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**Comparative quantitative review of the sustainability of novel food production methods**

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**Project Lead: Paul Hancock**

**Author: Tim Wilkes**

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# **Introduction**

The 2015 Paris Agreement of the United Nations Framework On Climate Change (UNFCC) [[1](#_ENREF_1)], is a legally binding treaty, agreed to by 175 countries[[1](#_ENREF_1)], which came into force on the 4th of November 2016. The treaty’s goal is to restrict the increase in global temperature to 1.5°C above pre-industrial levels which will only be achievable by a comprehensive reduction in global greenhouse gas (GHG) emissions across the energy; industry; transport; buildings; and agricultural sectors.

Subsequent discussions on UK Net-Zero emission targets [[2](#_ENREF_2)] have primarily been focused on reductions in CO2 emission levels, with the majority of current remedial efforts being directed at reducing fossil fuel combustion emissions. However, other potent GHGs, including methane (CH4) and nitrous oxide (N2O), are yet to attract as much public attention. Methane and nitrous oxide are primarily the biproduct of a variety of food production system (FS) practices, particularly those associated with agricultural activities [[3](#_ENREF_3)], and especially those concerned with the rearing of livestock. Due to the complex relationship between agricultural GHG and FS emissions, this may prove a far more difficult problem to address than in the case of CO2 emissions.

With the global human population projected to reach 9.8 billion by the year 2050 [[4](#_ENREF_4)], and global food production estimated to increase by 15% in the coming decades [[5](#_ENREF_5)]. Current food production practices, generally referred to as food systems (FSs), are credited with contributing up to thirty percent of total global GHG emissions. As an example, for the year 2019, FSs were estimated to have contributed approximately 16.5 Giga tons (Gt) of the global CO2 emissions, with the largest contribution for this arising from agricultural practices, their land use, and land-use change activities (~ 70%), with the remaining agricultural linked contributions originating from associated activities such as transport and retail [[6](#_ENREF_6)].

Significant reductions in GHG emissions from the FS sector may be attainable through improvements in production efficiencies and by the adoption of environment-based carbon sequestration [[3](#_ENREF_3)].

However, based on current FS emission modelling, a global increase in emissions of 80% from 2010 levels is likely to be surpassed by 2050 if no interventions are implemented [[7](#_ENREF_7), [8](#_ENREF_8)]. Although adoption of improved FS efficiencies (e.g., low-emissions interventions for improving production efficiency, promotion of carbon sequestration strategies; reduction in livestock-based protein consumption, and adoption of new low emission technology) may offset existing emission levels, current growth trajectories, particularly for livestock production, strongly indicate that even with more efficient FS, the growing global demand for food may actually increase net GHG emissions beyond currently mitigatable levels [[9](#_ENREF_9)]. Therefore the challenge must be to maintain a balance between productivity, food security, and environmental preservation [[10](#_ENREF_10)]. Next to a reduction in fossil fuel emissions, adoption of alternatives methods for food production, particularly those associated with dietary protein production through rearing of livestock, has become a global focus for reducing FS GHG contributions [[7](#_ENREF_7)].

The World Wildlife Fund (WWF) has described the need to shift global food systems toward plant-based diets to reverse biodiversity loss, encourage people to live within a global carbon budget, reduce greenhouse gas emissions (GHGE), and feed the global growing population on existing available land [[11](#_ENREF_11)]. To date, attention is primarily centred on identifying alternative protein sources (e.g., plant, algal, precision fermented) that require less resource intensive means of production and emit less GHGs.

The UK is currently witnessing an increasing interest in the development and commercialisation of sources of alternative dietary protein [[12](#_ENREF_12)]. A market for these products already exists within the UK, however, recent technological advances combined with the pressing need to pursue more sustainable sources of dietary protein has led to an acceleration in both innovation and product development in the sector, the result of which has been the introduction of both new and alternative protein ingredients and products to the market [[12](#_ENREF_12)]. These products have the potential to dramatically impact on the UK food systems, and consequently a number of reports have been commissioned by UK government to evaluate the implications of these developments and identify those solutions which exhibit potential to become established and aid in securing the UK food supply.

The four leading categories of alternative dietary protein, based on recent publications, are described, and evaluated in this review of the current scientific and grey literature. The main categories considered are: (i) Plant-based meat substitutes; (ii) Novel protein sources, inclusive of insects, microalgae and macroalgae (seaweeds); (iii) Precision fermented biomass, inclusive of fungal and bacteria; (iv) Cultured meat.



## **Plant-based**

## **Plant-based sector**

Conventional plant-based sources of dietary proteins (e.g., beans, legumes, nuts, and seeds) have been employed through a diverse range of food products (i.e., tofu, tempeh, hummus, and seitan), which have been used globally for centuries to aid in providing the protein requirements of the human diet [[13](#_ENREF_13)]. From 2010, when the implications of global warming were formerly recognised on an international basis [[14](#_ENREF_14)], an increasing number of alternative dietary protein (AP) products have been developed and evaluated, which include both plant-based meat and dairy product substitutes. Commercial products for plant-based meat substitutes (e.g., Impossible Burger[[1]](#footnote-1)), may help provide an important means to aid in the reduction of environmental, animal welfare, and the public health, issues associated with production and consumption of conventional meat-based protein products [[13](#_ENREF_13)]. However, from a health perspective, many of these new products tend to be more highly processed than traditional items, as a direct consequence of being developed to meet consumer preferences, and hence needing to replicate the appearance, texture, taste, and flavour of conventional animal derived products [[15](#_ENREF_15)]. The link between ultra/highly-processed food (UPFs) and the concept of unhealthy food within modern day dietary patterns is gaining recognition in the relevant literature [[9](#_ENREF_9), [15](#_ENREF_15), [16](#_ENREF_16)]. Also of concern is the contribution of UPFs to a decline in dietary quality and correlation with diet-related diseases, which is now recognised as an emerging and worryingly significant health issue [[17](#_ENREF_17)].

## **Consumer**

As indicated in the current literature, a major challenge with developing plant-based dietary protein alternatives is recreating the appearance, texture, and flavour of conventional meat products. While vegetarian and vegan consumers readily accept plant-based alternatives, the absence of many of the sensory properties provided with meat products, omnivorous and flexitarian consumers generally prefer that the alternatives resemble meat as much as possible to compensate for this [[18](#_ENREF_18)]. In addition, and from a consumers perspective of plant-based alternative proteins, there is a reported lower acceptance in terms of the “naturalness” and “clean label” compared with some traditional products. There are also negative connotations associated with these new products being associated with “product ultra-processing” which has been flagged as potentially deleterious to health in the media. This aspect of alternative protein products will need to be carefully addressed to improve public acceptance, but this will likely be through news and social media outlets rather than product improvement.

Not unexpectedly, even though many western consumers are aware of the impact meat production has on the earth, those willing to stop, or at least significantly reduce their meat consumption for environmental reasons, or who have already changed their diet for ecological concerns, remain a small minority [[19](#_ENREF_19)]. In addition, and as with many new products, there is a general reluctance of consumers to try new or unfamiliar products, however, ultimately, the key driver to repeat purchasing of a product is that of affordability when compared with already established choices.

## **Plant-based commercial**

Plant-based proteins are reported to be the most frequently employed source of protein used in preparing meat alternatives, with soy, wheat and fungal derived meat protein substitutes the most frequently used ingredients. Of the currently available sources, soy protein, the protein derived from soybeans (*Glycine max*), is the most utilised meat replacement protein, due to both availability and comparative low market price, but also because it contains all of the essential amino acids (EAA), although the presence of only low levels of methionine require supplementation to be considered in order to be adequate for human consumption [[20](#_ENREF_20), [21](#_ENREF_21)]. Soy also benefits from containing no cholesterol, being low in saturated fats, and providing a source of fibre, iron, calcium, zinc, and B vitamins [[21](#_ENREF_21)]. Traditionally, soy has been used to prepare protein rich products such as tofu (pressed coagulated soymilk curds), but more recently has been employed in the preparation of texturised vegetable protein (TVP) (70% w/w protein).

As an alternative to soy protein, wheat gluten, generally referred to as seitan [[22](#_ENREF_22)], has be utilised by some cultures as a traditional meat replacement. Wheat gluten is traditionally obtained by washing wheat flour dough with water until the starch granules have been removed and the insoluble gluten is left behind. The gluten can then be processed as required as its cohesive properties provide a meat-like texture to the products its employed with [[18](#_ENREF_18)]. Wheat gluten is also used in many vegetarian products in various countries and has been adopted in Western nations as a meat protein substitute. It is generally sold in block, strip and shaped forms in some supermarkets, and may eaten from the package as a high-protein snack. Powdered wheat gluten is also produced and sold as an additive for baking or used to make seitan. When used as an additive in baking, it adds elasticity to flours that would otherwise be low in gluten, (e.g., whole wheat flour or rye) and improves the rise of raw dough while adding texture to the final product [[23](#_ENREF_23)].

Varieties of fungi have also been added to plant-based protein products to help mimic meat, as their inherent cohesive properties provide the products with a meat-like texture [[24](#_ENREF_24)]. Legume proteins from pea, lentil, lupine or chickpea have also been used in the formulation of meat alternatives. Amongst these, pea-based protein is considered a promising candidate due to it containing all of the EAA, although levels of methionine are generally sub-optimal [[25](#_ENREF_25)].

Oilseed storage proteins, particularly those isolated from safflower (13% by dry mass) and rapeseed (25% by dry mass) have been employed as structuring agents with meat substitute products, as when heated, they promote a meat-like textures to products to which they are added All oilseed crops contain a combination of albumin, globulin and glutelin proteins [[26](#_ENREF_26)]. Most of these proteins are comprised of 2S, 7S, 11S and 15S fractions, with the ratio of which dependent on species and variety. Some oilseed proteins are deficient in sulphur-containing amino acids when compared to protein from animal sources, which may be overcome by supplementation with other sources [[27](#_ENREF_27)]. However, fiber, phytic acid and phenolics are common to all oilseed plants and may limit food applications [[26](#_ENREF_26)]. In addition, methodologies for efficiently extracting protein from oilseeds or flour derived from them have not yet been developed for general commercial use [[27](#_ENREF_27)].

Although farmers in the UK have succeeded in increasing food production levels during the last decades of the 20th century, yields of wheat, barley, potatoes, and sugar beet have been reported to have tripled, while milk yields have doubled. These achievements have been to the detriment of the environment. For example, the production of 1 kg of livestock derived protein has been estimated to require approximately 100 times more water than producing 1 kg of grain derived protein [[28](#_ENREF_28)] [[29](#_ENREF_29)]. Examining this on a dietary basis, then less than 0.4 ha of cropland is utilised to produce food for a plant-based protein diet, compared to approximately 0.5 ha of cropland for a meat-based protein diet [[28](#_ENREF_28)].

* 1. **Plant-based market**

The UK and European market for alternative dietary sources of protein are projected to grow to £6.8 billion by 2025 [[30](#_ENREF_30)]. Current estimates for meat (£1.3billion) and dairy substitutes (£2.7 billion) contribute to only 0.7% and 3% of the total livestock and dairy market share respectively [[30](#_ENREF_30)].

The UK plant-based dietary protein sector is currently dominated by imported materials, largely soya [[31](#_ENREF_31), [32](#_ENREF_32)]. However, a number of new processing facilities are currently being constructed which will aid with boosting domestic plant-derived protein production, and development of plant-based foods in the UK. These include a new facility being built by Naylor Farms[[2]](#footnote-2) (naylorfarms.com) in Lincolnshire for plant protein extraction from brassicas [[33](#_ENREF_33)], Plant & Bean by Griffith Foods and Gushen[[3]](#footnote-3), are constructing plant protein production plant at Boston, Lincolnshire, and Branston Ltd[[4]](#footnote-4) are in the final stages of finalising a £6 million potato protein extraction facility at their company site in Lincolnshire [[34](#_ENREF_34)].

The number of individuals consuming a plant-based diet is increasing progressively, according to the claims of different vegetarian and vegan societies, as well as a number of consulting companies [[35](#_ENREF_35)]. In the UK, it is now estimated that up to 21% of the population consider themselves flexitarian (vegetarian who eat occasionally food from animals) and 1 in 8 categorising themselves as being vegetarian or vegan [[35](#_ENREF_35)]. In global terms, it has been estimated that 40% of consumers are attempting to reduce their consumption of animal derived protein, while 10% avoid meat completely [[36](#_ENREF_36)]. These figures are supported by the fact that in terms of the current supply of alternative dietary protein the plant-based protein sector is reported to now be the fastest growing retail consumer trend [[37](#_ENREF_37), [38](#_ENREF_38)].

The current UK market for plant-based dietary proteins is estimated to be worth in the region of £1 billion [[32](#_ENREF_32)]. Predicted market growth (year-to-year growth in %) for plant derived livestock replacement dietary protein is in the region of 30% p/a, 48% p/a for non-dairy derived milks, and 38% p/a for non-dairy cheese. Current economic modelling projections indicate that this increase will primarily be driven through the expansion of start-ups rather than from any existing UK manufacturing base [[32](#_ENREF_32)]. This represent a significant opportunity for market growth, although considerable future financial investment will be required for the UK food industry to capitalise upon the opportunity.

Dietary protein substitutes derived from plants currently represent the fastest growing trend in the UK food sector, with sales reported to have grown by 73% during the period 2018-2020. This increase has been driven, in particular, by sales of plant-based milk and cheese, which have returned triple digit sales growth over the same period. Sector sales are estimated to likely achieve in the region of £1.1 billion livestock alternatives and £565 million for dairy alternatives by 2025. This represent a significant opportunity for market growth, although considerable future financial investment has been identified as being required at the production, processing, and product level for the UK to potentially capitalise upon. The plant-based milk alternatives market has also expanded considerably, more than doubling global sales from 2009 to 2015, and recognising USD 21 billion in sales[[39](#_ENREF_39)]. At the same time, reported sales in the US of plant-based yogurts, cheeses, and beverage creamers have grown by 55%, 43%, and 131% respectfully [[40](#_ENREF_40)].

**Challenges**

There are several barriers to the uptake of plant-based dietary proteins in place of traditional meat sources. These include the taste, appearance, colour and nutrition value of the alternative products [[41](#_ENREF_41)]. A major hurdle is the unpleasant flavour associated with many of the plant-based meat dietary protein substitutes, which is due to oxidation occurring between various components, as well as it being difficult to imitate various meat derived flavours [[41](#_ENREF_41)]. A second barrier is due to various plant proteins inducing allergic reactions on their consumption, particularly those found in the Leguminosae [[42](#_ENREF_42)]. Similarly gluten, the primary cereal protein, can result in chronic intolerances in certain individuals who are genetically susceptible to its triggering chronic damage to the small intestine (celiac disease) [[42](#_ENREF_42)]. However, a range of methods have been developed which can eliminate or inactivate these antinutritional factors [[43](#_ENREF_43)].

Additional barriers to plant-based dietary protein uptake include the current limited variety of available protein sources for the development of novel ingredients, the limited capacity for sustainable production within the UK (varieties, agronomy structure, environmentally safe crop husbandry), the lack of sustainable and efficient protein extraction procedures, and a lack of understanding of potential long term health risks posed by the consumption of these alternative dietary proteins. As alluded to previously, the extensive processing and dependence on various additives make non-meat alternatives unattractive as a result of current perception of ultra processed products. However, the principal barrier overall is the need to reduce costs, both for the raw materials employed, but that of the final commercial product [[32](#_ENREF_32), [44](#_ENREF_44)]. In general, higher prices are currently demanded by meat alternatives in comparison to conventional meat-based products , which is conceived as a major hurdle to adoption by many consumers [[45](#_ENREF_45)].

