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Microbial foods as a sustainable, healthy and resilient source of nutrients for the UK

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Headlines

Issues

- The UK's demand for protein is estimated to rise by 5% by 2030.¹
- Production of protein currently relies largely on animal agriculture in the UK and abroad.
- A rising dependence on imports (30–40% of most meals) creates vulnerability to external supply challenges and political shocks.
- Production of animal feed and animal products is the largest contributor to detrimental land-use change and agricultural carbon emissions world-wide.
- High consumption of animal products is associated with poor nutritional profile (such a high saturated fat intake, high cholesterol levels) and occurrence of digestive tract cancers. These pose population-level health risks for all ages.

Solutions

- Microbial foods are produced with the aid of microorganisms via processes such as fermentation. Microbial food products such as tempeh have been consumed in various human cultures for millennia.
- Production of microbial foods is much less resource intensive and more sustainable than current animal-based food production and import, with lower greenhouse gas emissions, land requirement, water use and pollution.
- Microbial foods can provide alternative sources of protein and fibre and be engineered to have a healthy nutrient dense profile.²
- The microbial foods industry has immense potential to become a successful sector in the UK. This is an opportunity for improving national food supply, economic growth and job creation.
- Investment in R&D and infrastructure is needed, paired with a collaborative regulatory office connected to entrepreneurs and researchers, to safeguard the UK's reputation as a leader in this sector.

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Objectives of the briefing paper

Imperial is home to experts in the fields of environmental policy, engineering biology, nutrition and customer-product interaction, and the UKRI Mission Hub on Microbial Food and Bezos Centre for Sustainable Protein. We have considered how microbial foods and ingredients can contribute towards replacement of animal food products with a healthier, more sustainable and secure alternative. Within this briefing paper, the term “microbial foods” refers to any food product or ingredient produced via microbial intervention, including precision fermentation, traditional fermentation, and biomass fermentation. We will discuss the role microbial foods could play in the UK food system through:

- evaluating the limitations of current food systems with regards to sustainability, nutritional value and resilience;
- introducing the history and different types of microbial foods;
- exploring the potential benefits of a more widespread adoption of microbial foods;
- examining barriers to general availability, affordability and adoption of microbial foods.

Box 1. Ideal properties of novel food products

Novel food products should be designed to meet a range of objectives to replace animal-based high-protein foods. By novel food, we refer to any food not commonly used for human consumption in the UK or EU prior to 1997. This box summarises the key criteria and ideal properties against which these products can be evaluated.

- **Affordable.** Price influences consumer food choices. Production methods must be economically efficient to ensure low-income households have access. This provides choice for the poorest in society.
- **Appealing to customers.** Consumer acceptance is critical to consumption; these foods must offer appetising taste, texture, aroma, and appearance.

- **Safe.** Novel foods must be free of toxins and safe to consume, with clear labelling of ingredients and allergens, along with fat, saturate, sugar and salt content.
- **Widely available.** Production methods must be scalable to ensure accessibility and presence across the retail spectrum, from local small shops to large supermarkets.
- **Convenient.** Novel food products should be familiar, simple and compatible, i.e. easy to prepare and fit in/incorporate with existing habits, culture and technology.
- **Sustainable.** Production should be designed to align with sustainability goals, maintaining low environmental impact and carbon footprint, minimising land use, water consumption and pollution, as well as being sited to reduce transport requirements.
- **Healthy.** Products should contribute positively to public health outcomes, supporting the overall well-being of the population. They should address current nutritional deficiencies, including fibre, minerals, vitamins and other micronutrients, while still providing a high-quality protein intake with low fat and low cholesterol.
- **Resilient/reliable.** Production systems must be resilient to both the direct impacts of climate change and to potential supply chain disruptions.
- **Compatible with current systems.** Production methods for novel foods should have the ability to integrate seamlessly with existing national food processing and distribution infrastructure.
- **Profitable.** An industry sector built around novel food production must demonstrate potential for economic success to attract investment, create jobs and contribute to national economic growth.

Section 1: The UK food system: challenges in sustainability, nutritional value, and availability

Introduction

Animal products provide high quality protein and essential micronutrients. These macro- and micro-nutrients support growth, development and repair. Their main production route from livestock, however, presents challenges for environmental sustainability, public health, and supply chain resilience. Animal-based foods are protein rich and contain important minerals such as iron and vitamin B12. Nevertheless, they have a negative impact on climate and resource use, and their high cholesterol and saturated fats content increases health risks such as cardiovascular disease and diabetes. The UK's reliance on imported animal feed contributes to deforestation and resultant biodiversity loss and carbon emissions, while also increasing the UK's vulnerability to supply chain disruption.

Addressing these challenges requires innovative solutions to protect the viability of the nation's food system. In June 2024, 13.6% of UK households reported experiencing moderate or severe food insecurity. Changes in consumption patterns, agriculture's vulnerability to climate change, and an increase in UK's population (expected to rise by 6.6 million by mid-2030) will further strain our food system.³

We need to increase our domestic food production, make healthy food available and affordable for all, and begin a transition towards a sustainable food system that does not negatively impact the environment. The UK is well situated to become a leader in the production of alternative proteins if, and only if, this transition is well supported through infrastructure development and clear regulations.

Challenges in environmental sustainability

The agricultural sector generates greenhouse gas (GHG) emissions through livestock, agricultural soils, stationary

and mobile combustion, and off-road machinery.⁴

Globally, an estimated 18-19% of GHG emissions stem from the combination of agriculture and the carbon losses associated with deforestation through land-use change (Figure 1). Agriculture alone contributes 10% of total global GHG emissions.^{5,6} In the UK, the agricultural sector accounts for approximately 11% of national GHG emissions, a total of 48 MtCO₂ equivalent.⁴ Addressing agricultural emissions is likely to play a critical role in the UK's commitment to reducing GHG emissions to at least 80% of 1990 levels by 2035.^{7,8} An estimated 58% of the UK's agricultural emissions are attributed to the supply of animal production pathways. Ruminant livestock, particularly cattle, are especially problematic due to their production of methane (28 MtCO₂ per annum), a potent greenhouse gas with a global warming potential 28 times that of CO₂.⁹ Carbon dioxide from machinery-related combustion contributes 14% of the UK's agricultural emissions. The remaining 28% is attributed to nitrous oxide from soil degradation and the use of synthetic fertilisers.⁴

In addition to GHG emissions, our current food system exerts an ecological burden through soil decline and land use change (Figure 1). While a level of grazing is needed to maintain certain landscapes, industrial agriculture is threatening the UK's soil biodiversity, as evidenced by the dramatic decline in invertebrates in arable habitats.^{10,11} As of June 2024, 67% of the total UK land area, i.e. 8.7 million hectares (ha), is used for agriculture, whereas the total area of woodland is only 14% (3.3 million ha).^{12,13} Including overseas land use, 85% of UK agricultural land footprint is allocated to grazing and crops grown for animal feed, which disproportionally supplies only 32% of our calories and 48% of our protein. For instance, the UK's demand for soy animal feed is associated with an estimated 850,000 ha of land abroad, mostly in Latin America, where it drives deforestation and biodiversity loss.¹⁴

These considerations are exacerbated by the low efficiency of resource-to-food conversions in animal food products. There are opportunity costs in terms of land and energy use in diverting grains and high-protein crops for animal feed rather than for direct human consumption.¹⁴ This inefficiency is especially evident in beef production, where approximately 3% of the calories in animal feed are converted into edible beef calories. Similarly, just

