J. Indian bot. Soc. (2023) Vol. 103 (2): 93-99

e-ISSN:2455-7218, ISSN:0019 - 4468

https://doi: 10.5958/2455-7218.2023.103.1.00

www.indianbotsoc.org

REVIEW ARTICLE

Plant and fungal-based meat analogues for mitigating the impacts of global warming

K. R. Shivanna

Abstract

Mitigation of the impacts of global warming, largely the result of emission of greenhouse gasses and deforestation, has become one of the serious challenges of this century for sustaining biodiversity and human welfare. Enormous increase in consumption of animal meat in recent years, particularly from ruminants, releases more greenhouse gases especially methane and nitrous oxide, and requires more agricultural inputs, and forms one of the major drivers of global warming. A steady decrease in meat consumption can be a major approach for mitigating the impacts of global warming. Several meat substitutes are being developed and introduced as healthier and sustainable alternatives to animal meat for humans as well as pets. These meat analogues are being produced from higher plants, microalgae and fermentation-derived fungal proteins (mycoproteins). Their environmental footprints are very much lower when compared to animal meat. A number of meat substitute products are already available in the market around the world. Although there are still some bottlenecks in upgrading the technology for cost-effectiveness and better consumer acceptance, it is definitely going to constitute a viable strategy for mitigating greenhouse gas emissions and help meeting the target of Paris agreement of limiting the global warming to 1.5ºC above pre-industrial level by 2100.

Keywords: Global warming, Greenhouse gas emission, Meat substitutes, Mycoproteins, Plant-based meat, Ruminant animal meat.

Introduction

Human-induced environmental changes particularly global warming have threatened human welfare and sustainability of biodiversity (Cebellos *et al*. 2017, IPCC Sixth Assessment Report 2021, Shivanna 2022 a-c). Mitigation of global warming, which is largely the result of emission of greenhouse gasses and deforestation has become the main challenge of this century. Younger generation around the world are very much concerned about the negative impact of climate change and are agitating to force their governments to adapt effective mitigation measures. According to a survey, 96.5% of the US citizens (27-45 years of age) are worried about the wellbeing of their existing and expected children in a climate-changed world (Schneider-Mayerson and Leong 2020). Ruminant meat (obtained principally from cattle, buffaloes, goats and sheep) has been the primary source of proteins for humans as well as pets. As the population of the world kept on increasing, the demand for animal meat has increased enormously over the years. According to the UN report, the world population is expected to reach 9.8 billion by 2050 and 11.2 billion by the end of the century. As average income of people is expected to increase, the trend would be to consume more resource-intensive, animal-based foods. Today the world production of meat is 4-5 times more than it was 50 years ago (Mahajan 2020). This has resulted in a significant increase in the population of livestock leading to the conversion of a large amount of forest land into farm and pasture lands for rearing the livestock. Out of 5 million hectares of average annual deforestation (2001-14) about 2.3 million hectares were used to grow crops and 2 million hectares to raise pasture (Sellare *et al.* 2022). Global livestock population is roughly 4.6 billion of which 3.6 billion represents ruminant livestock. Considerable meat is also consumed by several pets, particularly dogs and cats. In 2018, the number of pet cats and dogs around the world was estimated to be around 370 and 470 million, respectively; they consume food with

Ashoka Trust for Research in Ecology and the Environment (ATREE), Srirampura, Bengaluru, India

***Corresponding Author:** K. R. Shivanna, Ashoka Trust for Research in Ecology and the Environment (ATREE), Srirampura, Bengaluru, India, E-Mail: shivanna@atree.org

How to cite this article: Shivanna, K.R. 2023. Plant and fungal-based meat analogues for mitigating the impacts of global warming. J. Indian bot. Soc., 103(2):93-99. Doi: 10.5958/2455-7218.2023.103.1.00

Source of support: Nil

Conflict of interest: None.

Received: 13/02/2023 **Accepted:** 22/03/2023 **Published online**: 25/05/2023

considerable amount of meat component worth $134 billion each year (Knight and Satchell 2021, Knight *et al.* 2022).

