What's cooking?

An assessment of the potential impacts of selected novel alternatives to conventional animal products

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Lead Authors
Cleo Verkuijl, Stockholm Environment Institute (SEI), Harvard Law School; Rajeswari Raina, Shiv Nadar University; Robert Watson, University of East Anglia

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Authors
Ploy Achakulwisut, SEI Asia; Michael Carter, The Good Food Institute (GFI); Varun Deshpande, GFI India; Dolapo Enahoro, International Livestock Research Institute (ILRI); Shayna Fertig, GFI; Carsten Gerhardt, Kearney; Jonathan Green, SEI York; Ndaindila Haindongo, Food and Agriculture Organisation of the United Nations (FAO); Mario Herrero, Cornell University; Ana Maria Loboguerrero, Bioversity International - CGIAR; Daniel Mason-D'Croz, Cornell University; Tsakani Ngomane, University of the District of Columbia; Katie Noble, Leverhulme Centre for Anthropocene Biodiversity, University of York University of York; Oscar Rueda, Leiden University; Laura Scherer, Leiden University

Reviewers
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List of abbreviations

ASF	Animal source foods
CCAC	Climate and Clean Air Coalition
CIFOR	Center for International Forestry Research
COVID-19	Coronavirus disease
EFSA	European Food Safety Authority
FAO	Food and Agriculture Organization of the United Nations
FBS	Fetal bovine serum
FCR	Feed Conversion Ratio
FDA	Food and Drug Administration (USA)
FSANZ	Food Standards Australia New Zealand
GFI	The Good Food Institute
GHG	Greenhouse gas
IFAD	International Fund for Agricultural Development
ILRI	International Livestock Research Institute
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPES-Food	International Panel of Experts on Sustainable Food Systems
LCA	Life cycle assessment
NCD	Non-communicable disease
OECD	Organization for Economic Cooperation and Development
RCT	Randomized controlled trial
UNDESA	United Nations Department of Economic and Social Affairs
UNEP	United Nations Environment Programme
UNICEF	United Nations Children’s Fund
UPF	Ultra-processed food
USDA	United States Department of Agriculture
WHO	World Health Organization

Glossary

Animal sentience
Sometimes refers to the animal's capacity for any type of subjective experience, and sometimes to the capacity to have subjective experiences with a positive or negative valence, such as pain or pleasure (Browning and Birch 2022).

Animal source foods
Products sourced from animals. In this report, the term is used to refer to foods derived from animals, such as beef, pork, mutton, poultry, and dairy.

Antimicrobial resistance
A global public health issue characterized by the ineffectiveness of antibiotic, antiviral, antiparasitic and antifungal treatments stemming from inappropriate use of antimicrobials, often as a result of chemical and biological pollution from the pharmaceuticals, agriculture and healthcare sectors and municipal waste (UNEP 2023).

Biomass fermentation
The process of using microorganisms to make protein-rich food, where the microorganisms produced are themselves the primary ingredient.

Biopsy
Technique to collect tissue samples from living donor animals (Melzener *et al*. 2020).

Cell lines
Populations of cells that can be maintained for an extended period.

Cultivated meat
Meat produced directly from animal cells. This is done by extracting cells from a living animal and growing them in bioreactors. Cells can be differentiated into muscle, fat and other cell types to create products that have the same or similar three-dimensional structure, nutrition profile and organoleptic properties as conventional meat.

Culture media
Contains the nutrients and growth factors needed to cultivate cells outside an animal's body and culture the muscle, fat and connective tissue cells (O'Neill *et al.* 2020).

Enteric fermentation
A natural part of the digestive process in ruminant animals such as cattle, sheep, goats and buffalo. Microbes in the digestive tract, or rumen, decompose and ferment food, producing methane as a by-product (CCAC 2023).

Feed conversion ratio
A key characteristic describing requirements of crops per unit of end product; describes the efficiency of turning feed crops into animal meat products (Sinke *et al*. 2023).

Fermentation-derived products
Foods produced using biomass or precision fermentation. Biomass fermentation is the process of using microorganisms to make protein-rich food, where the microorganisms produced are themselves the primary ingredient. Precision fermentation uses microorganisms to produce specific functional ingredients, including proteins, vitamins and flavour molecules. These can be used in novel plant-based food to improve taste or texture, and in cultivated meat to enable more efficient growth (Figure 3.3).

Heme protein
Iron-containing proteins, such as leghemoglobin and myoglobin, which give plant-based meats a taste and aroma similar to that of conventional meat.

Just transition
Emphasizes that large socio-economic shifts including in response to climate change should be planned and implemented in a way that is socially fair. Its principles encourage governments to work with stakeholders to design policies that will help to minimize disruptions and maximize benefits for stakeholders affected by transition.

Macronutrient
Nutrients that provide calories or energy and are required in large amounts to maintain body functions and carry out the activities of daily life. There are three broad classes of macronutrient: proteins, carbohydrates and fats (WHO 2023a).

Micronutrient
Vitamins and minerals needed by the body in very small amounts. However, their impact on a body's health is critical, and deficiency in any of them can cause severe and even life-threatening conditions. They perform a range of functions, including enabling the body to produce enzymes, hormones and other substances needed for normal growth and development (WHO 2023b).

Mycoprotein
A fungal-derived protein source with a fibrous structure (Ahmad *et al*. 2022).

Non-communicable disease
Noncommunicable diseases (NCDs), also known as chronic diseases, are not transmissible directly from one person to another. NCDs tend to be of long duration and are the result of a combination of genetic, physiological, environmental and behavioural factors (World Health Organization [WHO] 2023).

Novel animal source food alternatives
Products with an appearance, taste, smell and texture similar to or even indistinguishable from conventional ASF, produced through new scientific approaches.

Novel plant-based foods
These products aim to replicate the sensory experience of animal products by combining plant protein (typically from soy or pea) with fats, vitamins, minerals and water (Figure 3.1).

Organoleptic experience
Sensory properties like flavour, aroma, texture, bite, moisture, mouthfeel, appearance and colour.

Foodways
The eating habits and culinary practices of a people, region, or historical period.

Functional diversity
An important component of biodiversity that characterizes the variability of functional traits within a community, landscape or even large spatial scales. It can influence ecosystem processes and stability (Ma *et al.* 2019).

Species richness
Represents a measure of the variety of species based simply on a count of the number of species in a particular sample (Fedor and Zvaríková 2019).

Precision fermentation
Uses microorganisms to produce ingredients, including particular proteins, flavours, vitamins and fats, to be added to a final food product. These can be used in novel plant-based food to improve taste or texture, and in cultivated meat to enable more efficient growth.

Protein fractionation
The extraction of protein from the rest of the plant.

Scaffolding
Materials used to support and guide tissue formation for tissue-engineered constructs include synthetic polymers, self-assembling peptides, extracellular matrix (ECM) molecules and plant- or fungus-derived materials (Bomkamp *et al.* 2021).

Sensory profile
Appearance, taste, smell and texture.

Zoonoses
Diseases that can spread between animals and people, moving from wild and domesticated animals to humans and from humans to animals (UNEP 2021b).

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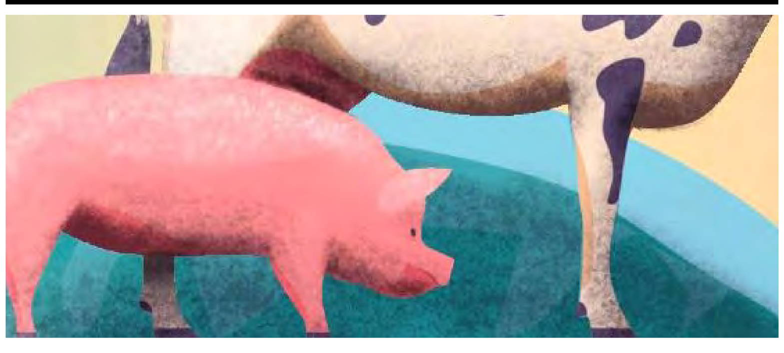

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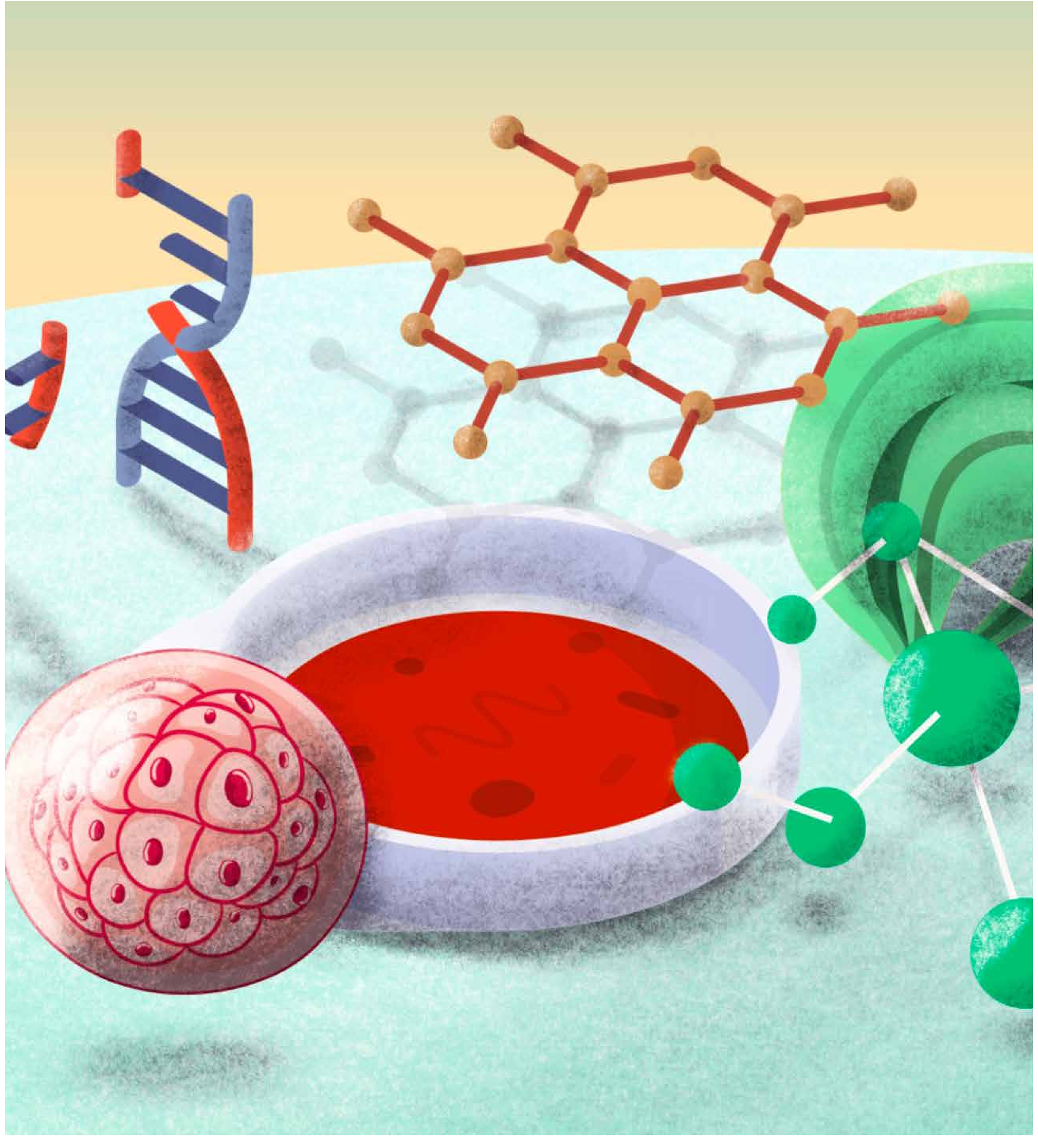

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Foreword

We are what we eat, and that makes us: unsustainable.

How we produce and consume food is contributing to Earth's triple environmental crisis: the climate emergency, nature and biodiversity loss, and pollution and waste, with livestock production and consumption playing a key role in all three.

Animal agriculture holds critical economic, social and cultural value. It is vital to the livelihoods of rural households especially in developing countries, and the global animal agriculture industry employs and provides healthy and protein-rich food for millions of people. Yet the animal agriculture industry is also a significant contributor to emissions of greenhouse gases – both direct animal emissions, and those associated with land clearing and growing animal food. Making room for more and more livestock and fodder crops is driving the loss of tropical forests, while excess animal manure and chemical fertilizers are polluting our groundwater, rivers and seas.

As global demand for meat and dairy products continues to rise, their production and consumption pose significant challenges for public health and animal welfare. Eating too much red and processed meat contributes to high rates of obesity and diabetes. Animal agriculture raises the risk of new zoonotic diseases and antimicrobial resistance. Many animals are raised and slaughtered in conditions that undermine their welfare.

It is clear that food systems, including the meat and dairy sector, must be part of the social and economic transformations required to halt and reverse the damage we are inflicting on Earth's natural systems. Achieving the Sustainable Development Goals, limiting global warming under the Paris Agreement and fulfilling the Kunming-Montreal Global Biodiversity Framework all depend on it.

The United Nations Environment Programme (UNEP) is committed to searching for science-based solutions and using its convening power. This work includes identifying and exploring emerging issues of environmental concern, including through the UNEP Frontiers reports.

This special edition of UNEP's Frontiers report explores the available evidence on novel plant-based foods, cultivated meat and fermentation-derived products as alternatives or complements to conventional meat and dairy that could potentially leave a much smaller environmental footprint.

The report provides an overview of scientific knowledge of these novel alternatives as elements of a wider reform of food systems. It examines the implications of their uptake for the environment and human health, as well as for societal dynamics and animal welfare. However, the full extent of their environmental, social and human health impacts is not yet fully understood. Drawing on examples from around the world, it also looks at the state of policies and regulations and identifies the tools that governments can use to steer the development of the sector.

The report also identifies where further research is urgently needed to plug knowledge gaps and inform growing public debate about the pros and cons of novel meat and dairy alternatives.

Novel alternatives to meat and dairy could play a positive role in a transformed global food sector, generating employment and technologies that power the sustainable economies of the future. But such a shift could also threaten a range of existing jobs as well as raise important questions about how it will affect disparities between the Global North and Global South and rural and urban communities, and further concentrate the market power of big companies.

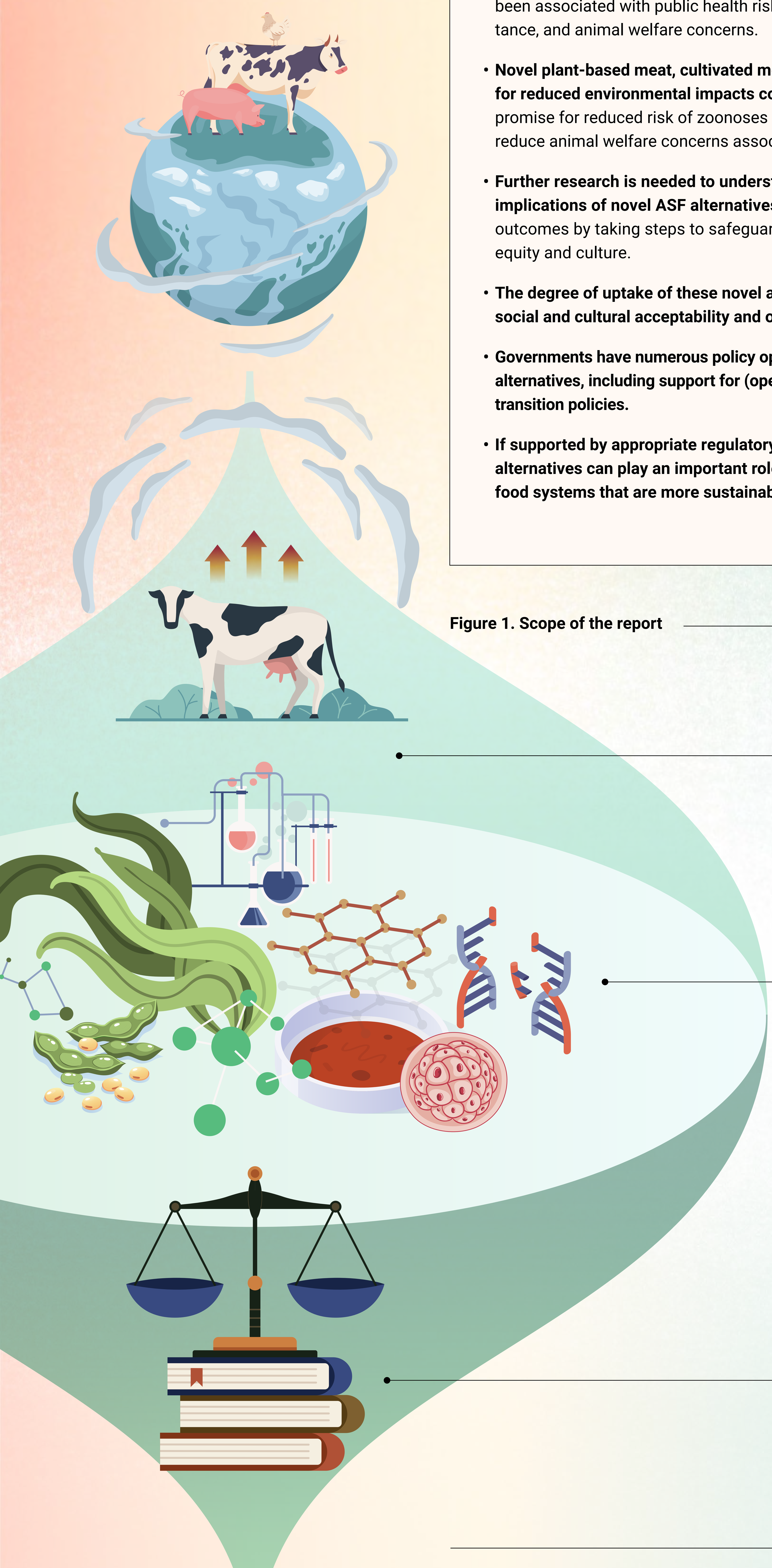
Policymakers have a particular responsibility for ensuring that any such transitions are socially fair and well managed, and do not undermine food security or result in a more inequitable world for social minorities, including women and Indigenous Peoples.

More and more people understand that we need to change our unsustainable ways. Mapping the frontiers of our knowledge, including of the impacts of what we eat and the potential of new technologies, can help us find the best path toward a better future.

Inger Andersen
Executive Director
United Nations Environment Programme

Key findings

- **Globally, food systems are responsible for about 30 per cent of the current anthropogenic greenhouse gas emissions driving climate change.** Animal products—including animal emissions, feed, changes in land use and energy-intensive global supply chains—account for almost 60 per cent of food-related emissions, for a total of 14.5–20 per cent of global emissions.
- **Impacts of the growing demand for animal source foods (ASF) take place in a context of unsustainable farming methods and overconsumption, especially in middle and high-income countries.** Overall, production and consumption significantly contribute to climate change, air and water pollution, biodiversity loss, and soil degradation.
- **While ASF are an important source of nutrition, high intake of red and processed meat is associated with increased risk of non-communicable diseases.** ASF production has also been associated with public health risks such as zoonotic disease and antimicrobial resistance, and animal welfare concerns.
- **Novel plant-based meat, cultivated meat and fermentation-derived foods show potential for reduced environmental impacts compared to many conventional ASF.** They also show promise for reduced risk of zoonoses and antimicrobial resistance, and can significantly reduce animal welfare concerns associated with conventional animal agriculture.
- **Further research is needed to understand the potential socioeconomic and nutritional implications of novel ASF alternatives.** Policymakers could also help maximize beneficial outcomes by taking steps to safeguard food security, jobs, livelihoods, social and gender equity and culture.
- **The degree of uptake of these novel alternatives will likely depend on their cost, taste and social and cultural acceptability and on how they are regulated.**
- **Governments have numerous policy options to explore and support the potential of novel alternatives, including support for (open-access) research and commercialization and just transition policies.**
- **If supported by appropriate regulatory regimes and governance instruments, novel ASF alternatives can play an important role, likely with regional differences, in a shift towards food systems that are more sustainable, healthier and less harmful to animals.**



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1. Introduction

2. Animal source foods significantly impact the environment, human health, socioeconomic dynamics and animal welfare

3. New technological solutions are being developed to provide an alternative to animal source foods

4. Policy and regulatory environments can significantly influence the future of alternatives

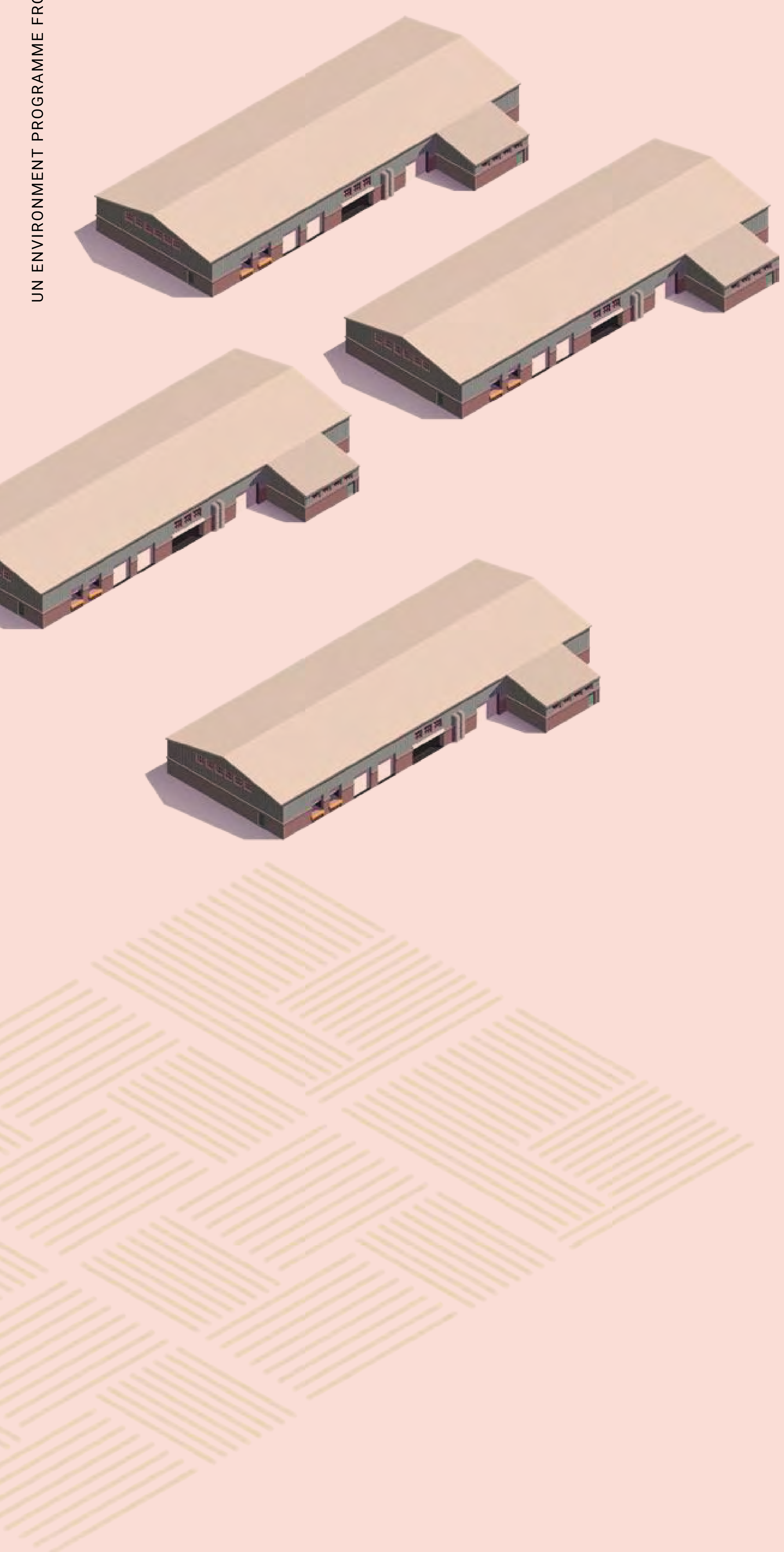
5. Conclusion

About this report

This report focuses on the potential environmental, health, social and animal welfare implications of the uptake of novel meat and dairy alternatives, in particular novel plant-based, fermentation-derived and cultivated products. A team of interdisciplinary experts has assessed the available evidence on the impacts of these alternatives in comparison with their conventional counterparts, identifying pertinent considerations for policymakers involved in regulating, investing in or providing other support for novel meat and dairy products and highlighting research gaps.

The report does not explore in depth how developing and shifting to novel alternatives compares with other strategies for reducing the negative impacts of the current meat and dairy industry, such as substituting meat and dairy with more traditional vegetarian and vegan products (e.g. tofu, tempeh), developing insects as a source of human and animal feed, promoting extensive and regenerative animal agriculture, reducing meat and dairy demand through pricing (e.g. meat taxes) or direct interventions to reduce animal emissions (e.g. feed additives). Neither does the report address fish and other aquatic animals, or meat from (other) wild animals.

Executive summary

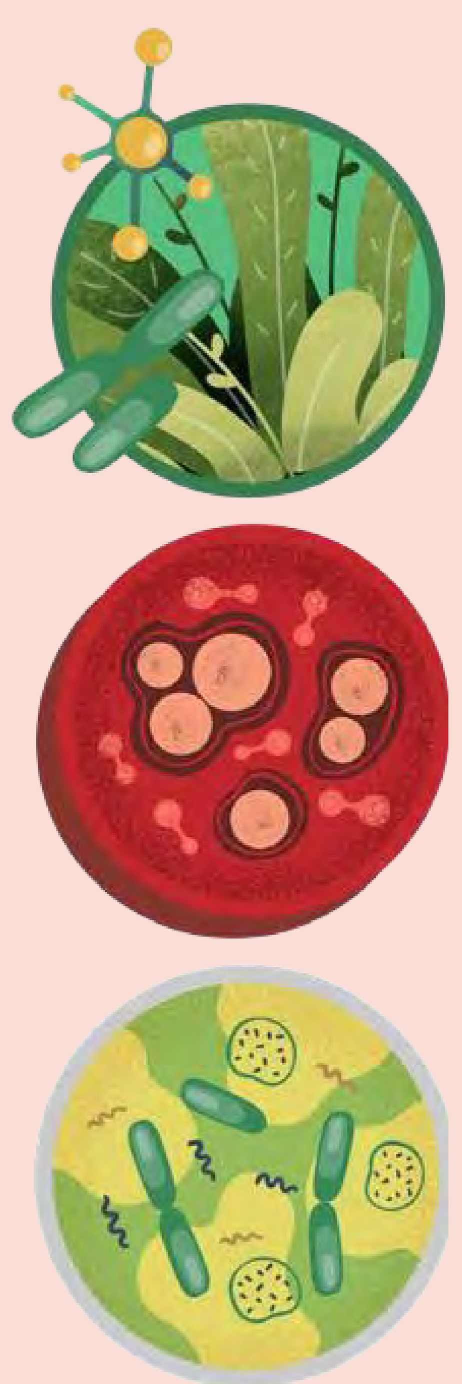


Globally, animal source food (ASF) contribute substantially to many countries' economies and are a major source of employment and income. They are also an important source of protein, vitamins, minerals and other nutrients, especially in food-insecure settings, and carry special significance for many demographic groups and cultures. At the same time, studies have generally found that high intake of red and processed meat is associated with increased risks of obesity and non-communicable diseases. Global production and consumption of ASF, including beef, pork, mutton, poultry and dairy have increased substantially in the last decades, with significant regional variations, as a result of population growth, rising incomes and generally supportive government policies, among other factors. Based on projected increases in population and per capita meat consumption, **current global meat consumption is projected to increase by 50 per cent or more by 2050 (notably with major regional differences).**

Animal agriculture, including animal feed production, is estimated to contribute 14.5–20 per cent of global human-caused GHG emissions, thus contributing significantly to human-induced climate change, as well as widespread air and water pollution, loss of soil structure and nutrients and loss of terrestrial, freshwater and coastal biodiversity. Furthermore, some livestock production systems have been linked to increased risk of zoonotic diseases and are associated with rising antimicrobial resistance. There are also animal welfare concerns as tens of billions of sentient animals are raised and slaughtered every year.

A number of approaches of varying feasibility and potential impacts have been proposed to address the environmental impacts of the livestock sector. These include investing in smaller-scale, extensive or regenerative livestock farms; direct interventions to reduce emissions from animal agriculture, such as feed additives; promoting reduced meat consumption in favour of whole plant sources of protein such as beans and lentils; and discouraging consumption of animal products with taxes or other policy levers. Thus far, such interventions have been limited, and are not achieving the desired impacts at the scale or speed necessary in the regions and amongst populations where such changes are most needed.

