TYPE Review
PUBLISHED 15 November 2023
DOI 10.3389/fsufs.2023.1038286

Check for updates

OPEN ACCESS

EDITED BY
Aida Turrini,
Independent Researcher, Scansano, Italy

REVIEWED BY
Ryuma Shineha,
Osaka University, Japan
Moona Rahikainen,
University of Turku, Finland

*CORRESPONDENCE
Kathleen L. Hefferon
✉ klh22@cornell.edu

RECEIVED 06 September 2022
ACCEPTED 13 October 2023
PUBLISHED 15 November 2023

CITATION
Hefferon KL, De Steur H, Perez-Cueto FJA and Herring R (2023) Alternative protein innovations and challenges for industry and consumer: an initial overview.
Front. Sustain. Food Syst. 7:1038286.
doi: 10.3389/fsufs.2023.1038286

Alternative protein innovations and challenges for industry and consumer: an initial overview

Kathleen L. Hefferon[1]*, Hans De Steur[2], Federico J. A. Perez-Cueto[3] and Ronald Herring[4]

[1]Department of Cell Biology and Genetics, Cornell University, Ithaca, NY, United States, [2]Department of Agricultural Economics, Ghent University, Ghent, Belgium, [3]Department of Food, Nutrition and Culinary Science, Umeå University, Umeå, Sweden, [4]Cornell Atkinson Center for Sustainability, Cornell University, Ithaca, NY, United States

Over one fourth of today's greenhouse gas emissions are the result of agriculture, with the production of meat representing a large portion of this carbon footprint. As the wealth of low- and middle-income countries continues to increase, the demand for animal-sourced protein, such as dairy and meat products, will escalate. At this point in time, livestock feed alone utilizes almost 40% of the world's cropland. The rapidly increasing world population, coupled with a need for environmental sustainability, has renewed our attention on animal-protein substitutes. Apprehensions over climate change have aided an acceleration in the research and development of alternative proteins, which may replace some animal-sourced protein over time. The alternative dairy and meat industry is developing at a yearly rate of 15.8% and is predicted to reach 1.2 trillion $USD by 2030. This emerging market incorporates new technologies in plant-made protein production, manufacturing of animal proteins by fermentation using microbial bioreactors, and accelerated production of cultivated (also known as cell-based) meat. These new technologies should change the global market drammatically. This article describes the history of the alternative protein industry and its' current status, then offers predictions of future pathways for this rapidly accelerating market. More speculatively, it discusses factors that lead to shifts in consumer behavior that trend toward the adoption of new technologies.

KEYWORDS

protein, sustainability, animal welfare, plant-based food, alternative meat, consumer, review

Introduction

As environmental sustainability becomes more imperative, the utility of animal-sourced food products has undergone extensive evaluation (Poore and Nemecek, 2018; Aschemann-Witzel et al., 2021). Livestock feed itself utilizes up to 40% of global cropland, and the need for meat products has grown alongside the increase in income across low- and middle-income countries (Sexton et al., 2019). Increased demand for arable land that can be used to produce animal protein is a significant cause of pollution, biodiversity loss and eutrophication through the excessive application of fertilizers. Simultaneously, more than 800 million people suffer from undernutrition and another two billion experience micronutrient malnutrition (Perignon and Darmon, 2022; World Health Organization, 2022). A doubling of food is needed to improve the nutritional status of the world's population; continuation of conventional patterns of agricultural production is estimated to create lower overall environmental sustainability, and accumulated in a sharp increase of greenhouse gas emissions of 80% (Aimutis, 2022).

Besides issues associated with sustainability, the over-consumption of meat is linked to multiple health issues including heart and cardiovascular disease and colorectal cancer (Micha et al., 2010; Wolk, 2017; González et al., 2020). Food-borne illnesses such as *Salmonella*, *E. coli* and *Campylobacter* are also associated with meat consumption; excessive use of antibiotics in livestock carries risks for human health as well (Fegan and Jenson, 2018; Lee et al., 2021).

Research into and development of animal protein replacements has resulted in an acceleration of innovation (FAO, 2022). The alternative dairy and meat industries are presently growing at a rate of 15.8%, with amplified appeal to mainstream consumers outside of the existing 'niche' markets (Specht, 2022). Meat alternatives produced presently have appealed particularly to the rapidly-growing sector of "flexitarian" consumers (Smart Protein, 2021).