The demand of global meat consumption is expected to increase by 68% over the 2000 base period by 2030 (FAO Interim Report 2006, World Agriculture: Towards 2030/2050). Apart from causing deforestation, ruminant animals significantly add to greenhouse gases, particularly methane and nitrous oxide, to the atmosphere (Sejian *et al.* 2016). Food production system is responsible for more than a third of greenhouse gas emissions (Crippa *et al.* 2021, Xu *et al.* 2021). Methane production in ruminant animals is associated with their special digestive system that converts plant materials which are not digestible by humans into nutritious food. Enteric fermentation by specific microbes harbouring in the rumen of these animals produce methane as a by-product during digestion (enteric methane or cow burps). Manure and fertilizers used in the production of animal feed act as major sources of nitrous oxide. Although livestock account for only 9% of global CO_2, they are responsible for the emission of 40% of methane and 65% of nitrous oxide, contributing to 14.5% of human-associated greenhouse gas emissions (Gerber *et al.* 2013). Methane 25 times and nitrous oxide 300 times have more global warming potential than CO_2. Limited CO_2 production from livestock farms is primarily associated with the burning of fossil fuels to run farm machinery and in the process of fertilizer production, and also release of carbon from cultivated soils. Meta-analysis of consolidated data of a large number of farms around the world show that emission of greenhouse gases in meat production is much higher compared to plant-based food sources (Fig. 1, Poore and Nemecek 2018).

Animal products provide 37% protein and 18% calories at global level, but consume as much as 83% of farmland and accounts for 56-58% emission of food-related greenhouse gases. Thus, production of animal meat in general and ruminant meat in particular have significant impact on climate change (Pelletier and Tyedmers 2010, Sejian *et al.* 2016). Environmental footprints of meat production is also much higher in terms of its water consumption (Pimentel and Pimentel 2003). In comparison to the year 1990, the global demand for meat, milk and eggs by the year 2050, is expected to increase by 60%, 30% and 80%, respectively (Sejian *et al.* 2016). To feed 9.8 billion people in 1950 at the present level of food consumption pattern, the world has to produce an additional 56% calories that would require 593 million hectares of additional agricultural land (nearly twice the size of India) and results in the emission of 11-gagaton more greenhouse gases (World Resource Institute 2018).

Conference of Parties of the UN (COP 26) held in 2021 in Glasgow highlighted the importance of reduction in greenhouse gas emissions and deforestation to prevent global temperature increase beyond 1.5°C by the end of the century, the goal of Paris agreement. Climate Action Tracker, a non-profit independent global analysis platform, however, feels that emission reduction commitments made by countries at COP 26, still lead to 2.4°C warming by 2100. So far, the primary emphasis to limit climate change has largely been focused on reducing fossil fuel emissions but according to recent reports (Clark *et al.* 2020, Zurik *et al.* 2022), even if fossil fuel emissions are halted immediately, emissions from the current trend of global food system alone would make it impossible to limit global warming to 1.5°C and difficult even to realize 2°C target by the end of the century.

The above scenario clearly highlights the need to limit the growth of livestock sector as one of the promising approaches to achieve Paris agreement target on global warming. In recent years public has become conscious of the need to sustain biodiversity and human welfare by mitigating the impact of global warming, and there is a trend for developing environment-friendly food habits without sacrificing the nutritional requirement. Toward this direction there is a strong desire to reduce the demand for animal meat in general and ruminate meat in particular. One of the strategies of mitigating negative impact of livestock sector is to develop substitutes for animal meat for humans as well as pets. Recent studies (Knight and Satchell 2021,

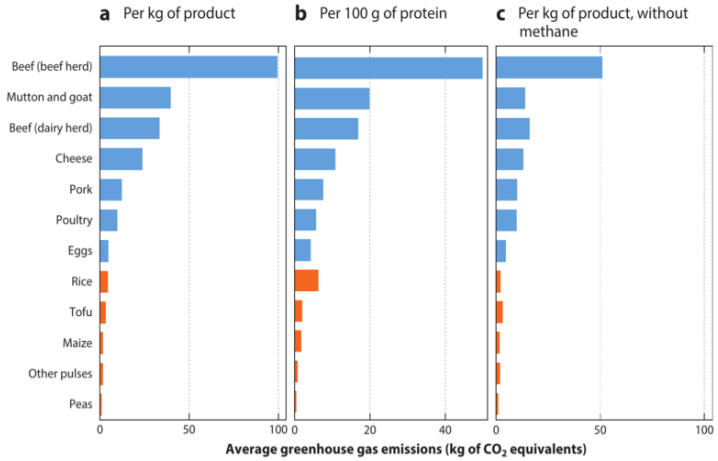

Figure 1: Comparative amount of greenhouse gas emission from different animal (blue) and plant (red) sources (Source Wikimedia Commons)

Knight *et al.* 2022) have shown that even for dogs and cats, vegan pet foods are as palatable as conventional food and fulfil their nutritional needs. Thus, there is enormous scope for reducing meat diet for cats and dogs also (https://www.newscientist.com › article › 0-vegan-pet-fo...).