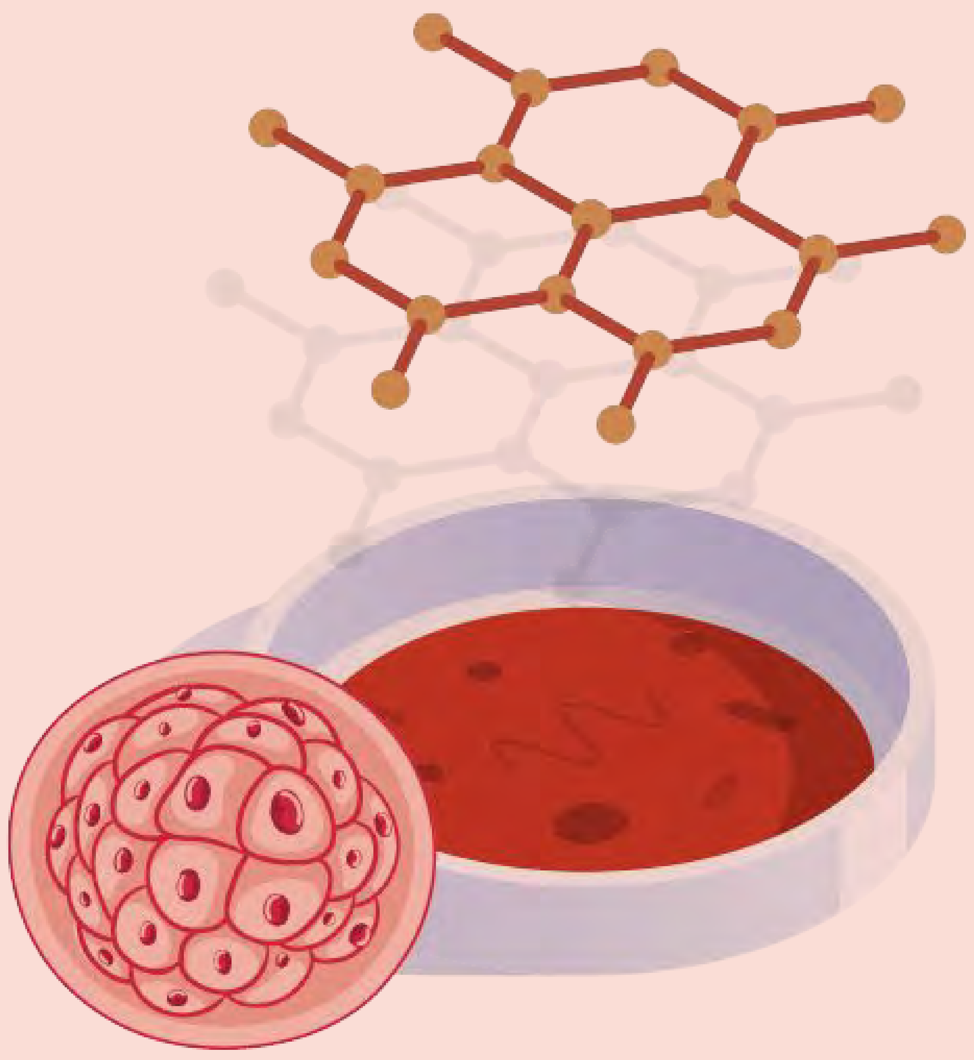
An additional approach that has attracted attention from policymakers and investors in recent years is to advance the development of novel alternatives such as novel plant-based, fermentation-derived or cultivated ASF products. These products have a sensory profile (i.e. appearance, taste, smell and texture) similar to or even indistinguishable from conventional ASF. These alternatives include:



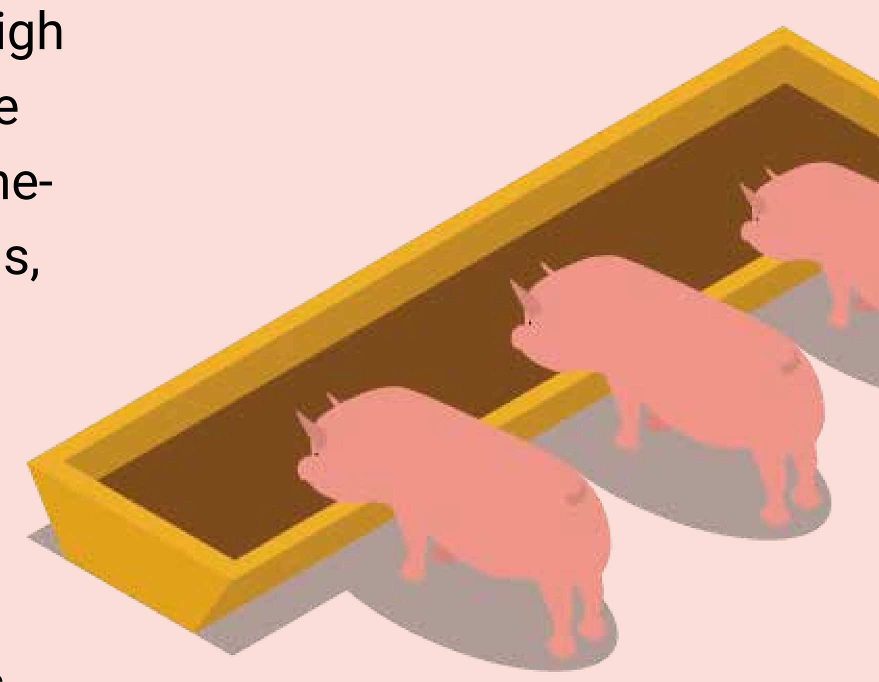
- **Novel plant-based products,** made from plant protein (typically from soy or pea) combined with fats, vitamins, minerals and water to closely imitate the sensory profile of meat.
- **Cultivated meat,** which is real meat made from animal cells grown in bioreactors.
- **Fermentation-derived products,** including:
  - *Biomass fermentation-derived products,* which are protein-rich foods created using the rapid growth of microorganisms that are themselves the primary ingredients; and
  - *Precision fermentation-derived products*, which use microorganisms to produce ingredients, including particular proteins, flavours, vitamins and fats, to be added to a final food product.

Forecasts for the growth of the novel meat alternatives industry vary widely. Projections for its share of total meat consumption range from 4 to 60 per cent by 2040, while projections for the market share occupied by each category of alternative also vary. This illustrates the inherent uncertainty of making predictions of uptake at this early stage of the industry's development. Significant technological advances are still required for these foods to become available at wider scale and to compete with conventional ASF on taste and price.

Assessing the environmental lifecycle impacts of novel ASF alternatives is difficult, as data is scarce, parts of the industry are not yet operating at scale and further developments are expected. **However, novel ASF alternatives already show strong potential for reduced environmental impacts compared to many conventional animal products.** From a GHG emissions perspective, the novel alternatives considered in this report compare especially favourably to beef, which is particularly high-emitting. Nevertheless, some novel products, including cultivated meat, can be energy-intensive to produce. Realizing their full emission reduction potential is therefore contingent on the use of low-carbon energy.



Targeted research is needed to comprehensively assess the public health implications of novel ASF alternatives as they develop. Both traditional plant-based foods and novel ASF alternatives are associated with reduced risk of zoonoses emergence and anti-microbial resistance. Diets that emphasize minimally processed, plant-based foods are generally associated with reduced risks of premature mortality and non-communicable diseases. However, novel plant-based products currently tend to be highly processed and have high amounts of salt, though opportunities to enhance their nutrient quality exist. Evidence on the health impacts of ASF alternatives using fermentation or cultivated from animal cells is limited.



Understanding the potential socioeconomic implications of novel ASF alternatives also requires further research. Nevertheless, it is clear that high uptake would disrupt current food systems with both positive and negative impacts for different stakeholders. Policymakers could help maximize beneficial outcomes by taking steps to safeguard food security, jobs, livelihoods, social and gender equity and culture.

ASF alternatives, including the novel forms discussed in this report, have the potential to drastically reduce harm to animals in the food system. Plant- and fermentation-based alternatives avoid the use of animals. Cultivated meat still involves the use of animals to obtain stem cells (through biopsies) and, in some cases, animal serum (for growth media). However, vastly fewer animals would be needed to support cultivated meat production, and companies are working towards eliminating the use of animal serum, with some proven successes.

The policy and regulatory environment for novel ASF alternatives is evolving rapidly, with many governments formulating and implementing new policies and policy instruments. Many countries and regions—including Brazil, China, the European Union, India, Israel, Singapore and the United States of America—have invested in the production of novel ASF alternatives. Some countries, including Australia, Brazil and Denmark, have provided incentives to producers, with tax exemptions, subsidies and support for energy and market development, while some countries, including China, India and the Netherlands, are also investing in research, human resources, curricula development and the promotion of sustainable practices in this emerging sector. In contrast, in 2023 Italy approved a draft bill that would ban production, import and export of food grown in laboratories, including cultivated meat.

Ways through which governments can support novel alternatives to become commercially viable include providing funding for research—in particular open-source research—and commercialization. Governments can also develop regulatory and approval frameworks that ensure food safety in a transparent and streamlined manner.

A shift away from unsustainable forms of production and consumption of conventional ASF and towards novel alternatives presents various uncertainties. Government decisions could facilitate increased environmental, social and health benefits through proactive policymaking to promote a just and sustainable transition. Governments could consider reducing and/or redistributing subsidies or other forms of support currently in place for industrial animal agriculture to ensure food prices reflect associated health and environmental costs.

International collaboration, including through joint research, development and harmonization of standards and international support, can also advance the uptake of novel alternatives, alongside other approaches for meeting global food security and nutritional needs.

Overall, novel ASF alternatives, if supported by appropriate regulatory regimes and governance instruments, can potentially play an important role in a shift towards food systems that are more sustainable, healthier and less harmful to animals, with likely regional differences. Equitable, evidence-informed policies are needed to ensure positive outcomes. Understanding of the implications of these technologies and their interactions with other environmental, health and social systems continues to evolve, highlighting the need for more research, especially open-source research. **Policymaking will benefit from additional independent assessments of the environmental, health and socioeconomic implications of novel food technologies, as well as a better understanding of which policies are most effective in regulating and/or promoting them, and in what geographical, socio-economic and, in some cases, cultural contexts they are best deployed.**

1. Introduction

Globally, food systems are responsible for about 30 per cent of the current anthropogenic GHG emissions driving climate change (Intergovernmental Panel on Climate Change [IPCC] 2021). In turn, animal products (including feed, direct emissions, land-use change and supply chains), account for almost 60 per cent of food-related emissions (Machovina, Feeley and Ripple 2015; Poore and Nemecek 2018; Zabel *et al.* 2019; Xu *et al.* 2021). More than three-quarters of the world's farmland is taken up by production of animal products (United Nations Environment Programme [UNEP] 2021b), but the environmental impact varies with the type of meat, modes of production (land, labour and capital intensity), production practices and the nature and magnitude of support (such as subsidies) from governments.

A shift away from land-intensive animal protein production systems, especially cattle farming, could free up land and water, dramatically reduce their carbon footprint and leave space for the restoration of degraded ecosystems, contributing to climate change mitigation and biodiversity protection (Machovina, Feeley and Ripple 2015). However, this is an enormous challenge made more complex by the economic, social and cultural importance of the sector. ASF can provide nutritional health benefits but also carry risks, depending on the food type and the context in which they are produced and consumed. For example, red meat is an important source of protein, vitamins (e.g. vitamins D, B6 and B12), minerals (e.g. iron, selenium and zinc) and other nutrients such as essential amino acids (e.g. lysine, threonine and methionine). At the same time, studies have generally found that high levels of red and processed meat consumption are associated with increased risk of non-communicable diseases (NCDs), particularly cardiovascular disease, type II diabetes and certain cancers (Clark *et al.* 2019; Figure 2.3). Increased risk of the emergence of zoonotic infectious diseases, such as avian flu, and of anti-microbial resistance is also associated with animal farming (Morand 2020; Wiebers and Feigin 2020; World Health Organization [WHO] 2017).

Changes in the way we produce, distribute and consume ASF must be steered in ways that ease, not exacerbate, the food insecurity that still plagues many parts of the world. About 800 million people are currently affected by hunger and are undernourished, and more than two billion suffer food and nutritional insecurity (Food and Agriculture Organization of the United Nations [FAO], International Fund for Agricultural Development [IFAD], United Nations Children's Fund [UNICEF], World Food Programme [WFP] and WHO 2022). Although both men and women play a significant role in smallholder food production, women's food security is more vulnerable to environmental and economic pressures (Rao *et al.* 2019).

In developed countries, growing numbers of people—from 'flexitarians' cutting down on meat to vegetarians eliminating it and vegans shunning animal products altogether—are reducing their intake of animal protein (Ajena *et al.* 2021). But these trends are projected to be outpaced by overall growth in ASF consumption globally, and most people continue to consume animal products, often for their flavour or for cultural or social reasons. Per capita consumption of ASF however remains low in many low- and middle-income countries, particularly among nutritionally vulnerable populations such as children under five years, and women of reproductive age (United Nations, 2021).

The significant impacts of animal agriculture raise questions of whether conventional ASF could be replaced with novel alternatives that appeal directly to meat-eaters at least in some regions. Classic plant-based ingredients such as tofu and seitan have a long history of being used as protein sources. However, these foods do not necessarily match the taste and texture of animal products that appeal to many consumers. New technologies are being used to address this, and include novel plant-based products, cultivated meat and products derived from biomass and precision fermentation (see Box 1.1).

In industrialized countries, retail sales of alternative proteins surpassed US$5 billion in 2021 (CE Delft and The Good Food Institute [GFI] 2021; Figure 3.4). This is modest compared with the value of the meat industry globally estimated at about US$900 billion in 2021 (Shahbandeh 2022), but significant for an emerging industry.

Already, plant-based sources provide 57 per cent of protein that humans consume globally (UNEP 2021c). Some predict that new ASF alternatives will provide a significant additional portion of the global protein supply within the next decade or two (Gerhardt *et al.* 2019; UNEP 2021b; GFI 2023a), though others are cautious about their potential market penetration

Box 1.1 Definitions

Novel plant-based foods aim to replicate the sensory experience of animal products by combining plant protein (typically from soy or pea) with fats, vitamins, minerals, water and other additives. This grouping does not include more traditional plant-based meat alternatives such as tofu, tempeh, seitan, mushrooms and jackfruit.

Cultivated meat is meat produced directly from animal cells. This is done by extracting cells from a living animal and growing them in bioreactors. Cells can be differentiated into muscle, fat and other cell types to create products with a three-dimensional structure and organoleptic properties similar or identical to those of conventional meat products.

Fermentation-derived products are foods produced using biomass or precision fermentation. Biomass fermentation is the process of using microorganisms to make protein-rich food, where the microorganisms produced are themselves the primary ingredient. Precision fermentation uses microorganisms to produce specific functional ingredients, including proteins, vitamins and flavour molecules. These can be used in novel plant-based food to improve taste or texture, and in cultivated meat to enable more efficient growth.

(Chriki and Hocquette 2020; Humbird 2021; IPES-Food 2022). An important question is whether, and to what degree, these new products can replace conventional ASF, or if they will merely complement them.

Amid rising public interest and debate, governments are beginning to respond. An increasing number of countries have begun to invest in research and in the production of alternatives to animal products (Section 4). On the other hand, a few countries are responding with bans and restrictive regulations, citing concerns such as impacts on current animal agriculture, farming communities and local culinary traditions (DeSoucey 2010; Sabelli 2023). Realizing the potential benefits depends on reducing the production and consumption of conventional ASF and significant substitution with new alternatives.

This report aims to advance the discussion of the potential role of novel ASF alternatives in contributing to a more environmentally sustainable, healthy and socially and morally acceptable food system. It focuses on three products—novel plant-based products, biomass and precision fermentation products and cultivated meat—and the production technologies involved. It seeks to assess available evidence on the impacts of these innovations and identify possible policies, further research and safeguards that could support them, if governments choose that course.

The report does not address more traditional vegetarian and vegan products (e.g. tofu, tempeh, mushrooms) or insects. Neither does it address fish and other aquatic animals, even though novel technologies may also have a role in shaping the development of the fishing sector.

The rest of this report is structured as follows:

Section 2 examines in more detail the current and projected regional and global demand for ASF and the environmental, human health, socioeconomic and animal welfare implications, recognizing the diversity of production systems. It discusses the need for a system-wide transformation to achieve a more sustainable, healthy and equitable food system, and briefly discusses the potential to decrease the environmental impact of the current food system through existing approaches.

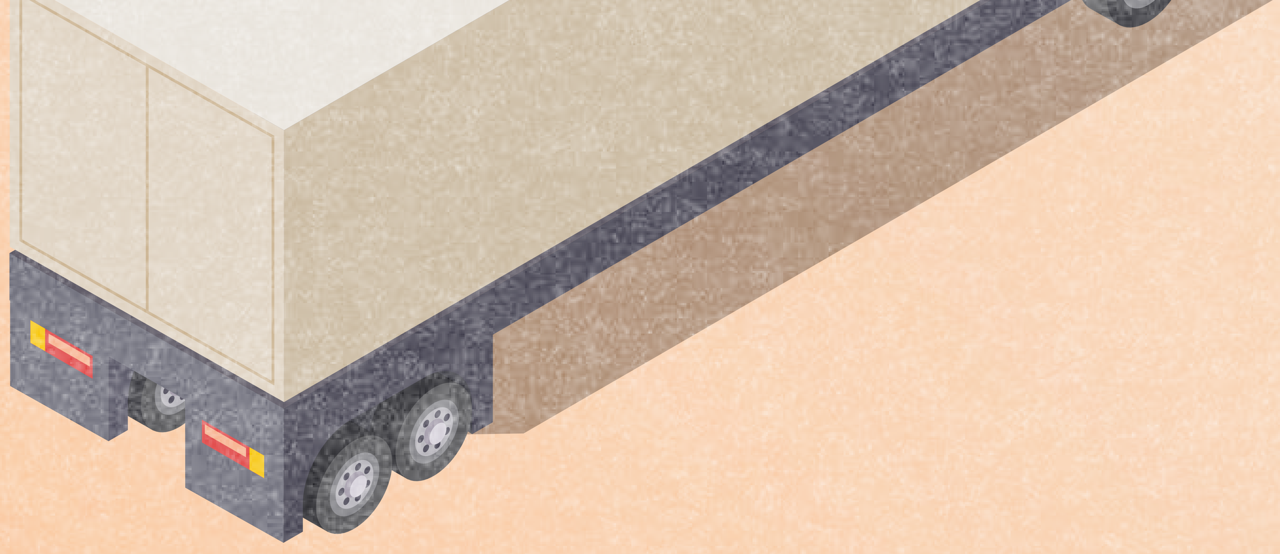
Section 3 discusses three types of novel alternatives to conventional animal products: novel plant-based products, fermentation-derived products and cultivated alternatives (described in Box 1.1). It also examines the available evidence on required inputs, current status and projected uptake of these novel foods, and considers their potential environmental, health, socioeconomic and animal welfare implications compared to conventional meat and dairy at varying levels of uptake.

Section 4 identifies and discusses policies that are already being implemented to regulate or stimulate novel ASF alternatives, and what options could be considered if governments and societies want to further support their uptake.

Section 5 presents the report's key conclusions and highlights remaining knowledge gaps.

Feeding a growing population with affordable, healthy, nutritious and safe food in an environmentally sustainable, socially acceptable and morally responsible manner is one of the greatest challenges of the 21st century. This report is intended to help shed light on both the potential and the limits of novel alternatives to conventional animal products in helping to meet this challenge.

2. Animal source foods significantly impact the environment, human health, socioeconomic dynamics and animal welfare



2.1 Global demand for animal source foods continues to increase

Rising demand is exerting immense pressure on food systems, with the livestock sector generally growing faster than other sectors. Global production of cereals increased by 14 per cent over the last decade, while production of meat, milk and eggs increased by about 15 per cent, 18 per cent and 22 per cent, respectively (FAO 2022). Much of the increase in demand for cereals (and some other crops) is linked to their use as livestock feeds (Organization for Economic Cooperation and Development [OECD] and FAO 2021). Over the past 60 years, total meat consumption has increased five-fold and per capita consumption has almost doubled (Figure 2.1). Factors including income growth, urbanization and globalization are driving the rising demand for livestock products, especially in emerging and lower income economies (Milford *et al*. 2019; Fukase and Martin 2020; Latino *et al.* 2020; Reardon *et al.* 2021). Population growth is also a key factor in less affluent regions, including many countries in Africa, where, incidentally, per capita intakes of ASF remains very low (Latino, Pica-Ciamarra and Wisser 2020). With global per capita meat consumption expected to increase by 0–0.5 per cent per year (Henchion *et al*. 2021) and global population expected to rise by 1 per cent per year (United Nations Department of Economic and Social Affairs [UNDESA] 2022) global meat consumption in 2050 is projected to be about 50 per cent or more greater than present.

Within the global food system, patterns of production and consumption vary considerably across and within regions. For example, per capita consumption of animal meat (the sum of beef, pork, sheep meat, goat and poultry) in Europe and North America is up to eight times that in Asia and Africa (Table 2.1 and Figure 2.1 show recent estimates of regional meat consumption). ASF can be a vital component of healthy, diverse diets, particularly for nutritionally vulnerable populations in low- and middle-income countries, e.g. children and women of reproductive age (Alonso, Dominguez-Salas and Grace 2019; International Livestock Research Institute [ILRI] 2019). On the other hand, health issues related to poor diet quality and the prevalence of obesity are increasing steadily in both rich and poor countries alike (Branca *et al.* 2020).

In addition to between-country variation, there is also significant within-country variation in the consumption of ASF. In some countries, specific consumer groups consume meat in amounts that exceed dietary protein requirements (Behrens *et al.* 2017).

Table 2.1 **Meat consumption per capita (kg per year)**[1]

Region	OECD-FAO Outlook
World	34.7
North America	95.3
Oceania	70.7
Europe	64.8
Latin America and Caribbean	59.6
Asia	27.0
Africa	12.7

Source: (OECD and FAO 2022; FAO 2023a; FAO 2023b; UNDESA 2023).

[1] These numbers are estimates with a range of uncertainty. Similar numbers were estimated by Shahbandeh 2022.

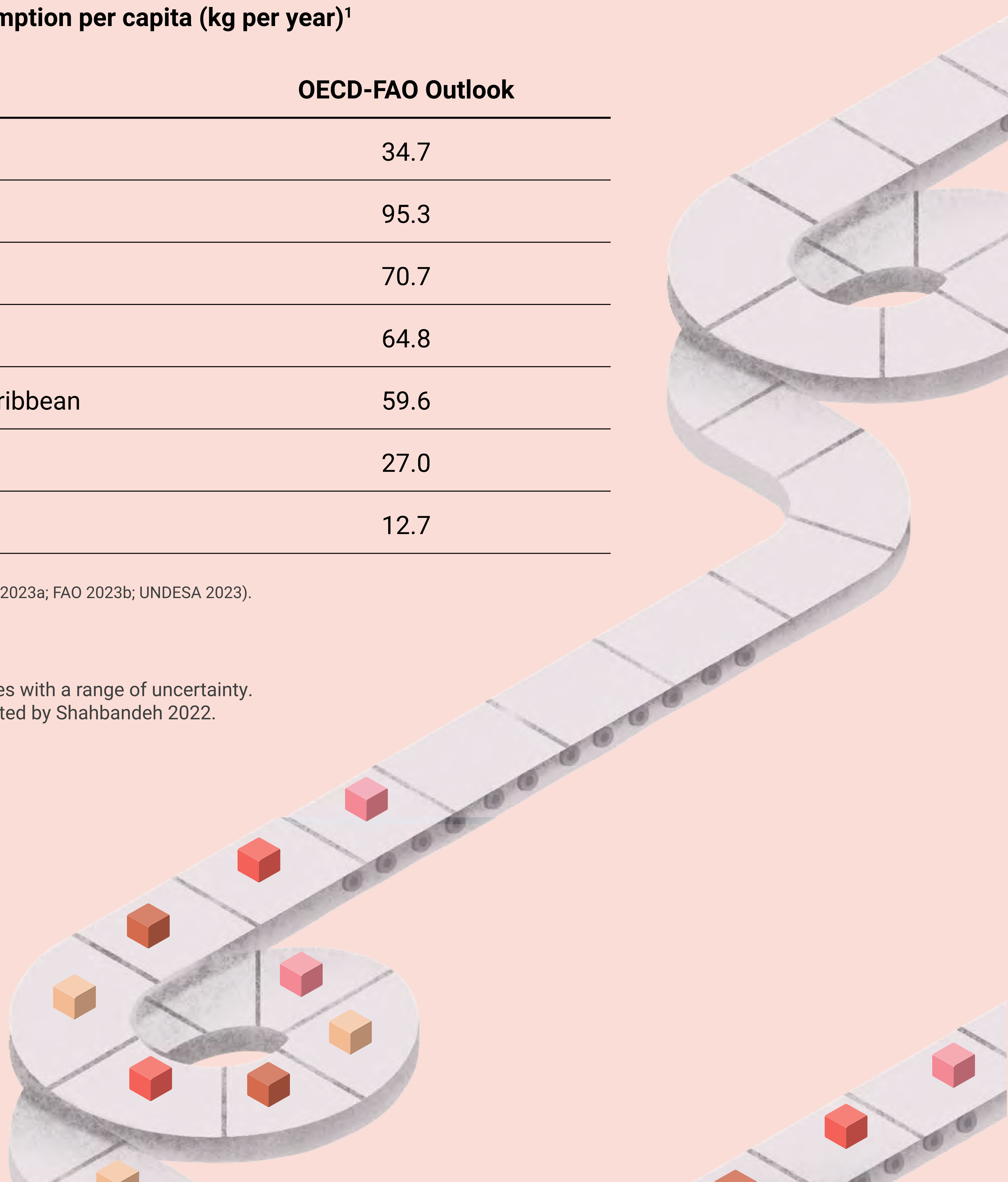
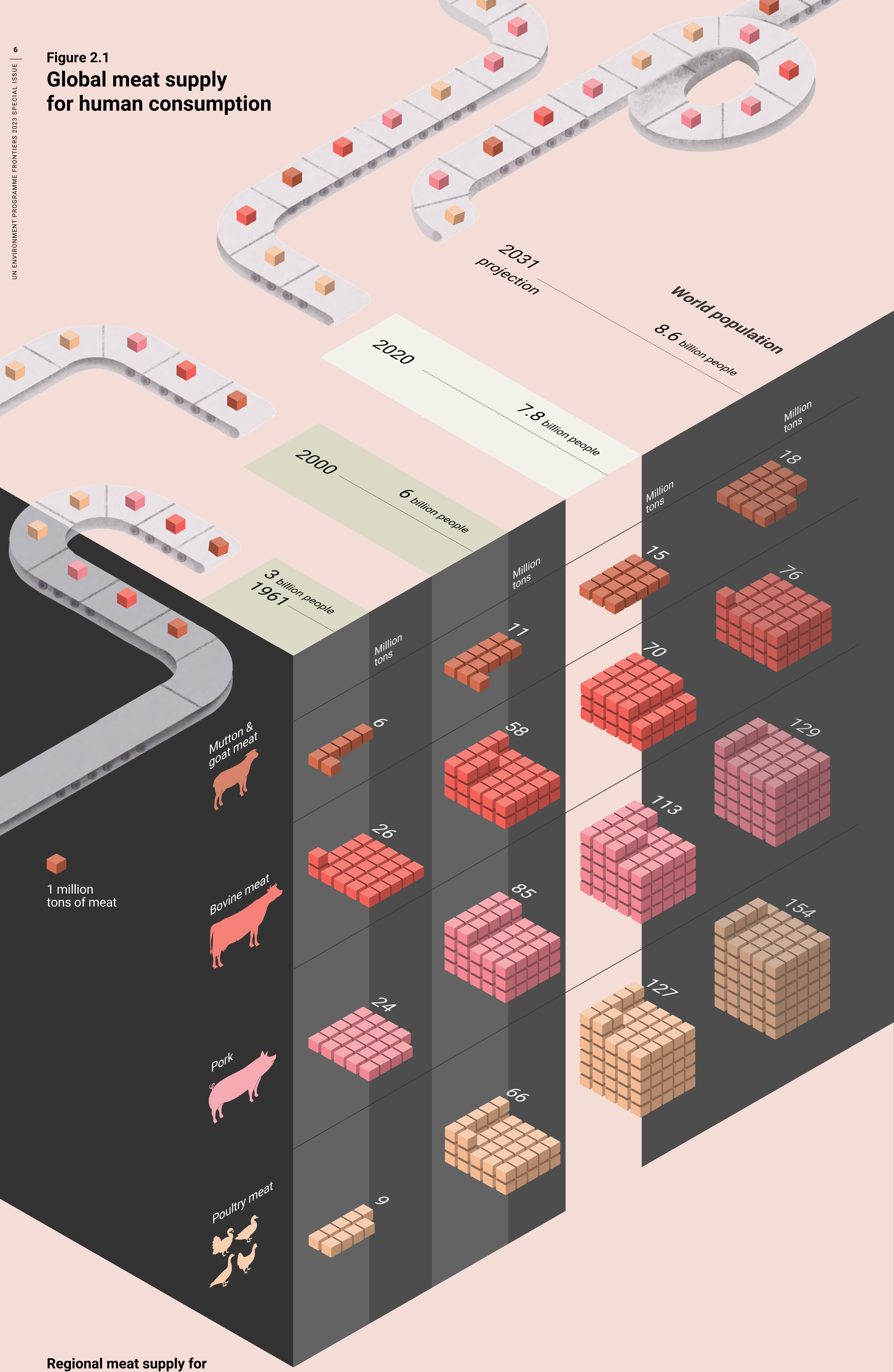
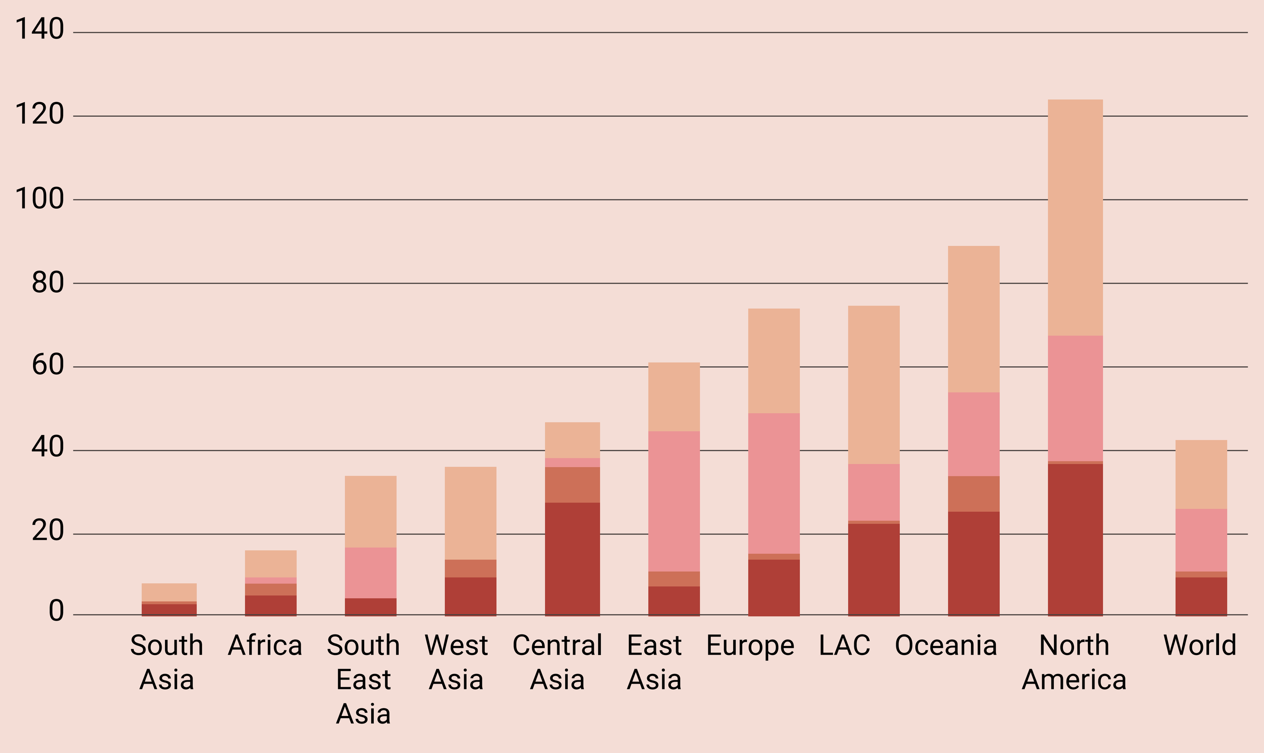
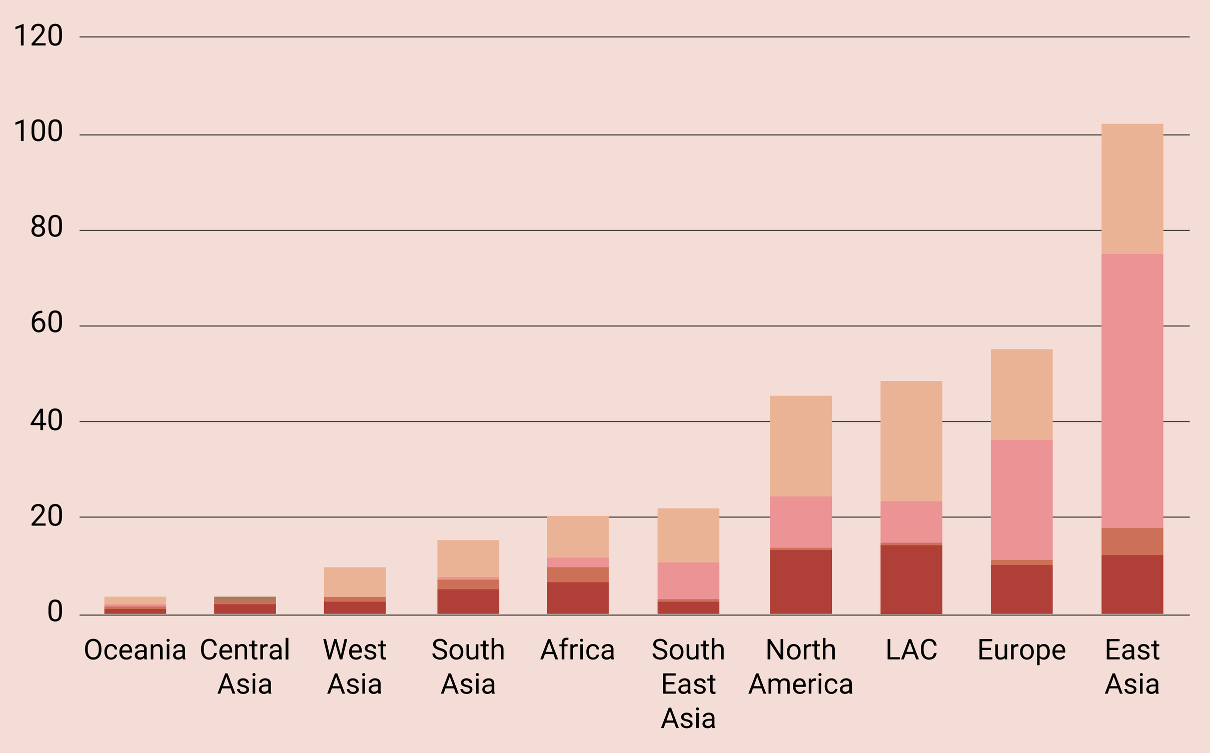


Figure 2.1
Global meat supply for human consumption







Source: (OECD and FAO 2022; FAO 2023a; FAO 2023b; UNDESA 2023).