For over 10 years, demand for alternative protein products from various sources has altered the marketplace (Lima et al., 2022). Alternative proteins can imitate the flavor, appearance and mouthfeel and even certain nutritional profiles of many animal products, while significantly reducing greenhouse gas emissions, land degradation and loss of diversity in wild places (Sexton et al., 2019). Finally, alternative protein can directly tackle animal welfare and ethical issues associated with animal meat production (Eckl et al., 2021). Substitutes for animal-sourced food protein respond to inter-connected concerns of sustainability, nutrition and ethical concerns toward the use of animals (Chai et al., 2019). Indeed, the demand for alternative protein will instigate a reassessment of the global food system, with sustainability being a new focal point, using evaluation methods that are not yet entirely clear.

Alternatives for low- and middle-income countries are especially difficult. Consumers in nations that have only recently improved incomes embrace meat as a correlate of wealth and status. Moreover, long-standing traditions around maintenance of livestock in rural cultures are not likely to change quickly (Parlasca et al., 2023). In contrast, consumption of meat in OECD nations has languished or in certain instances has even dropped (Onwezen et al., 2021). Increasing availability of alternative proteins will almost certainly affect conventional trading relations and affect rural communities in poorer nations in unpredictable, but significant ways.

Alternative protein development can be categorized into multiple pillars: plant-based protein as substitutes for animal protein, precision fermentation using microbes to produce animal ingredient proteins, fermentation with the goal of modifying taste and structure of plant based food, production of microbial biomass for food, and cell-based (cultivated) meat. These innovations in food and agriculture will significantly unsettle the international market (Lee et al., 2023). The following review describes the origins and current status of these three technologies, and proceeds to explore how they will impact inequality, food sovereignty and the prospects for social justice. The review discusses the challenge of consumer acceptance to meat alternatives and concludes with a forecast of future directions for this growing market.

An overview of alternative proteins

Plant-based protein such as seitan from wheat, or tofu or tempeh from soy, have been produced in Asian countries and consumed for centuries. This form of protein gained popularity in the late-twenteeth Century in Western countries. Plant-based protein is both traditional and novel. Increased interest in new foods based on plant products with nutritional benefits and sensory attributes resonate for consumers today. Food innovations can be characterized as maintaining the taste and texture that makes them as satiating as animal-based products.

More lately, a rekindled interest in powders and energy bars with high protein content, has become a fashionable trend in food products (Allied Market Research, 2022). Protein sourced from plants alone can transform meat-centric meals into nutrient-rich, healthy alternatives (Sexton et al., 2019). Alternative protein products that can have the same look, taste and mouthfeel as animal-sourced foods is the latest development, and allows the consumer to retain the sensory pleasures of meat and dairy that they know and love, in particular when price levels are different. Currently, plant-based products with a similar mouthfeel such as sausage and hamburger are produced using pea and soy protein, by companies such as Impossible Food and Beyond Meat. Plant proteins extracted from these crops are then mixed with additional ingredients and processed into a meaty texture (Sexton et al., 2019).

Functional analogs are needed to produce plant-based replacements for animal proteins. First, crops with the necessary ingredients (proteins, fats, and starches) must be identified and processed. Second, processing must reformat ingredients into a muscle-like texture that resembles meat. Product formulation to get the preferred taste and texture, yet retain the desired nutritional qualities may consist of manufacturing processes such as extrusion, kneading, and 3D printing, among others (Specht, 2022).

An overview of fermentation

Fermentation has had a place in our diets since the beginning of mankind. From yogurt to beer, cultures of microbes have been put to work to preserve food products, as well as improve nutritional content and taste. Fermentation is traditionally used to obtain umami taste in cereal and pulse-based foods such as soya sauce, tempeh or miso (Li and Siddique, 2018). Umami is otherwise provided by animal sourced foods (Walsh et al., 2020; Mouritsen and Styrbæk, 2021; Gao et al., 2022; Li et al., 2022; Wang et al., 2022), or in traditional cuisines (such as the Mediterranean) by combining onion, garlic, and tomato in preparations like sofrito (Vallverdú-Queralt et al., 2013). From a functional perspective, fermentation also facilitates the digestion of complex carbohydrates from cereals and pulses. Fermentation further contributes to enhanced taste in plant-based dairy alternatives (Tangyu et al., 2019), which are more likely to be consumed by women (Pandey and Ritz, 2021).