Any acceptable and sustainable meat substitute should not contain animal meat but need to be similar or comparable to it in colour, texture, flavour, taste and nutritional index. Several environmentally friendly alternative animal meat analogues from plants and cultured fungi, are now available in the market. This article gives an overview of the progress of these alternative substitutes to animal meat and highlights some of the initiatives being taken around the world in this direction. It also comments briefly on two other animal meat substitutes, edible insects and *in-vitro* meat.

Plant-based Substitutes

Higher Plants

Plants have been supplementing human diet ever since the time they were hunters and gatherers. After the onset of agriculture, plants continued to provide fully or partly staple and sustainable foods for humans. Present day humans are omnivores; the food is the combination of plant-based diet and animal meat for the majority of population. Routine plant-based diet, limited to vegetarians and vegans, may lack or contain low amounts of some vitamins (B12 and D), a few minerals (iron and zinc) and omega-3 fatty acids; these have to be made up through consumption of food rich in these components such as fruits, vegetables, whole grains, legumes, milk and other dairy products (Rizzo *et al.* 2016). With these additions, plant-based diet has been providing nutritious and sustainable food for humans for centuries.

Plants have been the obvious choice for developing substitutes for animal meat. Highly digestible proteins containing essential amino acids is the most important component of animal meat. Such plant-based meat proteins can be easily derived from legumes (soy, beans and lentils), cereals (barley, rye and wheat) and oilseeds (rapeseed, sunflower, cottonseed) (Singh *et al.* 2021). Many of the plant-based proteins are good alternatives to meat in their textural properties and amino acid composition. Plant-based meat industry until recently is concentrating on the development of burger patties, mince, and sausages; products such as seitan, tofu, yuba are already available in the market since long. In recent years a number of additional plant-based analogues such as impossible burgers and beyond burgers, veggie burgers, falafel, meat balls, and tempeh have also come up in the market (Rubio *et al.* 2020). Most of the presently available plant-based meat substitutes are also fortified with fibers, fatty acids, vitamins, minerals, flavour enhancers and colours. Some of them are also enriched further with microalgae like the green alga *Chlorella* or the blue-green algae *Nostoc,* or *Spirulina* or a yeast to improve their nutritive index in terms of certain essential vitamins and mineral components. According to Patrick Brown, the founder and Chief Executive of Impossible Foods, the nutritional value of any type of animal meat can be matched with about one twentieth of the cost by using readily available plant ingredients (see Leeming 2021). He is confident that animal-based food products all over the world would be replaced by plant-based or other substitute products within the next 15 years, and such a change is inevitable. Presently many meat industries have started a gradual switch over to plant-based proteins (https://www.cbinsights.com/research/future-of-meat-industrial-farming/).

For vegan consumers, vegan sausage, vegan meat shred, vegan meat tikka, vegan meat curry are some of the plant-based options available in the market. Several plant-based milks are also available for vegan consumers. Almond milk is the predominant one; others are prepared from oats, soya bean, coconut, pea and rice (Boerner 2022). In Western countries, the market for plant-based milk is largely driven by increasing incidence of lactose-intolerance for dairy milk. Sale of plant-based milks in the US in 2021 was $2.6 billion and the sale of dairy milk dropped by 2% (Good Food Institute). Although the cost of producing plant protein is significantly lower compared to animal protein, the high processing costs of these vegan products often increase their retail cost.-Another positive attribute of animal meat substitutes is their low fat content, absence of cholesterol besides being a good source of fibres (Table 1).

Table 1: Nutritional composition of some meat anlogues compared to animal meat preparations, given in bold (source: Good Food Institute, Fact Sheet 2022).