## **Regulation**

Current scientific and grey literature indicate the need for the development of appropriate labelling regulations for meat analogue products [[46](#_ENREF_46)]. The 2018 European Commission (EC) initiative on mandatory food labelling for non-vegetarian/vegetarian/vegan products proposed that pictorial labels be required on all food items to aid vegetarians and vegans identify suitable food products [[47](#_ENREF_47)] [[47](#_ENREF_47)]. However, at the time of writing, there remain no relevant legal definitions which would enable the indication of vegetarian or vegan compliant foods in either the UK or EU. The problem would appear to be due to the difficulty surrounding the use of meat terms when specifically labelling meat alternatives, owing to the limited number of current legal terms to describe meat products. Meat product regulations generally only refer to sales descriptions, but no language versions of terms for products such as sausage or steak. In contrast, dairy alternatives, particularly milk, have more restrictive regulatory barriers than for other alternative dietary proteins. Under current EU-based milk regulations, plant-based milk alternatives are not permitted to be labelled as ‘milk’, as milk is technically defined as a mammalian secretion under existing EU legislation[[5]](#footnote-5). This restriction also extends to milk products, including cream, butter, cheese, and yogurt. The regulatory situation is further complicated as outside of the UK and EU, for example Australia, the term “soy milk” is allowed. Regulatory challenges with respect to ingredient labelling and product naming are a further hurdle. For example, in the EU, France has banned the use of the term meat-like as well as related terms, including “vegetarian sausages” and “vegan bacon” as they may mislead consumers. In addition, substitutes made of soy or pea may not utilise terms such as “burger”, “steak”, or “sausage”. Other countries around the world have also adopted the same position [[45](#_ENREF_45)], the results of which are the current complicated arrangement of regulations between countries and also considerable uncertainty for prospect of future investment and innovation [[48](#_ENREF_48)].

## **Remarks**

Plant-based dietary protein products potentially offer a sustainable and acceptable alternative source of dietary protein instead of traditional meat for consumers. Conventional as well as emerging technologies have been successful in producing a variety of fabricated plant protein structures, that resemble meat-like products [[45](#_ENREF_45)]. However, scientific interest in plant-based alternatives has primarily been focused on the crude protein content of plant-based alternatives, but not the additional components (e.g., micro- and macronutrients) that are bioavailable through the consumption of meat and dairy-based sources. There is an evident need for more research in this area to explore the nutritional equivalence of alternative plant protein sources compared to meat and dairy derived proteins (e.g., is 1kg of plant-based product equivalent to 1 kg of meat and dairy, and a critical need to look beyond protein content alone). However, the current increasing growth and demand for alternative dietary protein may provide additional opportunities to explore new innovations.

# **Novel sources of alternative dietary protein**

## **Novel sources status**

The main novel sources for human dietary proteins described in the literature include edible insects, microalgae, cyanobacteria, and macroalgae (kelps and seaweeds). Although in many parts of the world these alternatives to livestock and dairy derived dietary protein are an established component of routine human dietary intake, for much of the developed western world, some of these may be considered novel food types. However, with respect to their production on an industrial scale, which would be required to feed a growing population, this may require their adoption into novel production technologies, as well as exposure to the constraints of manmade environments, thereby changing their concept as sustainable and low GHG emitting food sources. The current literature indicates a strong UK interest in exploring the potential for post-Brexit regulation with respect to the alternative dietary protein sector, with a focus on driving innovation and accelerating the home market. For example, the potential to leverage macroalgal (seaweed) harvest in the UK, for both food and bio-fuel production [[49](#_ENREF_49)], through exploiting the extensive accessible coastal waters which has received considerable recent interest and increasing support [[32](#_ENREF_32)]. Elsewhere, the International Platform of Insects for Food and Feed (IPIFF) is petitioning existing European member states to implement regulations from the European Commission [[50](#_ENREF_50)], to permit the commercialisation of a number of insect species as novel foods under the regulatory framework provided by Regulation (EU) 2015/2283 [[51](#_ENREF_51)].

## **Insects**

#### **Insect sector**

Insects have been consumed as part of the human diet for thousands of years and in numerous countries [[52](#_ENREF_52)]. Both the current scientific and grey literature suggest that edible insects may have the potential to become a major source of human nutrition in the near future, particularly as they can be produced more efficiently than conventional livestock [[53](#_ENREF_53)]. However, human consumption of insects, particularly in Western countries, is limited or even considered culturally inappropriate, resulting in them rarely being discussed as a viable part of food security agendas of international organisations

Insects are high in fats, protein and micronutrients, and can be produced with lower levels of GHG emissions and water consumption than that seen with conventional livestock-based practices [[54](#_ENREF_54)]. Rearing of insects for use in food and feed also benefits from their high efficiency for converting feed into consumable food, which is primarily due to the greater fraction of an insect that be consumed per mass of insect (up to 100%), compared to that seen for conventional livestock (typically 40%) [[55](#_ENREF_55)]. The high feed conversion efficiency generally observed with insects is also a result of their frequently rapid growth rates, with many species demonstrating an ability to reach maturity in comparatively short periods of time (e.g., days rather than months or years) compared to that seen with livestock [[55](#_ENREF_55)].

## **Insect consumer**

The results of a 2021 UK Food Standards Agency (FSA) commissioned Ipsos MORI survey of respondents aged between 16 and 75, living in England, Wales and Northern Ireland on alternative dietary protein [[56](#_ENREF_56)], indicated that 25% would consider eating edible insects, and that a primary driver for considering this originated from concerns for the environment. This was reportedly marginally lower than 34% who said they would consider eating cultured meat, 40% of who cited sustainability and environment issues as the reasons for doing so [[57](#_ENREF_57)]. In addition, half of the respondents indicated that they believed edible insects were safe to eat compared to 77% who perceived plant-based proteins as safe, and 3 in 10 (30%) who considered cultured meat as safe. However, 67% of respondents reported that nothing would make them consider insects, but 1 in 8 (13%) [[57](#_ENREF_57)]. Government have indicated that they would considering how businesses could be supported in entering the edible insect-based protein market, and how to guide interested bodies through the existing regulatory framework and risk analysis process for the introduction of novel food products [[56](#_ENREF_56)]. However, the stigma around eating insects will need to be tackled through consumer education and the use of insect proteins as processed ingredients rather than through direct consumption of insects themselves.

## **Insect commercial**

Insect protein is currently unable to compete on price with imported soya bean meal. However, this is likely to change, particularly if there is a major disruption to global trade or production, increases in agrochemical prices, or the introduction of trade barriers [[58](#_ENREF_58)]. Most of the insects consumed as part of the human diet are harvested from the wild [[58](#_ENREF_58)]. However, for species such as silkworms (*Bombyx mori*) and honey bees (*Apis mellifera*) have become domesticated as a consequence of their by-products, although in both cases the insects themselves may also be consumed as part of the human diet [[52](#_ENREF_52)]. Currently the most promising insect species for industrial production in the UK and EU are the black soldier fly (BSF), the common house fly, the yellow mealworm, the lesser mealworm, silkworm (*Bomby mori* ), and a number of grasshopper species [[59](#_ENREF_59)]. Domestic rearing of insects has been undertaken for many thousands of years, and has included practices such as sericulture (manufacturing of silk), apiculture (manufacturing of honey), as well as the biological control of pests and the production of compounds such as shellac and cochineal [[60](#_ENREF_60)]. The global numbers of farms producing insects on a commercial scale has been progressively increasing over the last decade [[61](#_ENREF_61)]. Western insect industries have been initiated primarily by entrepreneurial companies, and have obtained varying levels of financial support through crowdfunding and agreements large investors [[62](#_ENREF_62)].

The UK and EU insect sector is currently at a comparatively early stage in its establishment. Although there are a limited numbers of large farms in existence, the majority operate on only a small scale [[63](#_ENREF_63)], with insects produced primarily for use in fish feed and pet food, as this is currently permitted under UK and EU legislation [[64](#_ENREF_64)]. Current growth in the insect-feed market has been accompanied with increased interest in the potential use of insects to supplement or replace the human dietary intake of meat within the UK and Europe [[65](#_ENREF_65)]. To date, the majority of Western insect farms are small, with lower adoption of technology and mechanisation compared with conventional agricultural farms [[62](#_ENREF_62)]. Operationally, UK and European insect farms predominantly operate two separate production units, one for the maintenance of breeding colonies and second for the production of larvae from the eggs [[66](#_ENREF_66)]. Many insect farms will also undertake first-step processing following insect harvest by drying them. There are three basic business set-ups for insect farms operating in the UK and EU: farms that purchase eggs or small larvae from a supplier and focus on the fattening and maturation of the larvae; farms that encompass the entire production process, harvesting and initial processing (i.e. drying) of larvae; large-scale facilities, which cover all of the production steps as well as additional stages of processing (e.g. milling, de-fattening and the fractioning of proteins or fats).

Depending on the level of mechanisation, this may include drying machines and continuous feeding systems [[67](#_ENREF_67)]. Operational inputs include the feed for insects and the production environment. The latter is a crucial factor for the survival and optimal growth of insects and encompasses both the energy and water used for insect production, as well as during the first steps in biomass processing. On a production basis, the primary outputs of insect farms may include small larvae, grown larvae, and/or mature insects. The processing formats for these products may consist of live larvae, and/or dried larvae. Larger commercial production facilities may also produce insect meal, which requires some additional processing capability.

A number of significant hurdles have been reported to hinder the potential expansion of the insect farming industry, particularly with respect to production of products for human. Aside which insect species to physically employ, the issue of how best to develop efficient and environmentally friendly farming techniques remains a significant issue. To date a limited number of companies have developed and are retailing automated insect rearing systems, and of these many are in the trial phases. Hence, the majority of insect farms currently rely on manual labour to undertake operations such as feeding, collection, and cleaning [[60](#_ENREF_60)]. The extensive reliance on manual labour results in farm produced insects being comparatively expensive, compared to rearing conventional livestock, even when potential feed costs are low. In order for insects to become an economic source of alternative dietary protein, automation will need to become the norm in order to achieve lower prices for the end product. In addition to the labour costs, the insect rearing conditions employed, which includes temperature and light control, feed and water availability, feed quality and composition, prevention of microbial contamination, all need to be factored in to achieve successful commercial scale production, but which ultimately add to the costs [[60](#_ENREF_60), [61](#_ENREF_61)].

### **Insect market**

On a global basis, a variety of species are currently consumed on a regular basis (> 2000 species), and across multiple countries around the world (119 countries) [[58](#_ENREF_58)].To date, there has been limited consumer acceptance of insects as a food source in modern western countries [[68](#_ENREF_68)]. Historically, western countries are also associated with high animal derived product consumption rates per capita, and where a switch from animal-derived products to insect consumption would have a significant impact. However, there are indications that consumer attitudes (e.g., in the UK) may be changing [[69](#_ENREF_69)], and insect consumption becoming more acceptable, driven by less of an objection to dietary inclusion of insect-derived materials in existing foods, for example as in powdered form in flour [[70](#_ENREF_70)].

Economic data for human insect consumption primarily originates from South East Asia where numerous farms and trade routes have already been established [[71](#_ENREF_71)]. Current estimates for the value of insects imported by Thailand for use as food has been reported to be in the region of US$ 1.14 million /annum [[72](#_ENREF_72)]. In terms of species value, Thai insect market values range from US$ 3.00 /kg for farmed house cricket (*Acheta domesticus*), to US$ 10.65 /kg for wild weaver ants (*Oecophylla smaragdina*). These figures compare favourably with Thai market values for livestock, for example US$ 1.08 /kg for broiler chicken, to US$ 3.03 /kg for beef [[72](#_ENREF_72)]. The reported combined global estimate for food and feed usage of insects reported for 2015 was reported to be in the region of £25.1 million, with a predicted growth to over £398 million by 2023 [[71](#_ENREF_71)].

### **Regulatory**

As with conventional livestock systems, farmed insects need to be processed for human consumption. There are standards which govern the processing of conventional livestock, but as yet there are no best practices in place for insects, primarily due a lack of data on the impact of processing on food safety and nutritional content.

Currently, the insect proteins are regulated under animal by-products (ABP) guidelines, which hinder both use of cheap waste streams (e.g., manure, animal processing waste) and the utilisation of insect proteins in feed and food, due to the risk of contaminants and pathogen transmission. Further research and testing methodologies will need to be developed to mitigate these risks.

Regulations (EU) 2017/2469 and (EU) 2017/893 specify the requirements for making an application to request authorisation of a novel food for the UK and EU market, with particular attention to the substrate options that can be used to rear them. Although highly restrictive to the production and commercialisation of insect-based products in the UK and EU, they do ensure the safety of consumers, although at the cost of slowing the development of an industry with the potential to offer significant environmental and economic benefits [[15](#_ENREF_15)]. New scientific evidence and the identification of critical control points in the production and processing chain of insects protein production will be essential [[61](#_ENREF_61)].

### **Challenges**

Despite the potential insects offer as an alternative source of dietary protein, significant challenges for their adoption remain. Major issues include the likelihood of insects containing toxic compounds, food safety relating to allergic reactions, consumer acceptability, and current ambiguity surrounding insect regulation.

In terms of potentially toxic compounds linked to insects, Chitin (a structural nitrogen-based carbohydrate found in insects exoskeletons) is one such compound which may exhibit toxic effects due to negative effect on protein assimilation [[73](#_ENREF_73)]. However, chitin is high in fibre, and chitin extracts from shellfish exoskeletons have been approved for use as a source of fibre in cereals in some countries [[74](#_ENREF_74)]. The potential toxicity of additional insect related compounds has also been reported. Cryptotoxics and phanerotoxics are toxic substances that arise either from direct synthesis or by accumulation from an insects However, commonly consumed insect species are not associated with the presence of either category of compound, and studies of levels of hydro-cyanide, oxalate, phytate, phenol and tannins have all be identified as falling below levels toxic [[75](#_ENREF_75)]. However, data on anti-nutrient properties of edible insects are comparatively limited, and additional research will be required.

Arthropods, including insects, have been reported to induce allergic reactions in susceptible individuals. This is primarily caused by the presence of tropomyosin, arginine kinase, glyceraldehyde 3-phosphate dehydrogenase and haemocyanin [[76](#_ENREF_76)]. A recent review of cross reactivity/sensitivity with insects in individuals with known arthropod allergies indicated that all patients demonstrated an allergic reactions to insects[[77](#_ENREF_77)]. However, the data on allergen risk to insects are limited, but do indicate that individuals with crustacean allergies may react negatively on exposure to insects, and that there may be additional novel insect allergens to consider.

#### **Conclusion**

Based on the scientific literature, insects are indicated to possess sufficient levels of protein, fats, and micronutrients to make a positive contribution to human dietary needs, either through direct consumption, or via indirect use through their addition to animal feeds. Research has also demonstrated that insect farming can generate less of an environmental footprint, while providing a greater economic return than that seen for conventional livestock-based practices. Currently available scientific evidence suggests insects are unlikely to pose any significant microbial risks, although reports of allergic reactions to insects in individuals with previous arthropod allergies have been documented. However, although numerous individuals from Western societies are comfortable with insects being used as animal feed, they are hesitant on the prospect of consuming them directly. There are also significant challenges to be addressed, which include: how the small environmental footprint of insect farming may be retained where operations are scaled up commercially; how insects are to be fed on a commercial scale in a sustainable manner; and what do the regulations for insect farming, processing and storage need to encompass. Ultimately however, insects will only be able to provide a viable alternative to conventional livestock and diary derived protein if they can compete on an economic and environmental impact footing.