Fermentation as a technology has been used over the years for disciplines ranging from biofuel production to pharmaceuticals (Ciani et al., 2021). Fermentation is currently used to generate novel foods, such as proteins from non-animal sources (Li and

Siddique, 2018). Established use of fermentation comprises lactic acid bacteria to produce cheese and yogurt, and fungi to ferment soy into tempeh. Microbial biomass alone can be used to make the food product, in certain circumstances. For example, the mycelium based products of the company Quorn^{TM}, operating since 1985, are based upon filamentous fungi, which are grown in microbial bioreactors. Products generated require minimal processing and are extremely nutritious. Quorn makes use of food waste to produce its products, using mycelium specific fermenters, and creates a carbon footprint one tenth lower than beef (Quorn Press Release, 2020). This fungal company has a global retail sale of over $200 million USD and produces 25,000 tons (dry mass) per year. It is no surprise that mycoprotein is projected to increase annually by 20% as a source of commercial food protein (Cherta-Murillo and Frost, 2021). Precision fermentation makes use of genetic engineering to create novel pigments, flavorings, and proteins via microbes. Impossible Foods makes a plant based version of a hamburger with the heme protein included via precision fermentation (Ciani et al., 2021).

Controlled bioreactors used to cultivate microbes such as fungi or bacteria and generate either biomass or specific food ingredients would be significantly more efficient than the open field growth of crops. The carbon footprint of bioreactors is low; moreover, they can be built no non-arable land or within city centers reduces competition for arable land. Production can even take place in industrial zones, where CO_2, H_2 and other inorganic carbon sources could be utilized (Airprotein.com, Järviö et al., 2021).

An overview of cultivated meat production

Cultivated/cell-based meat as a science is approaching two-decades of laboratory research, with its origins in the pharmaceutical and biomedical industries. The technical compatibilities and prospects seem encouraging. As important is the question of how socio-cultural framings serve to alter, accelerate or impede cultivated meat to global acceptance and coverage. This trajectory can be thought of in terms of two critical waves, the first initiated by university-based projects that were initially driven by ethical concerns for animal welfare, culminating in a slowly but steadily growing knowledge base in the field. The second was concern for environmental sustainability, notably supported in part by philanthropy.

In 2011, a New Yorker article reported that the technology for cultivated meat was available at that time but lacked sufficient funding (Spectre, 2011). Shortly afterwards, philanthropic donors financed the development of the first lab grown burger at Maastricht University (O'Riordan et al., 2017). The cultivated meat space was quickly supported via investments by wealthy funders with a focus on breakthrough technologies which could address global challenges. The industry shifted again to a third stage with investments from corporations such as Cargill or other food multinationals, Tyson Foods and Nestle, since 2017. New companies have moved in as well, such as Memphis Meats (which raised 17 million dollars in Series A funding). Eat Just Inc (2020), the first cell-based meat company with regulatory approval and housed in Singapore, has cell based chicken out on the market in 2023 (EatJust.com). The Israeli startup Aleph Farms has also moved forward, bringing slices or whole-meat cuts based on cultivated meat to the marketplace.

The development of cultivated meat products that are dependable with respect to taste and texture requires multiple types of cells, including fat cells, muscle precursor cells and connective tissue (O'Neill et al., 2021). The choice of medium used for production can also have an impact on meat quality and taste. The cultivated meat industry has to date concentrated on two major products: the first being unstructured, such as sausage or hamburger, and the second being highly structured, such as chicken breasts or beefsteaks. Achieving the latter requires the use of stem cells grown for 40–50 generations in a bioreactor, with the media changed at certain points to promote proliferation into muscle, fat and connective tissue. Differentiated cells such as these are adherent and require attachment to a scaffold; as a result, new biomaterials, such as collagen and egg shell membranes, have been acquired which play the role of microcarriers (Andreassen et al., 2022). The sera used must be free of any animal product and have features that are food-grade acceptable (Hanga et al., 2020).