Product	*Calories*	*Total fat*	*Saturated fat (g)*	*Fibre (g)*	*Protein*	*Cholesterol (mg)*
Animal beef (113 g)	290	23g (70%)	9	0	19g (27%)	80
Beyond burger	230	14g (55%)	5	2	20g (35%)	0
Impossible burger	240	14g (53%)	8	3	19g (32%)	0
Vegan meat	270	16g (53%)	2.5	4	27g (40%)	0
Chicken nuggets (95 g)	290	18g (57%)	4	0	15g (21%)	40
Impossible chicken nuggets	240	12g (45%)	1.5	2	13g (22%)	0
Veggie chicken nugget	210	9g (38%)	1	4	14g (27%)	0

However, a few of these meat substitutes still face problems of consumers' preference and choice. For example, most of the soy used in these vegan foods comes from genetically modified (GM) crops that are still not readily accepted by a large number of people in the world. A proportion of the world population is also gluten-intolerant. Consumer acceptance of plant-based meat substitutes is quite high in China and India; it is still limited in some countries (Bryant *et al*. 2019). The challenges to overcome the problems associated in terms of taste, texture and cost of plant-based meat are being tackled.

Next-generation plant-based meat and dairy products are expected to become competitive with animal products in taste, price, and accessibility (Good Food Institute). The market for plant-based meat is growing steadily; retail growth in the US is increasing by double-digit every year. The retail market for plant-based food in the US grew from $6.9 billion in 2020 to $7.4 billion in 2021. Plant-based food sales grew three times faster than total food sales in 2021and 69% households are now buying plant-based food products (

https://www.plantbasedfoods.org › 2021-u-s-retail-sales...). The global market value of plant-based meat is expected to reach US$ 16.7 billion by 2026 (Kurek *et al*. 2022).

Good Food Institute, a non-profit international organization working to accelerate alternative protein innovation, gives details of many new initiatives being taken around the world to advance alternative protein research. These include: allotment of $5 million by California State to three campuses of the University of California, setting up of Plant Protein Innovation Centres in several countries and Tropical Food Innovation Lab being established in Brazil to explore rich plant biodiversity of the country. There has been a significant rise in marketing of plant-based proteins. Since Impossible Foods introduced plant-based patty, a number of brands such as Beyond the Meat, Beyond the Butcher, Before the Butcher, and Vegetarian Butcher have developed plant-based meat substitutes with taste, texture and flavor comparable to animal meat (Severson 2022, https://www.marketdatacentre.com/plant-based-meat-market-100). According to Plant Based Foods Association, advancing access to plant-based foods took centre stage at the White House Conference on Hunger, Nutrition and Health, held in September 2022.

Microalgae

Microalgae is another source of meat analogue. *Spirulina*, *Chlorella* and *Nostoc* are the main sources of meat analogues and are prevalent in food markets for many decades. Microalgae-based protein production demands much less water and land in-puts compared to raising the livestock or traditional crops. Companies such as Algama Foods and Odontella are making various algal food products. Algal foods are good sources of bulk proteins, polyunsaturated fatty acids, essential minerals and vitamins (Caporgno and Mythys 2018). Their proteins have high solubility and are considered safe as food components. Most of the microalgal products are marketed as food supplements in the form of pills and capsules in a large number of countries across the world. Microalgae in the form of whole cells or powder are also being incorporated in other innovative food products with potential health benefits (Caporgo and Mathys 2018, Fu *et al*. 2021).

Fungal Proteins (Mycoproteins)

Use of (non-poisonous) mushrooms as vegetables is quite common in several countries. The protein content of different mushrooms varies between 8.5% to nearly 40%. Although processed fungi-based meat such as burgers and sausages have been available on retail market for decades, their consumption is so far limited. Commercial mycoprotein products are obtained largely from fermentation of fungus, *Fusarium venenatum,* in a liquid culture medium by using sugar as the substrate (Matassa *et al.* 2016). It is marketed as Quorn since 1985 in the UK as a savoury pie by Sainsbury (Wikipedia). Now it is sold in a number of countries (Harrison and Johnson 2018). It has meat-like texture and flavour, and is well tolerated by humans with an extremely low allergic potential. It can be used to prepare vegetarian sausages, burgers or cutlets. Mycoproteins are considered to be healthy sources of essential amino acids, carbohydrates, vitamins and carotenes; they can be produced at lower costs without the limitations of climate and landscape (Hashempour-Baltork *et al.* 2020). Other desirable qualities of mycoproteins include its high quality with essential amino acids and dietary fibres and low in sodium, sugar, cholesterol and saturated fat (Finningan *et al.* 2010, Ismail *et al.* 2020).

