eu/help/glossary/eea-glossary/life-cycle-assessment#. There is an ISO standard on life cycle assessments: https://www.iso.org/standard/37456.html.

Meat substitute: a broad term that refers to any food that replaces animal meat in a diet. This can include plant-based products, fungi, or cultivated alternatives. A meat substitute is more about replacing meat in meals rather than replicating its exact appearance or taste.

Plant-based alternatives and plant-based meat: 'plant-based' alternatives refer to products made from plants that are alternatives to animal-based products. This includes plant-based meat (products using plants to recreate the characteristics of meat) but also plant-based alternatives to seafood, eggs, and dairy[80].

Processed products: foods that have been altered from their natural state through various physical, chemical, or biological methods to improve shelf life, flavour, texture, appearance, or convenience. There is no standard definition of levels of processing. For instance, while the NOVA system categorises foods into four groups based on the extent and purpose of processing, it is not widely accepted (Braesco *et al*. 2022).

Precision fermentation: a specialised form of microbial fermentation that uses advanced biotechnology, such as synthetic biology or genetic engineering, to programme microorganisms (such as yeast, bacteria, or fungi) to produce specific, high-value compounds, such as proteins, enzymes, fats, or other biomolecules. This method allows the production of animal-free and sustainable ingredients for food, medicine, and industrial applications.

Traditional fermentation: a process of using naturally occurring or intentionally added microorganisms (such as bacteria, yeast, or moulds) to convert raw food ingredients into products with improved flavour, texture, shelf life, and nutritional properties. This process typically relies on centuries-old methods and naturally available microbes, without significant genetic or technological modifications.

[80] https://gfi.org/science/the-science-of-plant-based-meat/

Abbreviations

CO_2	Carbon dioxide
CRI	Commercial Readiness Index
EASAC	European Academies Science Advisory Council
EFSA	European Food Safety Authority
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse gas
LCA	Life cycle assessment
SCP	Single-cell protein
TRL	Technology Readiness Level

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Contributors

Working group composition and timetable

This report is the result of multiple discussions in the EASAC Biosciences and Public Health Panel, the EASAC Bureau, and the EASAC Council from 2022 to 2025.

Guided by an initial scoping paper developed by the former Director of the Biosciences and Public Health Programme, Louise Leong, the project proposal was approved by the EASAC Council. EASAC's member academies nominated experts to form a Working Group composed of experts acting in an individual capacity and nominated by member academies of EASAC (see the list of Working Group members below).

The Working Group, chaired by Bert Rima, met several times online in 2022 and 2024 and held an in-person meeting in November 2024 at the Royal Academies for Science and the Arts of Belgium in Brussels.

Programme director (until May 2025)

Rosa Castro

Chair of the Working Group

Bert Rima, Royal Irish Academy

Working Group members

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Angela Bearth	Swiss Academies of Arts and Sciences
Rajeev Bhat	Estonian Academy of Sciences
Bernice Bovenkerk	Royal Netherlands Academy of Arts and Sciences (KNAW)
Marianne Ellis	Royal Society
Mónica Flores	Spanish Royal Academy of Sciences
Anne-Marie Hermansson	Royal Swedish Academy of Sciences
Therese Lindahl	Royal Swedish Academy of Sciences
Peter Neubauer	German National Academy of Sciences Leopoldina
Aifric O'Sullivan	Royal Irish Academy
Guy Poppy	Royal Society
Bert Rima	EASAC, Royal Irish Academy
Toni Ryynänen	Council of Finnish Academies
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EASAC is a network of the following European national academies and academic bodies. All EASAC member academies have endorsed this report in accordance with EASAC procedures. These include that all efforts have been made — with the nominations for the working group, during the writing phase of the report and through the independent review procedure — to ensure that this report reflects the best available scientific evidence. EASAC focuses with its recommendations on addressing topics and challenges for Europe at the transnational scale, and recognises that some of its member academies may need to weigh in national issues in the advice to their governments.

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The Royal Academies for Science and the Arts of Belgium
The Bulgarian Academy of Sciences
The Croatian Academy of Sciences and Arts
The Cyprus Academy of Sciences, Letters and Arts
The Czech Academy of Sciences
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