Animal cell culture requires carbon and nitrogen, as well as amino acids, sugars, salts, and growth factors in order to proliferate (Yao and Asayama, 2017). These components influence sensory properties, for example, umami can be created from the amino acids asparagine and glutamic acid (Kawai et al., 2002). The way that media is prepared will impact how muscle cells proliferate and differentiate in culture. As an example, myoblasts need distinct cytokines and growth factors to proliferate, including fibroblast growth factor, insulin growth factor, hepatocyte growth factor, transforming growth factor-β and cytokines such as tumor necrosis factor-α (Bentzinger et al., 2010). These signaling molecules are able to stimulate myogenesis through various metabolic pathways and are currently prohibitively expensive. One way to reduce the cost of animal-derived growth factors is to screen for sequence homology with their plant or fungal counterparts. Extracts of chickpea peptides, for example, can stimulate insulin associated cell signaling (Girón-Calle et al., 2008). In the long run, it will be critical to replace animal serum with media that lacks animal-sourced products. It may be possible to utilize other, complex ingredients to reproduce constituents of media, such as the use of molasses, in place of purified glucose (Lee et al., 2022).

To create cultivated meat products such as steaks and chicken breasts *in vitro*, a natural, edible scaffold framework must be established that recreates the microenvironment that cells adhere to Bhat et al. (2017). The scaffold is necessary for cell cultivation and must be biocompatible with the cells so that they can proliferate while still enabling the free flow of nutrients and oxygen. Scaffolds can be made by electrospinning (a technique used to conform a solution of polymers into a network of fibers), mold cast/ injectable systems (in which "bioink," comprised of cultured cells, is injected into a mold that resembles a cut of meat), and 3D extrusion printing (in which bioink is placed on an extruder, which is itself constantly moving, to create a product more like ground meat) (GFI.org, 2022; Lee et al., 2022).

Under a laboratory setting, a 2D system comprised of Petri dishes and/or tissue culture flasks offers mechanical support for cells; however, the muscle cells undergo altered gene expression and thus change their phenotypic properties and behaviors. Over time, the cells take the form of a monolayer and cannot be sustained indefinitely. Alternatively, a 3D scaffold matrix comprised of a hydrogel of crosslinked hydrophilic polymers as well as growth factors incorporated into cell adhesive molecules, can better functionalize muscle cells for cultivated meat (Li et al., 2022). For scale up, cell cultures that are supported by microcarriers are needed to reach the volumes required to satisfy market demand. These microcarriers could dissolve over time, be edible, or be readily extractable during processing (Lee et al., 2022). Microcarriers could also encapsulate growth factors, which are later released to promote cell proliferation or differentiation over time. For example, Mosa Meats uses a technology to grow cultured meat by incorporating pillars which scaffold the materialization of a hydrogel containing muscle cells (Post, 2013). These muscle cells then self-assemble to form contractable rings in order to foster skeletal muscle maturation.

The hard limit to cell division is a major challenge; cells eventually enter a phase of senescence after undergoing a specified number of divisions. The number of cell divisions could be extended by including the enzyme telomerase (Kumar et al., 2021). The requirement for animal free media is another challenge. Prior to the development of the cultivated meat industry, animal derived serum—such as fetal calf serum—has been used. To address animal welfare concerns, serum free media, containing animal serum replacements will be necessary (van der Valk et al., 2018). For example, since serum contains insulin, a recombinant version produced in microbial bioreactors can replaced its animal counterpart. As an example, the animal protein albumin could be replaced with analogous proteins from plant sources, such as the albumin storage proteins (Bueno-Díaz et al., 2021).

Research and development of cell based meat activates new interest across various disciplines: identifying stem cells from different types of livestock, the development of scaffolds, increasing the proliferation and differentiation of cells in culture, scaling up processes and the production of fetal bovine serum-free growth media from alternative sources such as plants and fungi. Increasing manufacturing would also demand additional, more physical challenges, such as enabling animal cell culture in a large bioreactor to withstand shear stresses (Seah et al., 2022). Attitudinal factors will play a major role in acceptance, whatever the technical advances. Chief among these are complicated relationships among consumer perceptions regarding animal welfare as well as the dietary health benefits/risks of continuing to consume animal products. Economics matters as well: it is possible that production costs may never be low enough to make cultivated meat a generalizable option. It is equally likely that plant-based products that substitute for meat, such as the Impossible Burger, may develop in sophistication to such an extent that cultivated meat becomes obsolete (Warner, 2019).