Meat production also varies considerably by region, with Asia being the largest producer (about 43 per cent of global supply), followed by Europe (about 21 per cent), North America (about 15 per cent, South America (about 14 per cent) and Africa (about 7 per cent) (Ritchie, Rosado and Roser 2019).

Government policies have contributed significantly to the development of current meat production systems. Decades of investment, incentives (e.g. subsidies) and international trade in industrial livestock products have come with a large cost to the environment (Chandel, Lal and Kumari 2019). Poultry, pork, mutton, beef and dairy are among the food products that benefit the most from government subsidies, a significant share of which are allocated to industrial production (Stoll-Kleemann and O'Riordan 2015). Moreover, environmental and health costs of meat production and consumption are not reflected in the price or labelling of ASF that reach the consumer. Consequently, animal products, especially those from intensive production systems, are often significantly under-priced (Mosquera 2018; McCormack 2021; Funke *et al*. 2022).

2.2 The current animal agriculture system contributes to climate change, pollution and biodiversity loss

The current food system is a significant contributor to human-induced climate change. It also contributes to the unsustainable use of natural resources and the pollution of land, air and water, and is a significant driver of biodiversity loss through the degradation and conversion of terrestrial, freshwater and marine ecosystems (Springmann *et al.* 2018).

The environmental impact of meat production varies with the type of meat, modes of production (land, labour and capital intensity), production practices and the nature and magnitude of support from governments. A shift away from land-intensive protein production systems could free up land and water, dramatically reduce their emissions, and create conditions for ecosystem restoration (Hayek *et al.* 2021; IPCC 2021; IPCC 2023).

2.2.1 Greenhouse gas emissions from animal agriculture significantly contribute to climate change

While the energy sector (production and use of fossil fuel energy, including for transportation) is responsible for over 70 per cent of anthropogenic GHG emissions (Gerber *et al*. 2013; IPCC 2022), the way people use land contributes around 30 per cent of total emissions, mostly from food production (Clark *et al*. 2020; Jackson *et al.* 2020; IPCC 2021; Eisen and Brown 2022). Overall, agricultural land use contribute around 70 per cent of food system emissions, with supply chain activities such as processing, retail and waste management contributing the rest (Crippa *et al*. 2021). IPCC (2022) estimated that agriculture, forestry and other land uses contributes 13 $GtCO_2eq$, 22 per cent of global GHG emissions. Regionally, Asia and the Americas (North, Central and South) are the largest contributors of food system emissions (FAO 2022).

Animal products—including animal feed, changes in land-use and energy intensive global supply chains—account for almost 60 per cent of food system GHG emissions (including methane, nitrous oxide and carbon dioxide), or between 14.5-20 per cent of total GHG emissions (Gerber *et al.* 2013, Xu *et al.* 2021).[2] Average emissions per kilogram of meat vary by up to a factor of 10, with beef having the biggest emissions footprint, and poultry the smallest (Xu *et al*. 2021). Emissions from cattle also vary widely, with significantly higher average emissions from beef cattle than dairy cattle (Xu *et al*. 2021). The largest producers of beef are Brazil, China, the European Union, India and the United States of America, and the largest exporters are Argentina, Australia, Brazil, India and the United States of America (Hocquette *et al*. 2018).

Direct emissions from livestock—through enteric fermentation and manure only—contribute 30-35 per cent of agricultural emissions (FAO 2021; UNEP and Climate and Clean Air Coalition [CCAC] 2021; FAO 2022), or about half of total animal product emissions. Cattle are the predominant contributors of methane emissions from enteric fermentation while pigs are the main source of nitrous oxide emissions from manure (UNEP and CCAC 2021).

Table 2.2 **Major contributions to GHG from different sources**[3]

Source	Contribution to total GHG emissions (per cent)
Energy (production and use)	~70
Agriculture/food systems	~30
Animal products (incl. feed, direct emissions, land-use change and supply chains)	14.5–20
Direct animal emissions	7.5–10

Methane, which is the second most emitted anthropogenic GHG after carbon dioxide, has a much more powerful per molecule warming effect in the atmosphere (Jackson *et al*. 2020; Saunois *et al*. 2020; UNEP and CCAC 2021), which coupled with its short atmospheric lifetime makes its emissions from livestock a focus of climate mitigation strategies (Arndt *et al*. 2022; Scoones 2022). The food system accounts for 60% of all methane emissions, with half of those coming from livestock farming and primarily from enteric fermentation (ClimateWorks Foundation 2023).

[2] Additional sources include a lower figure of 11 per cent, derived from the FAO's third version of the online Global Livestock Environmental Assessment Model (GLEAM), however, the underlying methodology used by the GLEAM is yet to be published and peer-reviewed. In contrast, Reisinger and Clark 2018, which uses a different carbon modelling methodology, mentions a higher estimate of 23 per cent (FAO 2023d).
[3] These numbers are estimates with a range of uncertainty.

2.2.2 Some animal agriculture systems contribute to air and water pollution and soil degradation

Beyond emissions, animal agriculture also contribute to other environmental issues. Livestock feed production accounts for more than 40 per cent of total agricultural water use (Heinke *et al*. 2020). The water footprint per unit of product is higher for animal products (especially beef) than for crops (Mekonnen and Hoekstra 2011; Gerbens-Leenes, Mekonned and Hoekstra 2013).

There is considerable variability in the impacts that different livestock products, production systems and supply chains have on the environment (Poore and Nemecek 2018; ILRI 2019; Adesogan *et al*. 2020). Extensive livestock production systems use fewer inputs, such as feed and chemicals, suggesting low environmental impacts. They can however be considered inefficient, compared to intensive systems, in their use of resources, given their low levels of ASF output (Bosire *et al*. 2015; Mottet *et al*. 2017; Willett *et al*. 2019; van Zanten, Muller and Frehner 2022). On the other hand, intensive cropping and industrialized livestock production systems are in many parts of the world driving nutrient mining, loss of soil structure (through compaction and soil erosion), and wide-spread air and water pollution (Sakadevan and Nguyen 2017; Hamza and Anderson 2005)

Run-off of fertilizers, pesticides and other chemicals to ground and surface waters have increased as crop production for food and livestock feed has intensified (Gerber *et al*. 2005; da Silva *et al*. 2010; Wang *et al*. 2017). Further, nutrient losses (particularly of nitrogen and phosphorus) have increased as a direct impact of livestock production expansion in many emerging countries (Gerber *et al*. 2005; Liu *et al*. 2017).

In intensive livestock systems such as those commonly found in the Global North, poor manure management and low nutrient use efficiency are associated with substantial loss of nutrients from the farming system to the environment (Gerbens-Leenes, Nonhebel and Krol 2010; Rothwell *et al*. 2020).

However, livestock can also deliver benefits. For instance, the use of animal manure in crop agriculture in many developing countries reduces the need for chemical fertilizers. Recycling of animal manure is widely practiced and contributes up to 24 percent of the nitrogen input into crop agriculture in the mixed crop-livestock systems of the developing world (Herrero et al., 2013). Livestock are also useful in the conversion of crop residue and plant protein and energy from sources typically not eaten by humans into high-value forms for human consumption (Varijakshapanicker *et al*. 2019; Barbieri *et al*. 2022). In fact, 86 per cent of food consumed by livestock is not currently eaten by humans and includes by-products, crop residues and grasses or fodder (Mottet *et al.* 2017).

2.2.3 Land use, land-use change, pollution and climate change associated with animal agriculture systems are important drivers of biodiversity loss

Land use and land-use change are the most important drivers of terrestrial biodiversity loss (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES] 2019; Scherer *et al.* 2020), and food systems are the biggest land user. While food systems occupy half of the habitable land (habitable land is 71 per cent of the land surface, not including glaciers and barren land), 77 per cent of agricultural land is used for the livestock sector. A significant percentage of land used for livestock (which includes land for growing crops, animal feed as well as pastures used for grazing) cannot be used for arable crops (Mottet *et al.* 2017, UNEP 2019, ILRI, International Union for Conservation of Nature [IUCN], FAO, World Wide Fund for Nature [WWF], UNEP and International Land Coalition [ILC] 2021) (Figure 2.1). Meat from ruminants like cattle and sheep has a particularly high land-use intensity (Poore and Nemecek 2018). Such land use also threatens Key Biodiversity Areas (sites critical for the persistence of global biodiversity), with beef production and pastures as main contributors to potential species loss (Sun *et al.* 2022). In areas where wild herbivores have disappeared, grazing livestock may partly replace their function within the ecosystem, subject to good management practices. However, such benefits to biodiversity are rare (Godfray *et al.* 2018).

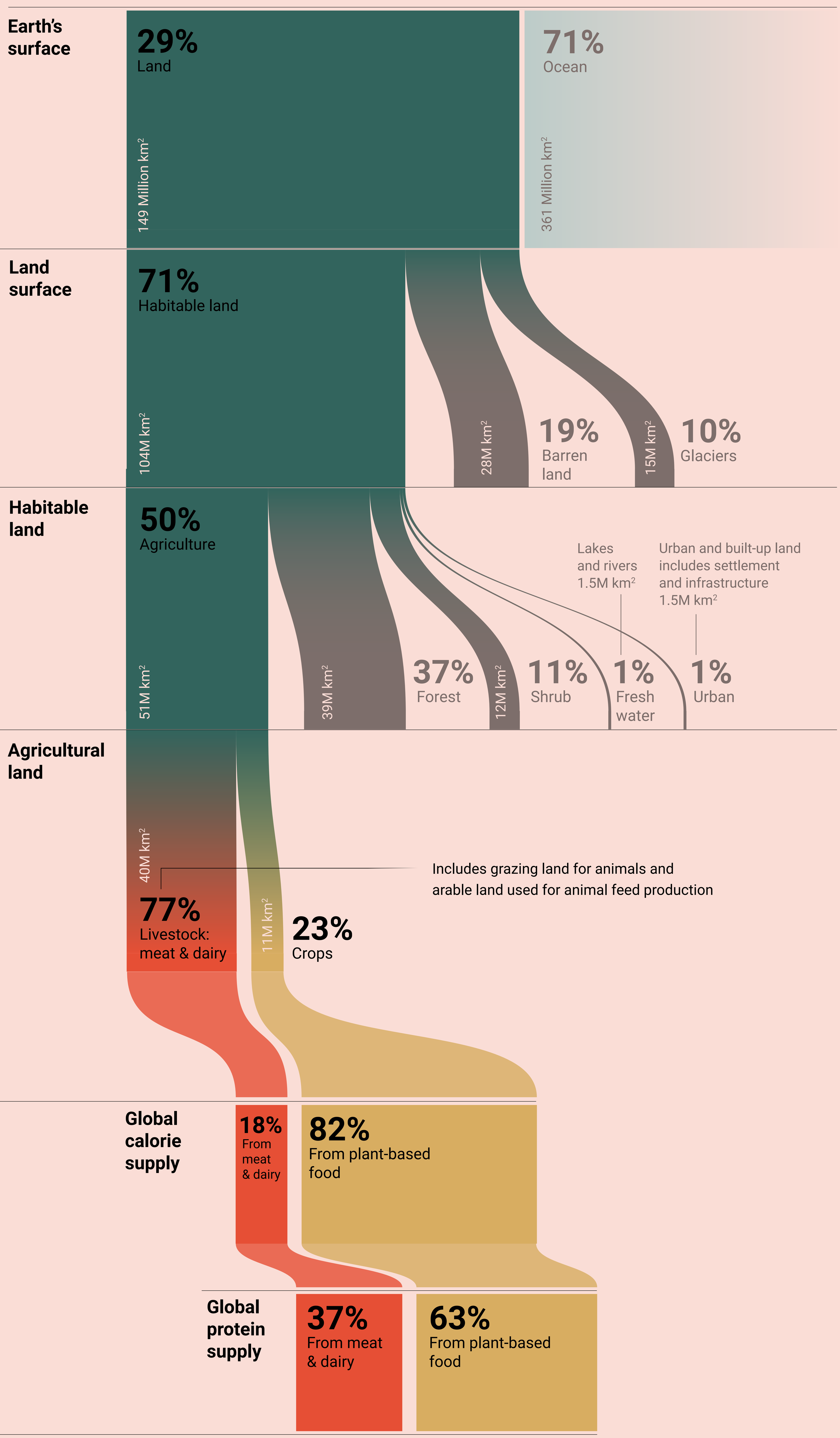
Figure 2.2
Global land use for food production

In the visualization we see the breakdown of global land area in 2019. 10% of the world's land area is covered by glaciers, and a further 19% is barren land, deserts, dry salt flats, beaches, sand dunes and exposed rocks. This leaves what we call 'habitable land'.

Half of all habitable land is used for agriculture.

There is a highly unequal distribution of land use between livestock and crops for human consumption. If we combine pastures used for grazing with land used to grow crops for animal feed, livestock accounts for 77% of global farming land. However, a significant percentage of this land cannot be used for arable crops.

While livestock takes up most of the world's agricultural land, it only produces 18% of the world's calories and 37% of total protein.



Source: (Source: FAO 2023c)

With rising demand for meat and dairy products, livestock production is increasing notably in developing, tropical countries that are rich in biodiversity, and this trend is projected to continue (Machovina, Feeley and Ripple 2015). The resulting biodiversity loss threatens food system resilience. For example, the expansion of agriculture is also a major driver of pollinator decline, and a considerable share of global crop production depends on animal pollination (IPBES 2016).

GHG emissions, to which livestock contribute considerably (as described above), contribute to climate change, thereby causing further loss of biodiversity. When climatic conditions, such as air and water temperature, precipitation and streamflow, exceed the niche limits to which a species is adapted, the geographical area in which it can live may shift or be reduced, and the more species are affected, the more biodiversity is threatened (Trisos, Merow and Pigot *et al.* 2020; Barbarossa *et al.* 2021; Scherer *et al.* 2023). A key issue is whether species can migrate fast enough to survive (IPBES 2019), assuming appropriate terrain is available.

Pollution from agrochemicals, such as fertilizers and pesticides used in crop production for human food, animal feed production and other uses also affects biodiversity (Bouwman *et al.* 2013; Nordborg *et al.* 2017). Emissions of nutrients such as phosphorus and nitrogen following fertilizer application can cause eutrophication of freshwater and marine water bodies, deplete oxygen and/or generate harmful algae blooms, and subsequently drive biodiversity loss (Glibert 2017). Oxygen depletion leads to so-called dead zones in coastal ecosystems that recently covered a total area the size of the United Kingdom of Great Britain and Northern Ireland (IPBES 2019). The toxic effects of pesticides harm more species than those targeted. Like fertilizers, they can eventually reach water bodies and reduce their biodiversity (Beketov *et al.* 2013). Moreover, pesticides enter the food chain, affecting also vertebrate species (Garcês, Pires and Rodrigues 2020).

Figure 2.3
Environmental impacts of current meat production

2.3 Animal agriculture is associated with both benefits and harms for public health

From a public health perspective, our current food systems result in a paradox of abundance and scarcity due to unequal distributions of and access to nutritious food: the world is both overfed and underfed. Recent estimates suggest that 9 per cent of the world's adult population are underweight while 39 per cent are overweight or obese (WHO 2021a, 2021b); around 800 million people go hungry while 930 million tons of food—17 per cent of the total available to consumers—goes to waste each year (FAO *et al.* 2022; UNEP 2021a). Malnutrition in all its forms—undernutrition, obesity and other diet-related risks—is one of the leading, preventable causes of poor health worldwide (Murray *et al*. 2020; Swinburn *et al*. 2019). Globally, in 2017, it was estimated that 11 million premature deaths—22 per cent of all deaths among adults aged 25 years or older—were attributable to sub-optimal diets, with different dietary risk factors being more dominant for certain genders and/or age groups (e.g. low intake of whole grains was the leading dietary risk factor for mortality among women) (Afshin *et al*. 2019).

In the past 50 years, globalization and intensification of food production systems—combined with urbanization, rising incomes, expansion of processed food markets by transnational corporations and other societal trends—have led to a homogenization of dietary patterns across the world towards a 'Westernized' diet consisting of relatively high consumption of ASF (Table 2.1), processed foods, refined grains and sugars and fats (Cordain *et al*. 2005; Cena and Calder 2020; Vermeulen *et al*. 2020; Wood *et al.* 2021; da Costa *et al*. 2022;). However, large variations in the types and amounts of ASF consumption still exist between and within countries (Miller *et al*. 2022).

Consumption of ASF can provide health benefits and risks, depending on the context and food type. ASF can be an important source of nutrients, especially for young children, pregnant or lactating women, and for people on low incomes with limited access to alternative nutrient-dense foods (FAO 2023e). In many developing countries ASF consumption is limited and nutrient intake remains suboptimal, reinforcing the need to tailor dietary guidelines to different regions and age groups to prevent exacerbating existing public health challenges (Fite *et al.* 2022; Miller *et al.* 2023). Nevertheless, it is possible to obtain a sufficient intake of essential nutrients without eating meat if a wide variety of other foods is available and consumed (Godfray *et al*. 2018). At the same time, in high-income countries with relatively high meat intake such as the United States of America and those in western Europe, epidemiological studies and meta-analyses have generally found that high intakes of red meat and processed meat are associated with increased risks of obesity, NCDs including cardiovascular disease, type II diabetes, certain cancers (with the strongest evidence to date for colorectal cancer) and premature death (Godfray *et al*. 2018; Clark *et al*. 2019; Swinburn *et al*. 2019; Santo *et al*. 2020; Farvid *et al.* 2021; Kazemi *et al*. 2021). The International Agency for Research on Cancer (IARC) of the World Health Organization classifies red meat as 'probably carcinogenic' and processed meats as a known cause of cancer for humans (Bouvard *et al.* 2015). Afshin *et al*. (2019) estimated that in 2017 around 155,000 premature deaths among adults worldwide were attributable to high intakes of red and processed meats.

To date, these epidemiological studies have predominantly been conducted in high-income Western countries where individuals with relatively lower meat consumption may also typically lead a more health-conscious lifestyle. Further research is needed to comprehensively assess the health outcomes of ASF consumption in other populations that consume different quantities and types of meat and have dissimilar confounding factors (such as lifestyle and methods of food preparation), especially in low- and middle-income countries where the average baseline meat intakes are much lower than those found in high-income Western countries (Godfray *et al*. 2018; Clark *et al*. 2019).

Compared with processed and red meats, the evidence of health outcomes is less conclusive for eggs, dairy products and poultry. Some dose-response and substitution studies have found that higher intake of these products is significantly associated with higher risks of incident cardiovascular disease and premature mortality (Zhong *et al*. 2019; Zhong *et al*. 2020; Zhong *et al*. 2021), whereas others find no statistically significant relationships or even reduced risks (Dehghan *et al*. 2018; Clark *et al*. 2019; Drouin-Chartier *et al.* 2020).

Beyond the nutritional dimension, ASF consumption and production are also associated with other public health implications (Santo *et al*. 2020). ASF are a reservoir for many foodborne pathogens such as *Salmonella, Campylobacter* and *E. coli* (Lianou, Panagou and Nychas 2017; Heredia and García 2018). Li *et al*. (2019) estimated that ASF were responsible for 35 per cent of the global foodborne disease burden in 2010.

The widespread and excessive use of antibiotics in animal agriculture has been linked to the rise of antimicrobial resistance in both animals and humans (Van Boeckel *et al*. 2015; Talebi Bezmin Abadi *et al*. 2019); globally, 73 per cent of all antimicrobials sold are used in animal agriculture (Van Boeckel *et al.* 2019). Animal agriculture expansion and industrialization, and wildlife trade and consumption, have also been linked to increased risk of zoonoses emergence (Jones *et al*. 2013; Bernstein and Dutkiewicz 2021). The majority (70 per cent) of emerging infectious diseases and almost all known pandemics (e.g. influenze, HIV/AIDS, COVID-19) are zoonoses (WHO 2020; IPBES 2020). For example, there is evidence to suggest that the SARS-CoV-2 virus was transmitted from bats to other wild animals, subsequently spilling from these into humans in live animal markets (Wegner *et al*. 2022). Without preventative strategies to address the underlying causes that bring wildlife, livestock and people into close contact, pandemics may emerge more often and with potentially more devastating impacts (IPBES 2020; Wegner *et al*. 2022).

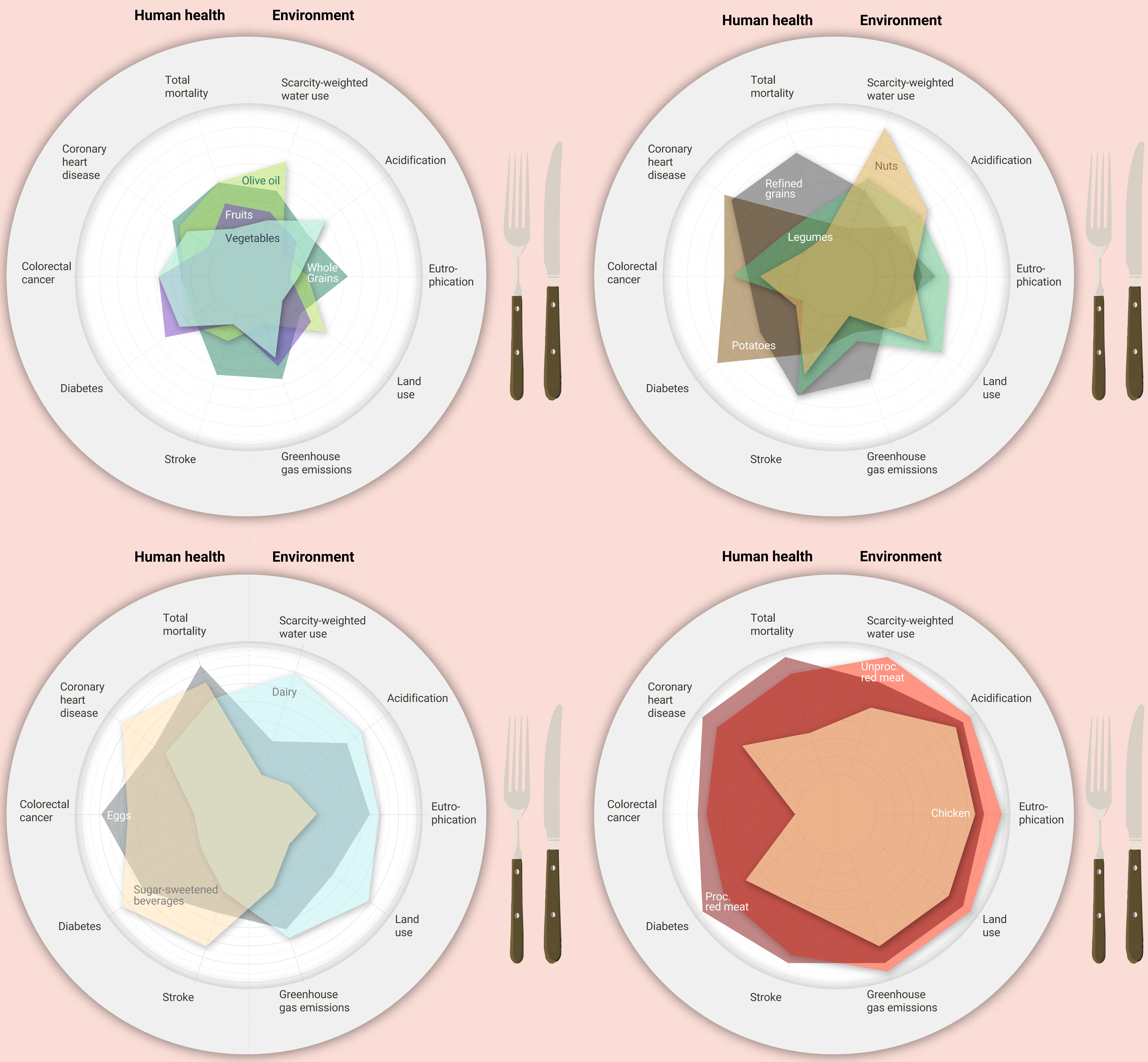
Intensive livestock farming can lead to harmful health impacts for industry workers and local communities. Occupational hazards include exposure to pathogens and toxic air pollutants, injuries due to handling of animals and operation of heavy machinery, and psychological stress in slaughterhouses (Myers 2010; Douglas *et al*. 2018; Ceryes and Heaney 2019; Slade and Alleye 2023). Neighbouring communities are at increased risks of developing respiratory illnesses, stress and other adverse health outcomes due to exposure to air, water, soil, noise and odour pollution from, for example, open animal waste pits in countries without adequate regulatory regimes (Greger and Koneswaran 2010; Casey *et al*. 2015; Johnston and Cushing 2020).

Figure 2.4

Health and environmental impacts of different foods

Foods associated with improved health (whole grain cereals, fruits, vegetables, legumes, nuts and olive oil), have among the lowest environmental impacts.

Inner circle: lower rank impact   Outer circle: higher rank impact

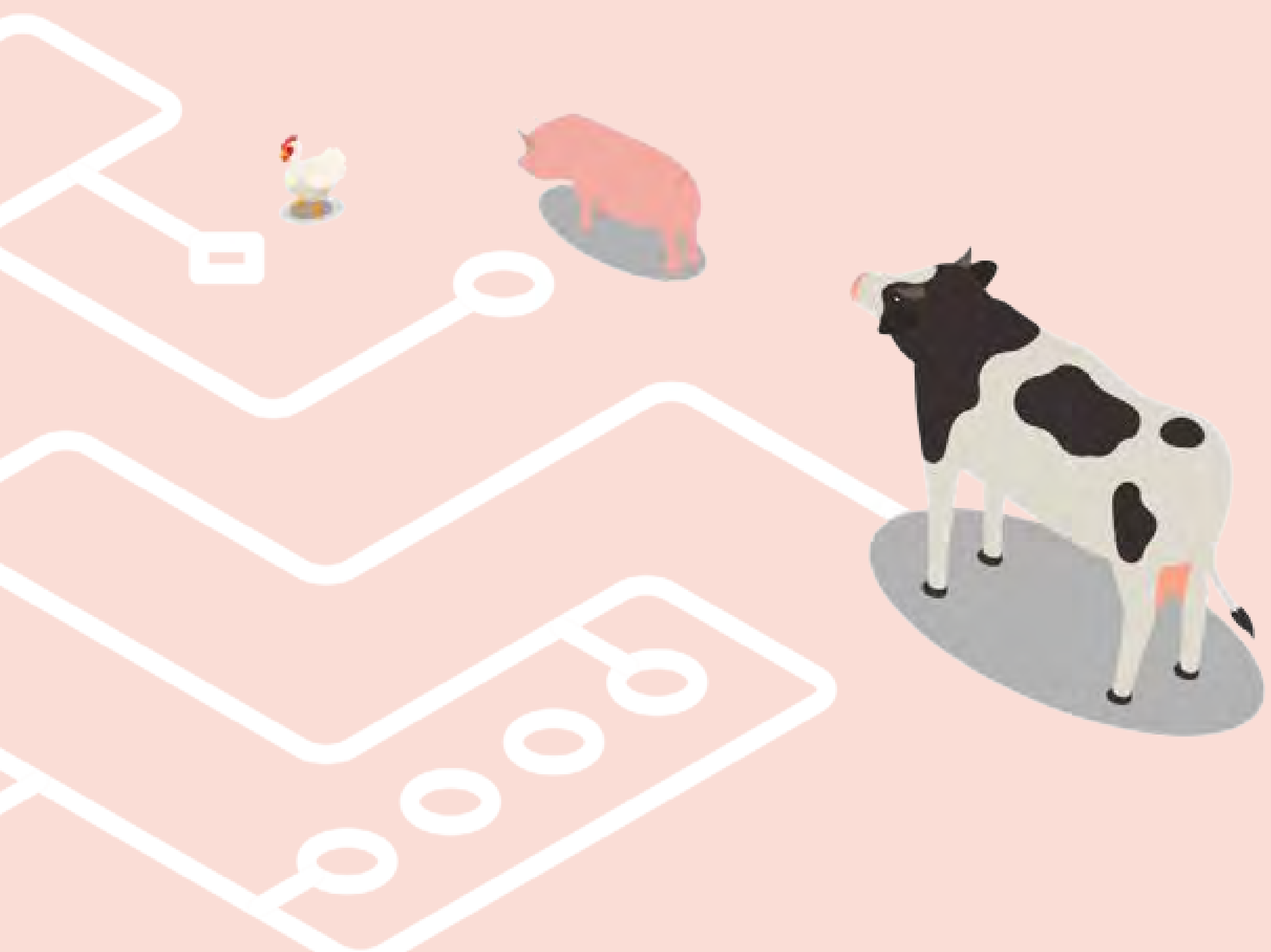


Food choices are shifting globally in ways that are negatively affecting both human health and the environment. Thus, dietary transitions toward greater consumption of healthier foods would generally improve environmental sustainability. These findings could help consumers, policy makers and food companies to better understand the multiple health and environmental implications of food choices. Meat has both positive and negative health effects — this figure highlights the adverse effects of excess consumption.