## **Microalgae**

### **Microalgae sector**

Microalgae can provide a number of beneficial nutritional compounds for the human diet, including lipids (e.g., omega 3), proteins, minerals as well as a range of exotic compounds such as chlorophyll [[78](#_ENREF_78), [79](#_ENREF_79)]. Foods containing microalgal products are already commercially available sold in the form of nutritional supplements, but also as ingredients included in baked goods and snacks [[79](#_ENREF_79)]. Large scale production of microalgae has the potential to provide a means of improving food security and reduce some of the environmental impact seen with conventional food production systems (e.g., agriculture, horticulture, and aquaculture).

### **Microalgal consumer**

In terms of abundance, the important classes of micro-algae are the diatoms (Bacillariophyceae), the green algae (Chlorophyceae), and the golden algae (Chrysophyceae). These micro-algae are all eukaryotes and distinguished by the presence of a nucleus and separate organelles for photosynthesis (chloroplasts) and respiration (mitochondria). Cyanobacteria (Cyanophyceae or blue-green algae) are frequented credited with belonging to micro-algae (e.g., Spirulina (*Arthrospira platensis* and *A. maxima*)). However, cyanobacteria are eubacteria and therefore prokaryotes which characteristically lack a membrane-bounded nucleus.

Algae contain lipids, proteins, and carbohydrates, and have been used for food, feed and fertilisers for centuries. Commercial culture of micro-algae species were initiated in the early 1960s using Chlorella, which was quickly followed by Spirulina (Arthrospira) [[80](#_ENREF_80)]. Large-scale micro-algae production has been established in Asia, India, the USA, Israel and Australia, with over 200 species of micro-algae under commercial culture globally [[80](#_ENREF_80)]. Traditionally, micro-algae such as Spirulina and Chlorella were sold as dietary supplements, and without any kind of processing, except for drying. Spirulina production is primarily undertaken in Asia and the USA, but Chlorella production is mainly undertaken in Asia. However, both algal species are also produced on a smaller commercial scale in a number of other countries (e.g., Mexico and Australia) [[81](#_ENREF_81)]. More recently, and in addition to sales of dried algae, high-value derivatives isolated from micro-algae species are being commercially produced. These include natural compound variants for use in specific applications, for example in infant formula, fish pigment enhancers, and dietary supplements [[82](#_ENREF_82)].

In terms of importance, the green algae *Haematococcus pluvialis* is commercially important as a source of astaxanthin, *Chlorella vulgaris* as a supplementary food ingredient, and the species Dunaliella as a source of β-carotene. Conversely, blue-green algae (Cyanobacteria) are known for their water polluting effect due to the production of toxins. Micro-algae may represent a potential source of food and feed. However, production technology for the large scale cultivation of micro-algae is still in the early phases of development [[80](#_ENREF_80)] [[80](#_ENREF_80)]. Further development of micro-algae culture technology is required in order to increase the scale of production while enabling the concomitant decrease in the cost of production.

The market for micro-algae-based food and feed products is well established and served by a large number of producers. However, microalgae may prove useful in other fields, including the production of bioethanol (fermentation) or biodiesel (conversion) [[80](#_ENREF_80)]. The use of micro-algae for the food and feed is becoming increasingly relevant as micro-algae derivatives (e.g., fatty acids, colourants, vitamins) may have the potential to be competitive with the same components from conventional synthetic sources [[80](#_ENREF_80)].

### **Microalgal commercial**

The choices of microalgal species currently employed in the production of SCP for human or animal consumption typically exhibit a protein content of between 60–70% per mass. However, actual protein content and respective amino acid profiles are dependent on which species and culture conditions are employed [[83](#_ENREF_83)]. For example, the protein content *Chlorella vulgaris* has been reported to vary between 51–58% by mass, and between 60–71% for *Arthrospira (Spirulina) platensis* [[83](#_ENREF_83)]. By comparison, microalgal protein content is typically more than for many other sources including, dried skimmed milk (38% by mass) [[84](#_ENREF_84)], soy flour (38% by mass) [[85](#_ENREF_85)], and peanuts (22% by mass) [[86](#_ENREF_86)]. In terms of nutritional value, the amino acid profile of microalgal species generally match the reference profiles for well-balanced protein, as defined by WHO [[87](#_ENREF_87)].

Most commercial products are currently produced from *Arthrospira platensis* and *Arthrospira maxima* (commonly retailing as spirulina). Other algal derived products are also licensed for human consumption, including Chlorella (marketed in the UK and EU by Roquette Klötze GmbH & Co), *Dunaliella salina,* primarily for β-carotene (Qianqiu Biotechnology Co., Ltd.,) and *Aphanizomenon flos-aquae* (marketed by Blue Green Foods LLC). Euglena Co. Ltd. (Suzuki, 2017) and Algaeon (<http://algaeon-inc.com/#products>) both products derived from Euglena, primarily β-glucan but also whole cell products.

### **Microalgae challenges**

Although the nutritional value of microalgae is well documented, their digestibility and overall nutritional value depend on both the individual strain concerned, and also the technology used for biomass production. An important limiting factor for human consumption is the high nucleic acid content that is metabolised to uric acid, which may result in adverse health effects, including gout and or kidney stones [[88](#_ENREF_88)] [[88](#_ENREF_88)]. Some species of cyanobacteria can potentially produce hepatotoxins and neurotoxins. Therefore, where microalgae have been cultured in open systems there is some risk of contamination from toxic cyanobacteria as well as other biological and non-biological contaminants, and relevant regulations are in place to ensure analysis of the biomass before processing is undertaken [[89](#_ENREF_89)].

Conventionally, natural stretches of open waters (lakes and ponds), or purpose-built lagoons have been employed in growing microalgae on a commercial basis. These open style systems are inexpensive to construct and run, but suffer from a number of limitations (e.g. cultures are not axenic; weather variability can hamper culture regulation, culture site liable to damage from pests and the environment) [[90](#_ENREF_90)]. Species routinely cultured in open pond facilities tend to be extremophiles, capable of growing in a highly selective environments (e.g., high pH, salinity or temperature) which discourages the growth of potential contaminating organisms [[91](#_ENREF_91)] [[91](#_ENREF_91)]. However, the future of microalgal culture will depend on the development of large-scale photobioreactors (PBRs) with the capability of operating under defined conditions with minimal risk of contamination [[92](#_ENREF_92)] [[92](#_ENREF_92)] (Wang et al., 2012). Compared to conventional open-air systems, closed systems can circumvent many of the problems they encounter. Several types of closed PBRs have been developed including tubulars, flat plates, and stirred tank reactors [[91](#_ENREF_91)]. Modularisation and fluid dynamics have been employed to assist with optimising PBR structural configurations to best comply with commercial scale-up requirements However, major constraints still exist around the efficient use of illumination sources [[91](#_ENREF_91)]. Additional methodologies will also require addressing in order to permit commercially viable scale-up to be achieved, which include reducing PBR carbon dioxide losses, improving the efficiency of algal culture mixing, and the removal of oxygen generated by the algae [[93](#_ENREF_93)]. A move to incorporate continuous cultivation to optimally improve yields will add new challenges in this field [[94](#_ENREF_94)].

### **Microalgae markets**

Production volume and market size for micro-algae products is relatively small in comparison to commodities such as wheat, which has an annual production volume in the region of 700 million tonnes. However, production volumes have progressively increased from a reported 1000 tonnes dry weight in 1999 to 9,000 tonnes dry weight by 2011. This represents a year on growth of 10 percent [[95](#_ENREF_95)], with the 2011 market having estimated global value of €2.4 bn [[96](#_ENREF_96)]. Although the production of micro-algae, primarily for the purpose of consumption, has a lengthy history, large-scale commercial production operations are still comparatively limited. Micro-algae production has primarily been targeted at the health food industry [[97](#_ENREF_97)]. However, more recently algae-based high value derivates, such as docosahexaenoic acid (DHA) have entered the market. DHA is essential for the growth and functional development of the brain in infants and is also required for maintenance of normal brain function in adults. Micro-algae derived DHA is now found in the majority of baby formulae sold in in the USA [[98](#_ENREF_98)] [[98](#_ENREF_98)]. In terms of gross production, literature suggests that Spirulina and Chlorella biomass are still produced in the largest volumes but flag their contribution to the potential markets for high-value products such as DHA / EPA, β-carotene and Astaxanthin. The commercial production of these derivatives is concentrated across a small number of producers, with the exception of Chlorella production which is distributed across multiple small producers [[80](#_ENREF_80)] [[80](#_ENREF_80)]. In terms of the UK and European share of the micro-algae market, published data for production volumes is generally only available for global, not regional estimates. However, experts currently estimate Europe’s production share to be currently around 5 per cent of global production [[80](#_ENREF_80)].

Critical to commercial micro-algae production is the scale of production undertaken, as this governs the economic viability of operations which requires a large initial capital expenditure and continued funding of going labour costs. As an example, it has been reported that for a 1 hectare (ha) production site, the mean cost per kilo dry weight of algae is around €17.72, whereas for a 100 ha production site the mean cost per kilo dry weight algae falls to €4.95 [[99](#_ENREF_99)].

In reality the largest plant currently producing Spirulina is only 44 ha in size [[96](#_ENREF_96)] which suggests that actual costs per kg dry weight in current production sizes will be higher. More realistic estimates of total cost per kg dry weight in an average sized production facility is considered to be in the region of €8 - €11 [[100](#_ENREF_100)]. However, these are projected figures based on the commonly cultures micro-algae types described by Norsker *et al* (2010) [[99](#_ENREF_99)] and Acien (2017) [[96](#_ENREF_96)]. For example, production costs for the carotenoid Astaxanthin from *Haematococcus* *sp* have been estimated to be on average greater than €30 per kg dry weight [[99](#_ENREF_99)]. For the production of pharma-grade (i.e., 99 per cent pure) Astaxanthin, more expensive extraction techniques are required, which may add between €10-€15 per kg to the total costs. Allowing for conversion rates and losses, production costs for pharma grade Astaxanthin are more likely to be in the range of €465/kg dry weight.

When comparing these figures for algae biomass production with other biomass sources, it is clear that currently, micro-algae production is not a cheap option, when compared with sources such as wheat straw which may be produced for €0.03 per kg [[100](#_ENREF_100)]. In addition, in the case of micro-algae-derived products (e.g., DHA), extraction costs come in addition to micro-algae production costs. There is generally only limited published information on the additional costs of micro-algae extraction technologies. Available examples include a 2007 estimate for oil extraction, which approximates to €1.32 per kg [[101](#_ENREF_101)].

### **Microalgae regulatory**

The use of microalgal biomass and/or its derived metabolites has become an innovative approach in the development of novel food products [[79](#_ENREF_79)]. In terms of the volume of microalgae-based products traded on the global market, then dried whole algae Spirulina occupies the largest proportion, with more than 12 000 tons of Spirulina biomass reported to be traded annually, of which approximately 70 per cent originates from in China, India, and Taiwan. Additional market contributions have been reported for *D. salina* (about 3000t for carotene), *A. flosaquae* (about 1500t for food), *H. pluvialis* (about 700t for astaxanthin), *C. cohnii* (500t of Docosahexaenoic acid (DHA)) and *Shizochytrium* (20t of DHA). Recent Credence Research market reports estimate the algal products market to reach US$ 44.6Bn by 2023. Chlorella and Spirulina have been widely commercialised in health food stores are one of the most nutritious foods known to man. These microalgae have also been used as feed for many types of animals (e.g., cats, dogs, aquarium fish, ornamental birds, horses, poultry, cows and breeding bulls). In addition, other microalgae including *Tetraselmis, Isochrysis,* and *Thalassiosira* have been used as feeds in aquaculture [[43](#_ENREF_43)].

### **Microalgae conclusion**

Microalgae have been used as food and feed for both humans and animals for decades, and only comparatively recently they have become more widely cultured and harvested at an industrial scale. Their role in providing an alternative source of dietary protein as well as their applications in the energy, and cosmetic industries are continuing to expand their product market, but a number of key challenges still need to be addressed.

# **Macroalgae (seaweeds)**

## **Macroalgae sector**

Algae are a diverse group of photosynthetic organisms both unicellular (microalgae) and multicellular (macroalgae) and have the ability to grow rapidly, efficiently use light energy, fix atmospheric CO2, and produce biomass [[90](#_ENREF_90)]. From archaeological evidence, algae have been a regular component of many humans diet for hundreds of years [[102](#_ENREF_102)] [[102](#_ENREF_102)]. Dietary consumption of macroalgae (seaweed) has been recorded as being undertaken along many European coastal areas, including France, Norway, Scotland, Wales and Ireland) [[102](#_ENREF_102), [103](#_ENREF_103)]. Macroalgae encompass both seaweeds and kelps, and have been reported to be good sources of dietary protein (up to 50% protein by dry weight) as well as other important nutritional elements [[104](#_ENREF_104)].Seaweed proteins are similar in quality to common plant protein sources such as peas, soy, and tree nuts. Furthermore, seaweed proteins from different species have complementary EAA profiles and can be mixed to form protein blends that nutritionally match conventional products such as milk and whey. In addition to protein, seaweeds contain a variety of compounds including essential fatty acids, dietary fibre, phenolic compounds, and vitamins [[105](#_ENREF_105)]. Mineral profiles also indicate seaweeds contain significant levels of calcium, magnesium, phosphorus, potassium, sodium, and iron [[106](#_ENREF_106)]. However, the literature highlights some concerns as to the safety of seaweed for general consumption. The presence of a number of toxicological hazards, including iodine, heavy metals and microbiological hazards (e.g., *Salmonella* sp) have been cited in the recent literature. As a consequence, organisations for food safety control generally require adherence to the Hazard Analysis and Critical Control Point (HACCP) principles when dealing with products derived from seaweeds [[107](#_ENREF_107)].

## **Macroalgae consumer**

Seaweeds have become a favoured commodity in European countries such as France, Ireland, and Norway. In countries such as China, Korea and Japan, seaweed is considered a valuable component of the human diet [[108](#_ENREF_108)]. Yet, in western countries, seaweeds are rarely employed as part of the normal diet, partially due to its unusual taste. However, research and development of products derived from seaweed is reported to be experiencing an increase in interest, as has the commercialisation of various functional components and nutraceuticals, primarily driven through an elevated consumer perception of the relationship between diet and health [[109](#_ENREF_109)]. The upward trend in interest and consumption is reportedly being driven by consumers recognising the benefits of consuming nutritionally balanced food via published research, and more progressively through social media channels. This increase in demand for alternative protein products, particularly that derived from seaweeds is currently driving strong market potential [[110](#_ENREF_110)].

## **Macroalgae commercial**

Seaweed production from UK wild harvest practices has been estimated to be in the region of 2,000-3,000 dry tonnes/annum [[49](#_ENREF_49)]. In addition, unknown quantities of subtidal kelp and storm-cast seaweeds are also routinely collected. The aquaculture of seaweeds in the UK is comparatively limited, and many of the existing UK farms are classified as research and development establishments rather than production facilities. However, pilot aquaculture facilities have been reported to have been established in Northern Ireland, Scotland (SAMS), the Shetlands (University of Highlands and Islands) and Wales (Swansea University). However, to date, the primary focus of these facilities has been on producing mainly brown seaweeds (e.g., *Saccharina latissima*, or sugar kelp) for use in biofuel evaluations [[49](#_ENREF_49)].