Other sources of protein

Unconventional crops offer another potential alternative for food and fodder production. Cattle, sheep and other ruminants can feed on both duckweed or microalgae (Domokos-Szabolcsy et al., 2023; Paterson et al., 2023). These high yielding crops generate economically competitive forms of fiber and protein, and yet will not compete with arable land needed for human food in the food industry, algae is frequently found both as a functional food and as a food supplement (Scieszka and Klewicka, 2019). For example, spirulina, an cyanobacteria, can also be used as an upcoming food product (Grosshagauer et al., 2020).

Insects can also be consumed as a protein source. Edible insects are high in nutritional composition yet have the ability to reduce both land use as well as the carbon footprint (Poma et al., 2017; FAO, 2021). Entomophagy was part of the early history of humans—for example, over 3,000 years in China—but has only recently become a strong trend in Western culture. In over one hundred countries, about 2 billion people practice entomophagy today (Barennes et al., 2015; Jongema, 2022). Insects have a substantial protein content, and can thus represent an unconventional substitute for human consumption. Several insect peptides that reside in food products contain anti-hypertensive, anti-microbial and antioxidant properties, contributing important health advantages (de Castro et al., 2018; Hall et al., 2018). The next challenge to be addressed is the creation of large-scale facilities for edible insect production, whereas cultural barriers to expanding consumption are significant but perhaps changeable (da Silva Lucas et al., 2020).

Circular food systems

In a circular food system, green technologies utilize food waste and reduce pressure on arable farmland. Alternative protein production can play a role in this process. Land use for livestock feed has been examined in terms of acreage required for grazing and acreage needed to produce feed crops. In the case of alternative protein, land would still be needed to generate feedstock. Yet, if we made our feedstock from microalgae instead of food crops on arable land, our land usage needed could be even further reduced (Lusk and Norwood, 2009; Rubio et al., 2020). In a similar fashion, proteins that are derived from insects can be produced using food waste residue in place of arable land (Barennes et al., 2015; da Silva Lucas et al., 2020).

Precision fermentation systems utilize microbial bioreactors to produce their products. As a result, these fermentors require glucose from grain crops to feed the cell cultures. These more often are corn or sugar beet and thus waste much needed arable land. The avoidance of conventional sugar carbon sources using autotrophic microbes have been used in bioreactors to produce food proteins. Since the gases CO_2 or CH_4 can be used as a feed source for these microbes, the actual waste from industrial plants can be used as the feedstock (Järviö et al., 2021). Net use of greenhouse gas emissions could be achieved in this way, increasing the environmental sustainability factor. The great advantage of this form of fermentation is complete independence from outdoor agriculture in terms of food and biofuel and from fossil fuel. An additional benefit is reduction of vulnerability to the economic fluctuations that govern our current energy and food systems (Verstraete et al., 2022). Although alternative protein production is still at an early stage, it is developing rapidly (Parodi et al., 2018; Pikaar et al., 2018; Tuomisto, 2019).

Social justice and the alternative protein landscape

The effect of the alternative food protein revolution on world agriculture is uncertain (Stephens et al., 2019). While intensive farming, particularly of livestock, is thought by some to be leading to environmental catastrophe, the way that a major shift to animal protein replacements might affect the life of farmers and others in the animal-sourced foods industry, as well as those who produce animal feed, is uncertain. Disruptive technologies such as cultivated meat and precision fermentation offer promise for resolving both environmental and animal welfare issues that remain problematic within our current food system (Sexton et al., 2019). It is estimated that this revolution to non-animal sourced meat will lead to the rewilding and reforestation of land previously used for farming, and the restoration of ecosystems. But questions on economic sustainability and resilience remain: what changes will we see in the global marketplace? How will livelihoods be altered in rural settings? And how will regional discrepancies in meat production and consumption, as well as development and uptake of these innovations, affect global agri-food systems?