Quorn is available in ready to cook forms and in a range of chilled vegetarian and vegan meals such as pizzas, cottage pie and also as products resembling sliced meat, hot dogs and burgers. The market for Quorn products is increasing worldwide. Production of Quorn results in very much less CO_2 emission and requires much less water when compared to that of any animal meat (Harrison and Johnson 2018). Similarly, the water footprint for mycoprotein is also about one tenth of that of beef and around half of that of chicken. Feed conversion ratio is also favourable; 2 kg of wheat is needed to produce 1 kg of mycoprotein compared to 12-24 kg needed to produce 1 kg of beef. A recent assessment (Humpenoder *et al.* 2022) on estimation of benefit of using microbial protein over the ruminant meat products has indicated that it can significantly reduce the rate of annual deforestation and related greenhouse gas emissions; even 20% of beef substitution with mycoprotein is estimated to result in the reduction of 55% of deforestation, 10% CH_4 emission and 5% NO_2 emission (Humpenoder *et al*. 2022). Thus, mycoprotein has the potential to offer clean green alternative to ruminate meat.

Conclusions

Development of sustainable food systems to provide healthy diets to increasing global population is going to be a major challenge in the coming years. As pointed out earlier, replacement of animal meat with other substitute proteins even partially could mitigate, to a considerable degree, the negative impacts of deforestation and emission of greenhouse gases (Clark *et al.* 2020, Li *et al*. 2022, Zurek *et al*. 2022). The impacts of climate change in increasing the frequency and intensity of natural calamities such as floods, droughts, cyclones, tornadoes and forest fires along with unpredictable weather and rising sea levels are causing massive human migration and sufferings. This has resulted in growing public realization of the need to change to ecofriendly, sustainable food systems. Unlike reduction in the use of fossil fuels through the use of renewable and alternative energy sources for which Governments around the world have to take major initiatives, reduction in the emission of greenhouse gases through the use of meat substitutes can be implemented to a great extent by conscious efforts of the public. In a randomized trial, students who were exposed to a single 50 min talk on climate impact of meat, ate 9% less meat-based meals over the next 3 years compared to those not exposed to the talk (Le Page 2023).

There has been a steady increase in the number of vegetarians/vegans in several countries such as USA, Australia, UK and New Zealand. The number of vegans in America, for example, grew by 600% from approximately 4 million in 2014 to 19.6 million in 2017 (Vegan Society 2019). Many Restaurants and Airlines have started adding new plant-based vegetarian and vegan options such as impossible burger and impossible meatballs which require 75% less land, 85% less water and emit 90% less greenhouse gases (https://simpleflying.com Airline News, https://vegnews.com/2022/3/plant-based-meat-delta). In fact, restaurants during COP 26 meeting (2021) at Glasgow served food that came with a carbon tag. A vegetarian restaurant in Bristol, UK, has put up in its menu carbon footprint of each item along with the cost (Euronews 2022/08/11 Climate change on the menu). For example the carrot and beetroot pakora with yogurt sauce produce just 16 g of CO_2, chef's salad with hummus, seeds and herbs produce 162 g CO_2. The menu notes that CO_2 emissions of a real beef burger (which is not served by the restaurant) is 10 times the amount of its vegan alternative. In recent years new meat substitutes for pets are also being developed and marketed. This market is growing fast; it was estimated to be US$ 8.7 billion in 2020, and is expected to reach 15.7 billion by 2028 (Knight *et al.* 2022). Majority of climate conscious customers have started counting carbon, not calories on the menu. These positive trends indicate that people are willing to transform their diet and food preferences in favor of meat substitutes as long as they are nutritious with acceptable taste.