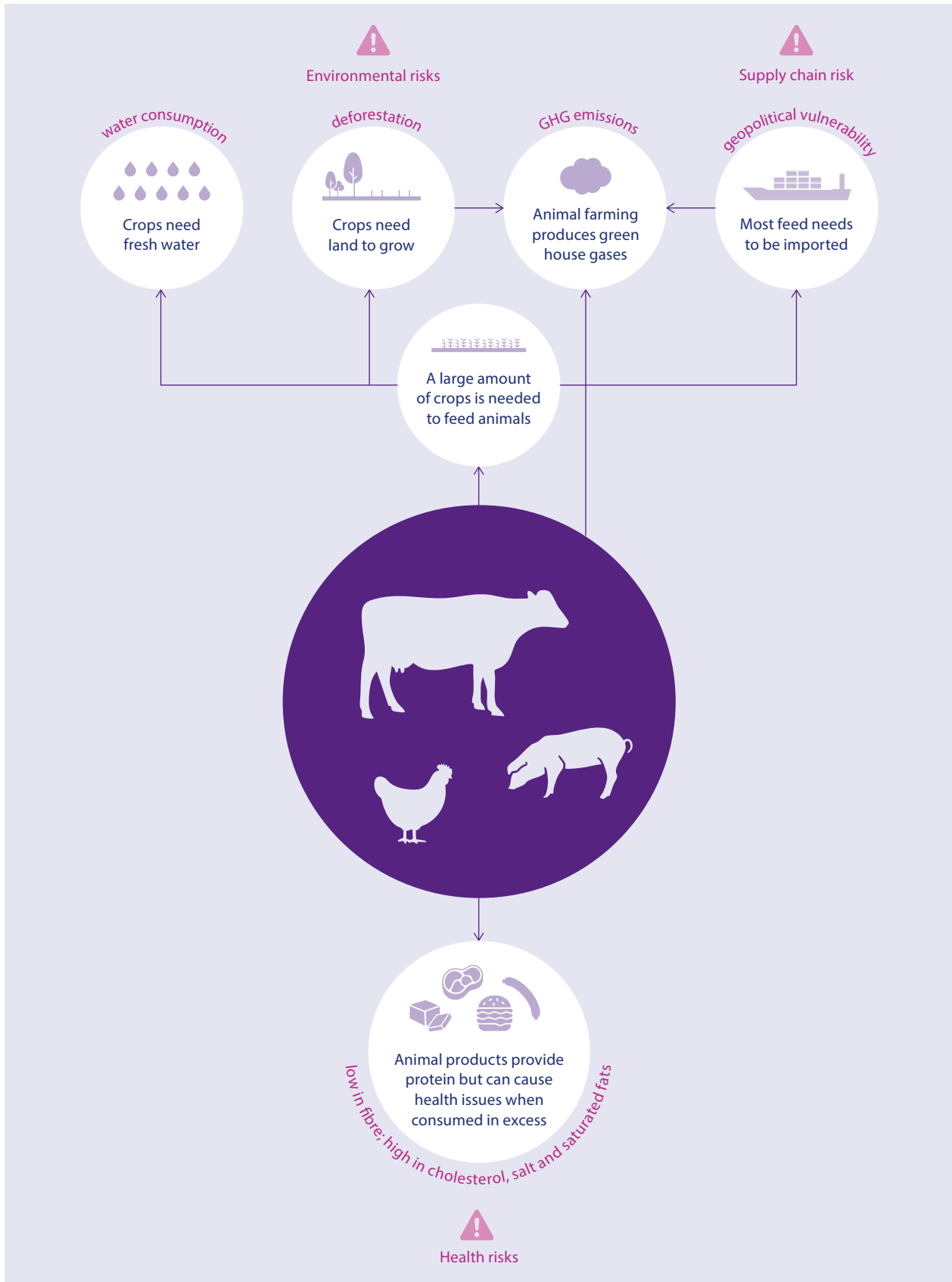


Figure 1. Current food production system centred around animal food products and associated risks.

2.5% of the protein in the feed becomes protein in the final animal product, underlining the substantial resource loss when crops are used to feed animals rather than people.¹⁵ Considering the substantial role agriculture plays in environmental sustainability, the Climate Change Committee (CCC) recommends that the UK reduces meat consumption by 40% by 2050 to lower emissions, implement low-carbon farming measures, and change how land is used to create woodland and restore peatland.^{8,16,17}

Challenges in public health: Nutritional challenges deficits in the UK

The UK faces important challenges from non-communicable diseases that arise from poor nutrition. The National Diet and Nutrition Survey Rolling Programme (NDNS RP) is a continuous survey designed to assess the nutritional health of the British population. This has been running since 2008, informing the government's dietary recommendations. The latest survey, published in 2019, highlighted that fibre intake consistently falls below government recommendations in all age groups, with adults consuming only about 20g per day of the recommended 30g.¹⁸ Saturated fat intake exceeds the recommended maximum of 10% of total energy in all age groups, ranging from 12.3% to 13.3% (Figure 1). This dietary pattern is linked to a wide range of risk factors that contribute to increased risk of non-communicable diseases including heart disease. While red and processed meats contribute importantly to protein, iron and certain mineral vitamin intakes, these lack fibre and are major sources of saturated fat in the diet. Guidance on healthy diets endorsed by the Department of Health and Social Care, indicate that typical UK diets contain too high a proportion of animal products, and recommended reducing red meat consumption by 78%.¹⁹

Obesity remains a pressing concern, particularly among children. The Health Survey for England estimated that 26% of adults in England are obese, a number expected to rise to 40% by 2035.^{20,21} In the UK, 10% of children are obese by age 5, increasing to 23% in children by age 10-11. Obesity is closely linked with a series of chronic diseases, ranging from type 2 diabetes, cardiovascular disease and some cancers, with a higher prevalence in the most deprived areas of the country.²² Obesity and related illnesses cost the National Health Service (NHS) an estimated £6 billion p.a. with a higher prevalence in the most deprived areas of the country.²²

Hidden hunger, which refers to micronutrient deficiencies (iron, zinc, vitamin A and D, calcium) is increasing in the UK, especially in women and young adults. Micronutrients intake has decreased in the last 20 years and hospital admissions in England from nutrition-related diagnoses have increased by more than 39% in the last decade.^{18,23}

Currently food products high in fat, sugar and salt are cheaper per calorie than healthy foods.²⁰ Access to healthy proteins from alternative sources that could address these nutritional challenges is currently limited by affordability and availability. Government figures show that 20% of UK households struggle to access good quality food at a reasonable price, instead turning to unhealthy, high calorie alternatives.²⁴ For instance, in the UK, plant-based alternatives to dairy milk are currently approximately 55% more expensive.²⁵ Similar differences in price and availability between animal-derived proteins and their plant-based substitutes exist for other foods including eggs, meats, and cheese. Despite plant-based products generally being less harmful to the environment, their production is affected by changes in climate and requires extensive land and water use. In addition, unlike animal-based proteins, some plant-based foods may not provide 'complete proteins' (see Box 2).

Box 2. What constitutes a complete protein?

Proteins are a mixture of 20 different types of molecular building blocks called amino acids. The human body can make 11 of these amino acids, however, we need to acquire the remaining nine, termed essential amino acids, from the food we consume. Protein quality refers to the essential amino-acid content of dietary proteins and their digestibility. The protein digestibility-corrected amino acid score (PDCAAS) is the metric used by FAO/WHO to compare various protein sources.^{26,27} A complete protein is a protein source that contains each of the nine essential amino acids. Fish, poultry, eggs, dairy products, beef and pork, and soy products represent sources of complete proteins with high PDCAAS scores. 'Incomplete' protein examples include nuts and seeds, whole grains, vegetables and legumes. Many plant-based protein sources are incomplete as a single item, a challenge overcome by a balanced diet including different plant-based protein sources. It is possible to have a good quality protein intake as a vegan or vegetarian by combining plant-based proteins that contain different amino acids.

Challenges in supply chains

The UK's food supply is dependent on imports, and therefore at risk of border closures, transport disruptions, and geopolitical tensions. Approximately 42% of the food consumed in the UK in 2023 came from abroad, particularly fruits and vegetables.²⁸ The UK imports foods from 160 countries; diversifying geographical sources of food decreases vulnerability to local conditions, such as

changes in national weather patterns.²⁷ However, 80% of imports come from only 22 countries, some of which face increasing agricultural insecurity due to climate change.²⁸

Similarly, the animal feed sector also relies on imports, with about £2.5 billion worth of animal feed imported in 2020, representing roughly 25% of the total feed cost and approximately 45% of actual feed use in the UK (Figure 1).¹⁴

Section 2: Microbial foods as a healthy and sustainable alternative to animal food products

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Microbial foods, foods derived from processes relying on microorganisms such as bacteria, algae, fungi/mycelia and yeast, can broadly be classified into three categories (Figure 2):

- **Traditional fermentation.** Fermented foods are created via food preservation methods where naturally occurring microorganisms transform raw ingredients, enhancing flavours, textures, and shelf life.
- **Biomass fermentations.** Microorganisms themselves are cultivated as a food source, often for their high protein content or other nutritional benefits. Biomass fermentation products are commonly named microbial protein, single-cell protein (SCP) and/or mycoprotein.
- **Precision fermentation.** Microorganisms are used as microbial cell factories to produce specific molecules or ingredients, such as fats, proteins, flavours, or other nutritional compounds, which are then purified for use in food products.^{29,30}

Microbial foods, especially those originating from **traditional fermentation**, have been an integral part of human diets for millennia, predating settled agriculture (Figure 2). Besides its use as a method of food preservation, fermentation also provided new products and flavours to our diet. Many familiar foods consumed daily, such as bread, cheese, and yoghurt, are products of microbial fermentation. It is estimated that up to one third

of global food consumption is composed of fermented foods. In addition to being nutritional staples, evidence is mounting that many fermented foods also provide health benefits including decreased risk of diabetes, cancer and cardiovascular diseases.^{31,32}

More recently, microorganisms themselves have been cultivated to produce edible biomass, commonly referred as single-cell protein (SCP), **mycoprotein** or microbial protein.³³ Mycoprotein is a protein-rich food source derived from fungal biomass fermentation and has been commercially available since the 1980s.³⁴ This development has been led by the UK-based multinational Marlow Foods (Quorn) (Box 4), which sells its mycoprotein-based products as a sustainable, meat-free alternative in various forms, including burgers, sausages, and mince. Several other companies (e.g. Adamo Foods in the UK; Enough, Mycorena in the EU; Meati Foods in the US) have since entered the mycoprotein market, researching new microorganisms to expand product offerings.