Foods associated with the largest negative environmental impacts—unprocessed and processed red meat—are consistently associated with the largest increases in disease risk. Foods high in sugars harm health but can have relatively low environmental impacts.

Source: Adapted from Clark *et al.* 2019

2.4 Animal agriculture operates within broader food system inequalities, while meat can carry important cultural and social significance



Food production is the world's single largest economic activity. Livestock, which contributes about 40 per cent of the global value of agricultural output and supports the livelihoods and food and nutritional security of almost 1.3 billion people (World Bank 2022), also has important cultural significance. Nevertheless, current patterns of food production and consumption, including those for ASF, are also associated with a range of negative social impacts.

Concerns have been raised about the loss of local food cultures, increase in food inequalities, power imbalances in food systems and the globalized procurement of foods, which increase food trade and distances across the value chain. Food justice and food sovereignty movements highlight class inequalities and power asymmetries in the food system that affect people's rights to culturally appropriate foodways (Motta 2021). While improved food systems have pulled millions of people from precarious food-insecure lives into healthy productive lives, they have also come with higher food and nutritional inequities, resulting from increasing environmental costs, social disruption and economic inequality (Ruttan 2005; Steffen *et al.* 2015; Krall 2022). The rise of obesity and diabetes in many countries has occurred in parallel with the globalization of food systems (Swinburn *et al*. 2019).

Animal agriculture has changed dramatically in recent decades, especially in industrialized countries. In the United States of America, small-scale farms have been replaced by factory farms that are often operated to satisfy corporate contracts (Hribar and Schultz 2010) so that an estimated 99 per cent of farm animals are raised in factory farms (Athnis 2019). Factory farming practices are currently also being exported to developing economies, such as India and South Africa, where the food produced is not necessarily for local consumption but for export (Jankielsohn 2015; Lam *et al*. 2017). Factors contributing to the increase of factory farming in developing countries include rising local demand, lower production costs, and potentially weaker environmental regulations (Lam *et al*. 2017).

The meaning of meat is significantly mediated by culture. Different animals may be sacred in one culture but widely consumed in another. A prime steak is a luxury in the United Kingdom of Great Britain and Northern Ireland and the United States of America for example, but the cow is sacred amongst Hindus (Chigateri 2010).

Specific meat dishes can be recognized as culturally significant at the national level (e.g. haggis in Scotland and hamburgers in the United States of America) and economically significant (e.g. beef in Argentina and lamb in New Zealand). In addition to this, meat consumption is gendered, and several studies have found that commonly men eat more meat than women (e.g. Raty and Carlsson-Kanyama 2010; Rosenfield and Tomiyama 2021). Meat and perceived masculinity are currently interconnected, and studies have found that men not only eat more meat than women but are also more reluctant to reduce their meat intake and can develop an increasing attachment to meat when they experience a threat to their perceived masculinity (Nakagawa and Hart 2019). Additionally, a high proportion of vegetarians in Western societies are female, potentially due to societal and cultural narratives surrounding gender and meat consumption (Modlinska *et al*. 2020).

2.5 Animal agriculture raises and kills tens of billions of sentient animals annually

Scientific evidence indicates sentience in terrestrial vertebrates, including the birds and mammals in our food system, meaning that they can feel and suffer (Proctor 2012; Browning and Birch 2022). The boundaries of what we consider worthy of moral consideration have historically expanded over time (Crimston *et al*. 2016), leading to increasing public concern for non-human animals. Such concern is reflected in some laws that recognize animal sentience (Blattner 2019; Browning and Birch 2022).

Currently, tens of billions of land animals are slaughtered yearly for meat (FAO 2022). Many farmed animals are kept in confined intensive systems. By the early 2000s, most pork, poultry meat and eggs came from intensive systems (Steinfeld, Wassenaar and Jutzi 2006). Yields per animal, as well as milk and other meat, have continued increasing (FAO 2022), indicating further intensification. Intensive systems deprive animals of some of their most basic physical and psychological needs (Poletto and Hötzel 2012). High stocking densities, poor housing conditions and rapid growth of the animals can lead to aggression-induced injuries and lameness (Madzingira 2018). Even under extensive conditions, animals can experience welfare loss from, for example, hunger and thirst, thermal stress and painful husbandry practices; some diseases are also more likely than under intensive conditions (Temple and Manteca 2020). Pre-slaughter handling and transport to the slaughterhouse can also cause stress (Rioja-Lang *et al.* 2019; Benincasa *et al*. 2020). Consuming meat from smaller animals (e.g. chicken instead of beef) might worsen animal welfare by affecting a substantially larger number of animals (Scherer *et al*. 2018; Mathur 2022).

Higher animal welfare does not always conflict with efficient farming. For example, improved animal welfare can lead to lower mortality and better product quality while justifying sales at a premium, all of which can have financial benefits (Dawkins 2017).

2.6 Interventions have been proposed to reduce the adverse environmental effects of the current animal agriculture system

Several different approaches have been proposed to address the environmental, health, social and animal welfare impacts of the current global livestock system. They include: reducing loss and waste of ASF; smaller-scale, extensive or regenerative approaches to livestock farming; direct interventions to reduce GHG emissions from animal agriculture such as feed additives; promoting the reduction of meat consumption in favour of whole plant sources of protein; and reducing consumption of meat through the use of a meat tax or similar policy lever.

Table 2.3 describes selected approaches to mitigating the impacts of livestock systems, many of which could be pursued in parallel. Assessing their potential goes beyond the scope of this report. However, the success of these approaches has so far been limited, suggesting more action is necessary to tackle the adverse impacts of the current livestock industry.

Table 2.3 **Selected proposed interventions to reduce adverse environmental impacts from animal agriculture**

Reducing food loss and waste	Reducing losses in production and along the supply chain, and waste at the retail, service and household level would address a significant factor in the environmental impacts of the global food system. Currently about 23 per cent of global meat production goes uneaten, of which 64 per cent is wasted at the consumption level, 20 per cent in manufacturing, 12 per cent in distribution and about 3.5 per cent at the primary production and post-harvest levels (Karwowska *et al.* 2021). Reducing this waste of resources and inputs along the supply chain would ease challenges related to land and water use, nutrient and yield loss, biodiversity and GHG emissions (FAO 2014; Scialabba 2019; UNEP and CCAC 2021).
Smaller-scale, extensive or regenerative livestock farms	Such farms, including integrated crop-livestock systems, have gained favour as a means to make meat production more sustainable. These approaches aim to reduce or eliminate antibiotic use, support more biodiversity, and conserve more natural resources compared to industrialized animal agriculture. The evidence in support of extensive livestock farming having a lower environmental impact is mixed, especially given the range of farming systems included and ways to measure their impact. Extensive, ‘pasture-based’ systems may cause lower carbon dioxide and nitrous oxide emissions than more intensive systems because they do not require feed grain (Cusworth *et al*. 2022). One study estimates that regenerative multi-paddock systems could reduce GHG emissions from livestock production by 35 per cent compared with industrial-conventional systems (Kleppel 2020). However, other studies show higher emissions associated with grassfed models due to longer finishing time and lower finishing weight (Lupo *et al*. 2013). Additionally, land requirements for extensive systems are much greater, with one lifecycle assessment indicating 2.5 times more land is needed for a multispecies pasture rotation system than a conventional, commodity system (Rowntree *et al*. 2020).
Feed additives	These have been posited as a way to suppress bovine methane emissions from enteric fermentation. However, the impact of these additives on emissions would be limited to animals held in feedlots; globally, many cattle (likely most cattle outside Australia, Canada and the United States of America) do not spend time on feedlots (Bechtel 2018; McBee 2022). In the United States of America, beef cattle that are grain-finished spend only 41 per cent of their 18-month-long lives on feedlots (Hayek and Garrett 2018).
Reducing meat consumption in favour of whole plant protein	This approach has the potential to address multiple problems caused by the current livestock system. Transitioning to plant-based diets could reduce diet-related land use by 76 per cent, diet-related GHG emissions by 49 per cent, and green and blue water use by 21 per cent and 14 per cent, respectively (Gibbs and Cappuccio 2022). The EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems has advocated for diets that are’ flexitarian’ – largely plant-based, but optionally including modest amounts of fish, meat and dairy foods – to boost both human and planetary health (Willett *et al.* 2019). However, per capita meat consumption continues to rise (OECD and FAO 2021). Examples of advocacy for dietary shifts attempted to date include countries from China to Spain urging citizens to eat less meat, and programmes like ‘Meatless Mondays’ in schools (Dutkiewicz 2021). Some interventions show potential promise, such as appealing to animal welfare concerns and individual lifestyle coaching (Bianchi *et al*. 2018; Mathur *et al*. 2021).
Meat taxes	A ‘meat tax’ similar to those levied on alcohol and tobacco has garnered support from some advocates. A meat tax in high-income countries could reduce demand and help to address the negative environmental and health-related externalities associated with meat consumption and production (Funke *et al*. 2022). Studies have looked at taxing meat products according to the intensity of their environmental impacts, including emissions, disease risk and impacts on biodiversity (Edjabou and Smed 2013; Vergeer *et al.* 2020). One concern around a meat tax is that it might unfairly affect low-income populations, but this could be addressed by a revenue recycling program (Vergeer *et al.* 2020). There are also concerns that a meat tax would not be politically feasible in all settings (Bonnet *et al.* 2020).

Against this backdrop, this report focuses on another potential intervention to address the challenge of rising demand for ASF: their substitution with novel alternatives. Proponents of novel alternatives argue that they can provide a similar or identical sensory experience to conventional meat and dairy products, while having fewer negative impacts on the environment, human health and animal welfare. The development of novel alternatives can be pursued alongside other strategies such as those described in Table 2.3 in efforts to achieve net-zero emissions and other global goals.

The remainder of this report focuses on the potential implications of the uptake of novel meat and dairy products as an alternative to conventional ASF.

3. New technological solutions are being developed to provide an alternative to animal source foods

Concerns about sustainability, food security and the environmental and public health impacts of industrial animal agriculture have spurred efforts to develop novel alternatives to conventional animal products that appeal to mainstream consumers. This has led to significant and ongoing innovations during the last decade, with today's options primarily appealing to the fast-growing segment of 'flexitarian' consumers across geographies including Australia, Brazil, China, Europe, the Russian Federation and the United States of America (Mattson 2017; BENEO Global Plant-Based Survey 2022). The novel alternatives sector aims to broaden this market to include a wider set of consumers.

This section dives deeper into three types of novel ASF alternatives; describes the production process for each product type; discusses prospects for, and challenges to, broader consumer and market uptake of these products; and considers the environmental, health, socioeconomic and animal welfare implications of these products, in comparison to conventional meat and dairy products.

3.1 Novel meat and dairy alternatives aim to mimic the taste and texture of animal source food

There are currently three main categories of novel alternatives to conventional meat and dairy products:

- **Novel plant-based** foods aim to replicate the sensory experience of animal products by combining plant protein (typically from soy or pea) with fats, vitamins, minerals, water and other additives (Figure 3.1). This grouping does not include more traditional plant-based meat alternatives such as tofu, tempeh, seitan, mushrooms and jackfruit.
- **Cultivated meat** is meat produced directly from animal cells. This is done by extracting cells from a living animal and growing them in bioreactors. Cells can be differentiated into muscle, fat and other cell types to create products with a three-dimensional structure and organoleptic properties similar or identical to those of conventional meat products (Figure 3.2).
- **Fermentation-derived products** are foods produced using biomass or precision fermentation. Biomass fermentation is the process of using microorganisms to make protein-rich food, where the microorganisms produced are themselves the primary ingredient. Precision fermentation uses microorganisms to produce specific functional ingredients, including proteins, vitamins and flavour molecules. These can be used in novel plant-based food to improve taste or texture, and in cultivated meat to enable more efficient growth (Figure 3.3).

Each of these technologies has seen significant recent and ongoing technological progress, with potential for further developments.

3.1.1 Novel plant-based meat uses new technological approaches to closely imitate the sensory profile of meat

The concept of plant-derived alternatives to ASF is centuries old and their prevalence and variety has steadily increased (Shurtleff and Aoyagi 2014). Many of these foods were designed with vegetarian consumers in mind, and early plant-based alternatives, such as tofu, tempeh and seitan, did not always try to replicate conventional meat. The early generations of 'veggie burgers' introduced in the 1960s and 1970s also were primarily aimed at vegetarians (Shurtleff and Aoyagi 2014) and their flavour profile did not necessarily seek to replicate that of meat. By contrast, novel plant-based meats are designed to match the organoleptic experience (i.e. flavour, aroma, texture, bite, moisture, mouthfeel, appearance and colour) of their animal-based counterparts as closely as possible (Kinney, Weston and Bauman 2019).

Plant proteins are the main ingredients of plant-based meat. How they are mixed and processed along with fats, and other nutrients as well as binders, flavourings (including salt) and colourants, significantly influences a product's properties (Kyriakopoulou, Keppler and van der Goot 2021). The development of a novel plant-based product involves three main steps: crop development, ingredient optimization and processing, and end-product formulation and manufacturing (see Figure 3.1 and Box 3.1 for more details).

Current novel plant-based meats on the market include beef, pork and chicken substitutes, among others. While sales of these products have been concentrated in North America and Western Europe to date, the largest sales growth is seen in Eastern Europe, Asia Pacific and Australasia and Latin America (GFI 2022a).

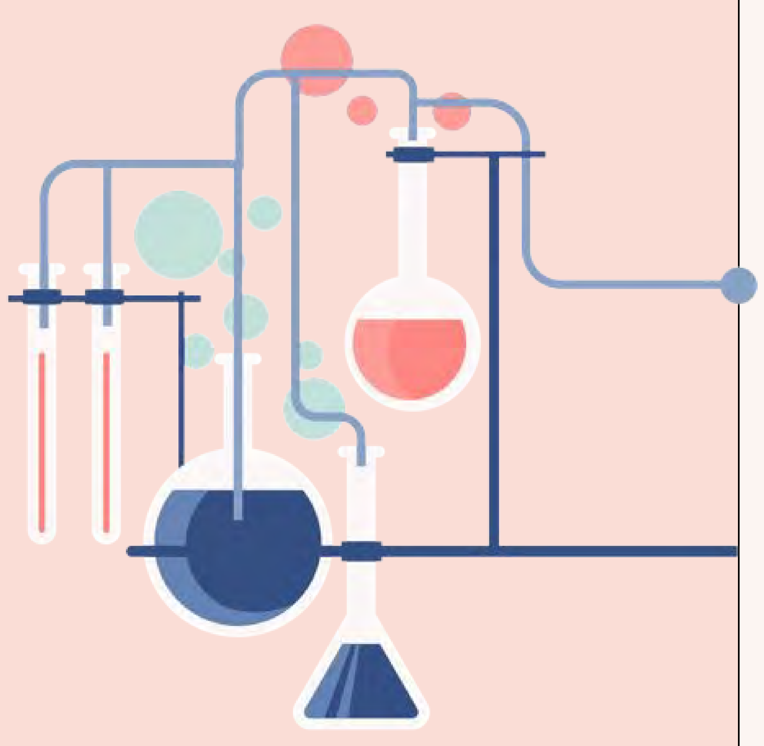
Figure 3.1
Novel plant-based meat

These products typically more closely resemble the sensory experience of meat than classic products, like tofu, using new scientific insights to imitate the sensory profile of meat more closely and complete the "meat-like" experience. Inputs include pea or soy protein, combined with oils and other functional ingredients, like plant-based binders, vitamins, spices or fermentation-derived ingredients, such as hemoglobin.

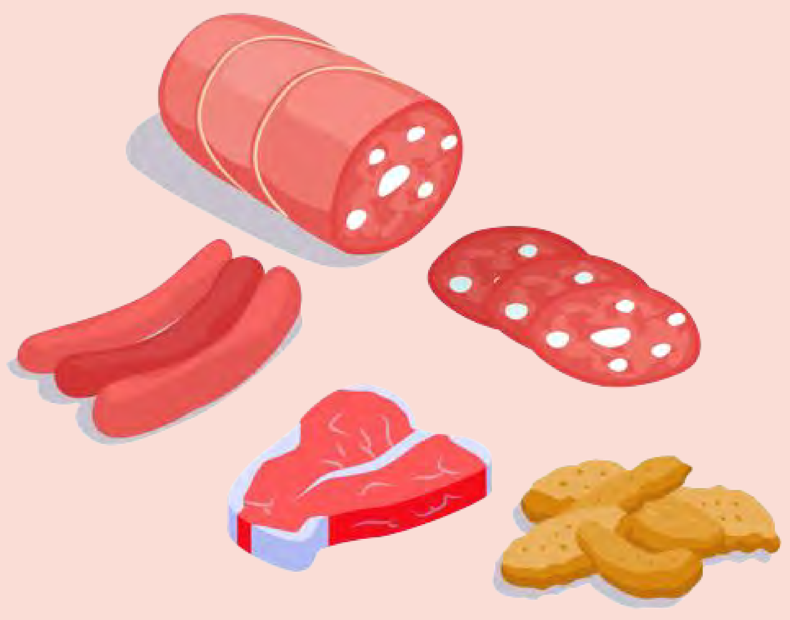
Source: adapted from Santo *et al.* 2020

Box 3.1 Plant-based meat production steps

Crop development: Plant ingredients, primarily proteins (Hertzler *et al.* 2020), serve as the raw material for novel plant-based meat. While animal protein structures and functions differ significantly from those of plant proteins, plant proteins have properties that can create similar end products. For example, mung bean and chickpea proteins have superior gelling properties compared with lentil, lupin and fava bean proteins (Kyriakopoulou, Keppler and van der Goot 2021) that can improve textures in plant-based meat products. Targeted crop breeding can help further improve plant proteins' nutritional value, functionality and palatability. Until recently, most plant-based products relied on proteins from commodity crops, such as soy, wheat or pea. Other sources such as sorghum, seaweed and chickpea are now being utilized and explored, expanding the options for product development and supply chain diversification.



Ingredient optimization and processing: Processing crops to create ingredients for food products has traditionally focused on oil and carbohydrate extraction. Protein fractionation and functionalization are relatively under-explored areas that could yield innovations useful in the development of novel plant-based foods (Sim *et al.* 2021). Improvements in the ingredient processing cycle are currently being made in areas including seed dehulling and milling (Vishwanathan, Singh and Subramanian 2011) and the kinds of fractionation employed (Galves *et al.* 2019; Vogelsang-O'Dwyer *et al.* 2020). Innovations in ingredient processing can influence taste and price and make downstream processes, such as formulation and texturization, less resource- and time-intensive.



End-product formulation and manufacturing: Producers strive to transform raw ingredients into products that replicate the cookability and organoleptic properties of restructured or whole-muscle conventional meat to closely reproduce the experience of diverse meat dishes and ingredients widely consumed globally. Formulations must therefore incorporate flavourings and other ingredients that deliver the sensory palette and nutritional qualities of animal meat. In some cases, product developers may alter the nutritional profile of plant-based meat to give it an advantage over conventional meat, for example by incorporating plant fibre. Once formulated, the ingredients of a product must be structured and shaped using manufacturing processes such as stretching, kneading, shear-cell processing, press forming, folding, layering, 3D printing and extrusion (Kinney, Weston and Bauman 2019).

Proponents of novel plant-based alternatives identify several ways to improve the products and reduce costs. These include:

- **Optimizing crops for protein content, quality and function.** There is potential to develop crop varieties geared specifically towards animal product alternatives. For example, crop strains could be gene-edited for traits such as protein content and functionality (Ku and Ha 2020; Nagamine and Ezura 2022). New technologies enabling high-throughput screening of crops for desired traits can accelerate the process.

- **Finding uses for co-products.** Rising demand for plant protein may create a surplus of plant starch and fibre. Finding uses for these co-products could reduce disposal costs and environmental impacts and generate additional revenue (Lima and Mellinger 2022). One use for co-products being explored is feedstock for protein production using fermentation technology.

- **Scaling plant protein fractionation.** Plant protein fractionation, or the extraction of protein from the rest of the plant, needs to scale in line with demand for plant-based meat. Recently, there has been significant investment made in scaling plant protein fractionation. For instance, several companies have set up large-scale pea protein factories to service growing global demand for ingredients optimized for novel plant proteins (Watson 2021).

- **Developing and scaling whole-muscle meats.** The development of plant-based alternatives to whole-muscle meat products (such as steaks or fillets), which are widely consumed across the world, is a challenge because of their fibrous textures and integrated pockets of fat. Newer manufacturing methods like 3D printing and shear cell technology are helping the industry to move toward this goal (Rubio, Xiang and Kaplan 2020).

3.1.2 Cultivated meat is made from animal cells grown in a culture medium

Cultivated meat is animal meat that is produced by cultivating animal cells in vitro. Producers of cultivated meat aim to arrange the same cell types in an identical or similar structure to animal tissues, thus replicating the sensory and nutritional profiles of conventional meat. Dutch scientist Mark Post unveiled the first cultivated meat burger on live television in 2013. Since then, the industry has grown to include more than 100 companies across the world backed by over US$1.9 billion in investments, while dozens more companies have formed to create technology solutions along the value chain (GFI 2022a). Cultivated chicken is the first and only product as of June 2023 to be available commercially, sold by one company in Singapore and the Unites States of America and one company in the United States alone (Firth 2020; United States Food and Drug Administration [FDA] 2023a).

The manufacturing process for cultivated meat (see Figure 3.2) begins with acquiring and banking stem cells from an animal. These cells are then grown in bioreactors filled with an oxygen-rich culture medium made of nutrients such as amino acids, glucose, vitamins and inorganic salts, and supplemented with growth factors and proteins. The result is differentiated cells, which fuse together and form muscle tissue. Cells are then harvested and prepared into final meat products.

Figure 3.2
Cultivated meat

Cultivated meat is genuine animal meat that is produced by cultivating animal cells directly rather than by slaughter of live animals, such as from farming and fishing. The aim of cultivated meat is to arrange the same cell types in the same or similar structure as animal tissues, thus replicating the sensory and nutritional profiles of conventional meat.

* These represent different potential inputs to create cultivated meat, and not all of them will be used in products that will be commercialized. For example, fetal bovine serum (FBS) is being phased out and is likely not to be used at scale given cost concerns.

Source: adapted from Santo et al. 2020

Major technological advances will be needed before cultivated meat becomes a mass market product. Efforts to overcome these barriers are underway across four main areas:

- **Cell line development:** For cultivated meat to replicate the variety of conventional meat products on the market, high quality cell lines (populations of cells that can be maintained for an extended period) from many species will be required. Researchers are working to develop and characterize new cell lines and to better understand the properties of different cell types that will determine their suitability for cultivated meat. Developing livestock cell sources that possess the necessary proliferative capacity, differentiation potential and efficiency for cultivated meat production is a key technical requirement for commercial scale-up (Reiss, Robertson and Suzuki 2021).

- **Culture media:** Cell culture media contains the nutrients and growth factors needed to cultivate cells outside an animal's body. It is a significant driver of the cost of cultivated meat. While animal-based cell culture media such as fetal bovine serum (see Section 3.6) have been in use for roughly a century, they have not been specifically designed with the requirements of cultivated meat in mind. A common industrial use of animal cell culture is currently the production of therapeutic monoclonal antibodies, which command much higher prices than meat products. To be viable at scale, cultivated meat production requires media that is low cost, animal ingredient-free, food-grade and food-safe, and that can regulate large-scale cell proliferation and differentiation. New approaches based on conventional culture media applications as well as industrial processes are being evaluated to advance media optimization for cultivated meat, with some success (O'Neill *et al.* 2020). There have been developments in research to develop animal ingredient-free formulations (Kolkmann *et al.* 2022; Messmer *et al*. 2022), with one product using serum-free media receiving regulatory approval in Singapore in January 2023 (GOOD Meat 2023).

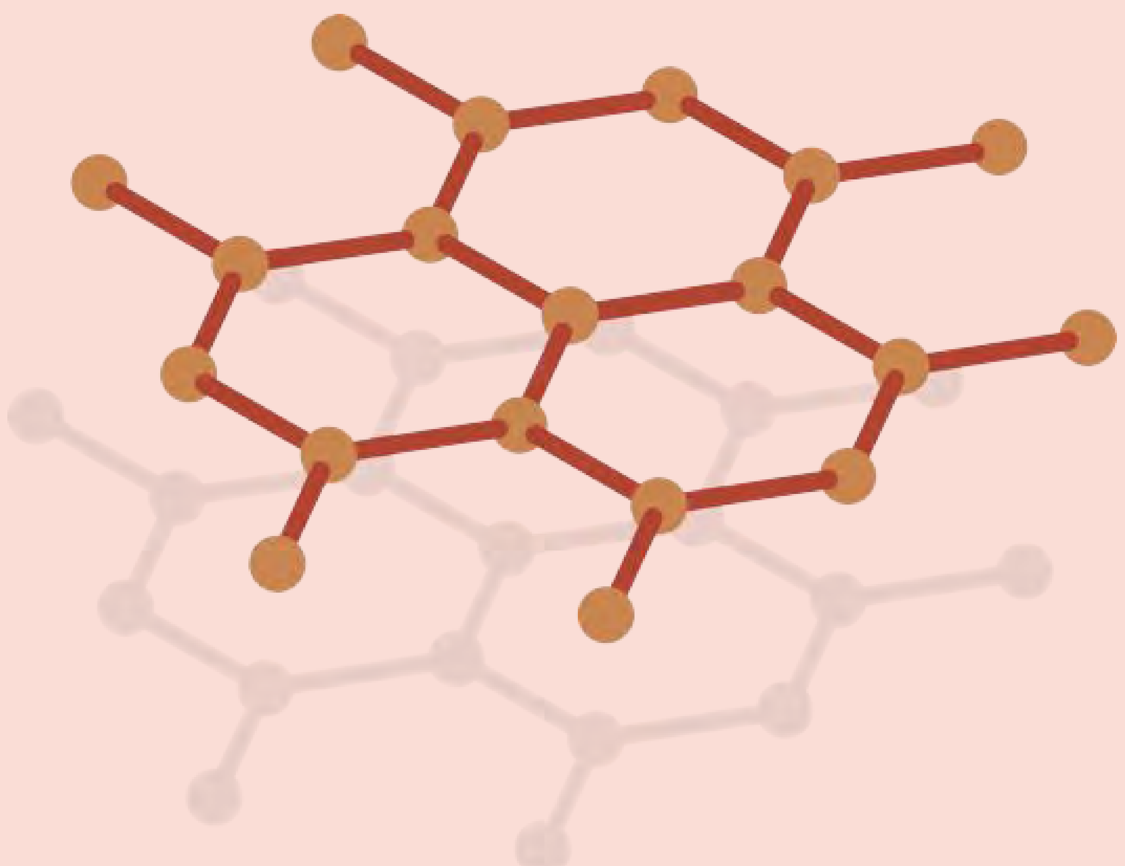
- **Scaffolding and other approaches to creating structure:** To reproduce whole-muscle meat products such as fillets and chunks, scientists are developing the use of three-dimensional scaffolding to support and guide tissue formation. Scaffolding can also facilitate nutrient, oxygen and waste transport during growth, and provide cues to help cells differentiate and mature. Scaffolding technologies have already been developed for use in biomedical tissue engineering. However, cultivated meat production comes with constraints related to the scale and cost of production as well as the necessary attributes of the final product, such as texture and food safety. While several promising avenues have been identified, including the use of precision fermentation to produce scaffolding (Singh *et al*. 2022), more research is needed to identify scaffolds capable of supporting the growth of high-quality meat while minimizing production costs (Bomkamp *et al.* 2021).

- **Production process design:** The production process for cultivated meat typically envisages lines of bioreactors outfitted with sensor equipment, integrated with cell-harvesting and food-processing equipment, and designed with automation in mind. Industry knowledge is still evolving regarding the best-suited bioreactors and technologies to develop a spectrum of cultivated meat product types (Vergeer, Odegard and Sinke 2021; Tuomisto, Allan and Ellis 2022). A variety of methods with different benefits and caveats offer potential for bringing cultivated meat production up to pilot and commercial scales (Meyer, Minas and Schmidhalter 2016). Several facilities for pilot-scale manufacturing opened globally in 2021 (GFI 2022a), and their performance could help inform industry efforts to further develop models for large-scale production.