In terms of commercial activities, twenty seven UK seaweed-based businesses were highlighted in a recent Cifas report [[49](#_ENREF_49)], of which sixteen employed seaweeds harvested in the UK. The majority of these companies produce seaweeds for use as food (or “sea vegetables”) or condiments. Other notable products produced include animal feed and supplements, chemicals (e.g. hydrocolloids), fertilisers, and nutraceuticals (e.g. nutrients and dietary supplements) [[49](#_ENREF_49)].

The limited number of operational UK seaweed businesses may be due to the number of barriers/challenges that currently exist to the development of seaweed production. The volume limitations of wild harvest production have been highlighted as a significant factor to low production quotas (arising from high costs of biomass production, shortages due to seasonality and the high levels of manual input on harvest). Options for a switch to aquaculture have been indicated as a possible resolution, but factors such as current high operational costs, environmental impact of seaweed farms, and an unclear regulatory framework (e.g., for marine licensing), have limited development of UK seaweed aquaculture [[49](#_ENREF_49)].

Macroalgae benefit from being easy to cultivate as they grown in freshwater and saltwater environments [[111](#_ENREF_111)]. The adoption of aquaculture has been reported to be growing in popularity as a response to guaranteeing production quotas in the face of increasing demand for algal biomass. Commercial aquaculture of macroalgae for biomass production is already a well-established industry in Asia, with a reported annual production of 32 million tonnes of aquatic algae in 2018 (primarily from aquaculture, and predominantly seaweed) [[112](#_ENREF_112)]. However, available cultivation methods and technologies are diverse and their application depends on the genus being cultivated [[113](#_ENREF_113)], although cultivated seaweeds have been reported to have a higher protein content compared to wild-harvested seaweeds [[114](#_ENREF_114)] as the latter tend to grow in environments that are often nutrient-limited.

Harvesting seaweeds is considered a sustainable practice, since seaweeds may be cultivated in large quantities, and without need of the resources required for plant-based alternatives, such as fertiliser, freshwater, and expanses of land [[115](#_ENREF_115)]. Initial product processing is comparatively simple and inexpensive, with post-harvest drying remaining the preferred method for preserving seaweed, as it maintains much of organoleptic quality while reducing the weight of the product ready for transportation [[116](#_ENREF_116)]. Rehydration, when required, results in most seaweeds generally regaining their original morphology. with only minor loss of nutrients. Post-drying, the seaweed normally undergoes processes such as milling, blending, and packaging based on the specific manufacturing requirements [[117](#_ENREF_117)].

In terms of adoption as an alternative protein source, seaweed may prove to be a viable long term protein source which offers a reduced environmental footprint while providing beneficial ecosystem services [[116](#_ENREF_116), [118](#_ENREF_118)].

## **Macroalgae market**

There is no comprehensive estimate of current UK seaweed (macroalgae) production. There are also no recent estimates of the wild seaweed stocks surrounding the waters of the UK, nor for the algal stock that could be sustainably harvested, with the exception of a 2010 evaluation of the Outer Hebrides [[119](#_ENREF_119)]. Seaweed production from UK wild harvest practices has been estimated to be in the region of 2,000-3,000 dry tonnes/annum. In addition to these figures, unknown quantities of subtidal kelp and storm-cast seaweeds are also collected.

The majority of UK seaweed-related businesses (a total of 27 were identified based on a web search) produce seaweeds for human consumption as food (“sea vegetables”) or condiments (10 out of 27 businesses identified), and for cosmetics (e.g., skin care; 9 out of 27 businesses). Other products, based on seaweeds and produced in the UK, include animal feed and supplements, chemicals (e.g. hydrocolloids), fertilizers and nutraceuticals (e.g. dietary supplements), while production of seaweed for bioremediation, or biofuel production is reportedly at an early development stage [[120](#_ENREF_120)]. There is currently only limited cultivation of seaweeds in the UK, although pilot seaweed farms are being developed at different sites, primarily for research and development, but mainly on biofuel technologies [[120](#_ENREF_120)].

Currently, more than 500 species of seaweed are collected and utilised worldwide [[121](#_ENREF_121)], although only 33 genera are harvested on a commercial basis [[122](#_ENREF_122)]. The global seaweed industry is estimated to be worth at least USD 6 billion per annum, with recorded production for 2015 being in the region of 30.4 million tons, of which 29.4 million tons were cultivated and the remaining 1.1 million tons harvested from the wild [[123](#_ENREF_123)]. China and Indonesia currently boast the largest markets for seaweed production, with China reportedly accounting for 50.8% of global production [[49](#_ENREF_49)]. Production of seaweeds in Asia and Africa are mainly from aquaculture, while in America and Europe production is almost entirely from the harvest of wild plants. In terms of sector growth, Indonesia, Peru, and France have demonstrated the largest recent growth in seaweed production from wild harvest, while Indonesia have shown the largest growth from aquaculture[[49](#_ENREF_49)] [[49](#_ENREF_49)]. Considering global harvest volumes, then as Asia accounts for the majority of seaweed production, then almost all of world production (~ 95%) is sourced from aquaculture [[49](#_ENREF_49)].

Seaweeds benefit from already having an established consumer market as a food source, particularly in Asia [[124](#_ENREF_124)]. Unfortunately, seaweeds appear to be a niche rather than mainline food in many Western countries [[125](#_ENREF_125)]. However, there are reported indications that a significant market for seaweeds and seaweed-containing products is emerging in the UK [[126](#_ENREF_126)]. Some regions of the UK already consume seaweeds as ingredients in traditional recipes and have done so for decades. *Porphyra umbilicalis* (purple laver) has been used to make ‘laverbread’, a traditional Welsh seaweed-based puree that is usually eaten alongside seafoods [[126](#_ENREF_126)]. An expanding range of seaweed and seaweed-based products, which include sushi, soups, snacks, and drinks are also now available to retail consumers in supermarkets and specialist retailers, with the many of the products now being sourced in the UK-sourced [[127](#_ENREF_127)].

### **Challenges**

A range of issues exist that limit the development of the seaweed market and production in the UK. The aquaculture of seaweeds in the UK is comparatively limited, and many of the existing UK farms are classified as research and development establishments rather than production facilities.

As there is currently a significant bottleneck in the seaweed supply chain which specifically relates to production capacity, and is due to the high costs of current seaweed production practices, and/or by limited (seasonal) supply of algal biomass Migrating seaweed production to aquaculture may help in address this problem; but a range of factors, including a lack of knowledge on operational costs, yields and potential ecological impacts of seaweeds farms, as well as an unclear regulatory context (particularly marine licensing), combine to limit the development in the industry.

In terms of commercial activities, only twenty seven UK seaweed-based businesses were identified in a recent Cifas report [[49](#_ENREF_49)], of which only sixteen employed seaweeds harvested in the UK.

The limited number of operational UK seaweed businesses may be due to the number of barriers/challenges that currently exist to the development of seaweed production. Volume limitations of wild harvest production have been highlighted as a significant factor to low production quotas (arising from high costs of biomass production, shortages due to seasonality and the high levels of manual input on harvest). Options for a switch to aquaculture have been indicated as a possible resolution, but factors such as current high operational costs, environmental impact of seaweed farms, and an unclear regulatory framework (e.g., for marine licensing), have limited development of UK seaweed aquaculture [[49](#_ENREF_49)]. In addition, the routine consumption of seaweed as a part of the human diet by the UK and EU population remains in the minority and very much a niche area.

### **Macroalgae regulatory**

At the time of compiling this report, no formal guidance or regulations apply globally that relate to food safety issues with respect to seaweeds, including provision normally referred to through the Codex Alimentarius Commission (CODEX), World Health Organisation (WHO) or Food and Agriculture Organisation of the United Nations (FAO) [[128](#_ENREF_128)]. However, some limited legislation specific to seaweed is covered by food regulations for the UK and EU, and thus, global dissimilarities exist in the evaluation of the safety of products made from seaweed [[129](#_ENREF_129)]. Therefore, concerns regarding the safety of seaweeds and products derived from it pose challenges to food safety authorities across world markets.

In terms of the UK market, no specific regulations relating to farming seaweed are in place, and existing licensing procedures primarily relate to fin and shellfish and may not always be applicable to seaweed farms. For example, the lack of information regarding the environmental impact of seaweed farming (e.g., operational noise, pollution, introduction of pests and pathogens) generates uncertainty on how to interpret relevant national and international regulations [[49](#_ENREF_49)]. This lack of specific information on potential environmental effects of seaweed farms has resulted in uncertainties for the regulators, primarily on how to interpret requirements under national and international regulations (for example, under which circumstances an EIA would be required).

In terms of consumer safety, although seaweeds do not produce endogenous toxins; there is the potential for the bioaccumulation of potentially toxic compounds, particularly iodine and heavy metals such cadmium, lead, mercury and arsenic. Additional toxic compounds have also been identified and isolated from seaweeds, including the cyanobacteria toxins aplysiatoxin and debromoaplysiatoxin, as well as number of prostaglandins [[130](#_ENREF_130)].

### **Macroalgae remarks**

Seaweeds are recognised to contain a significant amount of protein relative to their overall composition. They are also known to contain vitamins, minerals, antioxidants, and a variety of potentially beneficial compounds [[131](#_ENREF_131)]. While protein content varies depending on the species of seaweed considered, values generally range from 10% to 30% of its dry weight [[131](#_ENREF_131)]. Seaweed is considered a valuable source of plant-based protein, especially when considering vegetarian or vegan diets, as it provides a spectrum of essential amino acids. Therefore, including seaweed as a regular dietary addition can contribute to meeting daily protein requirements while providing additional health benefits associated with its nutrient content [[131](#_ENREF_131)].

In addition, sustainable seaweed cultivation may assist with addressing some of the key challenges facing global food security and environmental sustainability. Cultivation of seaweed generally requires limited input of freshwater, land utilisation, and fertiliser usage. In addition, the cultivation of may assist with carbon dioxide sequestration and mitigate the acidification of ocean seawater [[132](#_ENREF_132)].

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# **Precision fermentation**

# **Precision fermentation sector**

The term precision fermentation primarily relates to the process of single cell protein production (SCP), which itself is defined any protein derived from microbial sources in the form of biomass or extracted protein [[133](#_ENREF_133)]. SCPs are mainly produced as alternative sources of protein, although various secondary products may also be produced coincidently. A range of microorganisms have been employed in the production of SCP, and for both food and animal feed. However, adopting them for the specific production of SCP is a comparatively modern concept [[134](#_ENREF_134), [135](#_ENREF_135)].

Although there are examples of SCP production through the use of heterotrophic bacteria (e.g., Pruteen animal feed produced from methanol using *Methylophilus methylotrophus [*[*136*](#_ENREF_136)*]*), industrial scale production through the use of precision fermentation has almost exclusively been undertaken using yeast and fungi [[137](#_ENREF_137)]. Spent brewer’s yeast (*Saccharomyces cerevisiae*) has been sold for more than a century in yeast extract products such as MarmiteR (Unilever and Sanitarium Health Food) and VegemiteR (Bega Cheese Ltd.), with yeast extracts providing both a valuable source of B vitamins and also protein.

The production of SCP is currently undertaken using a limited number of microbial species, particularly with respect to that produced for human consumption. SCP produced for human consumption is also generally produced from food grade substrates, although there is considerable interest in developing production processes that can utilise waste materials sourced from the food and beverage industries, and in the future, from forestry and agricultural sources [[138](#_ENREF_138)]. With the adoption of algae for SCP production, the use of carbon dioxide as a substrate has become a reality, similarly the use of bacterial species will allow the use of methane as a novel source of carbon for SCP production [[137](#_ENREF_137)].

### **Bacterial SCP sector**

The use of bacteria for SCP has an extensive history, particularly for use in animal feed production [[139](#_ENREF_139)]. In terms of protein content, bacterial SCP is typically comprised of 50–80% protein by dry mass basis [[140](#_ENREF_140)], with an amino acid content comparable to FAO/WHO guidelines [[87](#_ENREF_87)]. As with fungal derived SCP, bacterial SCP typically has a high nucleic acid content (in the region of 8–12% by mass), and in particular RNA, and requires processing prior to usage as food/feed [[139](#_ENREF_139)]. In addition to protein and nucleic acid, bacterial SCP are also a source of lipid and B group vitamins.

Bacteria generally exhibit higher growth rates, higher protein content, with a greater proportion of essential amino acids than seen with many other microbes (yeast, fungi and algae) evaluated for use with SCP production [[141](#_ENREF_141)]. From a practical standpoint, utilisation of methane oxidising bacteria (MOB) is currently the most technically advanced and market-ready bacterial system for SCP production [[142](#_ENREF_142)]. SCP production employing methanotroph bacterial species has been the subject to extensive evaluation since the 1960s, and even to the point of commercial production, but was abandoned due to the economic constraints imposed by cheap soy meal imports [[143](#_ENREF_143)]. However, with increasing availability of biogas supplies as a cheap and abundant source of methane, for example, from anaerobic digestion (AD) of waste water in waste water treatment plants, MOB approaches are being reviewed by a number of interested [[144](#_ENREF_144)]. In addition to the availability of methane, AD systems may be used as a source of micro- and macro-nutrients [[145](#_ENREF_145)]. Sewage sludge-based AD contains high levels of ammonium content [[146](#_ENREF_146)], which provides a good nitrogen source for MOB as it can be directly incorporated into the bacterial cell biomass [[147](#_ENREF_147)].

### **Bacterial SCP consumer**

Bacterial SCP is currently predominantly employed in the production of aqua and animal feed [[148](#_ENREF_148), [149](#_ENREF_149)]. However, a recent consumer survey of 5000 participants conducted by German food-biotech start-up, Formo [[150](#_ENREF_150)] indicated that over 70% of respondents ‘definitely’ or ‘probably’ would buy their precision fermentation made dairy cheese.

### **Bacterial SCP commercial**

ICI have developed a bacterial SCP (Pruteen) for use as animal feed, which utilises *Methylophilus methylotrophus* biomass, and methanol as the substrate source. Pruteen was reported to comprise approximately 70% per mass protein and was used to supplement pig feed [[136](#_ENREF_136)]. However, although pilot Pruteen production proved successful as far as a proof-of-concept demonstration, at the time of inception it could not compete with the cheaper soya derived animal feeds, and production was discontinued.

More recently, the GHG methane has become the subject of some considerable interest as a potential substrate for SCP production. UniBio A/S[[6]](#footnote-6) and Calysta Inc[[7]](#footnote-7). have both developed fermentation technologies targeted at the production of animal feed SCP using methanotrophic bacteria and natural gas as the substrate. The approach developed at UniBio A/S is reported to be capable of producing up to 4 kg m−3 h −1 of their protein product, UniProtein®, which comprises approximately 70% per mass protein, and is approved for use in animal feed [[151](#_ENREF_151)].

Calysta Inc opened a pilot methane-based SCP facility in Teesside, England the UK during 2016 for the production of FeedKind®, their high protein animal feed. Founded in 2012, Calysta is now reported to a global leader in the field of SCP gas fermentation technology, and is currently in the process of building and commissioning the world’s first commercial FeedKind® production plant in Chongqing, China in venture with Adisseo [[152](#_ENREF_152), [153](#_ENREF_153)] with an estimated production capacity of 20,000 tonnes per year.