Finally, **precision fermentation** has been gaining traction recently for the sustainable manufacturing of bioidentical proteins (e.g. those found in milk or eggs), fats, flavour molecules, and vitamins. This progress is driven by advances in **engineering biology** (Box 3), cultivation techniques, and biochemistry. Precision fermentation was introduced to the food industry in the 1990s to produce chymosin, an enzyme in rennet essential to make cheese,

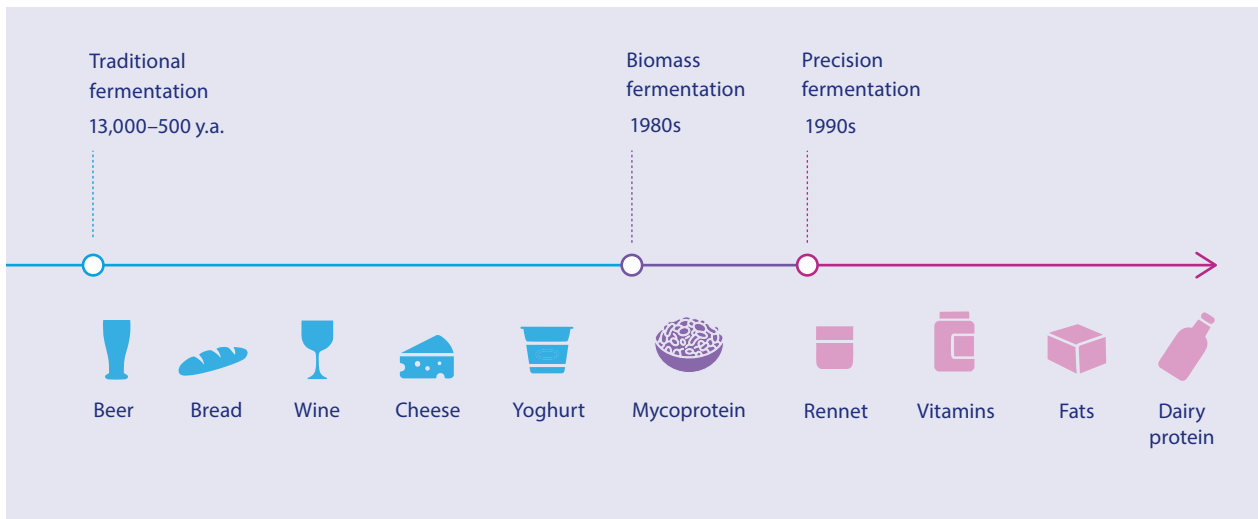


Figure 2. The history and types of microbial foods.

and vitamin B2, a nutritional supplement otherwise produced using chemical synthesis.^{35–37} Pioneering companies in the United States have made significant progress in creating animal-free dairy and meat analogues, and the technology is rapidly gaining momentum in the UK. A growing number of startups³⁰ (e.g. Better Dairy in the UK (Box 4); Perfect Day Dairy, Brave Robot and The Every Company in the US) are exploring precision fermentation to develop sustainable alternatives to traditional animal-derived ingredients, signalling a shift towards more environmentally friendly food production methods.

Box 3. Engineering biology as the key to unlock the potential of microbial food production

Microbial foods present an important opportunity within the UK's vision for engineering biology, a field identified by the UK Government as one of five critical technologies where the UK could be world-leading.³⁸ The UK Government's promise of future investment in engineering biology and the recent funding announcement of the 'Microbial Food Hub' are examples of the UK's interest in microbial food.^{38,39} Engineering biology is defined as the 'design, scaling and commercialisation of biology-derived products and services'. At its core, it enables the precise modification of biological systems for applications in food, pharma etc.⁴⁰ A well-known example of engineering biology is the production of insulin to treat diabetes. Originally produced in animals, 99% of current global demand for insulin is provided by precision fermentation.³⁵ The application of engineering biology to the food industry is focused on improving microbial strains to enhance various aspects of taste, texture, and nutritional value, which may

enhance consumer-level acceptance of novel microbial food products. Additionally, engineering biology may improve the yields and productivity of microbial food production through advances in bioprocess design, infrastructure and substrate processing, increasing the affordability of the resulting products. In traditional fermentation, advancements in engineering biology could lead to enhanced starter cultures. In biomass fermentation, better strains may optimise the flavour profile and overall consumer experience. Innovation in precision fermentation strains will accelerate the production of food ingredients that will enhance the nutritional value and consumer experience of dairy substitutes and plant-based alternatives for animal-derived protein. As the UK seeks to position itself as a leader in engineering biology, these applications in microbial foods represent a tangible and impactful area for innovation and growth.

General production principles of microbial foods

In traditional fermentation, raw ingredients are transformed through the action of microorganisms in an oxygen-deprived environment. Biomass and precision fermentation processes require a specific substrate for microorganisms to grow on and convert into food. This substrate usually consists of sugars derived from crops such as beets or corn. Additionally, research is ongoing to investigate the use of agricultural waste and residues, also called side streams, as substrates for microbial

fermentation to improve agricultural resource efficiency and reduce costs.³⁵

The production process itself consists of combining a mixture of substrate, nutrients, and water with the microorganism of choice in a bioreactor, a large metal cylindrical cultivation vessel.³⁴ In the case of biomass fermentation, once sufficient growth has been achieved, the microbial biomass is heated and purified to reduce the content of nucleic acids, ensuring compliance with food safety requirements.³³ Final processing steps aim to optimise the texture of the food product to mimic meat, this includes the use of binding agents such as egg albumin and agar.³⁴ In the case of precision fermentation, once growth is achieved, the target product is recovered and purified through downstream processing.

Manufacturing of microbial protein can be achieved at any location with access to the substrate and water required to grow biomass and the electricity and skilled labour necessary to operate a bioreactor.

Incorporating microbial foods as a supplement

Current consumer trends see microbial foods, specifically biomass and precision fermentation products, being consumed alongside animal products rather than being used as complete replacements. Companies such as Quorn, have capitalised on this, producing a new line of products which consist of a blend of animal-derived mince and mycoprotein. In other applications, fats and oils produced through precision fermentation are blended with plant-based meat alternatives to enhance their flavour and texture.

Box 4. Industry perspective:

Marlow Food Ingredients/Quorn is an example of a large-scale company and Better Dairy is an example of a small-scale company in the microbial foods sector.

Quorn

Quorn, established in the 1980s and based in the UK, produces mycoprotein from *Fusarium venenatum*, a microbe that generates biomass with neutral taste and meat-like texture.

Quorn launched the first commercial mycoprotein product in the world in the UK in 1985, following government approval and with the support of the supermarket chain Sainsburys. Quorn entered a market where there were no regulations for novel microbial foods and had to undergo extensive safety testing to prove the absence of mycotoxins in their products. It benefited from patient investors such as the entrepreneur Lord Rank, and became profitable in 1998. The company had the freedom to take risks and develop the infrastructure to enable bulk production. At the time of launching their first product, Quorn had one fermenter with a 40,000 litre capacity that was producing 1-2 tonnes of mycoprotein per day. They now have four 150,000 litre fermenters and can produce up to 40 tonnes per day.

Currently, Quorn has 855 employees and sells their products in 11 countries: UK, Australia, Switzerland, Denmark, Finland, Norway, Sweden, New Zealand, USA, Singapore and Ireland. Production takes place entirely in the UK. The mycoprotein production facility, Marlow Ingredients, is based in Billingham (North Yorkshire); the biomass is transported to two factories responsible for the transformation into different food products (sausages, nuggets etc), based in Stokesley (North Yorkshire) and in Methwold (Norfolk).

Quorn reports an increase in the market since 1985 as well as a change in their purchaser demography. Initially, microbial foods were marketed for vegetarians, while nowadays, flexitarians looking to eat less meat are driving the market. An increase in advertising the health benefits of mycoprotein paired with growing environmental concerns influence consumers' choices. The company, however, acknowledges that price is ultimately the big decider of consumer choice. The production of mycoprotein relies on sugar as substrate and utilities to power the bioreactors, both of which dictate the price per kilogram and are currently very volatile. The soaring production costs have translated into higher prices in the supermarket, which have led to a slowdown in sales.

Quorn is currently looking at increasing their export volume, especially to the Asian market. There are also plans to integrate new and diverse products, beyond biomass, into the portfolio.

From Quorn website and communication with Dr Mark Taylor, fermentation lead at Marlow Ingredients.

Better Dairy

Better Dairy, established in early 2020 and based in London, specialises in developing dairy alternatives through precision fermentation. Better Dairy is a startup, currently at the R&D phase with 32 employees, 75% of whom are scientists split into engineering, protein biochemistry, upstream and downstream processing, dairy science, food science and formulations. The company has already raised \$24m and their CEO, Jevan Nagarajah, acknowledges that there is an increasing number of investors interested in precision fermentation and engineering biology.

The product portfolio includes the production of casein (a protein in cow's milk) and non-dairy bioactives to create infant formula. The idea behind producing non-dairy casein is to generate a hormone-free, lactose-free and environmentally friendly cheese. The driver for dairy-free bioactives production is the current lack of animal-free alternatives to generate these products. Better Dairy currently has a 30 litre bioreactor, which they use for testing and developing new products. In order to scale-up for commercialisation, Better Dairy has been forced to partner with companies abroad that can supply the required infrastructure. The UK does not have this infrastructure available, and there are currently no contract manufacturers that can enable scale-up in the UK.

Better Dairy is currently applying for approval for their products as a "novel food" in the UK. The company sees a bright future ahead for microbial foods. They highlight the readiness of the technology and the increase in available talent, ideas and investment going into precision fermentation worldwide.