3.1.3 Fermentation-derived products produce protein-rich food using microorganisms

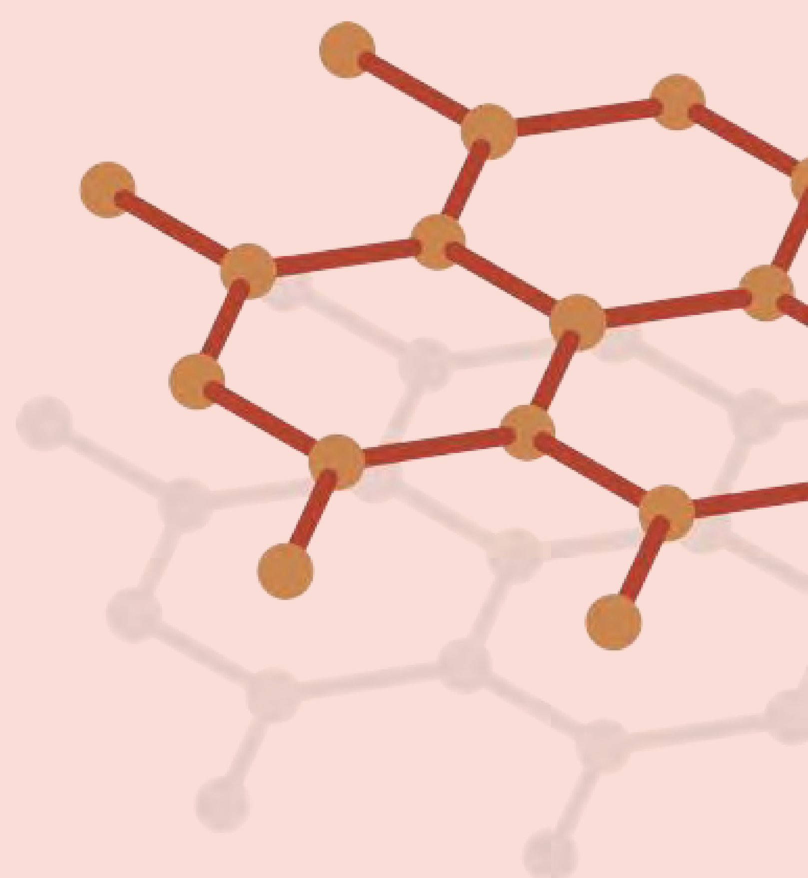
Fermentation has been used in food production for millennia, for example as a preservation technique, to make alcoholic beverages and to improve the nutritional value of foods like kimchi and tempeh. Over the past century, fermentation has found a much broader range of applications including in industrial chemistry, biomaterials, therapeutics and medicine, fuels and advanced food ingredients.

The vast diversity of microbial species, coupled with significant advances in synthetic biology, suggests that fermentation has significant potential for the development of novel alternatives to conventional animal products (Specht 2020). Fermentation is used in two primary ways to create such alternatives:



- **Biomass fermentation:** With this approach, the rapid reproduction and high protein content of many microorganisms is leveraged to efficiently produce large quantities of protein. The microbial biomass itself can serve as the main ingredient of a food product or as one of several ingredients in a blend. A range of microorganisms are being explored for their potential use in biomass fermentation, from yeasts to fungi and microalgae (Banks *et al.* 2022). Several companies use filamentous fungi species, which have an inherent meat-like fibrous texture and amenable flavour profile, as the base for their products (GFI 2023b). Some companies are also focused on microalgae that is grown without sunlight and instead fed sugar (GFI 2022a). Additionally, several companies are commercializing gas-fermented microbes that use carbon dioxide, methane or hydrogen as a carbon source to produce single-cell biomass protein (Marcellin *et al.* 2022).

- **Precision fermentation:** This approach refers to using microbes to produce specific functional ingredients (Teng *et al.* 2021). Precision fermentation rests on technology that is already used widely in the production of chymosin (the major enzyme in calf rennet) for cheese (Johnson 2006). In meat alternative applications, genetically modified microbes are used to produce ingredients including enzymes, flavouring agents, vitamins, natural pigments, proteins, fats and amino acids. These ingredients could improve functional attributes or sensory characteristics of cultivated or plant-based meats and have potential as scaffolding material or serum replacements in cultivated meat (Singh *et al.* 2022). Several companies are utilizing the technology to produce proteins such as casein and whey for plant-based cheeses and milks, or egg proteins such as ovalbumin for bakery applications. Some companies are producing iron-containing heme proteins, such as leghemoglobin and myoglobin, which give plant-based meats a taste and aroma similar to that of conventional meat.



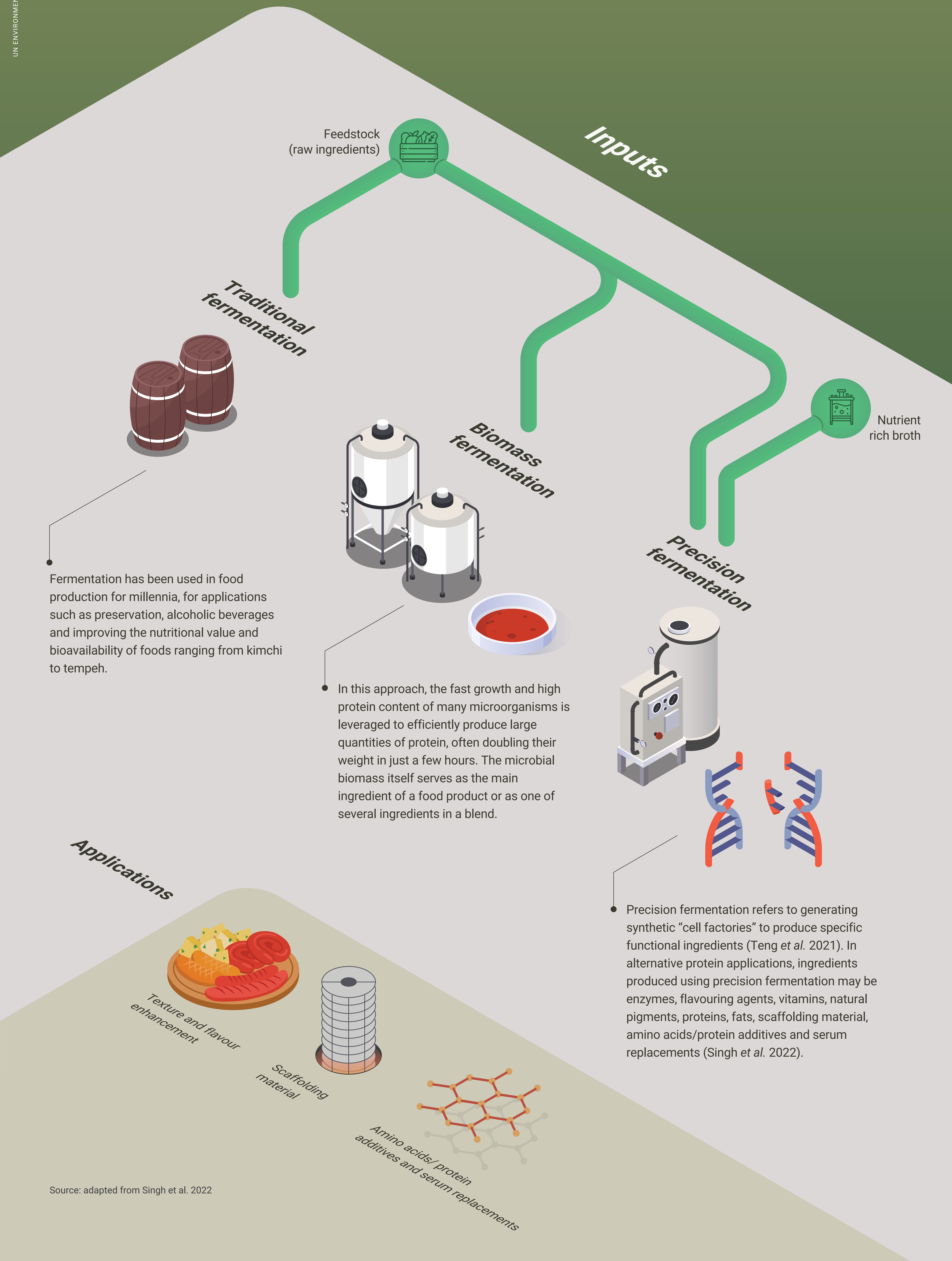
Both biomass and precision fermentation involve the following high-level steps: feedstock optimization, strain development and target selection, and final product formulation and manufacturing (see Figure 3.3 for more detail). Potential innovations in these areas include the use of high-throughput methods of strain selection to find new candidates for microbial protein production and the use of solid-state fermentation platforms to reduce risks and costs associated with scaling (GFI 2023b).

While the three categories of novel alternatives to conventional ASF have distinct characteristics, products utilizing more than one of these novel technologies may emerge. For example, plant-based meat could be combined with a small amount of cultivated meat in a product with a more meat-like sensory profile than plant-based meat at a lower cost than pure cultivated meat (Rubio, Xiang and Kaplan 2020). Hybrid products could also include conventional animal meat to increase their consumer appeal (Grasso and Jaworska 2020).

Figure 3.3

Types of fermentation

Fermentation approaches, both ancient and modern, provide important ingredients for our food systems. Microbes take input feedstock and nutrients and create complex outputs such as proteins, fats, flavouring agents or nutrient ingredients in a short period of time. These fermented products can range from ingredients for flavour and texture, center of plate protein portions, and even growth factors to support cultivated meat production.



Fermentation has been used in food production for millennia, for applications such as preservation, alcoholic beverages and improving the nutritional value and bioavailability of foods ranging from kimchi to tempeh.

In this approach, the fast growth and high protein content of many microorganisms is leveraged to efficiently produce large quantities of protein, often doubling their weight in just a few hours. The microbial biomass itself serves as the main ingredient of a food product or as one of several ingredients in a blend.

Precision fermentation refers to generating synthetic "cell factories" to produce specific functional ingredients (Teng *et al.* 2021). In alternative protein applications, ingredients produced using precision fermentation may be enzymes, flavouring agents, vitamins, natural pigments, proteins, fats, scaffolding material, amino acids/protein additives and serum replacements (Singh *et al.* 2022).

Source: adapted from Singh et al. 2022

3.2 There is a wide range of estimates for market share and consumer uptake of novel alternatives

The market for novel alternatives to conventional animal products has expanded since the first novel plant-based alternatives went on sale in 2016 (Strom 2016). Globally, as of 2021, the plant-based milk retail market had grown to US$17.8 billion, while the plant-based meat retail market has grown to US$5.6 billion (GFI 2022a).

In the United States of America, in 2021, plant-based meat sales were US$1.4 billion, up 45 per cent from 2019 and amounting to 1.4 per cent of total retail meat sales. Plant-based milk, a more mature category, accounted for over 15 per cent of all American retail milk sales (GFI and SPINS 2021). These novel products show some indications of displacing their animal-based counterparts, but more research is needed to confirm to what extent this is the case. Growing consumer demand for plant-based milk may be causing cow milk sales to drop somewhat faster than they otherwise would occur (Stewart *et al.* 2020). While novel plant-based meat is less mature, in one study at an American university, adding plant-based meat to menus resulted in it comprising 11 per cent of entrée sales, while the proportion of animal-based entrée sales decreased by 9 per cent, suggesting possible displacement (Malan 2020).

In Asia, the appetite for novel plant-based meat is forecast to grow significantly, with demand expected to increase by 200 per cent in markets like China and Thailand between 2020 and 2025, and an expected 25 per cent increase more widely across the region over the same time period (Arwanto *et al.* 2022; GFI 2022a). Plant-based meat can be prepared to suit diverse food cultures and palates in markets such as Singapore, India, Brazil and Japan. Areas of the world with smaller (but growing) markets for plant-based meat are Latin America and the Caribbean, the Middle East and Africa and Eastern Europe (GFI 2023a).

Early adopters of novel meat and dairy alternatives globally tend to be ‘flexitarian’ — omnivores who are reducing their consumption of animal meat due to a number of reasons, including environmental concerns (Szejda, Bryant and Urbanovich 2020). However, for the majority of consumers, these reasons will not be enough for them to regularly purchase novel meat alternatives, as taste and price factors will need to be addressed (Szenderak, Fróna, and Rákos 2022). Taste and price are consistently ranked as the top food purchase drivers, above health and environmental sustainability (International Food Information Council 2023). For plant-based meat specifically, consumers stated that taste was the most important factor, followed by price (Parry and Szejda 2019).

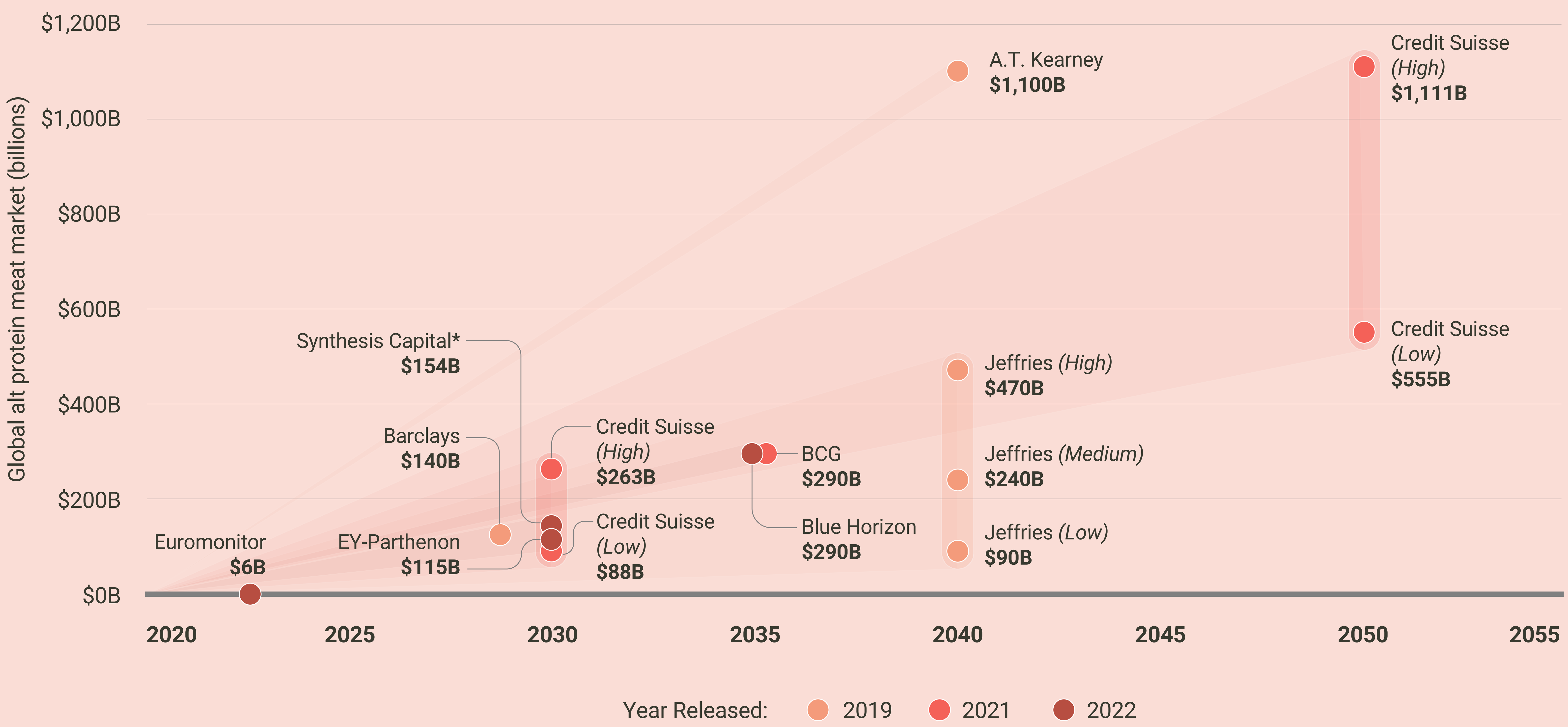
Perceptions of cultivated meat among early adopters are positive, with younger, internet-connected, flexitarian consumers even in countries with lower affinity for meat and food technology showing high levels of acceptance for cultivated meat (Bryant *et al*. 2019). However, it is important to note that not all consumers and governments are expected to react positively to cultivated meat, with food neophobia and uncertainties around safety and health potentially dissuading some consumers (Pakseresht, Kaliji and Canavari 2022). The Italian government has proposed a draft bill that would ban the production and commercialization of cultivated meat, with the stated goals of protecting human health and preserving the national agri-food heritage (Camera dei Deputati 2023; Sabelli 2023).

As shown in Figure 3.4, forecasts for the share of alternative meat sales (across novel plant-based, cultivated and fermentation-derived products) in total global meat sales (conventional and alternative) by 2040 vary greatly and range from 4 per cent[4] (US$90 billion) (Powell *et al.* 2019) to 60 per cent[5] (US$1.1 trillion) (Gerhardt *et al.* 2019). Similarly, estimates of the share of the market occupied by each product category vary significantly. One foresees cultivated meat and plant-based meat respectively occupying 35 per cent and 25 per cent of the total meat market by 2040 (Gerhardt *et al*. 2019). Another suggests the categories of novel alternative meats will comprise 16 per cent (plant-based), 5 per cent (fermentation-derived) and 1 per cent (cultivated meat) respectively, for a total of 22 per cent of the total meat market by 2035 (Witte *et al.* 2021).

It is worth noting that predictions to date about the development and uptake of plant-based and cultivated meat have tended to be too optimistic (Dullaghan 2021; Nogueira 2023). Cultivated meat in particular faces challenges to significantly scale-up production, such as bioreactor and media costs. Consumer acceptance levels will also impact market share (Bryant and Barnett 2018; Humbird 2021; Negulescu *et al.* 2022).

[4] Low end of the Jeffries forecast (Powell et al. 2019) assumes low overall growth in meat consumption (2 per cent annually from 2018–2040) due to health concerns, weak consumer confidence in novel alternatives due to product recalls, production techniques constrained by regulators, and no enactment of a meat tax.
[5] A.T. Kearney forecast (Gerhardt et al. 2019) assumes +3 per cent annual growth for overall meat consumption for 2025–2040 (-3 per cent compound annual growth rate for conventional meat, +9 per cent for novel plant-based alternatives, and +41 per cent for cultivated meat).

Figure 3.4
Global alternatives to conventional meat industry forecasts by year



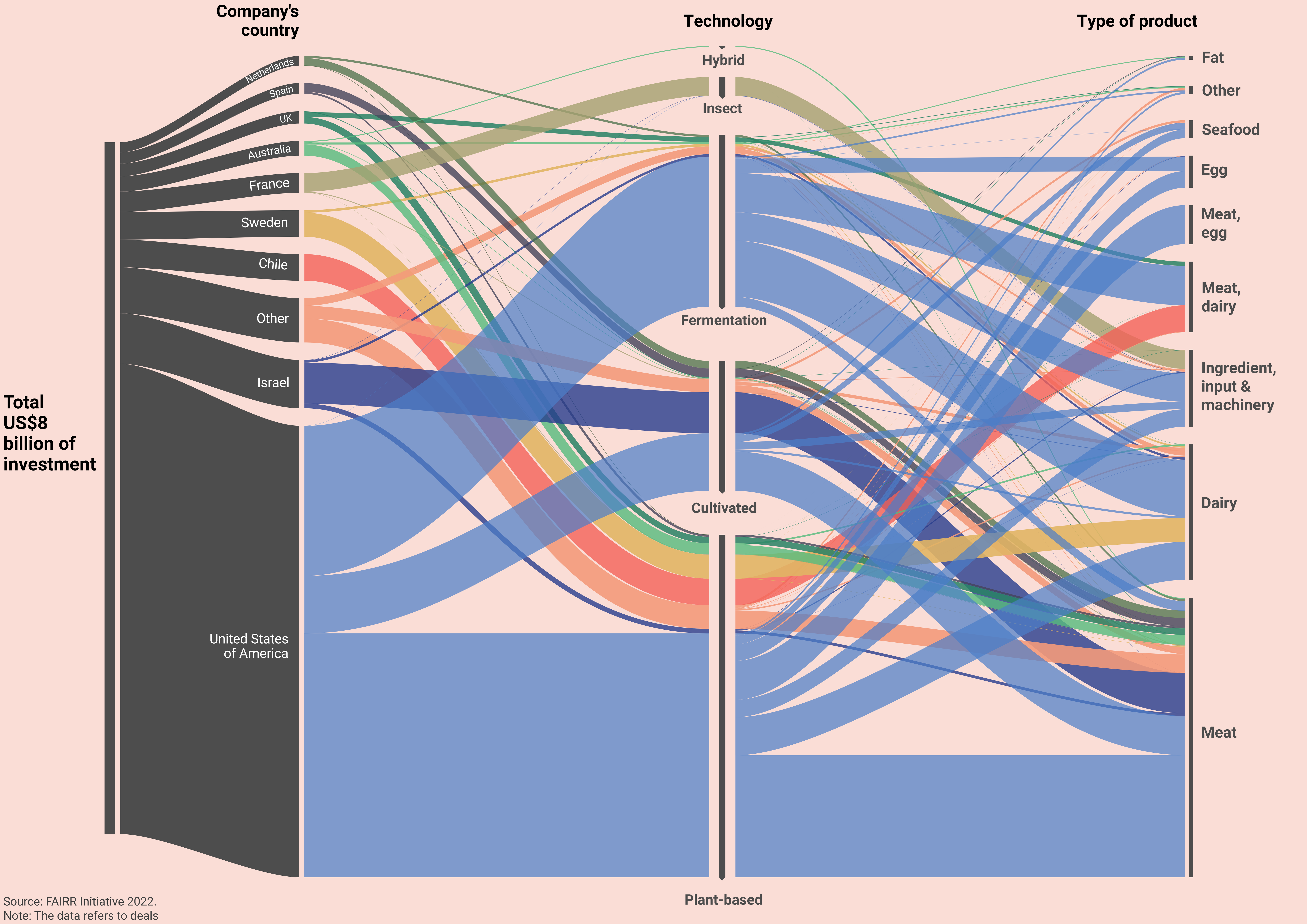
Source: GFI 2023c
Notes: *Some forecasts projected share of the total meat market rather than the industry size in dollars. For those forecasts, we estimated the dollar size of the alternative protein sector using EY's forecast for the total 2030 meat market. (Maeder *et al.* 2023)

The wide range of these estimates reflects the difficulty of making predictions in the early stages of the development of these novel technologies. Forecasts of significant uptake are predicated on a range of drivers across the areas of scientific and technological innovation, commercial and consumer trends and acceptance, and regulatory and government action. Workforce development is also important for the sector's growth (Specht *et al*. 2020).

Increased government support could help these products achieve taste and price parity with conventional equivalents and improve their accessibility to customers. A recent report estimated that US$10.1 billion in annual government support for research and manufacturing could see novel ASF alternatives take a 50 per cent market share by 2050 (ClimateWorks Foundation and Foreign, Commonwealth and Development Office, UK Government 2021). A techno-economic assessment of cultivated meat found that at a production cost of US$2.92 per pound (US$6.43 per kg), cultivated meat could be cost-competitive with some conventional meats by 2030 and serve as an affordable ingredient for plant-based and cultivated meat blends. Achieving this, however, assumes that producers can hit multiple process-optimization targets, and build facilities with the capacity to produce 10,000 tons of cultivated meat annually with an estimated cost of USD 450 million each (Swartz 2021; Vergeer, Odegard and Sinke 2021). Other analyses indicate that for plant-based meat to capture six per cent of the global meat and seafood market by 2030 (25 million metric tons of annual plant-based meat production), the industry would need to operate at least 800 model manufacturing facilities—each producing on average 30,000 tons of product annually—at a cost of at least US$27 billion (GFI 2023b). For reference, in 2022 alone, the United States of America invested US$1 billion to expand processing capacity for independent meat processors (United States, The White House 2022).

Figure 3.5

Breakdown of venture investments by company's country, technology type and type of product



Source: FAIRR Initiative 2022.
Note: The data refers to deals for the period 2020-2021.

By contrast, factors that could nudge novel meat and dairy alternatives onto a slower growth path include a lack of public and private investment in innovation and production to solve persistent technical challenges, a lack of clear regulation that impedes innovation, food safety issues or product recalls impacting consumer sentiment, and obstacles related to labelling or other roadblocks to technological progress or consumer acceptance (Gerhardt *et al.* 2019). Regulatory paths to market are particularly relevant, while global regulatory harmonization and development of standards will be important in obtaining religious certifications (e.g. halal, kosher). Additionally, cultural acceptance and trust of novel alternatives will be key to their adoption. For example, targeted gender-responsive communications may help foster trust and acceptance of this technology. As young men are more open to try cultivated meat in some countries, and men also comprise most meat consumers, this could be one avenue for driving behavioural change (Boereboom *et al.* 2022). Women may be more willing to opt for cultivated meat if informed of food safety advantages, for example if a product is described as free of antibiotics (Piochi, Micheloni and Torri 2022).

Reaching price parity will be a key driver of customer adoption. Price parity depends not only on reducing production costs for alternatives, but also on market developments that affect conventional meat costs. Higher input (feed) costs, meatpacker labour issues, wage inflation, avian influenza outbreaks and supply chain interruptions have recently drawn attention to the volatility—and price instability—of conventional meat (Ijaz *et al.* 2021; United States Department of Agriculture Economic Research Service 2022). Given the importance of reaching price parity, some cultivated meat companies are expected to initially launch hybrid products with plant-based meat to reduce costs (Watson 2020; Sawers 2022).

3.3
Novel meat and dairy alternatives have potential environmental benefits compared to conventional counterparts

3.3.1 Alternatives could reduce greenhouse gas emissions and use less land and water

Comparing the potential environmental impacts of novel meat and dairy alternatives to those of conventional farming is not straightforward. This is in part due to the variety of systems that could be considered 'conventional' farming—from extensive pasture-fed systems to intensive feedlots (Santo *et al.* 2020)—and their very different inputs and impacts. The assessments considered in this sub-section generally make comparisons primarily based on life cycle assessment (LCA) data of the typical conventional production systems of specific regions. These include intensive industrialized, extensive free-range and organic systems, and various combinations of these. Most of the assessments examine industrial and free-range systems in Europe and North America, but do not generally assess nondominant systems, such as smallholder farming systems, nomadic pastoralism and agropastoralism.

As discussed in Section 2, the role of different livestock production systems in generating different environmental outcomes is under discussion, with regenerative farming systems offering potential for some environmental gains. It thus matters what farming system the novel alternative product is being compared to. Overall, however, it is important to underline that diets in nations with high per-capita meat consumption tend to largely depart from the regenerative farming model, and that such models cannot meet the demand associated with current levels of meat consumption.

Another challenge for comparison is that the environmental impacts of meat and dairy, as well as of their novel alternatives, differ from one product to another. Much existing research focuses on ruminant farming and GHG emissions, where impacts from beef production are greater than for other livestock (de Vries and de Boer 2010), and the potential environmental gains from replacement, therefore, stand to be greater.

Furthermore, while various novel plant-based products are already available, and their environmental impacts relatively well understood, there are difficulties assessing the impacts of emerging technologies, particularly cultivated meat, where environmental analyses are currently limited. However, efficient feed conversion is a key characteristic that novel alternatives to animal products share, meaning that they require fewer crops per unit of end product (Sinke *et al*. 2023). ASF face greater conversion losses because feed also contributes to the energy needed to move, forage, stay warm and alive and grow non-meat organs (e.g. bones). Less feed translates to less land, fertilizer and pesticide use, resulting in lower scores on several environmental impact categories. To varying degrees, alternative meat and dairy products may require more energy than conventional meat and dairy to produce, so that the source of this energy—fossil fuels or low-carbon—becomes important in comparing impacts.

While more research is needed to assess the environmental impacts of novel alternatives to conventional animal products, existing insights are shared below.

3.3.2 Novel plant-based meat

While plant-based meat products typically incur a greater degree of processing and associated energy use than conventional plant-based foods, life cycle assessment (LCAs) suggest that, compared to conventional beef, they could use 30–50 per cent less energy whilst offering reductions of 86–97 per cent in land use and 67–89 per cent in GHG emissions (Rubio, Xiang and Kaplan 2020, Saget *et al.* 2021). Conventional pork and chicken also show substantially greater land use than novel plant-based meats (Rubio, Xiang and Kaplan 2020).

Given the significant land-use savings, replacing conventional meat with novel plant-based alternatives could make more land available for biodiversity conservation and restoration, renewable energy generation or less intensive agro-ecological approaches (Balmford *et al.* 2019; Newton and Blaustein-Rejto 2021; Tuomisto, Allan and Ellis 2022; Sinke *et al.* 2023). If used for restoration of natural habitats, it could contribute to achieving the goals of the post-2020 Global Biodiversity Framework as well as contributing to climate change mitigation and adaptation.

Regarding water, footprints for both conventional and plant-based alternatives are highly variable. For plant-based meat it is highly dependent on their main sources of protein and the manner of processing (Fresán *et al.* 2019, Potter *et al.* 2020).

It is important to note that novel plant-based meat comprises a range of products, each with specific characteristics and production contexts that will determine their impacts. The processing needed for some novel plant-based alternatives means that unless their energy mix is decarbonized, they can have a similar—or potentially higher—GHG footprint to some conventional meats, such as chicken and pork (Goldstein *et al*. 2017; Rubio, Xiang and Kaplan 2020). On the other hand, if low-carbon energy sources are used in the production of alternatives, GHG emissions tend to be lower than for conventional animal products (Tuomisto, Ellis and Haastrup 2014; Sinke *et al*. 2023).

3.3.3 Cultivated meat

Current research suggests that cultivated meat will have greater climate impacts than plant-based ASF alternatives particularly if low-carbon energy sources are not used (Tuomisto et al. 2022), and that they will have higher resource use (Smetana et al. 2015; Smetana et al. 2023). However, growing meat from cells could be more sustainable than conventional livestock rearing in terms of land and water and produce fewer GHG emissions if low carbon energy is used (Table 3.1).

To date, only seven anticipatory LCAs of cultivated meat have been published in peer-review scientific articles to quantify these possible benefits. Six of these LCAs are included here (Table 3.1).[6] The wide variation in projected impacts between these studies can be attributed to the methods employed, including the choice of system boundaries, data and hypothesized system processes. Smetana *et al.* (2015), for example, calculated the highest GHG emissions and energy requirements of all the studies due to changing the system design as outlined by Tuomisto and Teixeira de Mattos (2011) to cultivate the feedstock and cyanobacteria in a closed system rather than the previously modelled open-air pond. They also adopted a cradle-to-plate system boundary which includes some of the environmental impacts past the factory gate, such as transportation, packaging, storage, and cooking, which all other studies exclude. Also, Tuomisto and Teixeira de Mattos (2011) calculated cultivated meat's water footprint using both blue water (surface and ground) and green water (rainwater), whereas Mattick *et al*. (2015b) and Smetana *et al*. (2015) chose to exclude water use from their system boundaries entirely. Another methodological consideration is whether the varying nutritional content of different novel products are accounted for (in the LCAs in Table 3.1, only Smetana *et al*. (2015) included nutritional metrics).

[6] One of the 7 cultivated meat LCAs, Sinke and Odegard (2021) was updated and republished in 2023 as Sinke *et al.* (2023). Only the peer-reviewed, 2023 version has been included in this report.

For instance, where one kg of certain plant-based alternatives may contain less protein than one kg of animal-based meat, meaning additional volumes of the plant-based product would be required to achieve nutritional parity, there is not enough evidence currently to assess comparison when made on the basis of nutrient-based LCA.