Apart from plant and microbial substitutes, consumption of edible insects, which has been in practice in many tropical and semi-tropical regions since long (Tang *et al.* 2019), is another substitute for animal meat. A Canadian company, Entomo Farms, raises insects for human consumption. Raising of insects results in 100 times less greenhouse gas production than raising of cows. Insect-based meat analogue products, including insect-based burgers from Coop (Swiss food retailer) and insect fortified burger from Bugfoundation (German food company) (Hashempour-Baltork *et al.* 2020), are also being marketed in recent years. In vitro meat, also referred to as cultured meat or lab-grown meat, is another safe and environmentally-friendly potential meat analogue option (Langelaan *et al.* 2010, Kadim *et al.* 2015, Stephens *et al.* 2018, Kolodziejczak *et al.* 2022). It is prepared by culturing muscle-like tissue (stem cells) in aseptic liquid medium under strictly controlled conditions; thus it replicates the nutritional and sensory profile of conventional meat but bypasses animal husbandry and slaughter. In vitro meat products resemble the processed meat products and reduce the need for animal and agricultural resources required to produce traditional meat (Datar and Beti 2010). Extensive research is being carried out to optimise the technology; nearly $3 billion has been invested in research from both private companies as well as Government agencies to find a commercially viable way to produce cultured meat (Severson 2022). On 17 November 2022, the US Food and Drug Administration (FDA) gave approval to Upside Foods a start up in San Francisco to sell its lab-grown chicken (www.wired.co.uk/article/lab-grown-meat-approval).

Many of the animal meat analogues developed in recent years are almost indistinguishable from animal-based meat (Mark Wilson, National Geographic, Nov 2022, Ishaq *et al.* 2022). At present, Europe dominates the meat analogue market (Ismail *et al*. 2020). Apart from quality, the cost is an important factor for consumer acceptability. There has been a continuous improvement in the production technology of meat analogues and they are expected to become cost-effective in the coming years so that they can provide palatable, nutritious, clean and green alternative to animal protein without extra cost. Although global food production, in terms of calories, has so far kept pace with population growth, malnutrition due to insufficient consumption of quality proteins, vitamins and minerals is a major problem particularly in developing countries. Unhealthy food is reported to pose the world greater morbidity than does the use of alcohol, drugs, and tobacco combined (Willett *et al.* 2019). Meat substitute products have great potential in improving the nutritional health of the population and thus preventing premature deaths (Ritchi *et al.* 2018). Transport of food accounts for nearly one fifth of the carbon emission in the food supply system (Li *et al*. 2022). Moving fruits and vegetables generates twice the amount of CO_2 produced

by growing them. Therefore, apart from reducing the consumption of meat, consumption of locally produced food would reduce emission of greenhouse gases further.

The fourth and last instalment of the sixth assessment report of the United Nations Intergovernmental Panel on Climate Change (IPCC), that provides the most comprehensive updates on climate change, was released on 20 March 2023. It states that "the pace and scale of what has been done so far and current plans are insufficient to tackle climate change." The report emphasises that to achieve the goal of Paris agreement the world has to take quantum leap in climate action. All available evidences clearly show that environmental footprints of animal meat are very much higher in terms of deforestation, greenhouse gas emission, landscape degradation and water consumption when compared to meat substitutes. Animal meat diets of humans as well as pets in the coming years are bound to be replaced substantially by meat substitutes due to environmental, health and ethical concerns of consumers. This would add significantly to the efforts of the world to meet the goal of Paris agreement.

Acknowledgement and declarations

Author declares that there is no conflict of interest. Manuscript has been checked for text repetition by plagiarism check.

References

Boerner LK 2022 What's plant milk, and how do you milk a plant. *Chemical and Engineering News* Oct 11, 2022.

Bryant C, Szejda K, Parekh N *et al.* 2019 A Survey of consumer perceptions of plant-based and clean meat in the USA, India, and China. *Front. Sustain. Food Syst.* **3**: 11 doi: 10.3389/fsufs.2019.00011

Caporgno MP and Mathys A 2018 Trends in microalgae incorporation into innovative food products with potential health benefits**.** *Front. Nutr.* **5**:58. https://doi.org/10.3389/fnut.2018.00058

Ceballos G, Ehrlich PR and Dirzo R 2017 Biological annihilation via the ongoing sixth mass extinction signalled by vertebrate population losses and declines. *Proc. Natl. Acad. Sci. USA* **114**: E6089-E6096. DOI: 10.1073/pnas.1704949114

Clark MA, Domingo NGG, Colgan K *et al.* 2020 Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. *Science* **370**: 705-708. DOI: 10.1126/science.aba7357

Crippa M, Solazzo E, Guizzardi D *et al.* 2021 Food systems are responsible for a third of global anthropogenic GHG emissions. Nat. Food **2**: 198–209. DOI:10.1038/S43016-021-00225-9

Datar I and Betti M 2010 Possibilities for an in vitro meat production system. *Innovative Food Sci. Emerging Technol.* **11**: 13–22.