Better Dairy website and communication with Jevan Nagarajah, CEO of Better Dairy.

could result in a 50% reduction in deforestation and land-use-associated carbon emissions by 2050.⁴² Moreover, other models suggest an 80% reduction in environmental impacts attributable to diet could be achieved if animal-source foods in the European diet were entirely replaced with microbially-produced foods, including mycoprotein and milk from precision fermentation.^{41,43}

The potential agricultural land-use savings through wider adoption of microbial protein are also substantial. One study estimates that the production of a kilogram of mycoprotein uses 95% less land relative to a kilogram of beef, and up to 64% less than poultry.⁴¹ Consequently, incorporating more microbial protein into UK diets is likely to reduce overseas deforestation pressures by lowering the need for animal feed production and imports. The reduction in industrial intensive farming could also promote regenerative farming practices and even liberate land domestically, which could be used to contribute to sustainability targets (e.g. through government-supported tree planting schemes).^{44,45} The relative impact of these models varies due to geographical variations and different levels of animal-product food replacement, from 25% reduction to complete substitution. Nevertheless, all studies show consistent environmental improvements as a consequence of reducing animal-product food intake.

A range of strategies that rely on carbon dioxide as a substrate for microbial protein, instead of crop sugars, has been gaining traction due to the enhanced potential to reduce GHG emissions and land-use. These novel production methods may uncouple the production process from crop cultivation and provide benefits such as minimising soil degradation, and independence from climate-related substrate-supply shocks. Using carbon dioxide as the substrate for microbial food production, however, requires more electricity, therefore maximal GHG reduction potential could only be achieved when green energy is used.⁴⁶⁻⁴⁸ Any changes to production methods will require further safety analysis before the food is approved for human consumption.³³ Finnish company 'Solar foods' already produces microbial protein using CO₂. Their product 'Solein' has received regulatory approval as a novel food in Singapore and the US, with EU approval expected in 2026.

Microbial foods as an environmentally sustainable source of nutrients

Microbial foods have the potential to be produced more sustainably relative to traditional animal-derived protein by cutting GHG emissions and achieving land-use savings (Figure 3).⁴¹ This advantage is very clear with respect to beef, which is a particularly large source of GHG due to associated methane production. Studies estimate that replacing only 20% of beef with microbial foods globally

Health benefits of microbial foods

Microbial foods are high in protein and fibre, low in saturated fats and cholesterol and can be engineered to carry the same micronutrient profile as the animal equivalent, thereby offering health benefits compared to animal-derived products (Table 1).⁴⁹ There is strong

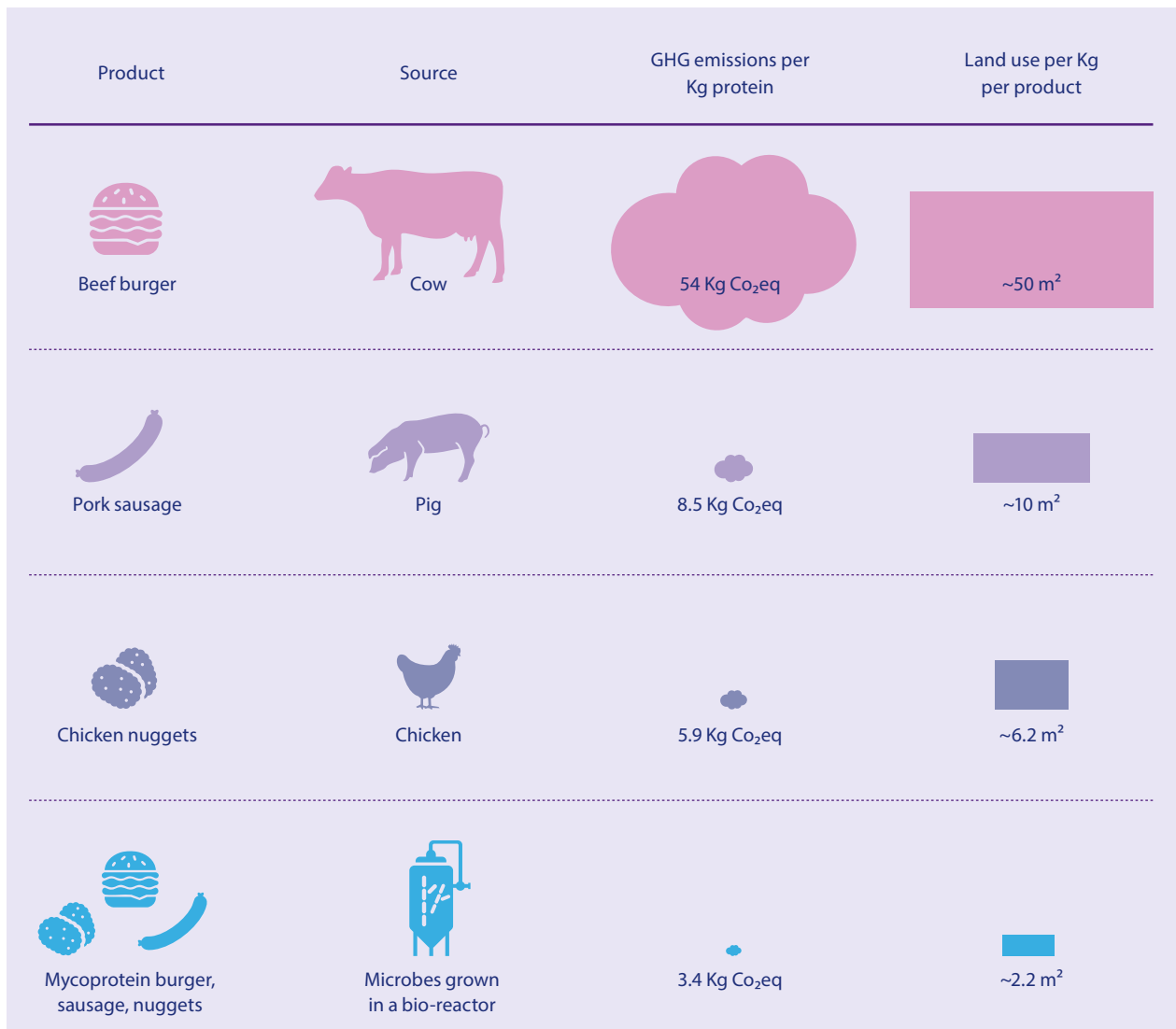


Figure 3. Comparison between animal-derived food products and microbial food products. Data obtained from Mazac et al., 2022 (doi: 10.1038/s43016-022-00489-9).

evidence that diets high in fibre are associated with lower risk of developing type 2 diabetes, bowel cancer and cardiovascular diseases.⁵⁰ Consuming mycoprotein as a meat substitute reduces cholesterol levels within as little as 3-4 weeks⁵¹⁻⁵³ and has been linked to decreased waist circumference and lower blood pressure, indicating improved cardiovascular health relative to diets including red meats.⁵⁴ Diets rich in mycoprotein also affect appetite regulation by increasing the sensation of satiation.⁵⁵ However, we lack long-term studies exploring the effect of mycoprotein as complete substitutes to meat, especially regarding the metabolites and nutrients generated during digestion of these novel foods.

The nutritional profile of microbial biomass can be specifically varied, but broadly includes essential vitamins such as B vitamins (biotin, folic acid), vitamin C, vitamin E, and carotenoids,⁵⁶ as well as minerals such as iron and zinc.⁵⁷ Microbial protein also contains all essential amino

acids and has a high protein digestibility-corrected amino acid (PDAAS) score (0.99, c.f. 0.92 for beef), rendering it a more nutritionally complete alternative than individual plant-based proteins (Box 2).⁵⁷⁻⁶⁰ The protein quality of microbial sources is similar to that of eggs and milk,⁵⁶ confirming its potential as a suitable substitute (Box 2). Furthermore, microbial foods and ingredients can be genetically designed to optimise particular properties for human nutrition (e.g. increasing the content of iron and other micronutrients).⁶¹⁻⁶³

Table 1. Nutritional value comparison between beef mince and mycoprotein.

Nutrient	Beef mince raw (100g) ⁶⁴	Mycoprotein QUORN (100g) ^{34,65*}	UK Government recommendation (19-64 years) per day, male (M), female (F) ⁶⁶
Protein (g)	19.7	11	55.5 (M) 45 (F)
Fibre (g)	0	6	30 (M) 30 (F)
Fat (g)	16.2	2.9	Less than 97 (M) 78 (F)
Of which Saturated fat (g)	6.94	0.7	Less than 31 (M) 24 (F)
Vitamin B9/ Folate (mcg)	14	16	200 (M) 200 (F)
Cholesterol (mg)	60	0	Less than 300 (M) 300 (F)
Carbohydrate (g)	0	3	At least 333 (M) 267 (F)
Energy (kcal)	225	85	2500 (M) 2000 (F)

*Different QUORN products have specific nutritional values.

Domestic and resilient supply chain potential

Microbial foods present an opportunity to increase the UK’s domestic food supply, in addition to significant advantages in land-use savings, GHG emissions and resilience to climate change. By producing substrate sugars locally and utilising them for microbial fermentation, the UK can reduce its vulnerability to international supply chain disruption (e.g. due to extreme weather events, climate change, or geopolitical tension). This approach aligns well with the country’s established sugar beet production, which could provide the primary substrate for various microorganisms.⁶⁷

Microbial fermentation can use agricultural by-products and waste streams as substrates, promoting circular economy principles by creating value from potentially discarded materials. This closed system production model means inputs can be made available at the same site where production takes place, increasing supply chain resilience. The controlled environment of a bioreactor also reduces dependence on weather conditions, allowing year-round food production and reducing vulnerability to climate shocks such as droughts or floods that impact traditional crops.⁵⁷ The use of carbon dioxide as a substrate provides an even more climate-resilient option by decoupling food production from land.