Due to the rapid development of cultivated meat technology and the lack of any proven commercial-scale production processes or facilities, accurately modelling the environmental impacts of high-volume cultivated meat production remains a challenge. However, LCA studies suggest that if renewable energy sources are used with the most carbon efficient production techniques, GHG emissions could achieve 2.3 kg CO_2-eq per kg of meat[7] (median; range 1.9-4.88 kg CO2-eq per kg of meat) on a cradle-to-gate basis (Tuomisto and Teixeira de Mattos 2011; Tuomisto, Ellis and Hastrup 2014; Mattick *et al.* 2015b; Tuomisto, Allan and Ellis 2022; Sinke *et al*. 2023). This is around 40 times less that estimates of emissions from conventionally produced beef of an estimated 26.2 to (99 kg CO_2-eq per kg of meat), and around a quarter of the global average emissions for conventionally produced chicken and pork (9.87 and 12.31 kg CO_2-eq per kg of meat, respectively) (Poore and Nemecek 2018).

The LCAs included here show high variations in GHG emissions volumes (Table 3.1) which, in conjunction with other methodological differences, can be largely attributed to their modelling of production systems with different energy sources and mixes. Energy sourcing has a substantial impact on the overall environmental impacts of cultivated meat. As emissions from cultivated meat are primarily anticipated to be in the Scope 1 and 2 categories, single actions such as powering facilities with renewable instead of conventional energy mixes are significantly more effective in attaining reductions than these actions could be for conventional animal agriculture, where most emissions are categorized as Scope 3,[8] therefore requiring a range of tools and actions to achieve similar emission reductions (*Sinke et al.* 2023).

As discussed in Section 3.1, cultivated meat products may include hybrid products, containing both cultivated meat and plant-based proteins. Such products could reduce the environmental impacts of alternatives, particularly during the cultivated meat industry's initial stages of technological development and commercial expansion. This potential has been outlined in a recent LCA (Kim *et al.* 2022) on a hybrid burger. The product, of which cultivated meat constituted 16.9 per cent of the total mass, was found to have life cycle environmental impacts comparable to those of commercially available novel plant-based burgers.

Compared to conventional meat production, all of the LCAs for cultivated meat foresee drastic reductions in land use of 97–99 per cent per kg for beef, 60–99 per cent per kg for pork and 43–98 per cent per kg for chicken (Table 3.1). Applying a more specific measure of land-use efficiency, the feed conversion ratio (FCR) of cultivated meat is estimated to be three times more efficient than conventionally farmed chicken, currently the most environmentally efficient form of livestock production (Sinke *et al*. 2023).

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[7] In this section, the word 'meat' refers to a generic, ground cultivated meat product. Meat types, such as chicken or beef, are not specified in the existing LCAs. Further detail can be found in Table 3.1.
[8] Scope 1 indicates GHG emissions from sources owned or controlled by the reporting entity; Scope 2 indicates indirect emissions associated with the production of electricity, heat or steam purchased by the reporting entity; Scope 3 indicates all other indirect emissions, i.e. emissions associated with the extraction and production of purchased materials, fuels and services, including transport in vehicles not owned or controlled by the reporting entity, outsourced activities, waste disposal, etc. (IPCC 2014).

Table 3.1 **Summary of different life cycle assessments for cultivated meat**

Authors	Year	Institution	Title	System boundary	Meat type	Greenhouse gas emissions[9] (CO_2-eq per kg)	Energy use (MJ per kg)	Land use (m^2a per kg[10])	Water Use (L per kg)
Sinke, Swartz, Sanctorum, van der Giesen and Odegard	2023	CE Delft; GFI; GAIA	Ex-ante life cycle assessment of commercial scale cultivated meat production in 2030	Cradle-to-gate	Cultivated meat product from land-based animal with 20–30 per cent dry matter content and 18–25 per cent protein content	2.21–24.8 (ReCiPe 2016[11])	116.48–481.70 (Cumulative Energy Demand (CED))	2.25–3.59 (ReCiPe 2016)	60-150 (Blue water and green water)
Tuomisto, Allan and Ellis	2022	University of Helsinki; University of Bath	Prospective life cycle assessment of a bioprocess design for cultivated meat production in hollow fiber bioreactors	Cradle-to-gate	Cultivated meat consisting of skeletal muscle tissue of unspecified species with 30 per cent dry matter and 20 per cent protein content	4.88–25.19 (ReCiPe 2016)	94.09–532.78 (CED)	1.84–6.89 (ReCiPe 2016)	120—540 (Blue water)
Smetana, Mathys, Knoch and Heinz	2015	German Institute of Food Technologies; University of Vechta	Meat alternatives: Life cycle assessment of most known meat substitutes	Cradle-to-plate	Unspecified	23.9–24.64 (ReCiPe 2008)	290.7–373 (ReCiPe 2008)	0.39–0.77 (ReCiPe 2008)	Not reported
Mattick, Landis, Allenby and Genovese	2015	University of Texas; Clemson University; Arizona State University; University of Minnesota	Anticipatory life cycle analysis of in vitro biomass cultivation for cultivated meat production in the United States	Cradle-to-gate	Cultivated meat product	3.15–22.28 (CML 2001[12])	43.46–315.88 (CED)	2.92–8.47 (Ecological footprint)	Not reported
Tuomisto, Ellis and Haastrup	2014	European Commission Joint Research Centre; University of Bath	Environmental impacts of cultivated meat: Alternative production scenarios	Cradle-to-gate	Ground cultivated meat product with 30 per cent dry matter content and 19 per cent protein content	2.3–3.4 (GWP[13] 100y - IPCC 2006)	38.7–60.9 (Energy Conversion Factor calculations)	0.46 (Not stated)	516.4 (Blue water – Pfister et al. (2009) water scarcity method)
Tuomisto and Teixeira de Mattos	2011	University of Oxford; University of Amsterdam	Environmental impacts of cultivated meat production	Cradle-to-gate	Ground cultivated meat product with 30 per cent dry matter content and 19 per cent protein content	1.9–2.2 (GWP 100y - IPCC 2006)	26–33 (Not stated)	0.19–0.23 (Not stated)	367–521 (Water Footprint Network (Hoekstra, et al. 2009)

[9] Large ranges for GHG emission estimates within individual studies exist primarily due to the modelling of production scenarios with different energy compositions, including renewable sources, non-renewable sources and mixes of both.
[10] In LCA, land use is expressed as 'm^2a crop-eq' which accounts for both land-use occupation and land-use transformation.
[11] A method in life cycle impact assessment that uses characterization factors, which indicate the environmental impact per unit of stressor.
[12] A database that contains characterization factors for life cycle impact assessment.
[13] Global warming potential.

3.3.4 Fermentation-derived products

Studies of the environmental impacts of novel food products from precision and biomass fermentation (Table 3.2) suggest that, overall, they have lower land use and water impacts than conventionally produced proteins, while potential reductions in greenhouse gas emissions are highly dependent on the source of energy used in their production (Sillman *et al*. 2020; Järviö *et al*. 2021; Perfect Day Inc. 2021); the gains can be significant if low-carbon energy is used.

Promising but not yet commercially available techniques such as methanotrophic and hydrogen-oxidizing chemosynthetic bacteria have the potential to deliver further land use and climate benefits in mycoprotein production, with the magnitude again dependent on the availability of low-emission energy sources (Sillman *et al*. 2020; Järviö *et al*. 2021; Humpenöder *et al.* 2022). Per-unit replacement of ruminant meat with more conventional techniques, such as from mycoprotein, already has the potential to reduce water and land use by 90 per cent and GHG emissions by 80 per cent (Hashempour-Baltork *et al.* 2020; Rubio, Xiang and Kaplan 2020), though the environmental benefits of replacing pork and poultry with mycoprotein are less clear (Smetana *et al.* 2015; Souza Filho *et al.* 2019; Rubio, Xiang and Kaplan 2020).

Table 3.2 **Summary of different life cycle assessments for fermentation-derived products**

Authors	Year	Institution	Title	System boundary	Product	GHG emissions (CO_2-eq per kg)	Energy use (MJ per kg)	Land use (m^2a per kg[14])	Water use or scarcity (L per kg)
Behm, Nappa, Aro, Welman, Ledgard, Suomalainen and Hill	2022	VTT Technical Research Centre of Finland; Fonterra Research and Development Centre; AgResearch Ruakura Research Centre; Riddet Institute, Masey University	Comparison of carbon footprint and water scarcity footprint of milk protein produced by cellular agriculture and the dairy industry	Cradle-to-gate	Precision fermented microbial milk protein (beta-lactoblobulin)	5.5–17.6	Not reported	Not reported	88–5031 (water scarcity)
Perfect Day Inc.	2021	Perfect Day Inc.	Comparative life cycle assessment of Perfect Day whey protein production to dairy protein	Cradle-to-gate	Precision fermented whey protein (Trichoderma reesei)	2.71	56.3	Not reported	73.9 (water use, scarcity not reported)
Järviö, Maljanen, Kobayashi, Ryynänen and Tuomisto	2021	University of Helsinki; Natural Resources Institute Finland	An attributional life cycle assessment of microbial protein production: A case study on using hydrogen-oxidizing bacteria	Cradle-to-gate	Biomass fermented hydrogen-oxidising bacteria (Xanthobacter)	0.52–7.83	101.2–240.2	0.003–0.047	1–2.5 (water scarcity)
Sillman, Uusitalo, Ruuskanen, Ojala, Kahiluoto, Soukka and Ahola	2020	Lappeenranta-Lahti University of Technology (LUT) University; VTT Technical Research Centre of Finland	A life cycle environmental sustainability analysis of microbial protein production via power-to-food approaches	Cradle-to-gate	Biomass fermented hydrogen-oxidising bacteria (Cupriavidus necator)	0.82–1.15	63.54	0.029–0.085	0.8–3.8 (water use)

[14] In LCA, land use is expressed as ‘m^2a crop-eq’ which accounts for both land-use occupation and land-use transformation.

3.3.5 Transparency is important for realizing all potential environmental benefits

As with all nascent technologies, it is difficult to accurately assess all the potential gains or risks resulting from the expansion of novel ASF alternatives until production operations are scaled up. On the one hand, bigger efficiency gains than those foreseen in current LCAs could result from greater scale and further investment in research and development. Other promising avenues to reduce life cycle impacts include the utilization and valorisation of by-products and waste streams, for example, as feedstocks for fermentation processes, for producing sugars for use in cultivated meat; or for conversion into ingredients for other foods (Koutinas *et al*. 2014; Smetana *et al*. 2018). Additional opportunities include diversifying feedstock to use locally available resources and reduce transportation distances (GFI 2022a).

On the other hand, while promissory narratives are necessary to attract investment in emerging technologies, they may also run the risk of over-promising. Transparency from the sector to share the assumptions behind their data is vital. Guthman (2022) invites reflection on the promise of greater resource efficiency that biotechnological solutions offer against the similar promises of industrial agriculture. Biotechnological solutions hold promise for the environment, but it is not a given. Ultimately, every step of the supply chain for ASF alternatives—from feed and energy production through to consumption and the processing of waste—must be scrutinized and the necessary safeguard measures put in place to fully realize potential benefits (Section 4 explores how policy can help to secure more sustainable outcomes).

3.4 Alternatives could reduce the risk of zoonotic diseases, antimicrobial resistance and foodborne illnesses; further research on nutritional implications is needed

Comparing the public health implications of novel ASF alternatives with those of their conventional counterparts should be considered across multiple dimensions, including risks of zoonotic diseases, antibiotic resistance, and foodborne illnesses, nutritional implications and impacts on workers and communities.

3.4.1 Reduced risk of zoonotic diseases, antimicrobial resistance and foodborne illnesses

A reduction in ASF production and consumption in favour of ASF alternatives is likely to lower the risks of zoonotic disease transmission, given decreased human-livestock interactions, habitat destruction and biodiversity loss (Santo *et al*. 2020). In general, livestock production contributes more to biodiversity loss than crop production for direct human consumption (Machovina, Feeley and Ripple 2015; Sun *et al*. 2022). ASF reductions will also reduce the risk of human exposure to antibiotics as well as the development of antimicrobial resistance. This is because crop agriculture uses much lower levels of antibiotics than livestock agriculture and aquaculture, accounting for an estimated 0.26–0.5 per cent of total agricultural antibiotic consumption in the United States of America, for example (Taylor and Reeder 2020). Meat alternatives created under sterile lab conditions should, in theory, also require much lower levels of antibiotic use than in industrial livestock operations (even if some antibiotic use during cell line development is still expected), whilst also reducing the risks of foodborne illnesses (Santo *et al*. 2020; FAO and WHO 2023).

3.4.2 Nutritional implications

The picture for nutritional health is more nuanced and unclear. Given the limited evidence to date on novel plant-based alternatives, further research is urgently needed to elucidate their full short- and long-term public health implications, including the potentially differentiated outcomes based on factors such as sex and age, in order to inform relevant policies and consumer choices. While ample evidence from longitudinal studies and randomized controlled trials (RCTs) conducted in adult populations suggests that dietary patterns that generally emphasize minimally processed, healthful plant-based foods (i.e. whole grains, vegetables, fruits, nuts, seeds and legumes) are associated with reduced risks of premature mortality and NCDs, including cardiovascular disease, type II diabetes, obesity and some cancers (Schwingshackl *et al*. 2017; Kim, Caulfield and Rebholz 2018; Clark *et al.* 2019; Kim, Willett *et al.* 2019; English *et al.* 2021), significant knowledge gaps remain in understanding the nutritional health implications of replacing intake of conventional ASF with novel plant-based alternatives (Santo *et al.* 2020; Wickramasinghe *et al.* 2021). In particular, two key lines of enquiry with respect to consumer health warrant further investigation: nutritional quality and production formulation and their respective non-communicable disease (NDC) outcomes.

Animal and plant proteins are both nutritious, and protein quality and quantity are often not compromised when shifting to a well-designed diet that is predominantly or wholly plant-based (Tso and Forde 2021). Still, the majority of novel meat alternatives rely on soy, wheat or pea protein isolates as their primary protein source; it is unknown whether this form of protein would offer similar nutritional benefits or NCD reductions as whole legumes (Hu, Otis and McCarthy 2019; Flint *et al*. 2023). In addition to protein quantity and quality, there is much else to consider regarding the nutritional quality and interchangeability of novel alternatives compared to traditional ASF, such as macronutrients (protein, carbohydrate, fat); micronutrients (vitamins and minerals); the absence, low quantity or reduced bioavailability of certain important micronutrients that are naturally found in traditional ASF such as iron, zinc and vitamin B12; metabolite composition; the content of health-sensitive nutrients (fat, sugar and sodium) and other added ingredients; and the method of preparation required for consumption (Tso and Forde 2021; van Vliet *et al.* 2021; Flint *et al*. 2023; Nolden and Forde 2023).

Novel meat alternatives can have comparable levels of protein, saturated fat and sodium to some traditional meat products, but no cholesterol and higher levels of dietary fibre (Bohrer 2019). To date, variations in both the study methods and in the available alternative products mean that the limited published evidence is inconclusive regarding the nutritional profile of novel meat alternatives compared to traditional ASF (Flint *et al*. 2023).

In general, novel plant-based products that mimic the sensorial qualities of ASF tend to be highly processed[15] and can have high amounts of sodium and saturated fats (Gehring *et al.* 2021; Tso and Forde 2021; Wickramasinghe *et al*. 2021; Flint *et al.* 2023). While food processing is not inherently bad and can help to improve product palatability and enable fortification, there is strong evidence linking consumption of ultra-processed foods with greater caloric intake and weight gain, as well as increased risks of a range of adverse health outcomes including cardiovascular disease and premature death (Hall *et al.* 2019; Lawrence and Baker 2019). High sodium intake is also the leading dietary health risk worldwide, especially amongst young men (Afshin *et al.* 2019). However, there is no evidence linking these adverse health outcomes to processed, novel plant-based alternatives, and the few RCTs that have been conducted to date found positive health outcomes. Results from a 16-week RCT conducted in California, United States of America with 36 participants suggest that replacing ASF intake with novel plant-based alternatives may lower several cardiovascular disease risk factors and body weight in healthy adults (Anderson and Bradley 2020; Crimarco *et al.* 2020). Another recent RCT found positive changes in the gut microbiome when substituting several meat-based meals weekly for modern plant-based alternatives (Toribio-Mateas, Bester and Klimenko 2021).

[15] The NOVA system classifies all foods and food products into four groups according to the extent and purpose of the industrial processing they undergo (Monteiro *et al.* 2019). Under this system, many plant-based alternatives can be classified as 'ultra-processed foods (UPFs)', which are defined as 'formulations of substances derived from foods, such as starches, sugars, fats and protein isolates, with little, if any, whole food, and often with added flavours, colours, emulsifiers and cosmetic additives' (Wickramasinghe *et al.* 2021). However, some have argued that the NOVA classification system is too simplistic and does not adequately evaluate the nutritional attributes of certain foods (Messina *et al.* 2022).

Even though fermentation has been used to process food for millennia and is known to generally increase its nutritional value and gut-microbiome-enhancing properties (Xiang *et al.* 2019), there is limited research on the health effects of foods produced via the more novel techniques of biomass and precision fermentation. Consumption of mycoprotein derived from fungal biomass fermentation has been associated with certain health benefits such as improved blood levels of cholesterol, sugar and insulin (Ahmad *et al.* 2022; Souza Filho *et al.* 2019). However, some commercial vegan or vegetarian products utilizing mycoprotein can be highly processed and contain high levels of salt (Bohrer 2019). Some plant-based meat alternatives contain heme iron produced by precision fermentation of genetically engineered yeast; while its health effects have not yet been studied, high intake of molecularly identical heme from red and processed meat has been associated with increased risks of type II diabetes, cardiovascular disease and cancers (Santo *et al.* 2020). That said, heme iron is only naturally found in ASF and is more bioavailable than non-heme iron found in plant-based foods; consumption of heme iron can therefore help to address iron deficiency concerns especially for women of reproductive age and pregnant and lactating women (Zimmermann and Hurrell 2007).

Since cultivated meat alternatives are not yet widely commercially available, there is little evidence available about their public health implications, including, for example, whether they will be biochemically similar to traditional meat given possible differences between post-mortem transformations in conventional meat and post-harvest transformations in cultivated meat (Fraeye *et al.* 2020; Santo *et al.* 2020).

In the absence of sufficient evidence, it would be incorrect to assume that all plant-based foods are inherently healthy. Some researchers have raised concerns that the established health benefits of traditional plant-based foods are being conflated with positive messaging around animal welfare and sustainability benefits for the newer alternatives, many of which come in the form of fast-food product categories such as burgers, nuggets, meatballs and sausages (Tso and Forde 2021; Flint *et al*. 2023; Nolden and Forde 2023). At the same time, these alternatives designed to mimic the sensory attributes of meat are more likely to displace or reduce traditional ASF rather than whole-plant foods in a person's diet (Gastaldello *et al*. 2022). Traditional ASF can also come in heavily processed forms and with high levels of sodium, and there is strong evidence linking high intake of red and processed meats to adverse health outcomes (see Section 2.3). Therefore, despite knowledge gaps about the nutritional health implications of novel ASF alternatives, it would also be incorrect to assume that all conventional ASF products are healthier.

Ultimately, the nutritional health implications of all novel ASF alternatives will vary with each product's specific formulation, nutritional composition and density, and what they are replacing in an individual's diet, as well as with physiological differences in the consumer such as age and sex (Hu, Otis and McCarthy 2019; Tso and Forde 2021; Marwaha, Beveridge and Phillips 2022). Further research is also needed to assess the specific impacts on pregnant women, children and unborn children. Opportunities and further technological innovations exist for developers to enhance the nutrient quality (such as in terms of macronutrient and micronutrient composition and density) while minimizing or eliminating undesirable substances (such as cholesterol, unhealthy fats, salt and sugar, antibiotics and hormones) and to diversify the formulation of all novel ASF alternatives (Flint *et al*. 2023; Nolden and Forde 2023).

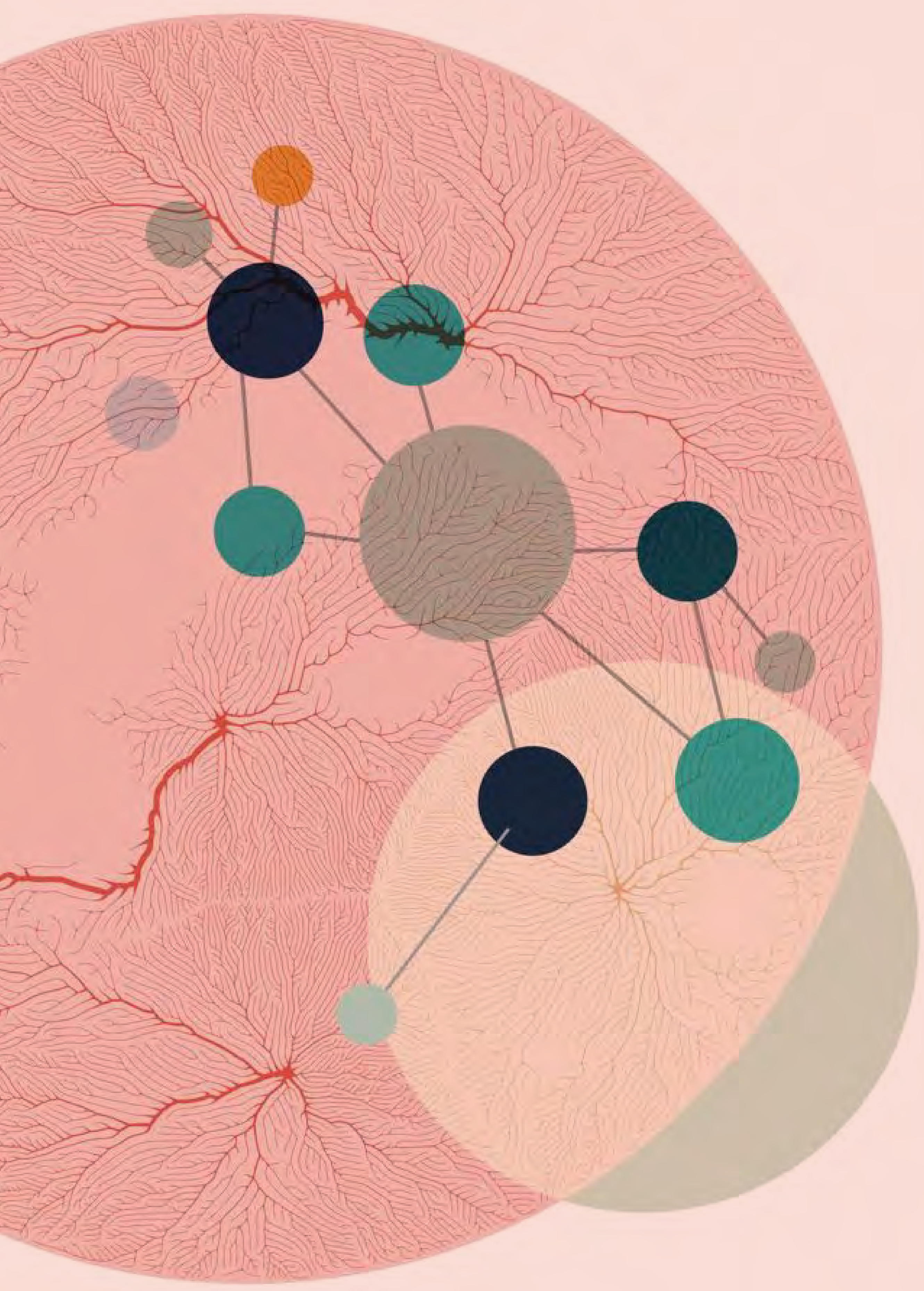
3.4.3 Impacts on workers and communities

To date, little is known about the existing or potential occupational health risks in the modern plant-based food industry (including novel plant-based foods, cultivated meat and fermentation); conditions are likely to be less hazardous than those in an industrial meat processing factory, but workers could still be exposed to dangerous chemicals used in the manufacturing process, such as hexane used in soy protein isolate production (Xiang *et al.* 2019; Santo *et al.* 2020). In terms of the health risks for nearby communities, issues associated with water contamination from nutrient runoff and use of pesticides that exist in today's crop production would persist (ibid). Still, modern plant-based alternatives are expected to generate less waste compared to ASF production and require fewer inputs (e.g., water, pesticides, fertilizers) for the same amounts of calories and protein (Rubio, Xiang and Kaplan 2020; Santo *et al.* 2020).

3.5 Socioeconomic impacts will depend on the degree of uptake of alternatives; more research is needed to fully understand these implications

A transition from conventional ASF to novel alternatives would likely be accompanied by significant socioeconomic impacts, including in areas such as rural employment and food security. The nature and magnitude of these potential impacts depends greatly on factors including the speed and degree of adoption of novel alternatives and the extent to which they replace or complement conventional ASF (see Section 3.2 for uncertainties in this regard).

To date, only a limited amount of research has evaluated the socioeconomic implications of novel ASF alternatives. Moreover, the available studies disproportionately focus on ethics and consumer acceptance (Stephens *et al*. 2018). Nevertheless, some researchers have begun to consider the wider impacts. Possible challenges include lost market and job opportunities for incumbents, agribusiness consolidation and further globalization of the food system, and unanswered questions about intellectual property rights of new technologies (Santo *et al*. 2020; Howard 2022; IPES-Food 2022). The literature also discusses opportunities these industries could bring, including new jobs and the redistribution of production to new areas and countries (Treich 2021).



Promoting a just transition will require policies that consider the distribution of these challenges and opportunities, paying particular attention to vulnerable and disadvantaged groups such as women, ethnic minorities, Indigenous Peoples and migrants, so inequalities are not further widened (Treich 2021; Verkuijl *et al*. 2022; see also Section 4). Inclusive planning and support involving policymakers, workers, communities, industry actors and other relevant stakeholders will be key in designing such policies (ibid).

Growth of the plant-based and cultivated meat industries may create more high-skilled jobs in certain regions (Treich 2021). ClimateWorks Foundation and the Foreign, Commonwealth and Development Office, UK Government (2021), suggests that, under a high innovation scenario, alternative proteins (including alternative dairy) could capture roughly half the global market for animal protein, have sales of US$1.1 trillion and employ about 10 million people globally by 2050. At the same time, changes in the distribution of labour may result in increases in unemployment in some sectors with impacts on livelihoods (Mason-D'Croz *et al*. 2022). Specifically, a significant reduction in conventional ASF production could drive major losses of employment in the animal farming and meat processing sectors. This will affect livestock and animal feed producers, farmworkers, meat processors and meat packing workers, among others (Mouat and Prince 2018; Stephens *et al*. 2018; Verkuijl *et al*. 2022).

Still, growth in the plant-based meat sector could create additional demand for various crops as sources of plant proteins, in turn creating opportunities for farmers that currently grow those crops or who could adopt them into their rotations (Verkuijl *et al*. 2022). Additionally, novel alternatives might in some cases create new opportunities for conventional livestock farming, for example to supply meat for blended products or raise livestock to supply cell lines for cultivated meat production (ClimateWorks Foundation and Foreign, Commonwealth and Development Office, UK Government 2021).

Rural populations could suffer if plant-based and cultivated meat shifts food production to cities, leading to losses in livelihoods, culture and traditions for rural producers and communities (Johnson and Lichter 2019; Pender *et al*. 2019; Morais-da-Silva *et al*. 2022). At the same time, alternative ASF production could create new jobs and opportunities in urban and peri-urban areas.

There are many uncertainties about how these novel food industries would be structured. They could present new opportunities for small businesses that target local food preferences (van der Weele and Driessen 2013; van der Weele and Tramper 2014; Stephens *et al*. 2018; Jönsson 2020; Treich 2021). However, potentially high barriers to entry (e.g. capital costs, intellectual property rights) and significant economies of scale in production could provide powerful incentives for industry consolidation (Morrison Paul 2003; Langemeier and Boehlje 2017; MacDonald 2017).

Across the conventional ASF sector there will be disparities in the adaptive capacity to respond to a shift towards novel alternatives. Most cultivated meat and plant-based product companies are owned by agribusinesses or start-ups headquartered in industrialized countries (Mouat, Prince and Roche 2019). Their success could further entrench economic and political power disparities between the Global North and Global South (Howard 2022; IPES-Food 2022). Additionally, large food companies, that have already invested heavily in the novel foods sector, could secure significant intellectual property rights related to novel foods, further concentrating their market power. The number of food patents filed globally for meat substitute products has been rising in recent years, mostly filed by large firms in the Global North (ibid). The extent of intellectual property rights that will be involved in the cultivated meat sector is unclear, though developments in seed patenting may offer some insights (Santo *et al*. 2020).

Novel alternatives have the potential to affect global supply chains, changing comparative advantages and the direction of trade flows of agricultural commodities. Trade in conventional ASF has grown significantly in recent decades, but is dwarfed by that in animal feed (Galloway *et al*. 2007). Nations where conventional animal products and feed make up a large portion of exports or of the economy could be vulnerable to a shift in global demand for agricultural commodities, in particular countries that rely on agricultural exports for foreign currency (Mancini and Antonioli 2022; Morais-da-Silva *et al*. 2022). By contrast, countries with little domestic animal agriculture may be able to replace some protein imports with domestically produced novel ASF alternatives and even benefit from export opportunities, with countries such as Israel and Singapore already investing in alternatives (Kamalapuram, Handral and Choudhury 2021; Morach *et al*. 2021; GFI 2023a).

The consequences of the adoption of novel alternatives for food security is difficult to assess *ex ante*. Some studies suggest that they could increase the availability of protein-rich foods to meet the nutritional needs of more people (Wan, Tai and Du 2021; Zhu and Begho 2022). However, poverty is a major driver of food insecurity (Sen 1983; FAO 2022), and as previously noted novel alternatives may disrupt the livelihoods of rural populations that are disproportionately poor and work in agriculture (Castañeda *et al*. 2018; Davis, Lipper and Winters 2022). Further research is needed to understand potential food security implications of novel ASF alternatives more fully, as outcomes may depend on the specific dynamics of local supply chains. Complementary agricultural and social support policies may be needed to support communities to adapt to change. This could include increased investment in areas including social safety nets, agricultural research and extension services (Chichaibelu *et al*. 2021), as well as incentives to ensure that freed-up resources such as land and water are used for activities that benefit the environment and food security.

3.6 Alternatives promise significantly reduced animal welfare issues

Replacing traditional ASFs with alternatives would significantly address the animal welfare issues associated with conventional livestock production (discussed in Section 2), by reducing the current need to raise, keep and slaughter billions of animals every year to supply products such as meat and milk. This is particularly the case for novel plant-based and fermentation-derived alternatives, which do not require the use of animals for their production.

In contrast to the other two categories of novel alternative, cultivated meat has, in its early development stages, relied on the use of animals, thereby raising a number of animal welfare concerns.