As with SCP from fungi, other developments in the production of bacterial SCP focus on upgrading various waste substrates or valorisation of wastewater treatment. UK-Dutch start-up Deep Branch1 also utilises gas fermentation technology, but via the activities of CO2 and H2 fixing bacteria in order to manufacture ProtonTM (>70% protein content) high protein feed for use in the aquafeed market. They are also one of ten stakeholders in project REACT-FIRST, an industrial/academic consortium with an interest in the chain of substrate to product [[22](#_ENREF_22)]. Power to Protein (PtP) and Solar Foods[[8]](#footnote-8) both also utilise gas fermentation technologies to produce microbial protein, with the former intending to capture nitrogen from wastewater in the form of ammonium [[153](#_ENREF_153), [154](#_ENREF_154)]. However, pilot studies found that growth was limited by insufficient gas mass transfer from microbubbles into the bacteria cells, and in the case of PtP achieving only 29% of target production rates [[153](#_ENREF_153)].

### **Bacterial SCP challenges**

As observed with commercial mycoprotein production, rapidly proliferating bacteria exhibit a high nucleic acid (RNA) content (typically >16% dry weight) [[155](#_ENREF_155)]. As a consequence, when bacterial SCP is produced for human consumption, the high nucleic acid content becomes a significant problem as ingestion of high levels of purine containing compounds (derived from RNA breakdown) increases the blood plasma uric acid concentration, which may result in gout and the formation of kidney stones [[156](#_ENREF_156)]. A variety of methods have been developed to address the problem [[157](#_ENREF_157)], including the utilisation of endogenous ribonucleases which can be activated with heat treatment (60–70°C), and is also the approach as used in the production of Quorn™ [[158](#_ENREF_158)]. Degraded RNA components can then diffuse out of the cells, but a significant loss in biomass (35–38%) as a consequence has been reported [[159](#_ENREF_159)].

A further safety challenge arises from the fact that many bacterial species can produce a variety of toxins, which limit the use of a large number of species for use with SCP production. The toxins can be extracellular (exotoxins), or membrane bound (endotoxins). For example, *Pseudomonas* spp. and *Methylomonas methanica* both yield high levels of biomass derived protein, but also produce exotoxins [[160](#_ENREF_160)]. Numerous bacteria produce exotoxins, which can include enterotoxin, erythrogenic toxin, alpha-toxin, and neurotoxin [[161](#_ENREF_161)]. These are an integral component of gram-negative bacterial cell walls, and are liberated upon lysis. However, exotoxins may be dealt with comparatively easily as they are present in soluble form in the culture media, and are generally heat labile [[162](#_ENREF_162)]. Conversely, removal of endotoxins is difficult as they form part of cellular components of gram-negative bacteria.

### **Bacterial SCP regulation**

### **Remarks bacterial SCP**

Literature indicates that optimised bacterial single cell protein production remains a laborious, costly and time intensive process. Technical advances in the field of microfluidics may assist with optimising fermentation conditions, however devices reliant on this technology are not yet industrially standardised, mass-produced, or made generally available to companies. Advances in the niche area of bacterial fermentation technology is reliant on availability of funding and expertise, and fortunately, the literature indicate that a rising number of microbial protein startups are receiving increasing levels of grant and private funding to aid in establishing their capability, rather than reliance of commercial loans from the. On a global scale, it appears there is significant potential for scaling up of many of the existing, small precision fermentation-based operations. However, in reality, many of these operations are currently at the low end of scale-up/scale-out evaluation, and are unlikely to come on stream in the near future while addressing significant challenges such as substrate sourcing and regulatory uncertainty arising from the use of substrates such as food waste or activated sewage sludge [[163](#_ENREF_163)]. Ultimately however, integration of various processes in the value-chain of microbial protein production with focused expertise from relevant stakeholders at each step could help to reduce environmental impact and increase performance.

### **Fungal SCP**

### **Fungal SCP sector**

A range of fungi have been evaluated for use as SCP, including *Saccharomyces*, *Fusarium*, and *Torulopsis*, and for which commercially available products are available [[139](#_ENREF_139)]. Fungi grown for SCP generally have a protein content of 30–50% by mass protein [[139](#_ENREF_139)], and with an amino acid composition that compares favourably with FAO/WHO guidelines [[87](#_ENREF_87)]. In addition to protein, SCP derived from fungi can also provide a valuable source of vitamins, primarily from the B-complex group, and the cell walls, which are rich in glucans, can contribute to dietary fibre. However, fungi also contain moderate to high levels of nucleic acid (7–10% w/w) [[139](#_ENREF_139)] which are too high for general human consumption and which require post biomass harvest processing in order reduce it to acceptable levels [[156](#_ENREF_156)].

Research and development of SCP with a variety of fungal species remains ongoing process and may lead to novel products or production processes at some point in the future. However, current research is primarily focused on the use of waste streams as substrates, for example sugarcane bagasse (e.g., *Penicillium janthinellum* with 46% protein) [[164](#_ENREF_164)]), whey (mixed yeast cultures) [[165](#_ENREF_165)] and mixtures of food industry waste, including orange and potato residues [[166](#_ENREF_166)].

### **Fungal SCP commercial (Mycoprotein SCP)**

Mycoprotein is the generic name given to the ribonucleic acid (RNA) reduced biomass of the filamentous fungus *F. venenatum* (ACC,culture PTA 2684) and which is produced using a continuous fermentation process [[167](#_ENREF_167)]. The development of mycoprotein originated in the early 1960s, when there was concern over the likelihood of a global dietary protein shortages. Developed by Marlow Foods in the UK, QuornTM was the result of a joint venture between Rank Hovis McDougall (RHM) and Imperial Chemical Industries (ICI). Produced by Marlow Foods (UK) and QuornTM mycoprotein was approved for general food use in the UK during 1985, and shortly after in the rest of Europe. The QuornTM meat protein substitute was the first mycoprotein-based product developed specifically for the human food market and is sold as a cooking ingredient but also as a meat substitute in a range of prepackaged meals.

### **Mycoprotein consumer**

All Quorn foods contain fungal mycoprotein as a primary ingredient, which is derived from the *Fusarium venenatum* fungus [[168](#_ENREF_168)]. For most of the Quorn product range, the cultured fungal biomass is dried, mixed with egg albumen binder, the texture adjusted, and the resulting product pressed into a variety of different forms. A vegan formulation is also now available where potato protein is employed as the binder in place of egg albumen [[169](#_ENREF_169)]. Quorn is primarily sold in the UK and Europe, but is now available in 14 other countries, including the USA, with the brand now owned by Monde Nissin.

In terms of environmental impact, production of QuornTM mycoprotein through the use of fermentation provides for a significantly reduced environmental footprint in terms of emissions, land and water usage in comparison rearing livestock [[137](#_ENREF_137)].

### **Mycoprotein commercial**

Mycoprotein is commercially produced by continuous flow fermentation of filamentous fungi, *Fusarium venenatum* on a glucose substrate. The process is run on a batch basis with each production run typically taking approximately 6 weeks from start to finish. Mycoprotein recovered from the culture as a paste ready for further processing [[170](#_ENREF_170)]. It is well tolerated by humans and exhibits an extremely low allergenic potential [[171](#_ENREF_171)]. It is currently employed as a main ingredient in wide range products of ready meals, including burgers, pastries, sausages and meat style pieces [[172](#_ENREF_172)].

The nutritional benefits associated with the intake of mycoprotein result from its chemical composition. The fungal hyphal cell walls are a source of fibre (chitin and glucan), the cell membranes provide a source of polyunsaturated fat and the cytoplasm a source of protein [[36](#_ENREF_36)]. Mycoprotein contains all the essential amino acids, and which contribute to a PDCAAS value of 0.91, based on an estimate of 78% digestibility [[34](#_ENREF_34)]. Mycoprotein contains no cholesterol is a good source of zinc, selenium, iron and vitamin B12 while being low in sodium.

### **Mycoprotein market**

The UK is currently reported to be the world leader in mycoprotein fermentation and as a result commercial scale production are already established [[172](#_ENREF_172)]. Since its launch in 1985, sales of Quorn products have steadily increased and by 2005 the brand occupied approximately 60% of the meat-replacement food market in the UK, with estimated annual sales in the region of £95 million [[173](#_ENREF_173)]. From 2006, Quorn products were available to purchase in the UK and Europe, and North America (Canada and United States), and from 2010 in Australia. The market for Quorn products has been reported to be increasing globally, particularly since the introduction of vegan defined products into its range [[168](#_ENREF_168)].

### **Mycoprotein challenges**

Development of SCP processes is driven by the need to find new sustainable sources of human dietary protein. The economic benefit of being able to utilise readily available substrates and waste streams has also been a driver, with SCP seen as having the potential to exploit the currently unprofitable biorefinery process and provide a viable means of reducing downstream processing costs associated with the disposal of a variety of different waste streams.

However, environmental concerns now play a significant role in driving the development of novel SCP products. This is seen particularly for SCP production processes which have the ability to utilise greenhouse gases (e.g., algal SCP using carbon dioxide [[134](#_ENREF_134)], bacterial SCP from methane [[136](#_ENREF_136)]). These processes may be economically unviable in the short term, principally due to problems in overcoming production scale-up, but may survive where environmental concerns, as well as economic concerns, are driving the development of SCP products produced from waste streams.

With SCP production in general, the raw material accounts for 62% of the total product cost, followed by 19% for charges attributed to the production process (e.g., labour, energy, consumables) [[167](#_ENREF_167)]. The primary influencing factor is therefore cost of the substrate, and this explains the quest for adoption of different substrates, particularly those from waste streams.

The economic viability of SCP production processes are dependent on a combination of production cost, level of capital investment required, and amount of profitability recognised. Current estimates for SCP production place the cost of raw materials in the region of 35 to 55% of the total manufacturing cost. Operational cost, which include labour, energy requirements and consumables typically account for 45-55% of the manufacturing costs [[166](#_ENREF_166)]. These figures indicate the difficulties encountered with establishing a facility and justify why the use of waste biomass is sometimes viewed as a means to reduce the substrate costs, where the substrate does not compromise the final product. The scale of production is also important to viability of SCP production, as there is a relationship between cost and scale of production. This is seen with the fact that continuous fermentation operations have been proven to be the most profitable ones and the majority of commercial SCP operations are those which have been adjusted to a continuous design [[174](#_ENREF_174)].

### **Mycoprotein regulation**

The regulatory framework for fermentation products is complex and difficult to navigate. Extensive product testing is required to register novel food products, including mycoproteins. as a food source, but Brexit may provide an opportunity for the UK regulatory bodies to streamline these processes.

Fungal SCPs typically exhibit a nutritionally favourable composition of lipids, protein, and fibre. Despite the protein produced being generally low in the amino acid methionine, the amino acid composition of fungal SCP generally meet with levels recommended by the FAO/WHO guidelines [[137](#_ENREF_137), [162](#_ENREF_162)]. In addition to being a good source of dietary protein, fungal SCP can also be employed to improve the nutritional functional properties of food products [[175](#_ENREF_175)].

### **Mycoprotein remarks**

The SCP market has become highly competitive in terms of the commercial products that are now available, with the plant-based and mycoprotein sectors currently competing for larger share of the retails market. For example, the value of the UK protein powder market for 2021 has been estimated at US$ 20.57 Billion and is projected to reach US$ 41.51 Billion by 2028 [[176](#_ENREF_176), [177](#_ENREF_177)].

Although, SCP protein currently provides a comparatively minor proportion of the human diet, increasing global demand for protein will make adoption of SCP sources increasingly attractive [[178](#_ENREF_178)]. The high growth rates typically seen with microbes, coupled with the ability to frequently utilise unique substrates, including carbon dioxide and or methane, offer processes which can achieve higher conversion efficiencies and/or sustainability than seen with traditional agriculture.

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# **Lab-cultured meat**

## **Lab-cultured meat sector**

Cellular agriculture as it has become called, is an emerging branch of biotechnology that aims to address issues associated with the environmental impact, animal welfare and sustainability challenges of conventional animal farming for meat production. Cultured meat may be produced by applying current cell culture practices and biomanufacturing methods to specific mammalian cell lines to generate tissues, or nutritional proteins for human consumption. However, significant improvements and modifications needed for the process to be considered both cost efficient and robust enough to be brought to production at scale for food supply [[179](#_ENREF_179)].

Most of the advanced work in this field is now undertaken within start-up companies, who are selective with the information they publish. Subsequently, it is be difficult to ascertain what specific progress is being made in the field in general.

## **Lab-cultured meat consumer**

Existing studies on consumer perceptions of cultured meat vary in their approach but suggest some commonality in finding that respondents provided a diverse spectrum of opinions, ranging from highly supportive to extremely disapproving, with shades of uncertainty in between [[163](#_ENREF_163)]. The dominant social issues related to cultured meat have primarily been ethics and consumer acceptance. The ethics literature generally reports supportive arguments for cultured meat [[180](#_ENREF_180)]. These are based on both the environmental and animal welfare benefits [[181](#_ENREF_181)].

The diversity of public opinions on cultured meat has been described in a number of scientific publications. Hocquette, (2015) [[182](#_ENREF_182)] evaluated the online survey responses of 1890 respondents, and identified three clusters of response, those in favour, those against, and those of no opinion. A separate survey of 673 participants in the US reported a similar findings, but with two thirds of the respondents commenting that they would willing to try cultured meat, but only one third commenting they would consider eating it on a regular basis [[183](#_ENREF_183)]. A variety of focus group studies have also been published, including those from the Netherlands [[184](#_ENREF_184)], Finland [[185](#_ENREF_185)] and the UK [[186](#_ENREF_186)]. The majority of these studies reported a diversity of responses which spanned from positive to negative, however the Finnish study indicated lower levels of support for cultured meat, while the Dutch study revealed that the more respondents had learnt about cultured meat, the greater the likelihood they would support it. In addition, analysis of social media content and comments on published news articles regarding cultured meat suggest the perceived unnaturalness of cultured meat may be a hurdle to adoption [[187](#_ENREF_187)]. However, the relevant literature generally reports supportive arguments by consumers for cultured meat, in particular when adopting a philosophically orientated approach [[180](#_ENREF_180)], but many of these accounts are based on environmental and animal welfare benefits and do not take in to account the economics of establishing successful cultured meat systems (e.g., economic cost to the consumer).

## **Lab-cultured meat commercial**

In terms of current sector status, US-based UPSIDE Foods (www.upsidefoods.com) (formerly known as Memphis Meats) released the first example of a cultured meatball in 2016, followed in 2017 by an example cultured poultry. Modern Meadow, a US-based start-up, has demonstrated a highbred substitute ‘steak and chips’ product, comprised of high-protein food products formed from cultured muscle cells combined with a hydrogel [[188](#_ENREF_188)]. There are also number of stage start-up companies known to have entered the field, as well as several University laboratories who have expressed an interest in the field (e.g., New Harvest funded Research Fellows at the Universities of Bath, Ottawa, and North Carolina State University) [[163](#_ENREF_163)].

Cultured meat technologies have the potential to deliver reduced water use, GHG emissions and land usage compared to conventional livestock meat production. This evaluation is based on a series of publications on “Life Cycle Assessment”, but all of which are based on hypothetical models for what form commercial scale cultured meat production might potentially take. In a comparison of cultured and conventionally produced meats, Tuomisto *et al*., (2011) [[189](#_ENREF_189)] determined that cultured meat production resulted in 78–96% less GHG emissions, 99% less land, 82–96% less water, and 7–45% less energy were used, depending on which species of animal it was compared to. Conversely, the projections published by Mattick *et al.,* (2015) [[190](#_ENREF_190)] indicate a trade-off between conventional and cultivated meat production, with the need for significant energy use by cultured meat production having a greater global warming impact than that seen with conventional livestock rearing practices. In a similar study, Smetana *et al.,* (2015) [[191](#_ENREF_191)] compared cultured meat to a range of meat substitutes (e.g., plant-based, mycoprotein, and dairy), and reported that their model indicated that cultured meat production was likely to have the greatest adverse environmental impact, primarily as a result of high energy requirements. However, all three studies noted that cultured meat technology possess significant scope for innovation which may result in an eventual reduction in energy requirements below those used in the published studies. Aside from projected adverse environmental impacts, cultured meat production may ultimately be less subject to biological risk (e.g., microbial contamination) and disease (e.g., Creutzfeldt-Jakob disease (CJD)) [[192](#_ENREF_192)].