Section 3: Acceptance of microbial foods

While many traditionally fermented foods are staples in the UK diet, novel food products derived from biomass fermentation and precision fermentation are relatively new. These currently contribute to only a small fraction of the human diet, and have little presence in supermarkets. The sustainability, health, and supply-chain resilience benefits associated with wider adoption of microbial foods can only be achieved through engagement of stakeholders such as producers, consumers, and policymakers.

Producer engagement and support

There are two types of producers involved in the microbial food industry: the substrate producers/crop farmers, and the microbial foods producers. Key considerations for **microbial foods producers** include the economic viability and scalability of microbial food production. This includes the initial capital investment required for facilities

and equipment as well as the potential for cost-effective scaling to meet market demand. These producers must also consider how microbial food production can be integrated with existing food production infrastructure to maximise efficiency and minimise disruption. Major food companies are exploring precision fermentation and entering the market by adding startups into their portfolio. Unilever, owner of ice cream brands such as Magnum and Breyers, has partnered with Perfect Day to launch lactose-free products using whey protein from fermentation.

The National Farmers Union (NFU) has set the goal of achieving net zero in England and Wales by 2040.⁶⁸ Wider adoption of current and novel microbial foods will help with this goal while presenting both challenges and opportunities for **farmers**. For crop farmers and those involved in plant-based agriculture, the shift away from animal feed production may pose less of a threat, as microbial foods will require plant-based inputs.⁶⁹ However, there are risks associated with changing crops, initial yield uncertainties and using new machinery.

For livestock farmers, a transition away from intensive livestock systems in a way that is equitable, profitable, and delivers public benefit, is crucial. Climate change already affects farming yields and alternative foods have the potential to offer a sustainable, financially viable and resilient future for farmers.⁶⁹ An increased demand for substrate crops for microbial fermentation and plant-based products may present one avenue for farmers in this transition. The critical need for workforce to support the shift to microbial food production may present another option, albeit bringing challenges related to know-how, upskilling and knowledge exchange.⁶⁹ A series of interviews with farmers from ProVeg International suggests there is unity around the environmental and economic benefits and highlights that transition solutions should be farm-appropriate and farmer-led.^{69,70}

An essential aspect of engagement with all producers is having confidence in the business case and securing markets for products. Microbial food producers must work closely with retailers to secure shelf space in supermarkets and develop effective marketing strategies to promote these novel products. Arranging tastings, providing recipes, and supporting the introduction of microbial foods into restaurant menus could present effective strategies to increase the market share of microbial food products.

Consumer acceptance

Consumer acceptance is a critical factor in the successful integration of microbial foods into the UK food system. Research into consumer habits shows that price, availability and food safety are the top factors during

food shopping (Box 5).⁷¹ Marketing is also a driver of food choice; effective communication strategies will be essential to positively influence consumers about the production processes, safety measures, and health benefits of microbial foods.

The sensory attributes of microbial foods, including taste, texture, and overall appeal play a crucial role in consumer acceptance. In the UK, the most popular beef product is mince, making up around 50% of beef consumption, so achieving steak-like texture is not always necessary.⁷² Producers and researchers must focus on developing products that meet or exceed consumer expectations in these areas by aiming to mimic well known and widely consumed products.

Box 5. Ultra processed food (UPF)

The NOVA food classification system, which categorizes foods based on level of processing, has placed many novel food products, including those derived from microbial and precision fermentation, in the “ultra-processed foods” (UPF) category. The UPF category is broad and does not differentiate between various subcategories of foods, varying from snacks and drinks to fermented and dairy products, which may lead to some potentially unwarranted concern with regards to microbial foods. Different types of UPFs have significantly different effects on health.^{75,76} Consistently identified as being the most detrimental group are ultra-processed meats, which notably represent a category where microbial and fermentation-derived alternatives could offer healthier substitutes. Given these findings and the broad nature of the UPF category, it may be misleading to group novel microbial foods with potentially harmful ultra-processed products. UK consumers would welcome more clarity and transparency on UPFs and there is an urgent need for a more informative, trusted and nuanced classification system. Targeted research to accurately assess the health impacts of these emerging foods would also be beneficial.⁷⁷

<https://committees.parliament.uk/writtenevidence/129437/pdf>

Price competitiveness with traditional food products will be a key determinant for incorporation of microbial foods into the diet. Environmental and ethical considerations, such as reduced land and water use, lower greenhouse gas emissions, and improved animal welfare, may also contribute to consumer acceptance. A recent study suggests that 73-77% of consumers report environmental impact as an important consideration when making a purchasing decision although only 7% of actual purchase decisions factor this in.⁷³ This mismatch may be due to

price as well as low awareness and lack of labelling to allow comparison of foods on environmental impact.⁷⁴ Hence, as production scales and efficiencies increase, it will be important to achieve price parity or advantage compared to conventional alternatives.

Policymaker implications and engagement

The implications of microbial foods for **policymakers** will be influenced by a range of factors related to national interests and public welfare. A primary consideration is the potential impact on food security and self-sufficiency. Microbial foods offer the possibility of reducing reliance on imports and enhancing domestic food production capacity, which aligns with broader food security objectives. A national food supply will also offer transparency, accountability and better controls to avoid situations such as the “horsemeat scandal” of 2013. Importantly, food origin also plays a crucial role in consumer choice.⁷¹

The economic impact of microbial foods’ disruption on traditional agriculture sectors must be carefully assessed and managed. Policymakers will need to consider potential net job displacements and economic shifts, while also recognising opportunities for job creation and economic growth in the microbial food sector. A report from Green Alliance estimated that, under the right conditions of innovation and regulatory support, the sustainable proteins sector (also including plant-based protein and cultivated meat) could create 25,000 UK jobs by 2035.⁷⁸

Adapting regulatory frameworks to accommodate microbial foods will be a critical task for policymakers. This includes establishing clear guidelines for safety assessment, labelling requirements, and quality control measures. The new “Regulatory Innovation Office (RIO)” was announced in October 2024 to support the growth of technology areas such as engineering biology, a sector closely linked to the development of microbial foods. Ensuring public health and safety through robust regulatory oversight will be fundamental in building trust and acceptance of microbial foods.

Imperial, in collaboration with food and life science contract research organisation RSSL, and The Supplant Company, has secured funding from Innovate UK to establish a ‘Novel Foods Expert Network for Regulatory Challenges’. A country first, this network will serve as a platform to accelerate the commercialisation and development of novel food products and technologies by advancing regulatory science in the sector.

Finally, policymakers must consider the international trade implications and export potential of microbial foods. Quorn, a British company, has been the model of mycoprotein production for overseas companies, and currently exports to 11 countries. Developing a supportive policy environment, similar to the one in Singapore, that fosters innovation and growth in this sector could position the UK as a leader in microbial food production and technology, potentially creating new export opportunities and enhancing the country’s competitive position in the global food market. This is an opportunity for the UK to contribute to systemic change in global food production practices, behaviours and supply chains and to lead on mitigating dietary emissions beyond UK borders.

Conclusions and policy recommendations

The UK Government published a 'Food Strategy' in 2022 outlining a series of objectives to deliver "a sustainable, nature positive, affordable food system that provides choice and access to high quality products that support healthier and home-grown diets for all".⁷⁹ The next 'Food Strategy' will be published in 2025 and will focus on four key areas: food security, health, environment, and economy.

The drive to create a long-term shift in our food system requires a transdisciplinary approach involving expertise in environment, public health, microbiology, engineering biology, farming, entrepreneurship, policy and marketing. Every aspect of our food system needs to be considered to achieve change; from substrate, energy and food producers to product transport, retail and consumers. We propose a three-theme approach: investing in technology, skills, and product development; establishing regulations to ensure safety and transparency of novel food products; and developing strategies to communicate the benefits of microbial food to consumers. These focal points agree with the highlighted areas in the House of Lords enquiry on seizing the opportunities from engineering biology: strategy, skills, regulation, infrastructure, investment, adoption and governance.⁴⁰

Theme 1. Product development

From 2012 to 2023, UK Research and Innovation (UKRI) invested £6.4m in fermentation-based food.⁷⁸ This number has increased substantially; in 2024, Imperial was awarded £14m to lead the Microbial Food Hub, one of the first centres in the world fully dedicated to microbial foods, and £15m funding to co-lead the Innovation Knowledge Centre in Alternative Proteins (NAPIC), directed by the University of Leeds. Also in 2024, Imperial was awarded \$30m from the Bezos Earth Fund to support the Bezos Centre for Sustainable Protein. In total, three Bezos Centres were created worldwide: one in the UK (with European reach), one in Singapore (with Asian reach) and one in USA (with American reach). In total, the UK Government has invested £75m in developing new sustainable foods since 2021, becoming the second largest funder of alternative proteins in Europe, only behind Denmark.⁸⁰ This rise in funding puts UK in an excellent position to seize opportunities in this field, including the development of IP for a new, sustainable and healthy protein economy.

In addition to research in universities, there are also 15 companies in the fermentation sector in the UK.⁷⁸ These are diversified in location, approach and business model. For example, Quorn, based in Yorkshire, leads in biomass production, while startup Better Dairy works on precision fermentation and is based in London (Box 4).