Cells for cultivated meat so far predominantly originate from biopsies performed on living animals. According to Melzener *et al*. (2020), a biopsy to obtain stem cells for cultivated beef muscle may involve removing small amounts of muscle tissue from an immobilized, sedated and locally anaesthetized cow with a needle or by making an incision. The animal's discomfort from a needle will probably be comparable to that from the taking of a blood sample, while for an incision biopsy, the level "will likely be greater, but still not substantial". It remains to be seen how many samples are taken per session, and how frequently an animal will be subjected to biopsies. In addition, competitive pressures could potentially lead to some similar forms of maltreatment to those commonly experienced by animals in the conventional livestock industry. It is also possible that animals from the conventional livestock industry would be among the providers of these biopsies.

Another ethical issue is the fate of animals no longer able to deliver effective cell samples. Research suggests that the muscle tissue of young (3-month-old) bulls yields significantly more stem cells than older or female animals (Melzener *et al.* 2021). A strong emphasis on animal welfare could involve allowing active and retired donor animals to live out their natural lives in "sanctuary-like" habitats (Dutkiewicz and Abrell 2021). However, economic and environmental incentives might motivate people to slaughter them before this, either to harvest their remaining useful cells or for conventional meat (Melzener *et al*. 2021).

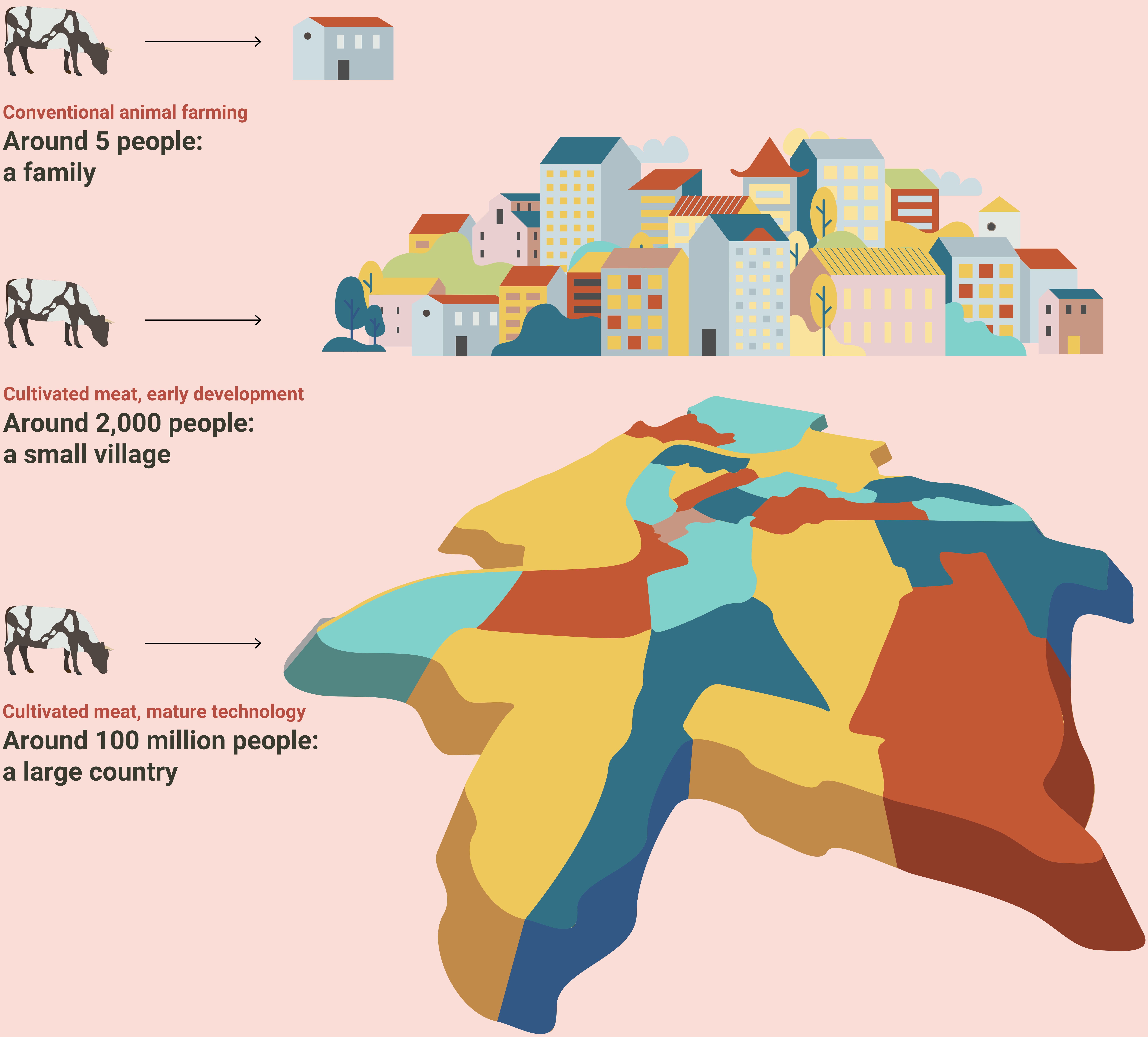
Crucially, however, the number of animals required to meet global meat demand would be dramatically smaller. In theory, cells taken from a single donor animal during twenty biopsies over their lifespan could yield cultivated beef equivalent to the meat of 400 cattle. Optimizing the cell proliferation process could see a single biopsy eventually replace millions of cattle (Melzener *et al.* 2021). Researchers are seeking to develop "immortalized" cell lines that can proliferate indefinitely (Reiss, Robertson and Suzuki 2021; Soice and Johnston 2021b) and could eliminate the need for repeated biopsies.

Cultivated meat production has also relied on fetal bovine serum (FBS) as a growth medium. FBS is taken from the fetus of a slaughtered pregnant cow through cardiac puncture without anaesthesia. It affects both the pregnant cows who are transported and slaughtered, and the fetuses who may already be mature enough to feel pain during and after the cow's slaughter (Jochems *et al.* 2002; Weber *et al*. 2021). Researchers are developing animal-free growth media for reasons of animal welfare as well as high costs and technical challenges associated with FBS (Messmer *et al.* 2022). In January 2023, a United States of America-based start-up received approval in Singapore to produce cultivated chicken based on serum-free media (GOOD Meat 2023).

Overall, novel ASF alternatives from plants and fermentation avoid the massive-scale animal welfare issues of conventional animal products. Cultivated meat has the potential to be similarly beneficial, though it still faces animal welfare challenges that companies are working to address through ongoing research and development (Chen *et al.* 2022).

Figure 3.6

Number of people a cow can feed for a year



Notes: Estimates are illustrative. The number in conventional animal farming is derived from FAOSTAT data, assuming 43 kg/capita yearly supply of meat globally in 2020 and 220 kg of cattle meat per animal based on the production quantity and the number of animals slaughtered in 2020. The number for cultivated meat under early development assumes that one animal donating cells could replace 400 cattle over its lifespan (Melzener *et al.* 2020). The number for cultivated meat as a mature technology assumes that one cow could potentially replace some 20 million cattle if optimized, although this number could even be substantially higher (Melzener *et al.* 2020).

4. Policy and regulatory environments can significantly influence the future of alternatives

Governments, mainly in high- and middle-income countries, have begun to explore policies and regulations to actively govern novel alternatives to conventional animal products. This may entail considering whether and how to accelerate their development and deployment, as well as ensuring that their emergence supports, rather than threatens, progress towards other societal goals. Evidence-based policy processes that include stakeholders are vital to ensure a transition towards more sustainable food systems that is just (Duncan *et al.* 2022; Webb *et al*. 2023).

The emergence of alternative proteins, including novel ASF alternatives, presents economic opportunities for some countries, and may present challenges to others; particularly those that may have constrained access to key inputs including energy, feedstocks, capital and technology necessary for a competitive alternative protein sector. Current plant-based products use crops like peas and soy that certain countries already have a strategic advantage in producing, and the development of a larger, higher-value market for these crops could support local economies and livelihoods. In addition, other crops may become viable inputs to novel plant-based products, with several governments investing in research and development for such new functionalities (Agritech Future 2022; Nutraceutical Business Review 2022; Change Foods 2022). Nations that are small, densely populated, unsuited for agriculture or otherwise dependent on imported food or feed may find promise in cultivated meat and fermentation technologies that enable the production of dietary protein without the associated land-use requirements (Hayek *et al.* 2021). As a global market develops for alternative proteins and ancillary products, such as bioreactors and cell-growth media, governments may also consider the advantages of fostering the development of a high-value addition sector.

4.1 Current policies impacting novel meat and dairy alternatives

The policy and regulatory environment is evolving quickly in response to the emergence of novel ASF alternatives. Several high- and middle-income countries have begun to take steps to enable and promote the development and uptake of these products. Conversely, other countries have adopted a more cautious or even oppositional stance towards novel ASF alternative, including restrictions or bans on their production or sale. The reasons for these restrictions may be multifaceted, including food safety concerns, societal or cultural resistance, lobbying by conventional ASF producers, the impact on traditional agriculture sectors, or knowledge gaps and uncertainty about these novel food products.

In order to share evidence of safety and help avoid potential misinformation, producers of novel alternatives such as cultivated meat companies can be encouraged to provide open, independently verified research on product safety and nutrition, given that the rigor and transparency of approval processes may vary by country (Holmes *et al*. 2022). Such independent verification could be funded through a mix of public and private financing.

An overview of recent policy and regulatory developments surrounding novel ASFs (Tables 4.1 and 4.2) indicates how some governments are responding to novel foods, including ASF alternatives.

Several countries have developed approval processes for novel foods, including carefully worded definitions of the term, to provide a pathway for producers to bring their products to market, including an obligatory review of their safety and nutrition by regulatory agencies (Table 4.2). These novel food frameworks typically cover cultivated meat and some fermentation-derived ingredients, but most novel plant-based products are exempt, given that most plants used in these products already have a precedent set for being used as food.

Some countries in both the Global North and Global South have moved actively to understand and foster the potential of novel ASF alternatives, for instance through support for research and pilot production facilities.

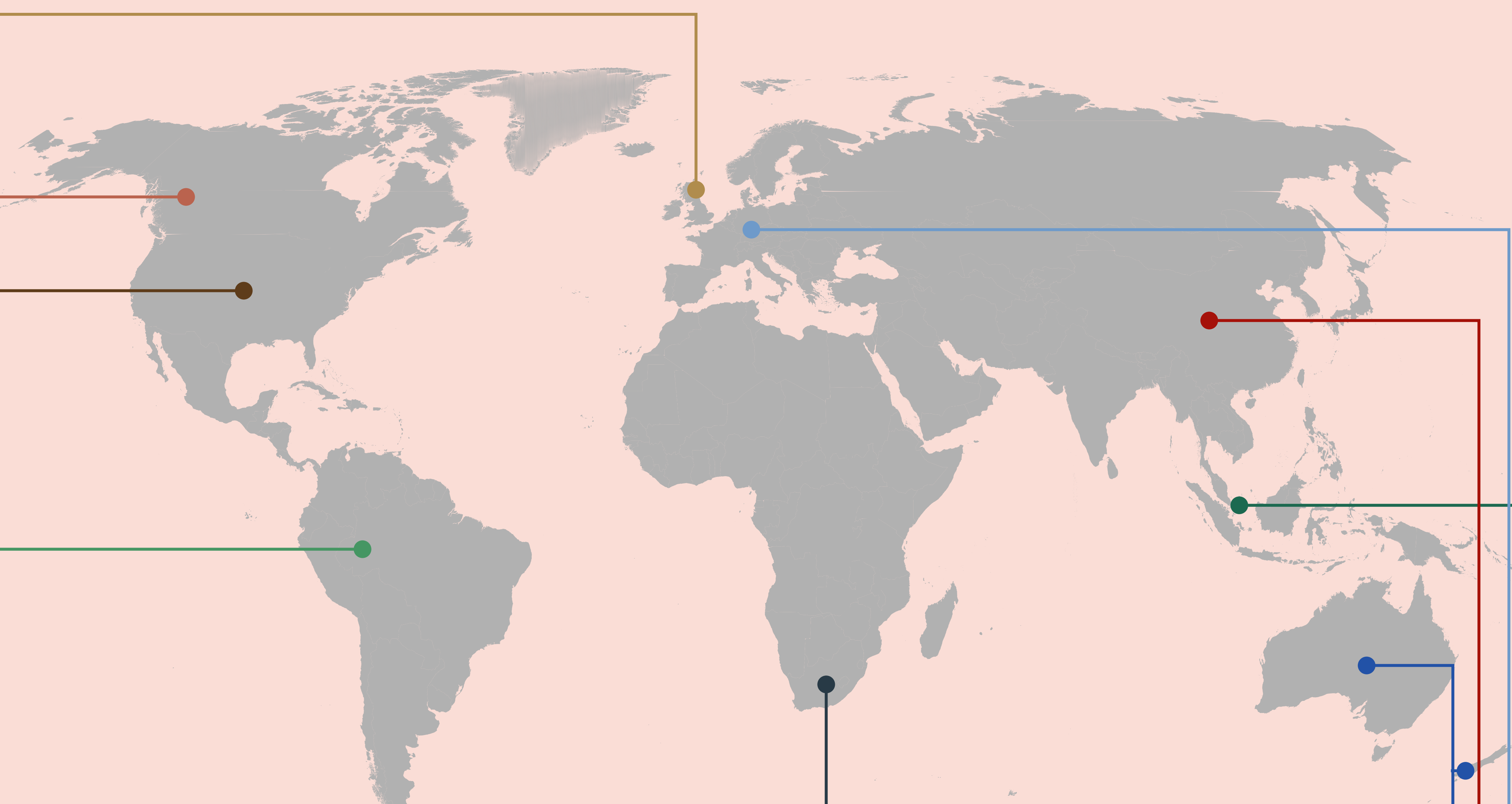
Some countries have adopted a more precautionary stance towards alternative ASFs. Plant-based cheeses have been banned in Türkiye (Southey 2022), while Italy has approved a draft bill that, would ban the production and commercialization of cultivated meat. The bill was presented as a measure to ensure “the protection of human health and the interests of citizens as well as preserving the agri-food heritage and its strategic importance for national interest” (Senato della Repubblica 2023; Sabelli 2023).

Table 4.1
Policy instruments targeting alternatives to conventional animal products

Policy instrument	Example countries	Remarks
Funding open-access science and/or research centres	Australia, Brazil, Canada, China, Denmark, The European Union, France, Germany, India, Israel, Japan, The Netherlands, Norway, Singapore, Republic of Korea, Spain, Sweden, Switzerland, The United Kingdom of Great Britain and Northern Ireland, The United States of America	Organizations implementing research and development initiatives are mainly national or provincial public science and technology organizations and public-private partnerships in food technology research.
Funding industry and/or manufacturing	Australia, Canada, China, Denmark, The European Union, Finland, France, Germany, Israel, Japan, The Netherlands, Oman, Qatar, Singapore, Republic of Korea, Spain, Sweden, The United Arab Emirates, The United Kingdom of Great Britain and Northern Ireland, The United States of America *(including state governments)*	These policy instruments include direct public production or investments in public-private production ventures and information campaigns as well as legal and market facilitation mechanisms. Government investments largely focus on strategic domestic industries, e.g. pulse-based ASF alternatives production in Denmark and Canada and fermentation infrastructure in Israel and Finland. A number of state-owned sovereign wealth funds, e.g. in Singapore, Oman and Qatar, are also making sizable investments in domestic novel alternative companies and/or projects.
Regulation	Canada, The European Union, France, India, Italy, Japan, Qatar, Singapore, South Africa, Switzerland, Türkiye, The United States of America	Labelling, market transparency and consumer trust-building campaigns are handled by public sector agencies. Other regulatory instruments include developing novel food approval processes and banning the production or sale of certain alternatives.
Financial incentives and instruments	Brazil, Denmark	Tax exemptions and other incentives to producers of novel alternatives, such as subsidies and support for inputs (e.g. protein-rich crops), market development.
Workforce development	Australia, China, India, The Netherlands, The United States of America	These policy instruments include professional training and the development of curricula to build knowledge and skills regarding novel ASF production and sustainable agri-food systems.

Source: Summarized from GFI State of Global Policy 2022 (GFI 2023a)

Table 4.2
Regulation of novel foods in selected countries



Brazil

The Ministry of Health is the main authority responsible for food regulation and safety assessments. It performs this role via the autonomous National Agency of Sanitary Surveillance (Agencia Nacional de Vigilancia Sanitaria [ANVISA]), which evaluates the safety of additives and ingredients in foods and regulates labelling.

Pre-market approval by ANVISA is required for novel foods and ingredients. Approvals are valid for five years and may be renewed (ANVISA 2022). Regulations in Brazil and other members of Mercosur, the South American regional organization, are increasingly aligned. Brazil is gradually replacing many of its food standards with official Mercosur standards, which are in turn influenced by European and US standards as well as the global Codex Alimentarius.

Canada

The Food Directorate, a federal authority under the government's Health Canada department, is responsible for setting standards, policies and regulations and providing advice and information on the safety and nutritional value of food.

Canadian regulations (Government of Canada 2023) define a novel food as:

- **a** a substance, including a microorganism, that does not have a history of safe use as a food;
- **b** a food that has been manufactured, prepared, preserved or packaged by a process that
  - has not been previously applied to that food and
  - causes the food to undergo a major change; and
- **c** a food that is derived from a plant, animal or microorganism that has been genetically modified such that:
  - the plant, animal or microorganism exhibits characteristics that were not previously observed in that plant, animal or microorganism,
  - the plant, animal or microorganism no longer exhibits characteristics that were previously observed in that plant, animal or microorganism, or
  - one or more characteristics of the plant, animal or microorganism no longer fall within the anticipated range for that plant, animal or microorganism.

Pre-market approval is required for a new substance, for an extension of the use of a permitted food additive, for permission to change the maximum level of a permitted food additive, or for authorization to add a new organism to the list of permitted sources of enzymes used as a food additive. The submission requires evidence that the food is safe for consumption.

In 2020, the Canadian Food Inspection Agency, which is part of Health Canada, sought public input on the labelling of plant-based meat alternatives. The resulting guidelines require labels to use the phrase 'simulated' followed by the meat or poultry type and the phrase 'contains no meat' or 'contains no poultry' in close proximity (Government of Canada 2020).

United States of America

US authorities do not specifically define or regulate novel foods. The Food and Drug Administration (FDA) considers any new food ingredient either as a food additive (requiring its pre-market approval) or 'generally recognized as safe' for specific uses (as classified by a panel of experts and determined independently of the FDA).

The FDA completed its first pre-market consultation for human foods made from cultivated animal cells in 2022 (FDA 2022). Such consultations are a step toward the formal approval of cultivated meat products, which also usually involves the USDA's Food Safety and Inspection Service. Terrestrial meat, poultry and catfish are considered livestock species, and therefore fall under the jurisdiction of the USDA, while cultivated fish of other species only requires FDA clearance. In 2023, USDA approved labelling and issued grants of federal inspection for cultivated meat for the first time, allowing two companies to begin sales of cultivated chicken.

United Kingdom of Great Britain and Northern Ireland

The United Kingdom of Great Britain and Northern Ireland defines novel foods as those 'not used for human consumption to a significant degree' in the United Kingdom or the European Union before 15 May 1997 (Food Standards Agency 2023).

Examples include:

- new foods, such as phystosterols and phytostanols used in cholesterol-reducing spreads
- Foods traditionally eaten in other countries, such as chia seeds
- Foods produced through new processes

There are two routes for new foods to gain approval for sale:

- Traditional food notification: a simplified route to authorize products that have been continuously used for 25 years by a significant number of people in a country outside the United Kingdom of Great Britain and Northern Ireland or European Union.
- Full application: a more complex route for foods that don't have a history of consumption in other countries. A number of documents need to be presented and should follow European Food Safety Authority guidance on the preparation and presentation of an application for authorization of a novel food.

The regulator received its first application for pre-market approval of cultivated meat through its novel foods process in mid-2023 (Cervera 2023).

Australia and New Zealand

A joint regulatory body, the Food Standards Australia New Zealand (FSANZ), maintains food standards that apply in both countries. The Australia New Zealand Food Standard Code regulates areas including labelling, additives, processing aids, nutritive substances, contaminants and the approval of new foods, including novel foods.

FSANZ defines a novel food as a non-traditional food that requires an assessment of the public health and safety considerations having regard to:

- **a** the potential for adverse effects in humans; or
- **b** the composition or structure of the food; or
- **c** the process by which the food has been prepared; or
- **d** the source from which it is derived; or
- **e** patterns and levels of consumption of the food; or
- **f** any other relevant matters. (Australian Government 2016)

Non- traditional food is defined as a food or substance that has no history of human consumption in the two countries (Australian Government 2016).

FSANZ approved soy leghemoglobin, a fermentation product used in plant-based meat, as a nutritive substance and a genetically modified food in 2020. The regulator received its first application for pre-market approval of cultivated meat in early 2023 (FSANZ 2023).

China

The Ministry of Health is responsible for drafting laws, regulations, policies and standards governing food and for supervising enforcement.

Novel or 'new resource' foods include raw materials or ingredients that have no significant history of consumption in the country (GFI 2023a).

'New food additives' require pre-market approval from the ministry. Legislation defines a new food additive as one not covered by the national food safety standards or approved for a permitted use by the ministry, or whose scope of use or dosage is increased (GFI 2023a).

European Union

The European Union updated its food regulations in 2015 to reflect developments in food science and technology. The new regulations define novel food as 'food that has not been consumed to a significant degree by humans in the EU before 15 May 1997', when the first regulation on novel food was published. In addition, a food product should be considered novel food 'when it results from a production process not used for food production within the Union before 15 May 1997, which gives rises to significant changes in the composition or structure of a food affecting its nutritional value, metabolism or level of undesirable substances' (Official Journal of the European Union 2015).

The EU regulation expanded the categories of novel foods to include, among others, whole insects and their parts, 'food with a new or intentionally modified molecular structure, as well as food from cell culture or tissue culture derived from animals, plants, microorganisms, fungi or algae, food from microorganisms, fungi or algae and food from material of mineral origin' (Official Journal of the European Union 2015, European Food Safety Authority Panel on Dietetic Products and Allergies 2016).

In the regulation, it is specified that the main purpose is to ensure a high level of protection of human health and consumers' interests.

Food businesses are responsible for determining whether their products are novel. The European Food Safety Authority (EFSA) carries out risk assessments on novel foods and the European Commission decides on authorizations (Lähteenmäki-Uutela *et al.* 2021). As of mid-2023, the authority has not received any applications for cultivated meat products (Sabelli 2023).

Singapore

The Singapore Food Agency's Guidance on Safety Assessment of Novel Foods (2023) specifies the information required to seek approval for a cultivated meat product.

The agency defines novel foods as 'foods and food ingredients that do not have a history of safe use' (Singapore Food Agency 2023). Substances with a history of safe use are those that have been consumed as an ongoing part of the diet by a significant human population (e.g. the population of a country), for a period of at least 20 years and without reported adverse human health effects.

In 2020, Singapore became the first country to approve the sale of a cultivated meat product.

South Africa

The Department of Agriculture, Land Reform and Rural Development (DALRRD) regulates plant-based meat products through the Food Safety Agency. The Department of Health's food control section additionally ensures food safety as an essential public health function and conducts risk assessments related to agricultural chemicals and food produced through biotechnology (DALRRD 2022; South Africa, Department of Health 2022).

In August 2022, DALRRD (2022) published new regulations regarding the classification, packaging and labelling of processed meat products intended for sale. The regulations define 'meat analogue' (also known as a meat substitute, mock meat or imitation meat) as products that:

- **a** approximate the aesthetic qualities (primary texture, flavour and appearance) and/or chemical characteristics of a specific type of meat; and
- **b** are made from non-meat ingredients and are available in different forms such as coarse ground meat analogues, emulsified meat analogues and loose fill.

Regulators face challenges regarding how novel foods are marketed. Whether novel ASF alternatives should be allowed to carry words such as 'meat', 'steak', 'burger' or 'milk' has sparked intense public and political discussion in several countries, and policymakers have reached widely varying decisions (Gleckel 2020; Taylor 2022; Demartini *et al.* 2022). Initial evidence suggests that labelling plant-based alternatives with these words does not cause consumers to think these alternatives come from animals, as some proponents of labelling restrictions have claimed, and that using these labels reduces confusion for consumers about their taste, potentially improving uptake (Gleckel 2020). Regarding cultivated meat and precision fermented animal proteins, it will be important to have clear labelling for those with allergies, given that those who are allergic to a certain type of ASF may also be allergic to its cultivated meat or fermented counterpart (Bryant 2020).

The regulation of cultivated meat has drawn considerable public scrutiny. Though designed to be (closely) identical to conventional meat at the cellular level, whether it is considered meat in law is a question that Singapore and the United States of America have so far answered in the affirmative. In 2020, Singapore became the first country to approve the sale of a cultivated meat product – cultivated chicken (Ives 2020). In the United States of America, oversight of cultivated meat from terrestrial animals is shared between the Food and Drug Administration (FDA) and the Department of Agriculture (USDA). As of June 2023, two producers have received approval to sell cultivated chicken products in the United States of America, having completed a premarket consultation with FDA, received approval on proposed labelling from USDA, and received a standard grant of inspection from USDA (Aubrey 2023; FDA 2023). The United Kingdom's Food Standard Agency, the Switzerland Federal Food Safety and Veterinary Office and Food Standards Australia New Zealand, the joint food regulator for the two countries, have all established that cultivated meat should be regulated through novel foods frameworks and have received applications for cultivated meat product through this process (United Kingdom, Food Standards Agency 2023; Food Standards Australia New Zealand [FSANZ] 2023; Morrison 2023). Government agencies in other countries have yet to determine how to regulate it. In Japan, authorities are developing a regulatory framework for cultivated meat while working with the private sector on industry standards to create consumer confidence (Derbes 2021). Canada, the European Union and Israel are developing pathways for cultivated meat products within their novel food frameworks (Table 4.2).

Precision fermentation-derived products may be covered within existing regulatory frameworks, given that the technology has a history of safe use in food and pharmaceutical applications (e.g. production of rennet and human insulin), and modern products are commonly ingredients with an established history of safe consumption (e.g. dairy and egg proteins). Nevertheless, precision fermentation-derived ingredients may also require approval as novel foods in some cases.

4.2 Potential policies to support novel alternatives to conventional animal source foods

Many countries have expressed an interest in promoting novel foods. These are predominantly high- and middle-income countries. Governments in countries including (but not limited to) Australia, Canada, China, the Netherlands, Israel, Singapore and the United Kingdom of Great Britain and Northern Ireland have declared support for and devised strategies to develop new food technologies, with stated policy goals ranging from food security to sustainability to economic opportunity (Mok, Tan and Chen 2020; Teng 2020; Canada, Agriculture and Agri-Food Canada 2022; Australian Government 2022; Ettinger 2023a; TU Delft 2022; United Kingdom Research and Innovation 2022). China and the United States of America—the world's two largest economies and significant players in the global livestock industry—have both expressed support for these technologies. China has explicitly included cultivated meat and other 'future food' in the Five-Year Plan of its Ministry of Agriculture and Rural Affairs (People's Republic of China Ministry of Agriculture and Rural Affairs 2021) and expressed plans to further develop these technologies (Liang and Lee 2022). The United States of America included alternative proteins in its national planning through the March 2023 'Bold Goals for U.S. Biotechnology and Biomanufacturing' report, in which USDA and the Department of Energy identify them as priorities to address climate, sustainability and food security issues (United States, The White House 2023).

There are several complementary approaches that governments can use to promote these technologies and their uptake. A range of policy options are discussed below. Some are already being pursued by a number of governments, while others are not yet widespread but could be considered by policymakers as part of a broader toolkit to support more sustainable and just food systems.

4.2.1 Policies targeting producers

Higher production and uptake of novel ASF alternatives depends on food producers perceiving the market as profitable and reliable, and then delivering products that can compete with conventional equivalents in terms of taste and price (Section 3.2). Governments can help producers reach these goals through research funding, commercialization funding and the development of appropriate regulatory frameworks.

Government support for research and development: research can be performed by government research agencies or contracted out to other institutions and should deliver open-access results. Examples of research priorities include breeding or engineering crops for higher protein yields, developing novel methods for texturizing plant-based proteins and developing bioreactors capable of supporting high-density and large-volume cell cultures (see also Section 3.1).

For example, in 2022, France's national research agency called for proposals to investigate novel uses for French-grown crops in plant-based meat and to develop new functionalities for microbes, algae and insects – priorities that would benefit France's economy and food systems (France, Agence Nationale de la Recherche 2022). In the United States of America, the USDA granted US$10 million to Tufts University to develop a centre of excellence in cellular agriculture (Nicholas and Silver 2021). Meanwhile Israel, among other projects, has provided a grant to a private cultivated meat company to develop an open-access screening system for cultivated meat inputs to reduce duplicative research and accelerate the pace of innovation (Shoup 2022).

Research performed to date, including that funded by governments, has resulted in a number of commercially successful products and ingredients, lower production and consumer costs and foundational technological developments. However, further research is needed to maintain progress in the field and to reach taste and price parity with conventional animal products. Governments around the world dedicated at least US$180 million in 2022 to research and development to improve novel ASF alternatives and associated production technology (GFI 2023a). However, to realize the potential for innovation to yield high quality alternative proteins, one recent analysis estimates that governments need to commit US$4.4 billion per year on research and development (for classic and novel plant-based products, fermented products, cultivated meat and insects) (ClimateWorks Foundation and Foreign, Commonwealth and Development Office, UK Government 2021). While private companies often invest in research and development, open-access public sector research enables the state to shape the market by focusing on areas that could benefit multiple actors or serve public interest, for example by identifying uses for domestic resources in alternative ASF products, developing alternatives to high-cost inputs, or devising lower-emission production processes (Holmes *et al.* 2022).

Government support for commercialization: governments can assist producers in establishing production facilities and infrastructure and in marketing newly developed products. Subsidies and tax concessions can reduce costs and incentivize actors across the supply chain, including farmers, equipment makers and distributors as well as manufacturers. For example, Denmark has announced a five-year programme that will pay 580 million kroner (US$81 million) in bonuses to farmers who grow input crops for plant-based products (Denmark, Ministry of Food, Agriculture and Fishers 2021).

Policy instruments like tax rebates, direct financial investments and loan guarantees to enhance producer interest in the space can also promote competition by reducing barriers to entry, for instance by reducing up-front capital costs of production facilities.

The aforementioned ClimateWorks Foundation and Foreign, Commonwealth and Development Office, UK Government (2021) analysis estimates that governments worldwide need to commit US$5.7 billion per year to commercialization in order to realize the potential benefits of alternative proteins.