Cultured meat production would still require some animals to provide donor cellular material, but considerably fewer than for conventional livestock rearing. From the perspective of animal protection, this would be a positive outcome. However, the driver behind this may be economically motivated as it may give rise to the possibility of considerably higher returns per animal than seen with conventional production practices [[163](#_ENREF_163)].

## **Lab-cultured meat Markets**

There are multiple small companies investigating the potential of lab meat cultivation. Cultures cannot currently be produced easily at scale. As such, this alternative protein industry is at an early stage of its development and not yet fully commercially available in the UK.

## **Lab-cultured meat Challenges**

A 2020 Government Accountability Office report issued to a House Committee described AP cell-cultured meats as a “business venture still in the research and development phase” [[73](#_ENREF_73)]. For the FDA and USDA to approve cell-cultured food products, manufacturers must provide information about animal tissue collection, growth medium, genetic engineering, scaffolding, production methods, product safety and composition, and antibiotic content [[73](#_ENREF_73)]. Even after cell cultured products are approved, they must compete with other branded AP plant-based products, consumers may not accept them, and it is unclear whether cell-cultured products will be approved for Kosher or Halal labelling to comply with Jewish and Islamic dietary restrictions [[74](#_ENREF_74)].

Affordable production of cultured meat coincident with a low GHG footprint may be achievable theoretically, however, the scale of production that would be required to make it a viable commodity is probably beyond current tissue engineering capabilities. Precedents can be taken from other large scale bioprocessing operations, such as the production of the mycoprotein foodstuff Quorn [[193](#_ENREF_193)].

To date, tissue engineering has largely been focused on medical applications such as regenerative medicine, and non-animal technologies for in-vitro models used for drug discovery and toxicology [[163](#_ENREF_163)]. Technically, the principles for producing cultured meat are roughly the same, but with cultured meat on a scale many times larger, and with the added caveat that the resulting product has to be affordable to the general public. However, in this respect, cultured meat is a product for consumption rather than a medical grade resource, and so the associated regulatory requirements are not as stringent, and the grade (purity) of raw materials need not as high as dictated for biomedical applications.

## **Lab-cultured meat regulation**

Prior to any cultured-meat product being placed on the UK market, it must be approved by The Food Standards Agency (FSA) under the “novel food” regulation (EU) 2015/2283 (as retained in UK law) [[50](#_ENREF_50)].

However, the primary regulatory challenge facing the UK cultured meat industry are based on current labelling and safety requirements. In terms of labelling, the Food Information to Consumers Regulations[[9]](#footnote-9), (assimilated UK law), will apply to all cultured meat products. These regulations require that any information supplied accompanying a food product must not mislead the consumer, in respect of product identity, composition, or manufacturing methods employed. This will require the producers of cultivated meat products ensure that both the information provided on the food label, and the manner in which it is provided does not deceive the consumer. This regulatory aspect is legally complicated by the use of non-defined ontology, and whether cultivated meat products could be described as ‘meat’, or if additional terms should be included to aid consumer clarity [[194](#_ENREF_194)]. Given the rapidly evolving technology involved, any regulatory frameworks that are agreed upon will likely be the subject of continuous revision change [[163](#_ENREF_163)]. In addition, as different forms of cultured meat products, production methods, and production facilities are developed, these may require the implementation of different regulatory approaches [[163](#_ENREF_163)]. Other policy issues yet to be resolved include, will the culture suites/bioreactors be designated agricultural facilities (which may affect business taxation rates), will waste products be designated as animal by products, and dealing with the possibilities for food fraud through mislabelling of cell-based and conventional meat products [[163](#_ENREF_163)].

In terms of safety, cultured meat producers will be legally responsible for demonstrating to the FSA that there are no safety risks to human health due to product consumption. Singapore have already approved the sale of cultivated meat, despite the available scientific data not ruling out the possibility of unforeseen risk to human health or the environment being introduced through the adoption of new, or upscaled production methods, which could include the potential risk of microbial and viral contamination. As a result, there may be a significant delay in FSA approval of any new cultured meat products [[195](#_ENREF_195)].

Literature indicates that current UK and EU regulatory provision for dealing with cultured meat production technology is inadequate and in need of significant revision. It is suggested that cultured meat products should theoretically be subject to novel food regulations [[196](#_ENREF_196)]. UK and EU Novel Food Regulation is indicated as the most likely pathway for the control of cultured meat production [[196](#_ENREF_196)]. However, key to this will be establishing whether cultured meat is definitively a product of animal origin. Should cultured meat be defined as being of animal origin, then regulation of production would be the responsibility of a series of different organisations. For example, muscle biopsies for harvesting cellular material together with the rearing of donor animals would come under Livestock, Animal Welfare & Slaughter Regulations, as administered by the Department for Environment, Food & Rural Affairs (Defra), The Animal and Plant Health Agency (APHA), the Food Standards Agency (FSA), as well as relevant Local Authorities. The cultured products would need to be controlled through specific food regulations via the FSA, Environmental Health, and Trading Standards. However, the literature highlights the scientific concern for overall product safety [[163](#_ENREF_163), [196](#_ENREF_196)], and requires an awareness of auditing from the outset of animal cell-based product development. What is clear, is that further evaluation of current regulatory requirements and existing provisions to confirm or dispel uncertainties over a variety of potential issues is required.

## **Lab-cultured meat remarks**

With respect to animal welfare, if cultured meat alternatives were to replace a small fraction of current meat production practices, this could significantly impact on the number of animals processed for human protein consumption, and supporting the ethical grounds for adoption of these products. However, based on current scientific evidence, cell-based meat substitutes will require additional technological development to address the currently required animal derived inputs such as foetal bovine serum. From a public health perspective, there has been only limited research on the food safety implications associated with consuming these meat substitutes alternatives, considering their requirements for the use of hormonal growth regulators and antibiotics [[194](#_ENREF_194)]. However, although this alternative has been proposed as a more sustainable approach for dietary protein production, the environmental impact of large-scale cultured meat production is still to be determined. Initial projections have indicated that switching to cultured meat production may reduce land use by 99% compared to rearing livestock. Unfortunately, the associated energy requirements, the need for very strict hygiene arrangements, coupled with the generation of potentially hazardous waste materials (expired culture media and antibiotic residues) currently make highly it inefficient in terms of energy, water and overall expenditure [[55](#_ENREF_55)]. In relative terms, a combination of energy costs coupled with GHG emissions generated during the production process have been estimated to be greater than that currently emitted by rearing livestock in the long term [[197](#_ENREF_197)], with the caveat that this is based on the assumption that we continue to employ carbon-based energy sources. Although cultured meat approaches to dietary protein production could provide a promising alternative, further evaluation will be required to explore options for reducing the current energy costs and environmental impact.

The possibility of producing small-scale cultured meat products for human consumption may be achievable on a commercial basis at some point in the near future, although in a basic format it is already possible to a degree. However, on a realistic timescale for delivery, and at a competitive price to that for established substitute meat products, the outcome is less definitive. Progressing from proof of principal demonstrations to commercial large-scale production presents a significant challenge for the technology, particularly with respect to the development of effective, ethically produced, and competitively priced culture media. General scientific opinion, as captured in the current literature, would place production of cultured meat on a scale that would be sufficient to impact on net-zero targets, decades away, if possible at all.

# **Overall recommendations**

To summarize, the increasing demand for sources of non-meat or dairy derived dietary protein are forecast to become a consolidated trend in the near future, particularly as the international community widens its search for new sources of dietary proteins to match the requirements of the growing global population. The current most exploited non-meat and dairy derived protein sources include plants, algae, bacteria, insects and fungi, as they are all considered sustainable, environmentally friendly, and able to yield sufficient protein of a quality to make them commercially viable prospects. However, despite the many recommendations cited in the current literature to decrease dietary intake of meat and dairy derived products, the impact of such advice appears minimal. Consumers remain the primary driver to expansion in the field, with consumption habit, cultural constraints, and perception of what represents healthy food taste, cost, and texture remaining major hurdles to acceptance. The health properties attributed to many of these novel foods may persuade additional consumers to consider adopting vegetarianism and veganism in the future. Successful global adoption of alternative dietary proteins and their respective FS will require greater consumer acceptance and understanding about these novel technologies and their potential benefits. On the technical front, a shift in the protein consumption habit will require a re-evaluation of current methods employed to assess their authenticity, quality and bioavailability of proteins from these novel sources. This will require the revaluation of the two main approaches to determining product protein quality: PDCAAS (protein digestibility-corrected amino acid score) and DIAAS (proteins digestible indispensable amino acid score).

Regulation of these new and novel products will be required, in order to accommodate various unique aspects of their composition and production. In particular, concerns have been raised about the potential presence of allergens or chemical contamination in the case of plants, insect, algal and cultured meat, raising questions about possible hazards to consumers, and while addressing a growing high demand for novel and existing sustainable protein sources to replace animal-based sources.

# **Bibliography**

1. Agreement, P. *Paris agreement*. in *report of the conference of the parties to the United Nations framework convention on climate change (21st session, 2015: Paris). Retrived December*. 2015. HeinOnline.

2. Skidmore, C., *Mission Zero: Independent Review of the UK Government's Approach to Delivering Net Zero.* 2022.

3. Clark, M.A., et al., *Global food system emissions could preclude achieving the 1.5 and 2 C climate change targets.* Science, 2020. **370**(6517): p. 705-708.

4. Desa, U., *World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100.* UN DESA| United Nations Department of economic and social affairs. un. org, 2017.

5. Alexandratos, N. and J. Bruinsma, *World agriculture towards 2030/2050: the 2012 revision.* 2012.

6. Tubiello, F.N., et al., *Pre-and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems.* Earth System Science Data, 2022. **14**(4).

7. Bajželj, B., et al., *Importance of food-demand management for climate mitigation.* Nature Climate Change, 2014. **4**(10): p. 924-929.

8. Conforti, P., *Looking ahead in world food and agriculture: perspectives to 2050*. 2011: Food and Agriculture Organization of the United Nations (FAO).

9. Springmann, M., et al., *Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail.* The Lancet Planetary Health, 2018. **2**(10): p. e451-e461.

10. Wright, I.A., et al., *Integrating crops and livestock in subtropical agricultural systems.* Journal of the Science of Food and Agriculture, 2012. **92**(5): p. 1010-1015.

11. Loken, B., *Bending the curve: the restorative power of planet-based diets.* 2020.

12. Short, S., Strauss, B., and Lotfian, P., *Alternative Proteins for Human Consumption*, S. Shima Barakat, Editor. 2022, Cambridge University.

13. Rubio, N.R., N. Xiang, and D.L. Kaplan, *Plant-based and cell-based approaches to meat production.* Nature Communications, 2020. **11**(1): p. 6276.

14. NASA, *NASA Research Finds 2010 Tied for Warmest Year on Record*. 2011.

15. Lawrence, M.A. and P.I. Baker, *Ultra-processed food and adverse health outcomes.* BMJ, 2019. **365**: p. l2289.

16. Costa, C.S., et al., *Consumption of ultra-processed foods and body fat during childhood and adolescence: a systematic review.* Public Health Nutrition, 2017. **21**(1): p. 148-159.

17. Monteiro, C.A. and G.J. Cannon, *The role of the transnational ultra-processed food industry in the pandemic of obesity and its associated diseases: problems and solutions.* World Nutrition, 2019. **10**(1): p. 89-99.

18. Day, L., et al., *Wheat-gluten uses and industry needs.* Trends in food science & technology, 2006. **17**(2): p. 82-90.

19. Sanchez-Sabate, R. and J. Sabaté, *Consumer Attitudes Towards Environmental Concerns of Meat Consumption: A Systematic Review.* 2019. **16**(7).

20. Berger, A., *Whole Raw Soybeans as a Cost Competitive Protein Supplement for Cows and Calves*, in *Beef Watch*. 2018, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

21. Lindsay, S.H. and L.G. Claywell, *Considering soy.* Nursing for Women's Health, 1998. **2**(1): p. 41-44.

22. Anwar, D. and E.-C. Ghadir, *Nutritional quality, amino acid profiles, protein digestibility corrected amino acid scores and antioxidant properties of fried tofu and seitan.* Food and Environment Safety Journal, 2019. **18**(3).

23. Kalin, F., *Wheat gluten applications in food products.* Journal of the American Oil Chemists' Society, 1979. **56**(3Part3): p. 477-479.

24. Kumar, P., et al., *Meat analogues: Health promising sustainable meat substitutes.* Critical reviews in food science and nutrition, 2017. **57**(5): p. 923-932.

25. Julson, E., *Pea Protein Powder: Nutrition, Benefits and Side Effects*. 2020.

26. Prakash, V. and M.S. Narasinga Rao, *Physicochemical Properties of Oilseed Protein.* Critical Reviews in Biochemistry, 1986. **20**(3): p. 265-363.

27. Moure, A., et al., *Functionality of oilseed protein products: A review.* Food research international, 2006. **39**(9): p. 945-963.

28. Pimentel, D. and M. Pimentel, *Sustainability of meat-based and plant-based diets and the environment.* The American journal of clinical nutrition, 2003. **78**(3): p. 660S-663S.

29. Pimentel, D. and M. Pimentel, *Sustainability of meat-based and plant-based diets and the environment1–3.* Am J Clin Nutr, 2003. **78**: p. 660S-3S.

30. Geijer, T. and A. Gammoudy, *Plant-based meat and dairy to become€ 7.5 billion market in Europe by 2025. ING*. 2022.

31. Rosegrant, M.W. and S.A. Cline, *Global food security: challenges and policies.* Science, 2003. **302**(5652): p. 1917-1919.

32. UK, I., *IUK-100622-Alternative Proteins Report*. 2022, UK Research and Innovation.

33. Vegconomist, *Naylor Farms Begins Constructing “World’s First” Brassica Protein Facility*, in *Vegconomist*. 2023.

34. Perrett, M., *Branston-to-open-new-6M-factory-to-extract-potato-protein*, in *Food Manufacture*. 2022, William Reed Business Media

35. Alcorta, A., et al., *Foods for plant-based diets: Challenges and innovations.* Foods, 2021. **10**(2): p. 293.

36. Aschemann-Witzel, J., et al., *Plant-based food and protein trend from a business perspective: Markets, consumers, and the challenges and opportunities in the future.* Critical Reviews in Food Science and Nutrition, 2021. **61**(18): p. 3119-3128.

37. Zhao, S., et al., *Meet the meatless: Demand for new generation plant‐based meat alternatives.* Applied Economic Perspectives and Policy, 2023. **45**(1): p. 4-21.

38. Bartashus, J., *Plant-based Foods Market to Hit $162 Billion in Next Decade, Projects Bloomberg Intelligence*, in *Bloomberg Intelligence*. 2021.

39. Silva, A.R., M.M. Silva, and B.D. Ribeiro, *Health issues and technological aspects of plant-based alternative milk.* Food Research International, 2020. **131**: p. 108972.