To motivate and lead innovation in the microbial food sector, the UK should:

- Fund medium-to-large infrastructure hubs to support production scale-up. Access to larger bioreactors and fermenters for pilot-scale research would facilitate the transition from 'lab to market' for startups and reassure private investors. A similar initiative, Bio Base Europe, has opened in Ghent, Belgium. Such infrastructure can be distributed geographically to support UK ownership of the supply chain.
- Promote the creation of skills training through university degrees and apprenticeships, leading to higher-wage jobs across this industry. Additionally, facilitate short courses focused on scale-up of processes and bioreactor training.
- Invest in building a circular economy approach to utilise waste from current crops or other processes as substrates for microbial food production, providing opportunities for farmers to contribute to the green transition.
- Support knowledge-sharing, mentoring and peer-to-peer learning among microbial food industry-entrants, such as farmers switching to microbial food substrate production.
- Continue investment in engineering biology for a targeted approach to microbial screening, strain development, safety, taste and texture improvements.
- Develop a database for sharing publicly funded research knowledge. This would include DNA sequences, successfully tested substrates, and a list of microorganisms with appropriate qualities for food production.
- Communicate to investors that the UK will have a stable long-term policy environment that is supportive of microbial foods.

Theme 2. Regulatory context

Current UK regulations are seen as a barrier to home market access. International markets with clear regulations such as the USA, Singapore or Israel are currently more appealing to companies, endangering the potential of the UK as a leading producer in this sector.⁸¹ The British Government announced the introduction of new legislation for Precision Breeding at the end of September 2024. Currently, however, the focus is on plants and animals with no mention of microbial foods.³⁹ This is a lost opportunity as genetic engineering of microorganisms is a more rapid process than in plants or animals, research cycles are shorter, and microbes can create products faster. This represents a block to innovation in microbial foods and is driving companies away from the UK and EU. The Food Standards Agency (FSA) currently includes novel microbial foods in the broad category of “novel foods”, a largely unspecified label applied to any food not commonly used for human consumption in the UK or EU prior to 1997. It currently takes an average of 2.5 years to get approval for new food and animal feed.^{80,82}

We propose that action is taken to:

- Create and foster a well-resourced and staffed agency to prepare regulations through co-creation with experts in the engineering biology, microbiology, food safety and healthcare sectors. The recently announced “Regulatory Innovation Office” and the FSA sandbox on cell cultivated products are considered steps in the right direction.⁸⁰ An additional sandbox focused on microbial foods would also be appropriate.
- Support startups by opening a dialogue early on during the regulation process, allowing questions and promoting engagement between regulators and entrepreneurs.
- Modernise regulations to adapt to the diversity of novel food alternatives, with a focus on safe outputs (e.g. milk proteins, burgers) rather than production methods.
- Include microbes in the new ‘Precision Breeding’ legislation.
- Align regulations and trade agreements to promote exports of microbial foods produced in the UK, starting with international agreements on key definitions.
- Simplify the nomenclature and labelling of alternative foods to avoid siloing of products in website searches or association of microbial foods and ingredients with unhealthy UPFs (Box 5).⁸³

Theme 3. Demand

The Alternative Proteins Association (APA) was created in 2022 to promote the value of alternative proteins in the UK. Both the UK Government and APA have published reports demonstrating the environmental and health costs of our current food system. These findings should be communicated to the public as part of the effort to change the way we consume food, and to promote a change in consumer preferences. Information given to consumers must include actionable material to enable them to compare products and make informed purchasing choices, such as clear and trusted graphical front-of-pack product labelling.

British consumers already buy more alternative protein products than most Europeans.⁸¹ In the short-term, microbial foods can help reduce meat consumption by the population, rather than entirely substituting it, to the benefit of public health and the environment.

- Increase taxes on unhealthy foods coupled with investment to make healthy foods more affordable (a potential initiative supported by 72% of the UK public).⁸⁴ Measures to make unhealthy foods more expensive and healthy foods less expensive are among the most effective interventions for changing consumption patterns.⁸⁵ The recently introduced “Soft Drinks Industry Levy”, commonly known as the “sugar tax”, has demonstrated the positive impact of such initiatives.
- Build trust through transparent communication about how microbial foods are produced. Labels should display the origin, production method, nutritional value and the safety checks performed for each product.
- Promote and market alternative food products in both government-funded awareness campaigns and product advertising to highlight the environmental, health and resilience benefits of a national food supply that minimises carbon emissions, frees up land and provides better nutrients.
- Support a market for microbial foods through public sector catering:⁸⁶ The NHS has recently signed a partnership with Quorn to provide blended mycoprotein-meat products in hospitals.⁸⁷ Schools, hospitals and prisons in the UK serve 830m meals per year⁸⁸ and could help to more quickly reduce costs through economies of scale.
- Promote the sales of microbial foods not only in large supermarkets but also in smaller shops (e.g. convenience stores), where low-income households tend to do their shopping.
- Include microbial foods in official national dietary recommendations.

In summary, our current food system presents three key challenges. Livestock agriculture is a major contributor to GHG emissions and causes other environmental harm, while it is also vulnerable to the consequences of global warming and extreme weather events. Our current diets lead to health inequalities and contribute to increased rates of obesity. The UK's food supply chains are exposed to external political shocks due to our heavy reliance on imports. Microbial foods present an opportunity to reduce the environmental impact of our diets while, in parallel, meeting the nutritional needs of the wider population, and minimising the UK's dependency on imports.

These recommendations are designed to contribute positively to the UK's economic growth, improve food security and help to reduce the current environmental and health crises by capitalising on the nation's track record in microbial foods.

References

1. Mordor Intelligence (2024). United Kingdom Protein market size & share analysis - Growth trends & forecasts up to 2030. <https://www.mordorintelligence.com/industry-reports/united-kingdom-protein-market>.
2. World Economic Forum (2019). Meat: the Future series. Alternative Proteins. https://www3.weforum.org/docs/WEF_White_Paper_Alternative_Proteins.pdf.
3. Office for National Statistics (2024). National population projections 2021-based interim. <https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/bulletins/nationalpopulationprojections/2021basedinterim>.
4. Department for Environment, F.& R.A. (2024). Agri-climate report 2023. <https://www.gov.uk/government/statistics/agri-climate-report-2023/agri-climate-report-2023>.
5. Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., and Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat Food* 2, 198–209. <https://doi.org/10.1038/s43016-021-00225-9>.
6. Rosenzweig, C., Mbow, C., Barioni, L.G., Benton, T.G., Herrero, M., Krishnapillai, M., Liwenga, E.T., Pradhan, P., Rivera-Ferre, M.G., Sapkota, T., et al. (2020). Climate change responses benefit from a global food system approach. *Nat Food* 1, 94–97. <https://doi.org/10.1038/s43016-020-0031-z>.
7. UK Parliament (2008). Climate Change Act 2008 (c.27). <https://www.legislation.gov.uk/ukpga/2008/27/contents>.
8. Climate Change Committee (2020). The Sixth Carbon Budget. The UK's path to Net Zero. <https://www.theccc.org.uk/publication/sixth-carbon-budget/>.
9. Office of the European Union L., P., and Luxembourg, L. (2024). Regulation (EU) 2024/1787 of the European Parliament and of the Council of 13 June 2024 on the reduction of methane emissions in the energy sector and amending Regulation (EU) 2019/942. <http://data.europa.eu/eli/reg/2024/1787/oj>.
10. Environment Agency (2019). The state of the environment: soil. https://assets.publishing.service.gov.uk/media/5cf4cbaf40f0b63affb6aa55/State_of_the_environment_soil_report.pdf.
11. Perry, M. (2018). The hidden cost of UK food: soil degradation. <https://sustainablefoodtrust.org/news-views/the-hidden-cost-of-uk-food-soil-degradation/>.
12. Department for Environment, F.& R.A. (2024). Agricultural Land Use in United Kingdom at 1 June 2024. <https://www.gov.uk/government/statistics/agricultural-land-use-in-england/agricultural-land-use-in-england-at-1-june-2024#section-1---detailed-results>.
13. Forest Research, and Braby, D. (2024). Forestry Statistics 2024 Chapter 1: Woodland Area & Planting. https://cdn.forestresearch.gov.uk/2024/10/Ch1_Woodland-WA-amendment.pdf.
14. WWF (2022). The Future of Feed: How low opportunity cost livestock feed could support a more regenerative UK food system. https://www.wwf.org.uk/sites/default/files/2022-06/future_of_feed_full_report.pdf.
15. Shepon, A., Eshel, G., Noor, E., and Milo, R. (2016). Energy and protein feed-to-food conversion efficiencies in the US and potential food security gains from dietary changes. *Environmental Research Letters* 11. <https://doi.org/10.1088/1748-9326/11/10/105002>.
16. Climate Change Committee (2025). The Seventh Carbon Budget Advice for the UK Government. www.theccc.org.uk/publications.
17. Climate Change Committee (2022). Government's Food Strategy, "a missed opportunity" for the climate. <https://www.theccc.org.uk/2022/06/13/governments-food-strategy-a-missed-opportunity-for-the-climate/>.
18. Public Health England (2020). National Diet and Nutrition Survey: Years 9 to 11 of the Rolling Programme (2016/2017 to 2018/2019). <https://www.gov.uk/government/statistics/ndns-results-from-years-9-to-11-2016-to-2017-and-2018-to-2019>.
19. Scarborough, P., Kaur, A., Cobiack, L., Owens, P., Parlesak, A., Sweeney, K., and Rayner, M. (2016). Eatwell Guide: modelling the dietary and cost implications of incorporating new sugar and fibre guidelines. <https://doi.org/10.1136/bmjopen-2016>.
20. Dimpleby, H. (2021). National Food Strategy. <https://www.nationalfoodstrategy.org/>.
21. Baker, C. (2023). Obesity Statistics. <https://commonslibrary.parliament.uk/research-briefings/sn03336/>.