Finnigan T, Lemon M, Allan B and Paton I 2010 Mycoprotein, life cycle analysis and the food 2030 challenge. *Aspects Appl. Biol.* **102**: 81–90.

Fu Y, Chen T and Chen SHY 2021 The potentials and challenges of using microalgae as an ingredient to produce meat analogues. *Trends Food. Sci. Tech.* **112**: 188-200. https://doi.org/10.1016/j.tifs.2021.03.050

Gerber PJH, Steinfeld B, Henderson A *et al.* 2013 Tackling climate change through livestock—A global assessment of emissions and mitigation opportunities; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy.

Good Food Institute 2022 Fact Sheet: Plant based meat nutrition, August 2022.

Harrison R and Johnson R 2018 Mycoprotein production and food sustainability. *Microbiology Today* 07 August 2018 (Microbes and Food).

Hashempour-Baltork F, Khosravi-Darani K, Hosseini H *et al.* 2020 Mycoproteins as safe meat substitutes. *J. Clean Prod.* **253**:119958

Humpenoder F, Bodirsky BL, Weindl I *et al*. (2022) Projected environmental benefits of replacing beef with microbial protein. *Nature* **605**: 90–96. https://doi.org/10.1038/s41586-022-04629-w

IPCC Sixth Assessment Report 2021 The sixth assessment report on climate change. https://www.ipcc.ch/report/ar6/ wg1/

Ismail I, Hwang Y-H and Joo S-T 2020 Meat analogue as future food: a review. *J Animal Sci. Tech.* **62**: 111-120. https://doi.org/10.5187/jast.2020.62.2.111

Ishaq A, Irfan S, Sameen A, Khalid N 2022. Plant-based meat analogs: A review with reference to formulation and gastrointestinal fate. *Curr. Res. Food Sci.* **5**: 973-983.

Kadim IT, Mahgoub O, Baqir S, Faye B and Purchas R 2015 Cultured meat from muscle stem cells: a review of challenges and prospects. *J. Integr. Agric.* **14**: 222-233

Knight A and Satchell L 2021 Vegan versus meat-based pet foods: Owner-reported palatability behaviours and implications for canine and feline welfare. *PLoS ONE* **16**(6): e0253292. https://doi.org/10.1371/ journal.pone.0253292

Knight A, Huang E, Rai N and Brown H 2022 Vegan versus meat-based dog food: Guardian-reported indicators of health. *PLoS ONE* **17**(4): e0265662. https://doi.org/10.1371/journal.pone.0265662

Kołodziejczak K, Onopluk A, Szpicer A and Poltorak A 2022 Meat analogues in the perspective of recent scientific research: A review. *Foods* **11**: 105 https://doi.org/10.3390/foods11010105

Kurek MA, Onopiuk A, Pogorzelska-Nowicka E *et al.* 2022 Novel protein sources for applications in meat-alternative products—insight and challenges. *Foods* **11**: 957. https://doi.org/10.3390/ foods11070957

Langelaan MLP, Boonen KJM, Polak RB *et al.* 2010 Meet the new meat: tissue engineered skeletal muscle. *Trends Food. Sci. Technol.* 21: 59-66.

Le Page M 2023. Students ate less meat for three years after a talk on climate impact. *New Scientist* 2 March 2023

Leeming J 2021 Meet the food pioneer whose meat replacements are rocking the gravy boat. *Nature* **590**: 176. https://doi.org/10.1038/d41586-021-00264-z

Li M, Jia N and Lenzen M 2022 Global food-miles account for nearly 20% of total food-systems emissions. *Nature Food* **3**: 445-453. doi: 10.1038/s43016-022-00531-w

Mahajan B 2020 Rising meat consumption, climate change and pandemics: Untangling the multilevel connections. *ORF Young Voices* Jan 23, 2020

Matassa S, Boon N, Pikaar I and Verstraete W 2016 Microbial protein: future sustainable food supply route with low environmental footprint. *Microbiol. Biotechnol.* **9**: 568-575.