Developing appropriate regulatory frameworks: legal and regulatory frameworks are critical for allowing companies to bring novel foods such as ASF alternatives to market in a timely fashion. Novel foods approval processes differ by jurisdiction but usually require producers to prove the safety of their products. This can include performing animal testing, convening independent boards of experts or running full-scale production runs before market approval. Given that some of today's ASF alternative products are unique among foods in their formulation and production methods, review processes can take significant time. However, as the sector develops, regulators can consider adapting approval processes to support efficiency, while ensuring that safety standards are maintained. Producers of novel ASF alternatives are encouraging governments to work with industry experts to determine how to evaluate the safety of cultivated meat in ways that support innovation and reduce uncertainty in this area (GFI 2022).

In the longer term, governments could consider developing approval processes tailored to specific types of products (e.g. cultivated meat) outside of their respective novel foods processes. This would allow applicants to better understand the relevant approval processes and regulators to specialize in this category. For example, FSANZ in Australia and New Zealand and Health Canada in Canada already collaborate on genetically modified foods, with one agency performing the safety assessment and the other serving as a peer reviewer, reducing duplicative efforts for both regulators and applicants (FSANZ 2022). Similar opportunities to streamline approval processes for ASF may emerge. Beyond developing more streamlined approval processes, governments can play a critical role in setting up independent mechanisms to analyse and compare environmental and health claims for novel ASF alternatives.

4.2.2 Policies targeting consumers

As well as supporting the supply of ASF alternatives, government policy can stimulate consumer demand.

Labelling: information on food labels can make alternative products more attractive. Currently, most consumers choose their foods based on cost and taste (Danley 2020). However, many novel ASF products have not yet reached price and taste parity with conventional animal products. Until then, consumers will need some other reason, such as sustainability, nutritional value or animal welfare, to choose these products. Moreover, the importance of environmental and ethical considerations to consumers may grow, for instance if price and taste differences between conventional ASFs and novel alternatives shrink. Governments who want to promote more sustainable consumption could look to develop clear labelling standards, in particular to facilitate comparison between similar products, where labels have been shown to be most effective in informing consumer choice (Bauer and Reisch 2019).

Public information campaigns: beyond labelling, consumer acceptance of novel ASF products will depend in part on the information people are exposed to (Post *et al*. 2020). Governments could coordinate public information campaigns (potentially in partnership with industry) to inform consumers. Specifically, they could provide scientifically grounded information on the relative environmental impacts of ASF and various alternatives to guide consumer choices towards more sustainable products. They could also choose to address consumer concerns around the nutritional value of novel ASF alternatives. There is precedent for this type of campaign; for example, in the United States of America, programmes run through the USDA exist for beef, dairy and numerous other commodities, using industry funds to sponsor consumer marketing programmes (USDA 2011). The European Commission provides tens of millions of euros each year to promote agricultural products from the EU, including animal meat products (Boffey 2020). Working with the media can be valuable in this regard: there are indications that media attention can shape public perceptions of food technologies, including cultivated meat (Bryant 2020). Nevertheless, these activities may face competing messaging from parts of the food industry (Sexton *et al.* 2019). Governments should work to ensure that consumers receive accurate, complete and relevant information on new technologies and products to reduce the potential for misleading or incorrect information.

As well as stimulating private demand, governments can use public procurement to support the purchase of novel alternatives in settings such as public schools, hospitals and government offices. This could include advance market commitments to purchase given quantities of products in advance of their commercial availability (GFI 2021; Systemiq 2023).

4.2.3 Policies to support a sustainable and just transition

Like any significant societal transition, a transition from conventional ASF towards novel alternatives presents various uncertainties and risks regarding its scale, speed and impacts. Government decisions and industry actions can help to maximize environmental, social, health and animal welfare benefits and minimize harms from the rise of this new industry.

Environmental measures: there are likely several environmental benefits associated with shifts away from conventional ASF consumption towards novel ASF alternatives, as detailed in Section 3.3. These include potential reductions in the use of resources such as land and water. Whether this potential is fully realized will depend on how the food system and overall economy respond to the structural changes created by the adoption of alternative proteins, and if freed resources are reallocated to other economic activities (Mason-D'Croz *et al.* 2022). To increase the likelihood of realizing environmental gains, governments can strengthen policies to encourage the conservation and sustainable use of land and other resources. Such approaches would be consistent with agreed international targets on climate change and biodiversity.

Furthermore, there remain a range of potential, non-negligible environmental impacts from the alternatives industry itself. These include impacts from inputs (e.g. farming of ingredients such as soy, peas, coconut oil and cocoa butter requiring land, fertilizer, chemicals, water and energy), to waste streams generated by alternative protein production processes (Coca 2023; Holmes *et al.* 2022). The novel alternatives industry has an incentive to be seen as a leader on sustainability and could work to secure a leadership role in sustainable supply chains. However, major alternative protein companies currently lack sustainable sourcing policies (Coca 2023).

In addition to voluntary actions by industry, government measures can play an essential role in supporting more sustainable outcomes. For example, as discussed in Section 3, alternatives to ASF are likely to offer slight to significant GHG emission reductions depending on production methods and supportive public infrastructure. Government policies can help to ensure potential emission reductions are realized by, for instance, transitioning electricity grids to renewable sources and encouraging sustainability-focused innovation in food technology development. Such shifts would also be consistent with those needed to achieve the goals of the Paris Agreement.

Social measures: shifting away from a farmed animal-centred food system to one that features alternative ASF will bring changes to the agricultural workforce. Moreover, (rural) communities may be affected by significant changes in incomes and livelihoods as well as in food cultures and social norms. Consumers may also be affected by food prices changes, depending on how both novel and conventional food markets develop.

The principles of a just transition encourage governments to work with stakeholders to design policies that will help to minimize disruptions and maximize benefits for people affected. While the need for a just transition towards a sustainable energy system and recommendations for ecologically and socially just transitions from the prevalent food-energy-water system (Giampietro *et al.* 2013) have been articulated, the need to act immediately has gained traction more recently (Anderson 2019; Verkuijl *et al*. 2022; Just Rural Transition 2023).

Structural changes associated with novel alternatives may favour urban economies at the expense of rural ones more dependent on agriculture and conventional ASF production. Policies can be targeted to help alleviate some of these disruptions. For example, governments can provide more robust social safety nets that can increase citizens' resilience and adaptive capacity, while helping to ensure economic access to healthy diets (Barrett *et al.* 2022). Farmers and landowners facing economic losses could be supported in return for the provision of public goods such as carbon storage, biodiversity conservation and valued landscapes (Verkuijl *et al*. 2022). Investments and policies can pay special attention to vulnerable population groups, including ethnic minorities and migrant workers, who make up a significant part of the workforce of the meat supply chain in many countries (Eurofound 2019; Fremstad, Rho and Brown 2020). Governments can support research designed to gain a better understanding of how the proliferation of novel alternatives will affect food security in different contexts (Section 3.5) and tailor policies accordingly.

As some of the world's largest corporations enter the alternative ASF space through investment or acquisition, there are concerns about further consolidation of the food system in the hands of a few powerful actors who can strongly influence products and prices, while smaller producers are further marginalized (Treich 2021; Howard 2022; IPES-Food 2022). There are also concerns that centralized production of ASF alternatives may be vulnerable to supply chain disruptions and deliver homogenized products that fail to meet local dietary preferences (Soice and Johnston 2021a).

Governments could proactively explore options to prevent strong consolidation of the market, including actions to restrict takeovers that could endanger innovation and fair competition (de Streel and Larouche 2015). Governments can also support open-access research to reduce barriers to entry related to intellectual property and encourage a broader landscape of companies to engage with this emerging industry (Holmes 2022). They could also support smaller-scale companies and decentralized production to create potentially more responsive and resilient supply chains (Soice and Johnston 2021a). More broadly, governments could re-evaluate competition policy to assess if it is incentivizing behaviour that contributes to social welfare and environmental objectives (Dolmans 2020; Holmes 2020; Malinauskaite 2022).

Health measures: It is important for government regulators to ensure the application of robust and transparent safety standards and approval procedures to ensure that novel ASF alternatives, some of which involve processes and formulations new to the food industry and require exacting standards of hygiene, are safe to eat and deserving of consumer confidence (see Section 4.1).

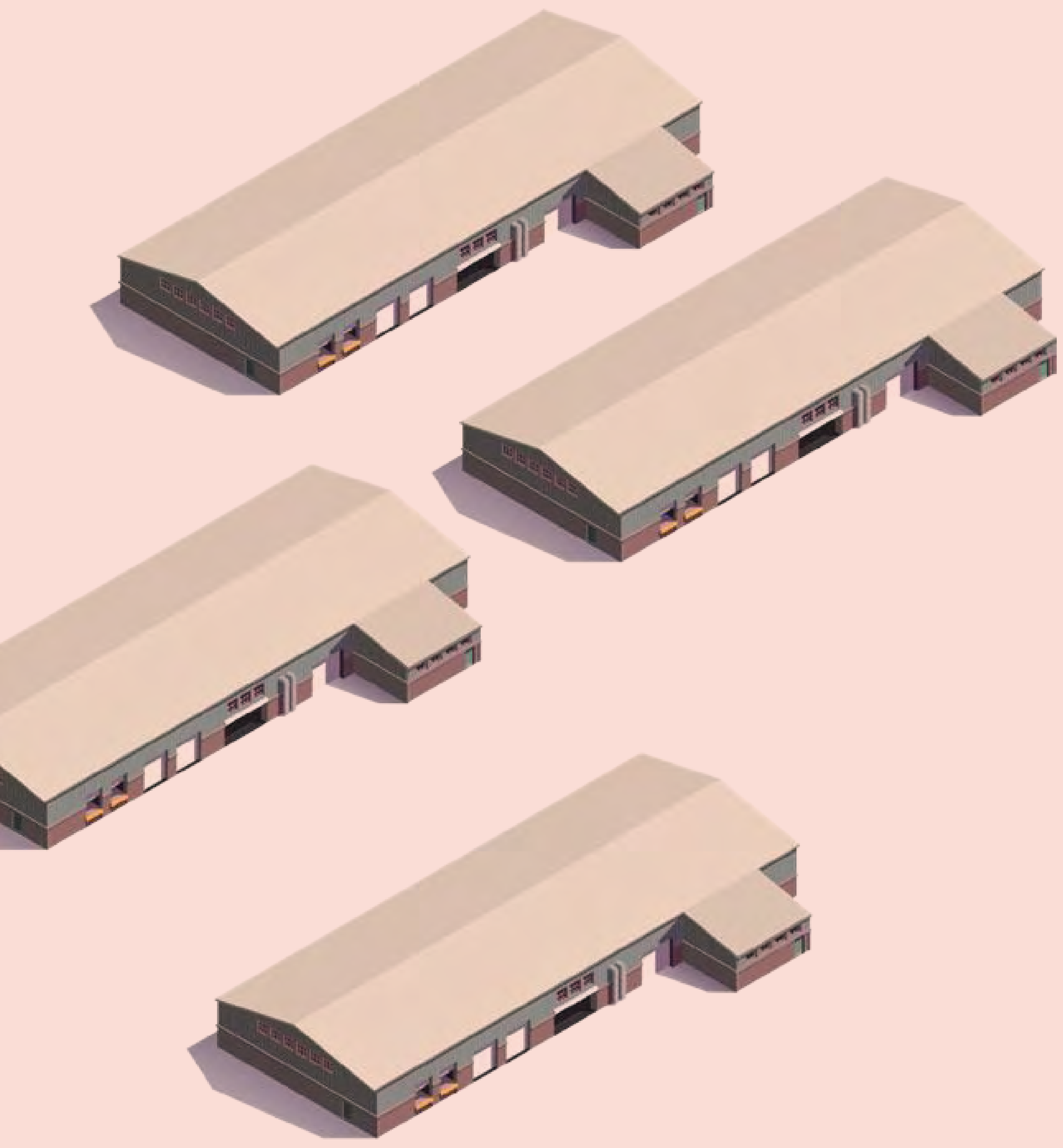
As discussed in Section 3, novel alternatives are likely to have certain health benefits over conventional animal products, particularly in areas such as reduced risk of zoonoses and antimicrobial resistance. At the same time, questions remain about the nutritional value of (certain) novel alternatives (Section 3.4) and the consequences of regularly consuming ultra-processed foods (Pagliai *et al*. 2021). Governments can proactively address these concerns by supporting research designed to enhance the nutritional content and monitoring the health consequences of novel foods. For example, the USDA's aforementioned grant to a university will help support research to improve the nutritional content of cultivated meat, among other goals (Nicholas and Silver 2021). Other support could also include government funding for randomized control trials focused on assessing the nutritional implications of alternatives.

Animal welfare measures: There is increasing recognition that justice considerations in food systems transitions must go beyond humans and extend towards non-human animals (Kaljonen *et al*. 2021). Novel plant-based meat and fermentation-derived products do not rely on the use of animals. However, cultivated meat requires on innovations to eliminate the need for animals, including repeated biopsies and animal-based growth media. Replacing FBS as a growth media is a key priority.

Overall, animal welfare benefits from novel alternatives can only be gained if they replace conventional animal products, rather than being consumed alongside them. Investment in novel alternatives could consider current animal welfare impacts in order to prioritize the replacement of conventional products with the most severe animal welfare impacts (Scherer *et al.* 2018).

4.2.4 Policies to support an enabling environment

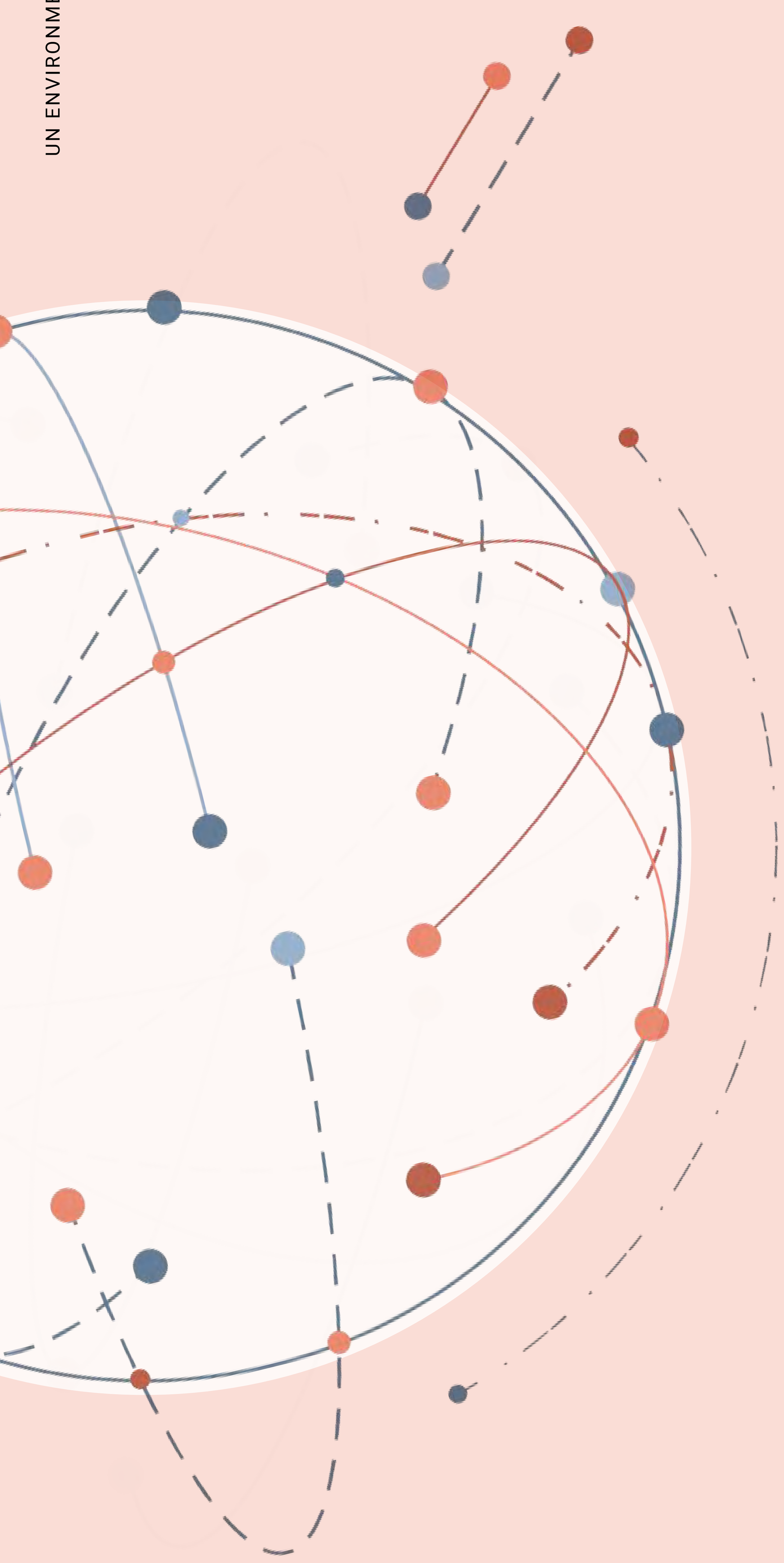
The current food system has been shaped significantly by longstanding policy choices and market dynamics that tend to favour conventional ASF. These include subsidies for conventional farming, a general absence of pricing for environmental externalities, regulatory exemptions and government-backed advertising support, all of which serve to keep the price of meat artificially low and social and environmental externalities high, thereby distorting the competitive landscape (Boffey 2020; Pieper, Michalke and Gaugler 2020; FAO *et al*. 2021; McCormack 2021). There are several measures governments can take to help address or prevent such distortions and give sustainable foods, including alternatives to conventional meat and dairy, a fair opportunity to establish themselves and gain market share:



Addressing existing fiscal support to conventional animal products: governments can review and revise current fiscal policies to ensure that they are contributing to wider social and environmental objectives. This could involve repurposing subsidies and tax breaks to encourage healthier and more environmentally sustainable outcomes (Gautam *et al*. 2022; Springmann and Freund 2022). Given the links between conventional ASF and negative health and environmental outcomes, this could include phasing out or reducing fiscal support for conventional ASF production and consumption. Poultry, pork, mutton and beef are among the foods that benefit most from government support, with the majority of such support going to industrial production (FAO *et al*. 2021). An analysis of major EU and United States of America agricultural policies between 2014-2020 found that public funding for novel technologies is smaller than that for animal products by factors of 1,200 in the EU and 800 in the US. Approximately 1000 times more public funding went to livestock farmers, compared to plant-based and cultivated meat (Vallone and Lambin 2023).

Reflecting externalities in pricing: governments could incentivize more sustainable and healthy food systems by better internalizing environmental and health externalities in the prices of products (Hendriks *et al*. 2023). Such interventions could be levied at different parts of the supply chain, including point of sale (e.g. in supermarkets), point of production (e.g. farms), or point of processing (e.g. meat processing companies). Based on data from 2019, the environmental and human health costs of the United States of America's food system have been estimated at close to double the value of food expenditure at market prices, with conventional ASF significant drivers of these external costs (Rockefeller Foundation 2021). Taxes like those on sugary drinks have proven effective in reducing the consumption of unhealthy sodas in Mexico, the United States of America and the United Kingdom of Great Britain and Northern Ireland (Lancet Editorial Board 2020; Scarborough *et al.* 2020). Modelling studies have also suggested that taxes on red and processed meat could contribute to improved health and environmental outcomes (Springmann *et al.* 2018), particularly if combined with subsidies and price supports for healthier foods (Springmann *et al.* 2017). At the same time, as discussed in Section 2, there are risks that taxes targeting environmental costs (e.g. carbon taxes) may introduce inequalities for consumers (Vergeer *et al.* 2020), or have consequences relevant to animal welfare, if they change relative prices of animal products, encouraging increased consumption of smaller animals such as chickens and fish (Springlea 2022). This underscores the need to consider the impacts of policy interventions holistically across different societal goals.

Avoiding bans and unnecessarily restrictive labelling: emerging alternatives to ASFs face regulatory restrictions in several regions. These include restrictions or bans on the use of terms such as 'meat', 'steak', 'burger', 'sausage' and 'milk' in the labelling and marketing of such products.



Although research is limited, it is conceivable that labelling restrictions will make it more difficult for alternatives to compete with conventional animal products, for instance if this leads to segregated product placement (e.g. in a vegetarian sector in the grocery store) (Piernas *et al*. 2021), or to labelling that is less attractive to consumers. In the case of some regulations, such as production and sales bans, this may be the policy's explicit goal.

4.2.5 Multilateral Cooperation

The development of novel ASF alternatives will likely benefit from international collaboration. Several complementary avenues are available to governments:

Collaboration on research and development: governments can collaborate in the research and development of novel ASF alternatives. For example, the Singapore-Israel Industrial R&D Foundation, a collaboration between the countries' entrepreneurial development agencies, awarded a grant to two companies (one based in each country) to jointly develop 3D-printed cultivated fish (Steakholder Food Ltd 2023). Another example is a 2023 grant funded by research agencies from Sweden and Austria, along with the EU, awarded to two companies (one based in each country) to develop a 3D-printed mycoprotein product (Ettinger 2023b). Attempts to work beyond bilateral efforts with multi-state organizations to coordinate research could further reduce duplicative efforts and accelerate the pace of innovation globally.

International support: If there is demand from recipient countries, collaboration with and support from international financial institutions or bilateral cooperation, in partnership with the private sector, could also be considered to build expertise and/or establish production capacities for novel ASF alternatives in middle- and low-income countries. Such an approach would mirror other forms of international sustainable development support, technology transfer and other forms of cooperation in areas such as energy and climate.

Supportive trade policy: international trade plays a critical role in many agricultural value chains and can make global food systems more resilient to shocks (Baldos and Hertel 2015). Nevertheless, international trade can also facilitate the offshoring of the environmental burden of production (e.g. embedded emissions) and contribute to the globalization of food systems and diets associated with negative health and environmental outcomes (Hawkes 2009). Phytosanitary measures are important protections for human (e.g. food safety) and planetary health (e.g. control of non-native species), but divergent regulatory standards can contribute to delays at borders and sometimes act as protectionist non-tariff barriers (Aginam 2008). International harmonization of these standards would help create larger markets for alternative proteins by making it easier for producers to attain the necessary economies of scale. Policymakers could also consider including novel ASF alternatives in agreements that liberalize trade in environmental goods. Efforts to better align trade policy with environmental objectives could contribute to more sustainable food systems, and in practice would likely favour novel alternatives compared to conventional ASFs.

Development of international food safety standards: Governments can engage with multilateral institutions such as Codex Alimentarius (run jointly by the FAO and WHO), which proposes international standards for food safety and regulation, to support recommendations that ensure timely, efficient and safe approval processes for novel ASF alternatives so that they can compete fairly with conventional equivalents. In April 2023, the FAO and WHO jointly released a report on cultivated meat safety, with the stated goal of equipping authorities (particularly in low- and middle-income countries) with up-to-date scientific knowledge for consideration in potentially important regulatory actions (FAO and WHO 2023).

5. Conclusion

Current rates of ASF production and consumption are a significant contributor to global GHG emissions, land and water use, deforestation, pollution and biodiversity loss. Moreover, the livestock industry is associated with a range of health risks, including the emergence of zoonoses, growing antimicrobial resistance through overuse of antibiotics and increases in several types of NCDs associated with high levels of red and processed meat consumption. ASF production also raises a host of animal welfare issues.

It is important to recognize that the distribution of ASF consumption and production is highly uneven, and the impacts vary depending on a range of factors, including animal product type and rearing methods used, and subsidies to livestock industries and markets. Nevertheless, it is evident that, overall, current global production and consumption risks undermining several critical environmental and health goals. To counter these risks, significant changes are needed in the way the world produces and consumes ASF, and calls are growing for regions with high levels of ASF production and/or consumption to reduce them.

A range of options are available to help mitigate the impacts of ASF on our environment and health, as this report briefly discusses. Examples of these options include regenerative livestock farms, feed additives to reduce emissions, reducing subsidies for the livestock sector, and internalizing externalities into the price of meat. Thus far, such interventions have been limited and are not achieving the desired impacts at the scale and speed necessary. With meat consumption projected to grow by about 50 per cent or more by 2050 as incomes and population levels continue to rise, such a scenario puts the achievement of several Sustainable Development Goals at risk.

In recent years, there has been growing attention to the role that novel ASF alternatives, including novel plant-based, cultivated and biomass and precision fermentation-derived products, may be able to play in supporting a shift away from ASF consumption by closely mimicking or even replicating the sensory experience of ASF. The private sector has invested significant sums in the sector over the past decade. Governments are also investing in research and development related to novel alternatives to ASF, including for reasons of environmental protection, food security and economic competitiveness.

As discussed in this report, novel meat and dairy alternatives may be associated with a range of benefits, compared to their conventional counterparts (see Table 5.1):

- **Environmental –** Compared to their conventional counterparts, novel meat and dairy alternatives may in many cases be associated with reduced GHG emissions; reduced land use; and reduced pollution from animal waste and agricultural chemicals. This may help contribute to several international environmental goals such as those under the Paris Agreement and Kunming-Montreal Global Biodiversty Framework.

- **Human health –** Novel meat and dairy alternatives can generally be expected to reduce risks associated with the emergence of antimicrobial resistance and zoonoses.

- **Animal welfare –** Replacing conventional meat and dairy with novel alternatives would significantly reduce the number of animals being reared and killed for food, often in conditions that raise concerns about their welfare.

It should be noted that different novel ASF alternatives may have different environmental, health and social implications. These benefits could potentially be significant, but there are also challenges and limitations associated with these novel products, depending on the technology.

For example, the production of some novel ASF products, such as cultivated meat, is highly energy intensive. Realizing the full climate potential of novel ASF alternatives is thus contingent on using low-carbon energy, which in turn depends on governments' ability to transition to a low-carbon economy consistent with their commitments under the Paris Agreement.

In addition, there is currently limited evidence on the nutritional health implications of substituting conventional ASF with novel alternatives. Impacts may depend on the degree of processing and the levels of salt and saturated fats in novel products.

There are a number of practical questions that will impact the potential of novel alternatives to ASF to contribute to a more sustainable, healthy and humane food system. Even if these novel products offer clear and significant benefits, to what degree will they replace or complement conventional products, since the benefits only accrue through substitution? Can they be produced on a large enough scale at a price that is competitive with conventional meat and dairy, especially if the cost of conventional products remains artificially low because of government subsidies and the failure to internalize their environmental and health costs? Will consumers across vastly different socioeconomic and cultural realities accept the novel products that reach the market?

Important questions surrounding the social implications of novel alternatives have received limited attention and remain to be clarified. For instance, how would a shift from conventional meat and dairy consumption and production towards novel alternatives affect stakeholders, especially in the Global South, small-scale farmers, Indigenous Peoples, and taking into account gender differences? Improving global food security is a policy priority for many countries, yet the ways that novel alternatives may impact food security in different regions remains understudied. And while the rise of alternatives could both displace jobs and create new ones, it may also support the further consolidation of food production in the hands of big corporations, which may create efficiencies but also come at a cost, such as a lack of diversity of products and of local ownership of food systems. Can societies manage such transitions fairly while maximizing benefits and minimizing downsides?

Policies, regulations, incentives and awareness-raising will be needed to achieve positive and just outcomes, while minimizing risks and disruptions. While some governments are actively promoting novel alternatives, including through research and development, others are moving to protect their livestock industries and/or other animal product producers by restricting or banning some novel alternatives. Given the number of important evidence gaps, transparent decision-making and increased government support for research is needed to improve understanding of the environmental, health and social implications of these novel alternatives, and which policies and investments are most effective for governing these technologies and realizing their potential.

Building a more sustainable, healthy and just food system is a priority for the achievement of many of the Sustainable Development Goals. With the right policies in place, novel ASF alternatives may be able to contribute positively to this critical endeavour.

Table 5.1

Overview of the environmental, health, social and animal welfare implications of novel plant-based, cultivated meat and fermentation-derived alternatives, compared to conventional meat and dairy products

This table presents the relative environmental, health, social, and animal welfare implications of selected novel plant-based, cultivated and fermentation-derived meat and dairy alternatives, compared to conventional industrial meat and dairy products, drawing upon the scientific evidence and analysis presented in this report.

- ● (red) Higher impact
- ● (yellow) Equivalent or very similar impact
- ● (green) Lower impact
- ● (grey) More research needed
- ○ Not addressed in this report

Environment[1]

		Novel plant-based products	Cultivated products	Fermentation-derived products
Land use		Lower impact	Lower impact	Lower impact
Water use[2]		More research needed	Lower impact	Lower impact
Biodiversity and habitat loss[3]		Lower impact	Lower impact	Lower impact
GHG emissions, when fossil fuel energy is used as the energy source for alternatives	Poultry production	More research needed	Equivalent or very similar impact	More research needed
	Pork production	More research needed	Equivalent or very similar impact	More research needed
	Beef production	Lower impact	Lower impact	Lower impact
	Dairy production	Not addressed in this report	Not addressed in this report	Lower impact
GHG emissions, when low-carbon energy is used as the energy source for alternatives	Poultry production	Lower impact	Lower impact	Lower impact
	Pork production	Lower impact	Lower impact	Lower impact
	Beef production	Lower impact	Lower impact	Lower impact
	Dairy production	Not addressed in this report	Not addressed in this report	Lower impact

Health

	Novel plant-based products	Cultivated products	Fermentation-derived products
Risk of emerging zoonoses	Lower impact	Lower impact	Lower impact
Risk of antimicrobial resistance	Lower impact	Lower impact	Lower impact
Nutritional quality and dietary health outcomes	More research needed	More research needed	More research needed

Social

	Novel plant-based products	Cultivated products	Fermentation-derived products
Food security	More research needed	More research needed	More research needed
Job gains/losses[4]	More research needed	More research needed	More research needed
Changes in inequalities, e.g. global South and North, rural-urban, gender	More research needed	More research needed	More research needed

Animal welfare

	Novel plant-based products	Cultivated products	Fermentation-derived products
Number of animals affected by food production	Lower impact	Lower impact[5]	Lower impact

Source: Authors' summary assessment

[1] The environmental assessments considered for this report are primarily based on life cycle assessment data of the typical, or "conventional", meat and dairy production systems of specific regions, including intensive industrialised farming systems, extensive free-range production, organic systems and various combinations of these. Most utilize a combination of data sources, including both industrial and free-range systems typical of Europe and North America, but do not generally assess nondominant systems such as smallholder farming systems.
[2] Novel plant-based chicken and pork products have received only limited attention in terms of their water use, and more research would be beneficial.
[3] Although most analyses focus on land savings potential, land use is the largest driver of biodiversity loss, and as a result biodiversity gains are therefore likely (Balmford *et al*. 2019).
[4] It is likely that jobs will be lost in the livestock industry sector, while will be gained in the novel alternatives sectors. More information can be found in Section 3.5.
[5] If animal-free growth medium is used.

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United Nations Avenue, Gigiri
P.O. Box 30552, 00100 Nairobi, Kenya
Tel. +254 20 762 1234
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