Approval of food proteins that are not animal-sourced will change from one country the next, and from culture to culture (FAO, 2022). Asia provides some real optimism; there has been greater consumer acceptance of protein from novel sources in India and China, for example, than in the US (Bekker et al., 2017). India as a subcontinent of many cultures is well known for being largely vegetarian, and as a result, the acceptance of technologies with respect to novel food products remains unclear. Political priorities matter, as well. Both animal welfare as well as environmental sustainability issues are coming to the forefront more quickly in certain political systems and not in others. Livestock maintained in American or European agriculture differ substantially than those managed in India or Latin America. For example, sub-Saharan owners of livestock could maintain a nomadic lifestyle and care for small herds of animals, whereas American livestock owners might manage tens of thousands of animals under industrial conditions. Differences arise in terms of the management of infectious disease pressures or the food safety of animal products, including use of antibiotics (Stevens et al., 2022). In the Americas for example, much environmental degradation has occurred in regions such as the Amazonian Forest, the Chaco region and the plains in Argentina, in order to produce either livestock for meat or the feedstock required to maintain them.

Industrialized countries exhibit the most readiness to develop and support alternative sources of animal protein (Hopkins et al., 2023). A colonial heritage with trade dependence means that richer countries have traditionally influenced food production beliefs and behavior in low- and middle-income trading partners (Paarlberg, 2009). Will nations long disadvantaged by the global economic system accept pressures to follow the inclinations of more industrialized countries or assert divergent cultural values associated with livestock production, as increased national income leads to increased demands for animal meat (Sexton et al., 2019)? How will these changes impact the global market with respect to imbalances between the Global North and South (Jarosz, 2011)? Might alternative proteins help to achieve food security and further develop the economies of low- and middle-income countries? Little research currently available sheds light on these difficult challenges (Tilman and Clark, 2014). Whereas, plant-based consumers experience new sensory experiences from a diversity of plant sources, consumers of animal sourced foods tend to be attached to the taste of meat (Perez-Cueto, 2020).

Consumer behavior toward the alternative protein movement

The increased attention toward novel foods with environmental benefits at policy and industry level has led to a large body of consumer studies on environmental-friendly foods (Vermeir et al., 2020)—such as plant-based alternative proteins (Aschemann-Witzel et al., 2021); cultured meat (Bryant and Barnett, 2018); and algae, pulses, and insects (Hartmann and Siegrist, 2017; Onwezen et al., 2022).

Plant-based diets are those diets that privilege foods of plant origin. Such diets go from vegan to flexitarian. Vegan diets exclude any type of foods of animal or insect origin. Vegetarian diets vary depending on whether they include dairy (lacto-vegetarian), eggs and dairy (lacto-ovo vegetarian), fish (pescetarian) or small amounts of meat and other foods of animal origin (flexitarian). Omnivores, however, can eat all foods consumed by the other dietary lifestyles.

Most consumer surveys show that few people (about 5%) following vegetarian diets (including vegans) (e.g., Pieniak et al., 2009; Pérez-Cueto et al., 2010; Verbeke et al., 2011); few in this group were complying with nutritional recommendations (Pérez-Cueto et al., 2012). Attempts to define this dietary lifestyle were made (Derbyshire, 2017), but revealed the complexity of the behavior and its implications. Flexitarian is a "flexible" term, coined for Millennials that prefer not being classified in limiting boxes, and that can include people within a very large range of consumption, from low or null meat and dairy intake to even heavy animal sourced food consumers. By 2021, at least one third of mainstream consumers identify themselves as flexitarians according to a recent EU consumer survey. These flexitarians expressed a common desire to eat more sustainably and adhere to ethical principles of consumption (Bechtold et al., 2022). The use of the term plant-based has been advocated as a neutral term (Faber et al., 2020; Storz, 2022) that is free from ideological tones (Dickstein et al., 2022), but the definition of a "plant-based" diet is unclear. For many, it is equivalent to vegan diet choices, whereas to others it is equivalent to a flexitarian eating lifestyle (Faber et al., 2020; Onwezen et al., 2021; Palmieri and Nervo, 2023; Takeda et al., 2023).

Traditional diets in Europe historically were largely vegetarian (Leggett and Lambert, 2022). It was only in the past 100 years that the society turned to predominantly meat and dairy consumption, partly because of increasing income, food security policy measures, and later by the effects of Common Agricultural Policy (CAP). Dietary recommendations have also been instrumental in supporting the belief that protein of animal origin is of superior quality when paired with varied consumption of fruits, vegetables and pulses. Urgent calls for healthier and more sustainable eating practices are met with both consumer inertia

(Willet et al., 2019; Vaidyanathan, 2021) and pressure from interest groups (Sievert et al., 2021).