22. Metcalfe, S., and Sasse, T. (2023). Tackling obesity - Improving policy making on food and health. <https://www.instituteforgovernment.org.uk/sites/default/files/2023-04/tackling-obesity.pdf>.
23. Devlin, H. (2023). Surge in number of people in hospital with nutrient deficiencies, NHS figures show. *The Guardian*. <https://www.theguardian.com/uk-news/2023/dec/21/surge-in-number-of-people-in-hospital-with-nutrient-deficiencies-nhs-figures-show>.
24. Department for Environment, Food & Rural Affairs (2021). United Kingdom Food Security Report 2021: Theme 2: UK Food Supply Sources. <https://www.gov.uk/government/statistics/united-kingdom-food-security-report-2021/united-kingdom-food-security-report-2021-theme-2-uk-food-supply-sources>.
25. The Food Foundation (2025). The Broken Plate 2025. <https://foodfoundation.org.uk/>.
26. Schaafsma, G. (2000). Criteria and Significance of Dietary Protein Sources in Humans. The Protein Digestibility-Corrected Amino Acid Score 1. *J. Nutr* 130, 1865–1867.
27. Verkuijl, C., Raina, R., Nadar, S., Watson, R., Achakulwisut, P., Carter, M., Deshpande, V., Enahoro, D., Fertig, S., Gerhardt, C., et al. (2023). An assessment of the potential impacts of selected novel alternatives to conventional animal products. What's cooking? <https://doi.org/10.59117/20.500.11822/44236>.
28. Department for Environment, F. & R.A. (2024). Food statistics in your pocket. <https://www.gov.uk/government/statistics/food-statistics-pocketbook/food-statistics-in-your-pocket>.
29. Verkuijl, C., Raina, R., Nadar, S., Watson, R., Achakulwisut, P., Carter, M., Deshpande, V., Enahoro, D., Fertig, S., Gerhardt, C., et al. (2023). An assessment of the potential impacts of selected novel alternatives to conventional animal products. What's cooking? <https://doi.org/10.59117/20.500.11822/44236>.
30. Good Food Institute (2023). State of the Industry report. Fermentation. <https://gfi.org/resource/fermentation-state-of-the-industry-report/>.
31. Wastyk, H.C., Fragiadakis, G.K., Perelman, D., Dahan, D., Merrill, B.D., Yu, F.B., Topf, M., Gonzalez, C.G., Van Treuren, W., Han, S., et al. (2021). Gut-microbiota-targeted diets modulate human immune status. *Cell* 184, 4137–4153.e14. <https://doi.org/10.1016/j.cell.2021.06.019>.
32. Leeuwendaal, N.K., Stanton, C., O'toole, P.W., and Beresford, T.P. (2022). Fermented Foods, Health and the Gut Microbiome. *Nutrients* 14, 1–26. <https://doi.org/10.3390/nu14071527>.
33. Nevalainen, H. (2020). *Grand Challenges in Fungal Biotechnology* Springer, ed. (Springer).
34. Derbyshire, E., and Ayoob, K.T. (2019). Mycoprotein: Nutritional and Health Properties. *Nutr Today* 54, 7–15. <https://doi.org/10.1097/NT.0000000000000316>.
35. Weplanet (2024). Reboot food: The policy and evidence base for the Reboot Food Manifesto. <https://www.rebootfood.org/>.
36. Ledesma-Amaro, R., Serrano-Amatriain, C., Jiménez, A., and Revuelta, J.L. (2015). Metabolic engineering of riboflavin production in *Ashbya gossypii* through pathway optimization. *Microb Cell Fact* 14. <https://doi.org/10.1186/s12934-015-0354-x>.
37. Averianova, L.A., Balabanova, L.A., Son, O.M., Podvolotskaya, A.B., and Tekutyeva, L.A. (2020). Production of Vitamin B2 (Riboflavin) by Microorganisms: An Overview. Preprint at *Frontiers Media S.A.*, <https://doi.org/10.3389/fbioe.2020.570828>.
38. Department for Science, I. & T. (2023). National Vision For Engineering Biology. DSIT. <https://www.gov.uk/government/publications/national-vision-for-engineering-biology/national-vision-for-engineering-biology>.
39. UK Government (2024). New legislation to support precision breeding and boost Britain's food security. 2024. <https://www.gov.uk/government/news/new-legislation-to-support-precision-breeding-and-boost-britains-food-security>.
40. Lord, B., Lord, R., Of, L., Lord, B., Viscount, S., Lord, D., Lord, S., Lord, L., Lord, W., Baroness, N., et al. (2025). Don't fail to scale: seizing the opportunity of engineering biology. <https://publications.parliament.uk/pa/ld5901/ldselect/ldsctech/55/55.pdf>.
41. Mazac, R., Meinilä, J., Korkalo, L., Järviö, N., Jalava, M., and Tuomisto, H.L. (2022). Incorporation of novel foods in European diets can reduce global warming potential, water use and land use by over 80%. *Nat Food* 3, 286–293. <https://doi.org/10.1038/s43016-022-00489-9>.

42. Humpenöder, F., Bodirsky, B.L., Weindl, I., Lotze-Campen, H., Linder, T., and Popp, A. (2022). Projected environmental benefits of replacing beef with microbial protein. *Nature* 605, 90–96. <https://doi.org/10.1038/s41586-022-04629-w>.
43. Westhoek, H., Lesschen, J.P., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., Leip, A., van Grinsven, H., Sutton, M.A., and Oenema, O. (2014). Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. *Global Environmental Change* 26, 196–205. <https://doi.org/10.1016/j.gloenvcha.2014.02.004>.
44. Faustine Wheeler, A., Collas, L., Barker, P., Goss, S., Coates, T., Raw, S., Oakley, N., Owen Thanks also to Blanche Shackleton, M., Pegg, L., and Dunn, M. (2025). Farming at the crossroads: how farmers are navigating the agricultural transition. <https://green-alliance.org.uk/publication/farming-at-a-crossroads-how-farmers-are-navigating-the-agricultural-transition/>.
45. Department for Environment, Food & Rural Affairs, and Goldsmith, & R.A. and E.A. and L. (2020). £3.9 million to drive innovative tree planting. Department for Environment, Food & Rural Affairs. <https://www.gov.uk/government/news/39-million-to-drive-innovative-tree-planting>.
46. Järviö, N., Maljanen, N.L., Kobayashi, Y., Ryyänänen, T., and Tuomisto, H.L. (2021). An attributional life cycle assessment of microbial protein production: A case study on using hydrogen-oxidizing bacteria. *Science of the Total Environment* 776, 145764. <https://doi.org/10.1016/j.scitotenv.2021.145764>.
47. Jahn, L.J., Rekdal, V.M., and Sommer, M.O.A. (2023). Microbial foods for improving human and planetary health. *Cell* 186, 469–478. <https://doi.org/10.1016/j.cell.2022.12.002>.
48. Linder, T. (2024). What next for mycoprotein? *Curr Opin Food Sci* 58, 101199. <https://doi.org/10.1016/j.cofs.2024.101199>.
49. Finnigan, T.J.A., Wall, B.T., Wilde, P.J., Stephens, F.B., Taylor, S.L., and Freedman, M.R. (2019). Mycoprotein: The Future of Nutritious Nonmeat Protein, a Symposium Review. *Curr Dev Nutr* 3, 1–5. <https://doi.org/10.1093/cdn/nzz021>.
50. McKeown, N.M., Fahey, G.C., Slavin, J., and Van Der Kamp, J.W. (2022). Fibre intake for optimal health: how can healthcare professionals support people to reach dietary recommendations? *The BMJ*. <https://doi.org/10.1136/bmj-2020-054370>.
51. Turnbull, W.H., Leeds, A.R., and Edwards, G.D. (1990). Effect of mycoprotein on blood lipids. *Am J Clin Nutr* 52, 646–650. <https://doi.org/10.1093/ajcn/52.4.646>.
52. Turnbull, W.H., Leeds, A.R., and Edwards, D.G. (1992). Mycoprotein reduces blood lipids in free-living subjects. *Am J Clin Nutr* 55, 415–419. <https://doi.org/10.1093/ajcn/55.2.415>.
53. Pavis, G.F., Iniesta, R.R., Roper, H., Theobald, H.E., Derbyshire, E.J., Finnigan, T.J.A., Stephens, F.B., and Wall, B.T. (2024). A four-week dietary intervention with mycoprotein-containing food products reduces serum cholesterol concentrations in community-dwelling, overweight adults: A randomised controlled trial. *Clinical Nutrition* 43, 649–659. <https://doi.org/10.1016/j.clnu.2024.01.023>.
54. Farsi, D.N., Gallegos, J.L., Finnigan, T.J.A., Cheung, W., Munoz, J.M., and Commene, D.M. (2023). The effects of substituting red and processed meat for mycoprotein on biomarkers of cardiovascular risk in healthy volunteers: an analysis of secondary endpoints from Mycomeat. *Eur J Nutr* 62, 3349–3359. <https://doi.org/10.1007/s00394-023-03238-1>.
55. Bottin, J.H., Swann, J.R., Cropp, E., Chambers, E.S., Ford, H.E., Ghatei, M.A., and Frost, G.S. (2016). Mycoprotein reduces energy intake and postprandial insulin release without altering glucagon-like peptide-1 and peptide tyrosine-tyrosine concentrations in healthy overweight and obese adults: A randomised-controlled trial. *British Journal of Nutrition* 116, 360–374. <https://doi.org/10.1017/S0007114516001872>.
56. Linder, T. (2019). Making the case for edible microorganisms as an integral part of a more sustainable and resilient food production system. *Food Secur* 11, 265–278. <https://doi.org/10.1007/s12571-019-00912-3>.
57. Graham, A.E., and Ledesma-Amaro, R. (2023). The microbial food revolution. *Nat Commun* 14, 1–10. <https://doi.org/10.1038/s41467-023-37891-1>.
58. Li, K., Qiao, K., Xiong, J., Guo, H., and Zhang, Y. (2023). Nutritional Values and Bio-Functional Properties of Fungal Proteins: Applications in Foods as a Sustainable Source. *Foods* 12, 1–18. <https://doi.org/10.3390/foods12244388>.
59. Lappi, J., Silventoinen-Veijalainen, P., Vanhatalo, S., Rosa-Sibakov, N., and Sozer, N. (2022). The nutritional quality of animal-alternative processed foods based on plant or microbial proteins and the role of the food matrix. *Trends Food Sci Technol* 129, 144–154. <https://doi.org/10.1016/j.tifs.2022.09.020>.