40. FutureBridge *Changing Dynamics from Dairy to Alternative Dairy*. Future Bridge, 2020.

41. Claeys E, S.S., Balcaen A et al, *Quantification of fresh meat peptides by SDS–PAGE in relation to ageing time and taste intensity.* Meat Science, 2004. **67**(2): p. 281-288.

42. Riascos, J.J., et al., *Hypoallergenic Legume Crops and Food Allergy: Factors Affecting Feasibility and Risk.* J. Agric. Food Chem, 2010. **58**(1): p. 20-27.

43. Arntfield, S., *Proteins from oil-producing plants*, in *Proteins in food processing*. 2018, Elsevier. p. 187-221.

44. Perez-Cueto, F.J.A., et al., *How barriers towards plant-based food consumption differ according to dietary lifestyle: Findings from a consumer survey in 10 EU countries.* International Journal of Gastronomy and Food Science, 2022. **29**: p. 100587.

45. Sha, L. and Y.L. Xiong, *Plant protein-based alternatives of reconstructed meat: Science, technology, and challenges.* Trends in Food Science & Technology, 2020. **102**: p. 51-61.

46. Hadi, J. and G. Brightwell, *Safety of Alternative Proteins: Technological, Environmental and Regulatory Aspects of Cultured Meat, Plant-Based Meat, Insect Protein and Single-Cell Protein.* 2021. **10**(6).

47. Boukid, F., et al., *vegan alternatives to processed cheese and yogurt launched in the European market during 2020: a nutritional challenge?* Foods, 2021. **10**(11): p. 2782.

48. Pelkmans, J. and A. Renda, *Does EU regulation hinder or stimulate innovation?* 2014.

49. Capuzzo, E. and T. McKie, *Seaweed in the UK and abroad–status, products, limitations, gaps and Cefas role.* Defra <https://www>. gov. uk/government/publications/the-seaweed-industry-in-theuk-and-abroad, 2016.

50. Union, E., *Regulation (EU) 2015/2283 of the European Parliament and of the Council on novel foods, amending Regulation (EU) No 1169/2011 of the European Parliament and of the Council and repealing Regulation (EC) No 258/97 of the European Parliament and of the Council and Commission Regulation (EC) No 1852/2001 (2013/0435 (COD). OJ L 327, 11.12.2015, p. 1–22.*, in *Regulation (EU) 2015/2283*, u.P.a.o.t.C.a. Commission, Editor. 2015.

51. Union:, E., *Commission Implementing Regulation (EU) 2021/882 of 1 June 2021 Authorising the Placing on the Market of Dried Tenebrio molitor larva as a Novel Food under Regulation (EU) 2015/2283 of the Commission Implementing Regulation (EU) 2021/882 of 1 June 2021 Authorising the Placing on the Market of Dried Tenebrio molitor larva as a Novel Food under Regulation (EU) 2015/2283 of the European Parliament and of the Council, and Amending Commission Implementing Regulation (EU) 2017/2470; European and of the Council, and Amending Commission Implementing Regulation (EU) 2017/2470; European*, in *Commission Implementing Regulation (EU) 2021/882*, E. Union:, Editor. 2022, European Union:: Luxemburg

52. Bodenheimer, F.S. and F. Bodenheimer, *Insects as human food*. 1951: Springer.

53. Abbasi, T. and S. Abbasi, *Reducing the global environmental impact of livestock production: the minilivestock option.* Journal of Cleaner Production, 2016. **112**: p. 1754-1766.

54. Huis, A.v., *Potential of Insects as Food and Feed in Assuring Food Security.* Annual Review of Entomology, 2013. **58**(1): p. 563-583.

55. Alexander, P., et al., *Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use?* Global Food Security, 2017. **15**: p. 22-32.

56. Jarchlo, A.I. and L. King, *Alternative proteins: Consumer survey*. 2021, Food Standard Agency, London.

57. McDougal, T., *Survey: 25% of UK consumers happy to try edible insects*, in *All About Feed*. 2021, Misset International,.

58. Van Huis, A., *Edible insects are the future?* Proceedings of the Nutrition Society, 2016. **75**(3): p. 294-305.

59. Anand, H., A. Ganguly, and P. Haldar, *Potential value of acridids as high protein supplement for poultry feed.* International Journal of Poultry Science, 2008. **7**(7): p. 722-725.

60. Rumpold, B.A. and O.K. Schlüter, *Potential and challenges of insects as an innovative source for food and feed production.* Innovative Food Science & Emerging Technologies, 2013. **17**: p. 1-11.

61. Niyonsaba, H.H., et al., *Profitability of insect farms.* Journal of Insects as Food and Feed, 2021. **7**(5): p. 923-934.

62. Dossey, A.T., J.T. Tatum, and W.L. McGill, *Chapter 5 - Modern Insect-Based Food Industry: Current Status, Insect Processing Technology, and Recommendations Moving Forward*, in *Insects as Sustainable Food Ingredients*, A.T. Dossey, J.A. Morales-Ramos, and M.G. Rojas, Editors. 2016, Academic Press: San Diego. p. 113-152.

63. Mancuso, T., L. Pippinato, and L. Gasco, *The European insects sector and its role in the provision of green proteins in feed supply.* Calitatea, 2019. **20**(S2): p. 374-381.

64. Fels-Klerx, H.J.v.d., et al., *Food Safety Issues Related to Uses of Insects for Feeds and Foods.* Comprehensive Reviews in Food Science and Food Safety, 2018. **17**(5): p. 1172-1183.

65. Mancini, S., et al., *Exploring the Future of Edible Insects in Europe.* Foods, 2022. **11**(3): p. 455.

66. Halloran, A., et al., *Edible insects in sustainable food systems*. Vol. 10. 2018: Springer.

67. Ites, S., et al., *Modularity of insect production and processing as a path to efficient and sustainable food waste treatment.* Journal of Cleaner Production, 2020. **248**: p. 119248.

68. Janzen, H.H., *What place for livestock on a re-greening earth?* Animal Feed Science and Technology, 2011. **166-167**: p. 783-796.

69. Jamieson, S., *Bug burgers and cricket crepes: Britain's first insect restaurant opens in Wales.* Telegraph (24 October 2015), 2015.

70. Little, K., *Burger chain adds bugs to the menu… on purpose.* CNBC (29 June 2015), 2015.

71. Dobermann, D., J.A. Swift, and L.M. Field, *Opportunities and hurdles of edible insects for food and feed.* Nutrition Bulletin, 2017. **42**(4): p. 293-308.

72. Hanboonsong, Y., *Edible insects and associated food habits in Thailand.* Forest insects as food: humans bite back, 2010. **173**: p. 182.

73. Belluco, S., et al., *Edible insects in a food safety and nutritional perspective: A critical review.* Comprehensive reviews in food science and food safety, 2013. **12**(3): p. 296-313.

74. DeFoliart, G.R., *Insects as human food: Gene DeFoliart discusses some nutritional and economic aspects.* Crop protection, 1992. **11**(5): p. 395-399.

75. Shantibala, T., R.K. Lokeshwari, and H. Debaraj, *Nutritional and antinutritional composition of the five species of aquatic edible insects consumed in Manipur, India.* Journal of Insect Science, 2014. **14**(1).

76. Srinroch, C., et al., *Identification of novel allergen in edible insect, Gryllus bimaculatus and its cross-reactivity with Macrobrachium spp. allergens.* Food Chemistry, 2015. **184**: p. 160-166.

77. Ribeiro, J.C., et al., *Allergic risks of consuming edible insects: A systematic review.* Molecular nutrition & food research, 2018. **62**(1): p. 1700030.

78. Ferreira de Oliveira, A.P. and A.P.A. Bragotto, *Microalgae-based products: Food and public health.* Future Foods, 2022. **6**: p. 100157.

79. Sousa, I., et al., *Microalgae in novel food products.* Food chemistry research developments, 2008: p. 75-112.

80. Enzing, C., et al., *Microalgae-based products for the food and feed sector: an outlook for Europe.* JRC Scientific and policy reports, 2014: p. 19-37.

81. J.J, M., *Microalgae-commercial potential for fuel, food and feed.* Food Science & Technology, 2012. **26**(1): p. 28-30.

82. Spolaore, P., et al., *Commercial applications of microalgae.* Journal of bioscience and bioengineering, 2006. **101**(2): p. 87-96.

83. Wild, K.J., H. Steingaß, and M. Rodehutscord, *Variability in nutrient composition and in vitro crude protein digestibility of 16 microalgae products.* Journal of animal physiology and animal nutrition, 2018. **102**(5): p. 1306-1319.

84. Skanderby, M., et al., *Dried milk products.* Dairy powders and concentrated products, 2009: p. 180-234.

85. Singh, P., et al., *Functional and edible uses of soy protein products.* Comprehensive reviews in food science and food safety, 2008. **7**(1): p. 14-28.

86. Singh, B. and U. Singh, *Peanut as a source of protein for human foods.* Plant Foods for Human Nutrition, 1991. **41**: p. 165-177.

87. Joint, F. and W.H. Organization, *Protein and amino acid requirements in human nutrition: report of a joint FAO/WHO/UNU expert consultation*. 2007: World Health Organization.

88. Gantar, M. and Z. Svirčev, *Microalgae and cyanobacteria: food for thought 1.* Journal of phycology, 2008. **44**(2): p. 260-268.

89. Grobbelaar, J.U., *Quality control and assurance: crucial for the sustainability of the applied phycology industry.* Journal of applied phycology, 2003. **15**: p. 209-215.

90. García, J.L., M. de Vicente, and B. Galán, *Microalgae, old sustainable food and fashion nutraceuticals.* Microb Biotechnol, 2017. **10**(5): p. 1017-1024.

91. Xu, L., et al., *Microalgal bioreactors: Challenges and opportunities.* Engineering in Life Sciences, 2009. **9**(3): p. 178-189.

92. Wang, B., C.Q. Lan, and M. Horsman, *Closed photobioreactors for production of microalgal biomasses.* Biotechnology advances, 2012. **30**(4): p. 904-912.

93. Gupta, P.L., S.-M. Lee, and H.-J. Choi, *A mini review: photobioreactors for large scale algal cultivation.* World Journal of Microbiology and Biotechnology, 2015. **31**: p. 1409-1417.

94. Havlik, I., T. Scheper, and K.F. Reardon, *Monitoring of Microalgal Processes*, in *Microalgae Biotechnology*, C. Posten and S. Feng Chen, Editors. 2016, Springer International Publishing: Cham. p. 89-142.

95. Guedes, A.C., H.M. Amaro, and F.X. Malcata, *Microalgae as sources of high added‐value compounds—a brief review of recent work.* Biotechnology progress, 2011. **27**(3): p. 597-613.

96. Acién, F., et al., *Photobioreactors for the production of microalgae*, in *Microalgae-based biofuels and bioproducts*. 2017, Elsevier. p. 1-44.

97. Chacón‐Lee, T. and G. González‐Mariño, *Microalgae for “Healthy” Foods—Possibilities and Challenges.* Comprehensive Reviews in Food Science and Food Safety, 2010. **6**(9): p. 655-675.

98. Winwood, R.J., *Recent developments in the commercial production of DHA and EPA rich oils from micro-algae.* Ocl, 2013. **20**(6): p. D604.

99. Norsker, N.-H., et al., *Microalgal production--a close look at the economics.* Biotechnology advances, 2011. **29**(1): p. 24-27.

100. Carlsson, A., et al., *Outputs from EPOBIO Project: micro-and macroalgae utility for industrial application*. 2007, York, UK: CPL Press.

101. Chisti, Y., *Biodiesel from microalgae.* Biotechnology advances, 2007. **25**(3): p. 294-306.

102. Bocanegra, A., et al., *Whole alga, algal extracts, and compounds as ingredients of functional foods: composition and action mechanism relationships in the prevention and treatment of type-2 diabetes mellitus.* International Journal of Molecular Sciences, 2021. **22**(8): p. 3816.

103. Ścieszka, S. and E. Klewicka, *Algae in food: a general review.* Critical Reviews in Food Science and Nutrition, 2019. **59**(21): p. 3538-3547.

104. Bourgougnon, N., A.-S. Burlot, and A.-G. Jacquin, *Algae for global sustainability?*, in *Advances in botanical research*. 2021, Elsevier. p. 145-212.

105. Gamero-Vega, G., M. Palacios-Palacios, and V. Quitral, *Nutritional Composition and Bioactive Compounds of Red Seaweed: A Mini-Review.* Journal of Food and Nutrition Research, 2020. **8**(8): p. 431-440.

106. Xu, J., et al., *An overview on the nutritional and bioactive components of green seaweeds.* Food Production, Processing and Nutrition, 2023. **5**(1): p. 18.

107. Banach, J., et al., *Alternative proteins for meat and dairy replacers: Food safety and future trends.* Critical Reviews in Food Science and Nutrition, 2023. **63**(32): p. 11063-11080.

108. Abreu, M.H., R. Pereira, and J.-F. Sassi, *Marine algae and the global food industry.* Marine algae, biodiversity, taxonomy, environmental assessment, and biotechnology. CRC Press, Bocca Raton, FL, 2014: p. 300-319.

109. Thakur, M., K. Singh, and R. Khedkar, *Phytochemicals: Extraction process, safety assessment, toxicological evaluations, and regulatory issues*, in *Functional and preservative properties of phytochemicals*. 2020, Elsevier. p. 341-361.

110. Abu-Ghannam, N. and E. Shannon, *Seaweed Carotenoid, Fucoxanthin, as Functional Food*, in *Microbial Functional Foods and Nutraceuticals*. 2017. p. 39-64.

111. Doubleday, Z.A. and S.D. Connell, *Weedy futures: can we benefit from the species that thrive in the marine Anthropocene?* Frontiers in Ecology and the Environment, 2018. **16**(10): p. 599-604.

112. FAO, *What's new*, in *Algae can play a greater role in food security and nutrition*, FAO, Editor. 2020, Food and Agriculture Organisation of the United Nations.

113. Kim, J.K., et al., *Seaweed aquaculture: cultivation technologies, challenges and its ecosystem services.* Algae, 2017. **32**(1): p. 1-13.

114. Angell, A.R., et al., *The protein content of seaweeds: a universal nitrogen-to-protein conversion factor of five.* Journal of applied phycology, 2016. **28**: p. 511-524.

115. Embling, R., et al., *‘Edible seaweeds’ as an alternative to animal-based proteins in the UK: Identifying product beliefs and consumer traits as drivers of consumer acceptability for macroalgae.* Food Quality and Preference, 2022. **100**: p. 104613.

116. Raja, K., V. Kadirvel, and T. Subramaniyan, *Seaweeds, an aquatic plant-based protein for sustainable nutrition - A review.* Future Foods, 2022. **5**: p. 100142.

117. Ahmed, A.B.A., et al., *Seaweed polysaccharides and their production and applications*, in *Seaweed Polysaccharides*. 2017, Elsevier. p. 369-382.

118. Reynolds, D., et al., *Seaweed proteins are nutritionally valuable components in the human diet.* The American Journal of Clinical Nutrition, 2022. **116**(4): p. 855-861.

119. Burrows, M., M. MacLeod, and K.K. Orr, *Mapping the intertidal seaweed resources of the Outer Hebrides.* 2012.

120. Gegg, P. and V. Wells, *The development of seaweed-derived fuels in the UK: An analysis of stakeholder issues and public perceptions.* Energy Policy, 2019. **133**: p. 110924.

121. Mouritsen, O.G., *Seaweeds: edible, available, and sustainable*. 2013: University of Chicago Press.

122. Inniss, L., et al., *The first global integrated marine assessment.* United Nations. Accessed at on 5th February, 2016.