Pelletier N, Tyedmers P 2010 Forecasting potential global

environmental costs of livestock production 2000–2050. *Proc. Natl. Acad. Sci. USA* **107**: 18371-18374. https://doi.org/10.1073/pnas.1004659107

Pimentel D and Pimentel M 2003 Sustainability of meat-based and plant-based diets and the environment. *Am. J. Clinical Nutrition* **78** (suppl): 660S–663S.

Poore J and Nemecek T 2018 Reducing food environmental impacts through producers and consumers. *Science* **360**: 987-992 DOI: 10.1126/SCIENCE.AAQ0216

Ritchie H, Reay DS and Higgins P 2018 Potential of meat substitutes for climate change mitigation and improved human health in high-income markets. *Front. Sustain. Food. Syst.* **2**:16 https://doi.org/10.3389/fsufs.2018.00016

Rizzo G, Lagana AS, Rapisarda AMC *et al.* 2016 Vitamin B12 among vegetarians: status, assessment and supplementation. *Nutrients* **8**: 767. doi:10.3390/nu8120767

Rubio NR, Xiang N and Kaplan DL 2020 Plant-based and cell-based approaches to meat production. *Nat. Commun.* **11**: 6276.

Schneider-Mayerson M and Leong KL 2020 Eco-reproductive concerns in the age of climate change. *Climatic Change* **163**:1007–1023. https://doi.org/10.1007/s10584-020-02923-y

Sejian V, Bhatta R, Malik PK *et al.* 2016 Livestock as sources of greenhouse gases and its significance to climate change. In: *Greenhouse Gases,* Moya BL and Pous J (eds) Intech Open, London. https://doi.org/10.5772/62135

Sellare J, Borner J, Brugger F *et al.* 2022 Six research priorities to support corporate due-diligence policies. *Nature* **606**: 861-863. doi: 10.1038/d41586-022-01718-8

Severson K 2022 The new secret of chicken recipe? Animal cells. *New York Times* https://www.nytimes.com/2022/02/15/dining/cell-cultured-meat.html

Shivanna KR 2022a Climate change and its impact on biodiversity and human welfare. *Proc. Indian Natl. Sci. Acad.* **88**: 160-171. https://doi.org/10.1007/s43538-022-00073

Shivanna KR 2022b The plight of bees and other pollinators, and its consequences on crop productivity. *Resonance* **27**: 785-799. https://doi.org/10.1007/s12045-022-1372-8

Shivanna KR 2022c. Impact of light pollution on nocturnal pollinators and their pollination services. *Proc. Indian Natl. Science Acad.* **88**: 626-633. https://doi.org/10.1007/s43538-022-00134-w

Singh M, Trivedi N, Enamala MK *et al.* 2021 Plant-based meat analogue (PBMA) as a sustainable food: A concise review. *Eur. Food Res. Technol.* **247**: 2499–2526.

Stephens, N, Silvio LD, Dunsford I *et al.* 2018 Bringing cultured meat to market: technical, socio-political, and regulatory challenges in cellular agriculture. *Trends Food Sci. Technol.* **78**: 155–166

Tang C, Yang D, Liao H *et al.* 2019 Edible insects as a food source: a review. *Food Prod. Proce. Nutri.* **1**: 8. https://doi.org/10.1186/s43014-019-0008-1

Vegan Society 2019 Statistics https://www.vegansociety.com/news/media/statistics

Willett W, Rockstrom J, Loken B *et al.* 2019 Food in the anthropocene: the EAT–*Lancet* Commission on healthy diets from sustainable food system. *Lancet* **393**: 447-492. DOI: 10.1016/S0140-6736(18)31788-4

World Resource Institute 2018 How to sustainably feed 10 billion people by 2050, in 21 Charts. https://www.wri.org/insights/how-sustainably-feed-10-billion-people-2050-21-charts

Xu X, Sharma P, Shu S *et al.* 2021 Global greenhouse gas emission from animal-based foods are twice those of plant based foods. *Nature Food* **2**: 724-732 https://doi.org/10.1038/s43016-021-00358-x

Zurek M, Hebinck A and Selomane O 2022 Climate change and the urgency to transform food systems. *Science* **376**: 1416-1421. DOI: 10.1126/Science.abo2364