60. Hertzler, S.R., Lieblein-Boff, J.C., Weiler, M., and Allgeier, C. (2020). Plant proteins: Assessing their nutritional quality and effects on health and physical function. *Nutrients* 12, 1–27. <https://doi.org/10.3390/nu12123704>.
61. Xue, Z., Sharpe, P.L., Hong, S.P., Yadav, N.S., Xie, D., Short, D.R., Damude, H.G., Rupert, R.A., Seip, J.E., Wang, J., et al. (2013). Production of omega-3 eicosapentaenoic acid by metabolic engineering of *Yarrowia lipolytica*. *Nat Biotechnol* 31, 734–740. <https://doi.org/10.1038/nbt.2622>.
62. Wang, Y., Liu, L., Jin, Z., and Zhang, D. (2021). Microbial Cell Factories for Green Production of Vitamins. Preprint at Frontiers Media S.A., <https://doi.org/10.3389/fbioe.2021.661562>.
63. Jahn, L.J., Rekdal, V.M., and Sommer, M.O.A. (2023). Microbial foods for improving human and planetary health. *Cell* 186, 469–478. <https://doi.org/10.1016/j.cell.2022.12.002>.
64. Pinchen, H., Powell, N., Church, S., and Finglas, P. (2021). McCance and Widdowson's The Composition of Foods Integrated Dataset 2021. <https://www.gov.uk/government/publications/composition-of-foods-integrated-dataset-cofid>.
65. Quorn mycoprotein nutritional profile <https://www.quornnutrition.com/importance-of-micronutrients>.
66. Public Health England (2016). Government Dietary Recommendations. <https://www.gov.uk/government/publications/the-eatwell-guide>.
67. Department for Environment, Food & Rural Affairs (2022). Agriculture in the United Kingdom 2022: Crops. UK Government. <https://www.gov.uk/government/statistics/agriculture-in-the-united-kingdom-2022/chapter-7-crops>.
68. National Farmers Union (NFU) (2019). Achieving Net Zero: Farming's 2040 goal. <https://www.nfuonline.com/media/jq1b2nx5/achieving-net-zero-farming-s-2040-goal.pdf>.
69. Proveg International (2022). Amplifying farmers' voices: Farming perspectives on alternative proteins and a just transition. <https://proveg.org/report/amplifying-farmers-voices/>.
70. Crawshaw, C., and Piazza, J. (2023). Livestock Farmers' Attitudes towards Alternative Proteins. Sustainability (Switzerland) 15. <https://doi.org/10.3390/su15129253>.
71. D'angelo, C., Gloinson, E.R., Draper, A., and Guthrie, S. (2020). Food consumption in the UK: Trends, attitudes and drivers. https://www.rand.org/pubs/research_reports/RR4379.html.
72. AHDB (2021). Beef: international comparisons. <https://ahdb.org.uk/beef-international-comparisons#:~:text=The%20impact%20on%20carcase%20value,is%20consumed%20as%20minced%20beef>.
73. Elmor, L., Ramos, G.A., Vieites, Y., Andretti, B., and Andrade, E.B. (2024). Environmental sustainability considerations (or lack thereof) in consumer decision making. *International Journal of Research in Marketing*. <https://doi.org/10.1016/j.ijresmar.2024.08.003>.
74. Potter, C., Pechey, R., Clark, M., Frie, K., Bateman, P.A., Cook, B., Stewart, C., Piernas, C., Lynch, J., Rayner, M., et al. (2024). Effects of environmental impact labels on the sustainability of food purchases: A randomised controlled trial in an experimental online supermarket. *PLoS One* 19. <https://doi.org/10.1371/journal.pone.0309386>.
75. Fang, Z., Rossato, S.L., Hang, D., Khandpur, N., Wang, K., Lo, C.H., Willett, W.C., Giovannucci, E.L., and Song, M. (2024). Association of ultra-processed food consumption with all cause and cause specific mortality: population based cohort study. *BMJ*, 1–10. <https://doi.org/10.1136/bmj-2023-078476>.
76. Cordova, R., Viallon, V., Fontvieille, E., Peruchet-Noray, L., Jansana, A., Wagner, K.H., Kyrø, C., Tjønneland, A., Katzke, V., Bajracharya, R., et al. (2023). Consumption of ultra-processed foods and risk of multimorbidity of cancer and cardiometabolic diseases: a multinational cohort study. *The Lancet Regional Health - Europe* 35, 1–13. <https://doi.org/10.1016/j.lanepe.2023.100771>.
77. UKRI, S.B.S.A. (2024). Public perceptions of ultra-processed foods. <https://sciencewise.org.uk/2024/11/public-perceptions-of-ultra-processed-foods/>.
78. Good Food Institute (2023). Sustainable proteins in the United Kingdom. An ecosystem review. https://gfi-europe.org/wp-content/uploads/2023/08/UK-ecosystem-report_Full_25aug23_final.pdf.
79. Department of Environment Food & Rural Affairs (2022). Government food strategy. <https://www.gov.uk/government/publications/government-food-strategy/government-food-strategy>.

80. Good Food Institute (2025). Policy and regulatory progress on protein diversification since the National Food Strategy. <https://gfieurope.org/blog/analysis-finds-uk-government-has-invested-75-million-in-alternative-protein-innovation-since-2021-national-food-strategy/>.
81. Bryant, C., and Nicholles, B. (2024). Alternative Proteins: The Opportunity and Benefits for the UK Economy. <https://bryantresearch.co.uk/insight-items/institutional-change-protein-transition/>.
82. Food Standards Agency (2024). Regulated Products Reform Update. <https://www.food.gov.uk/board-papers/regulated-products-reform-update#return-to-top>.
83. Alternative Proteins Association (2023). Recommendations on the Labelling of Alternative Proteins. <https://www.alternativeproteinsassociation.com/labelling-report-2023>.
84. Martínez-Jiménez, M., Brinsden, H., and Sassi, F. (2024). Public attitudes towards food taxes for healthy eating in the United Kingdom. MedRxiv <https://doi.org/10.1101/2024.10.15.24315520>.
85. Garnett, T., and Finch, J. (2016). What can be done to shift eating patterns in healthier, more sustainable directions? FCRN. Food Source. Chapter 10. <https://www.tabledebates.org/chapter/what-can-be-done-shift-eating-patterns-healthier-more-sustainable-directions>.
86. Carmichael, R. (2019). Behaviour change, public engagement and Net Zero. A report for the Committee on Climate Change. <http://www.imperial.ac.uk/icept/publications/>; <https://www.theccc.org.uk/publication/behaviour-change-public-engagement-and-net-zero-imperial-college-london/>.
87. Future of Protein Production (2024). Quorn teams up with NHS for “hybrid revolution.” <https://www.proteinproductiontechnology.com/post/quorn-teams-up-with-nhs-for-hybrid-revolution#:~:text=UK%20brand%20Quorn%20is%20shaking%20up%20the%20menus,impact%20of%20hospital%20food%20while%20maintaining%20patient%20satisfaction>.
88. Leith, P., Burman -British, A., Association, D., Alexander, D., Bowen -British, L., Cartz -British, M., and Shelley, P. (2020). NHS hospital food review. Department of Health and Social Care. <https://assets.publishing.service.gov.uk/media/5f930458d3bf7f35e85fe7ff/independent-review-of-nhs-hospital-food-report.pdf>.

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Declaration of interest

Gary Frost has received educational grants from Quorn to support PhD students over the last 12 years. Both Quorn and Better Dairy are project partners on the Microbial Food Hub, the National Alternative Protein Innovation Centre, and the Bezos Centre for Sustainable Protein.

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The Bezos Centre for Sustainable Protein at Imperial is at the forefront of the alternative protein revolution, using advanced Engineering Biology to address global challenges in sustainability, food security, and climate change. The Centre reimagines the global food system to make it more sustainable, healthy, equitable, and resilient while accelerating the transition to alternative proteins. The Bezos Centre at Imperial, with a European reach, works in close collaboration with the Bezos Centres in the USA and Singapore to address international challenges.

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