123. Ferdouse, F., et al., *The global status of seaweed production, trade and utilization.* Globefish Research Programme, 2018. **124**: p. I.

124. Fleurence, J., et al., *What are the prospects for using seaweed in human nutrition and for marine animals raised through aquaculture?* Trends in food science & technology, 2012. **27**(1): p. 57-61.

125. Palmieri, N. and M.B. Forleo, *The potential of edible seaweed within the western diet. A segmentation of Italian consumers.* International Journal of Gastronomy and Food Science, 2020. **20**: p. 100202.

126. Adams, J., *An overview on seaweed uses in the UK: Past, present and future.* 2016.

127. Bouga, M. and E. Combet, *Emergence of Seaweed and Seaweed-Containing Foods in the UK: Focus on Labeling, Iodine Content, Toxicity and Nutrition.* Foods, 2015. **4**(2): p. 240-253.

128. Hurtado, A., et al., *Report of the expert meeting on food safety for seaweed–Current status and future perspectives.* 2022.

129. Lähteenmäki-Uutela, A., et al., *European Union legislation on macroalgae products.* Aquaculture International, 2021. **29**(2): p. 487-509.

130. Cheney, D., *Toxic and harmful seaweeds*, in *Seaweed in health and disease prevention*. 2016, Elsevier. p. 407-421.

131. Polyak, E., et al., *Food and sustainability: Is it a matter of choice?* Sustainability, 2023. **15**(9): p. 7191.

132. Ross, F.W., et al., *Potential role of seaweeds in climate change mitigation.* Science of the Total Environment, 2023. **885**: p. 163699.

133. O'Donovan, C.B., et al., *Can metabotyping help deliver the promise of personalised nutrition?* Proceedings of the Nutrition Society, 2016. **75**(1): p. 106-114.

134. Janssen, M., R.H. Wijffels, and M.J. Barbosa, *Microalgae based production of single-cell protein.* Current Opinion in Biotechnology, 2022. **75**: p. 102705.

135. Ritala, A., et al., *Single Cell Protein-State-of-the-Art, Industrial Landscape and Patents 2001-2016.* Front Microbiol, 2017. **8**: p. 2009.

136. Johnson, E.A., *Biotechnology of non-Saccharomyces yeasts—the ascomycetes.* Applied microbiology and biotechnology, 2013. **97**: p. 503-517.

137. Ritala, A., et al., *Single cell protein—state-of-the-art, industrial landscape and patents 2001–2016.* Frontiers in microbiology, 2017. **8**: p. 2009.

138. Anbuselvi, A., S. Mahalanobis, and M. Jha, *Optimization of single-cell protein using green gram husk and Bengal gram husk using yeast.* Int. J. Pharm. Sci. Rev. Res, 2014. **28**: p. 188-190.

139. Nasseri, A., et al., *Single cell protein: production and process.* American Journal of food technology, 2011. **6**(2): p. 103-116.

140. Anupama, R.P. and P. Ravindra, *Value-added food: single cell protein.* Biotechnology advances, 2000. **18**(6): p. 459-479.

141. Khoshnevisan, B., et al., *Urban biowaste valorization by coupling anaerobic digestion and single cell protein production.* Bioresource Technology, 2019. **290**: p. 121743.

142. Strong, P., et al., *A methanotroph-based biorefinery: potential scenarios for generating multiple products from a single fermentation.* Bioresource technology, 2016. **215**: p. 314-323.

143. Øverland, M., et al., *Evaluation of methane-utilising bacteria products as feed ingredients for monogastric animals.* Archives of Animal Nutrition, 2010. **64**(3): p. 171-189.

144. Dedysh, S.N. and P.F. Dunfield, *Cultivation of methanotrophs.* Hydrocarbon and lipid microbiology protocols: Isolation and cultivation, 2017: p. 231-247.

145. Tsapekos, P., et al., *Proteinaceous methanotrophs for feed additive using biowaste as carbon and nutrients source.* Bioresource Technology, 2020. **313**: p. 123646.

146. Barua, S., et al., *Microbial electrolysis followed by chemical precipitation for effective nutrients recovery from digested sludge centrate in WWTPs.* Chemical Engineering Journal, 2019. **361**: p. 256-265.

147. Tays, C., et al., *Combined Effects of Carbon and Nitrogen Source to Optimize Growth of Proteobacterial Methanotrophs.* Frontiers in Microbiology, 2018. **9**.

148. Zamani, A., et al., *Evaluation of a Bacterial Single-Cell Protein in Compound Diets for Rainbow Trout (Oncorhynchus mykiss) Fry as an Alternative Protein Source.* Animals, 2020. **10**(9): p. 1676.

149. Carter, J.F. and L.A. Chesson, *Food forensics: stable isotopes as a guide to authenticity and origin*. 2017, crc Press.

150. Zollman Thomas, O. and C. Bryant, *Don't Have a Cow, Man: Consumer Acceptance of Animal-Free Dairy Products in Five Countries.* Frontiers in Sustainable Food Systems, 2021. **5**.

151. Leth, T., *UNIBIO WINS ‘GREEN 2023 ENVIRONMENT AND CLIMATE AWARD*. 2023, UNIBIO: Kalundborg Municipality of Denmark

152. Inc, B., *Microbial company press releases 2020-2021*, in *Technology*. 2021, Bloomberg Inc.

153. Banks, M., et al., *Industrial production of microbial protein products.* Current Opinion in Biotechnology, 2022. **75**: p. 102707.

154. Williams, R., *Turning toward the Sun.* South Atlantic Quarterly, 2021. **120**: p. 151-162.

155. Trevelyan, W.E., *Chemical methods for the reduction of the purine content of baker's yeast, a form of single‐cell protein.* Journal of the Science of Food and Agriculture, 1976. **27**(3): p. 225-230.

156. Edelman, J., A. Fewell, and G. Solomons. *Myco-protein—a new food*. in *Nutr Abstr Rev Clin Nutr*. 1983.

157. Sinskey, A. and S. Tannenbaum. *Removal of nucleic acids in SCP*. in *Single Cell Protein II, International Conference on Single Cell Protein*. 1975.

158. Anderson, C., et al., *The growth of microfungi on carbohydrates in Single-Cell Protein II*. 1975, MIT Press, Cambridge, Massachusetts.

159. Ward, P.N., *Production of food*. 1998, Google Patents.

160. Rudravaram, R., et al., *Bio (Single Cell) protein: issues of production, toxins and commercialisation status.* Agricultural wastes, 2009: p. 129-153.

161. Ekenvall, L., et al., *Single cell protein as an occupational hazard.* Occupational and Environmental Medicine, 1983. **40**(2): p. 212-215.

162. Ravindra, P., *Value-added food:: Single cell protein.* Biotechnology advances, 2000. **18**(6): p. 459-479.

163. Stephens, N., et al., *Bringing cultured meat to market: Technical, socio-political, and regulatory challenges in cellular agriculture.* Trends in food science & technology, 2018. **78**: p. 155-166.

164. Rao, M.B., A. Varma, and S.S. Deshmukh, *Production of single cell protein, essential amino acids, and xylanase by Penicillium janthinellum.* BioResources, 2010. **5**(4): p. 2470-2477.

165. Yadav, J.S.S., et al., *Mixed culture of Kluyveromyces marxianus and Candida krusei for single-cell protein production and organic load removal from whey.* Bioresource Technology, 2014. **164**: p. 119-127.

166. Aggelopoulos, T., et al., *Solid state fermentation of food waste mixtures for single cell protein, aroma volatiles and fat production.* Food chemistry, 2014. **145**: p. 710-716.

167. Stanbury, P.F., A. Whitaker, and S.J. Hall, *Principles of fermentation technology*. 2013: Elsevier.

168. Finnigan, T.J.A., et al., *Mycoprotein: The Future of Nutritious Nonmeat Protein, a Symposium Review.* Current Developments in Nutrition, 2019. **3**(6).

169. Fellows, P.J., *6 - Food biotechnology*, in *Food Processing Technology (Fourth Edition)*, P.J. Fellows, Editor. 2017, Woodhead Publishing. p. 387-430.

170. Wiebe, M.G., *QuornTM Myco-protein-Overview of a successful fungal product.* Mycologist, 2004. **18**(1): p. 17-20.

171. Hashempour-Baltork, F., et al., *Mycoproteins as safe meat substitutes.* Journal of Cleaner Production, 2020. **253**: p. 119958.

172. Finnigan, T., *Mycoprotein: origins, production and properties.* Handbook of food proteins, 2011: p. 335-352.

173. Post, Y., *Quorn to get a higher profile as Premier buys maker for £172m".* in *Yorkshire Post*. 2006.

174. Ugalde, U. and J. Castrillo, *Single cell proteins from fungi and yeasts*, in *Applied mycology and biotechnology*. 2002, Elsevier. p. 123-149.

175. Razzaq, Z.U., et al., *Characterization of single cell protein from Saccharomyces cerevisiae for nutritional, functional and antioxidant properties.* Journal of food measurement and Characterization, 2020. **14**: p. 2520-2528.

176. Kiran Pulidindi, K.A., *Protein Powder Market Size By Source (Plant-Based {Soy, Spirulina, Hemp, Rice, Pea} Animal-Based {Whey, Casein, Egg, Fish, Insect}) By Application (Human Nutrition Supplement, Animal Nutrition Supplement), Distribution Channel, & Forecast, 2023 - 2032*. December 2022, Global Market Insights Inc.

177. Bashi, Z., et al., *Alternative proteins: The race for market share is on.* McKinsey & Company: Denver, CO, USA, 2019: p. 1-11.

178. Colgrave, M.L., et al., *Perspectives on Future Protein Production.* Journal of Agricultural and Food Chemistry, 2021. **69**(50): p. 15076-15083.

179. Post, M.J., et al., *Scientific, sustainability and regulatory challenges of cultured meat.* Nature Food, 2020. **1**(7): p. 403-415.

180. Dilworth, T. and A. McGregor, *Moral steaks? Ethical discourses of in vitro meat in academia and Australia.* Journal of Agricultural and Environmental Ethics, 2015. **28**: p. 85-107.

181. Schaefer, G. and J. Savulescu, *The Ethics of Producing In Vitro Meat.* Journal of Applied Philosophy, 2014. **31**.

182. Hocquette, A., et al., *Educated consumers don't believe artificial meat is the solution to the problems with the meat industry.* Journal of Integrative Agriculture, 2015. **14**(2): p. 273-284.

183. Wilks, M. and C.J.C. Phillips, *Attitudes to in vitro meat: A survey of potential consumers in the United States.* PLOS ONE, 2017. **12**(2): p. e0171904.

184. Van der Weele, C. and C. Driessen, *Emerging profiles for cultured meat; ethics through and as design.* Animals, 2013. **3**(3): p. 647-662.

185. Vinnari, M. and P. Tapio, *Future images of meat consumption in 2030.* Futures, 2009. **41**(5): p. 269-278.

186. O'Keefe, L., et al., *Consumer responses to a future UK food system.* British Food Journal, 2016. **118**(2): p. 412-428.

187. Welin, S., *Introducing the new meat. Problems and prospects.* Etikk i praksis-Nordic Journal of Applied Ethics, 2013(1): p. 24-37.

188. Marga, F.S., *Dried food products formed from cultured muscle cells*. 2016, Google Patents.

189. Tuomisto, H.L. and M.J. Teixeira de Mattos, *Environmental impacts of cultured meat production.* Environmental science & technology, 2011. **45**(14): p. 6117-6123.

190. Mattick, C.S., et al., *Anticipatory life cycle analysis of in vitro biomass cultivation for cultured meat production in the United States.* Environmental science & technology, 2015. **49**(19): p. 11941-11949.

191. Smetana, S., et al., *Meat alternatives: life cycle assessment of most known meat substitutes.* The International Journal of Life Cycle Assessment, 2015. **20**: p. 1254-1267.

192. Post, M.J., *Cultured meat from stem cells: Challenges and prospects.* Meat science, 2012. **92**(3): p. 297-301.

193. Wiebe, M., *Myco-protein from Fusarium venenatum: a well-established product for human consumption.* Applied microbiology and biotechnology, 2002. **58**: p. 421-427.

194. Santo, R.E., et al., *Considering Plant-Based Meat Substitutes and Cell-Based Meats: A Public Health and Food Systems Perspective.* Frontiers in Sustainable Food Systems, 2020. **4**.

195. EFSA Panel on Nutrition, N.F., et al., *Safety of Yarrowia lipolytica yeast biomass as a novel food pursuant to Regulation (EU) 2015/2283.* EFSA Journal, 2019. **17**(2): p. e05594.

196. Petetin, L., *Frankenburgers, risks and approval.* European Journal of Risk Regulation, 2014. **5**(2): p. 168-186.

197. Lynch, J. and R. Pierrehumbert, *Climate impacts of cultured meat and beef cattle.* Frontiers in sustainable food systems, 2019: p. 5.

1. Impossible Foods Inc. is a company that develops plant-based substitutes for meat products. The company's signature product, the Impossible Burger, was launched in July 2016 as a vegan alternative to beef hamburger. In partnership with Burger King, Impossible Whoppers were released across the United States by summer 2019. The company also makes plant-based sausage and chicken products [↑](#footnote-ref-1)
2. Naylor Farms, Naylor Nutrition have developed a cold extraction process, capable of producing high protein-plus ingredients from whole cabbage. The company have been granted planning permission to build a new 2,500m² agricultural processing plant on its farm in Spalding, Lincolnshire. [↑](#footnote-ref-2)
3. Gushen Biological Technology Group Co., Ltd ([gsjt.com](http://www.gsjt.com/en/page-5838.html)) is a Chinese manufacturer of non-GMO soy proteins. Current estimated production capacity extends to in the region of 40,000 tons/year of isolated soy protein,50,000 tons/year of concentrated soy protein,10,000 tons/year of textured soy protein and textured soy protein concentrate, 10,000 tons/year of soy dietary fibre, plus 2,000 tons/year of soy lecithin. [↑](#footnote-ref-3)
4. Branston Ltd, a UK potato supplier have partnered with technology provider Root Extracts to develop a potato plant protein for use in vegan and vegetarian food. This will involve converting secondary grade low-value potatoes into functional plant-based protein and will also generate starch-based products for use in manufacturing. [↑](#footnote-ref-4)
5. Regulation (EU) No 1308/2013 of the European Parliament and of the Council of 17 December 2013 establishing a common organisation of the markets in agricultural products and repealing Council Regulations (EEC) No 922/72, (EEC) No 234/79, (EC) No 1037/2001 and (EC) No 1234/2007 [↑](#footnote-ref-5)
6. Unibio is a pioneering venture in the biotechnology sector with core competences within fermentation technologies. Unibio International was incorporated in 2014, and its 100% owned subsidiary company was incorporated in 2001.The UK address is located at 2 Royal College Street, Camden, London NW1 0NH, and the administrative headquarter is located at Langebjerg 1, 4000 Roskilde, Denmark. [↑](#footnote-ref-6)
7. Calysta is a multinational biotechnology firm based in San Mateo, California. The company develops industrial processes that utilize microorganisms to convert methane into protein [↑](#footnote-ref-7)
8. Solar Foods is a Finish food-tech startup, which is developing processes to manufacture a protein powder called Solein that has potential as a protein ingredient in food production. [↑](#footnote-ref-8)
9. Regulation (EU) No 1169/2011 Of The European Parliament And Of The Council of 25 October 2011, on the provision of food information to consumers [↑](#footnote-ref-9)