Despite these obstacles, it is clear that transitioning to less meat-intensive diets could aid in reducing chronic disease due to poor dietary habits and contribute to mitigating climate change (Vaidyanathan, 2021). Factors that influence progress on the specific issue of replacing meat with alternative protein—besides animal welfare and environmental considerations – are age, gender, education and health status. Other motivators consist of cost, trust in science/neophobia, media coverage and convenience. The plant-based alternatives are the most well-established meat substitutes, as consumers are already familiar with them (Schosler et al., 2015).

A summary picture of consumers of alternative protein includes highly educated, young, left-leaning urbanites (De Boer and Aiking, 2011) and those who already consume little or no meat (Verbeke et al., 2011). Drivers pertaining to consumer acceptance include health and environmental benefits, convenience, familiarity and appearance and taste (Eckl et al., 2021). Women in general are more prone to adopt to plant-based diets (Nakagawa and Hart, 2019; Satija et al., 2019). Commonly known barriers to adopting plant-based diets include lack of skills, cognition about balanced eating, perceived hardships such as finding meal options when eating out, finding recipes, as well as perceptions of the inadequacy and tastelessness of a meatless diet (Pohjolainen et al., 2015; Reipurth et al., 2019; Hielkema and Lund, 2021).

While consumer acceptance is greatest for plant-based alternatives and moderate for cultured meat, it is lowest for insect-based protein (Onwezen et al., 2022). Nevertheless, there is heterogeneity in consumer acceptance and willingness-to-pay for specific types of insects and insect-based foods across and within countries (Dagevos, 2021). Edible insects are challenging for Western culture, on the other hand, cell-based meat is not yet available in the market. Despite growing interest in Europe, with various insect types approved as novel foods, consumers are often reluctant to shift, resulting in lower acceptance rates of insects as food (Iannuzzi et al., 2019). Yet reports indicate that higher willingness to consume shredded insect products rather than whole insects. However, for mainstream EU consumers, insects are the most distrusted (Smart Protein, 2021) and least accepted alternative protein (Onwezen et al., 2022), despite the growing number of approvals of insect types as novel foods. The demand to understand what drives consumer acceptance of such alternative proteins is paramount (Slade, 2018). Several barriers have been identified to explain this, such as cultural influences (e.g., insects might be viewed as pest insects), health and safety concerns (e.g., unsafe and causing diseases), negative sensory perceptions (e.g., flavor, appearance, texture) and attitudes (e.g., about sustainability, neophobia) (Van Huis, 2013). However, exposure and positive tasting experiences have shown to stimulate adoption of insect-based food products, especially in Western countries (Wendin and Nyberg, 2021). Price sensitivity is variable; consumers are typically willing to pay for insect-based products, especially if information on benefits is presented. If not, or if the insects are visible, consumers often prefer a price that is equal to, or lower than conventional products (de-Magistris et al., 2015; Kornher and Schellhorn, 2019; Lombardi et al., 2019). While insect-based foods are increasingly promoted, overall acceptance in regions where insects are not part of traditional consumption patterns is expected to be longer than for other alternative protein sources and will require (Franceković et al., 2021) increased efforts to overcome barriers of familiarity, taste and emotional connotations (Ardoin and Prinyawiwatkul, 2021).

Cultured meat presents a different picture. An increasing number of products are projected to hit the market in the coming years, leading to growth in consumer research on cultured meat, especially after Eat Just became the first commercialized product in Singapore in 2020. In their systematic reviews, Bryant and Barnett (2018, 2020) demonstrated that cultured meat would be positively embraced by a large share of consumer populations, as illustrated by their willingness to try and buy, though not necessarily as a permanent replacement of conventional meat. Aside from regional and country differences, acceptance of cultured meat currently appeals to the group of young, highly educated, males (Bryant and Barnett, 2020), as well as non-vegetarians (Verbeke et al., 2021) or frequent meat consumers (Baum et al., 2022). Research shows that people who frequently consume large amounts of meat also show a higher level of acceptance of cell based meat (Stevens et al., 2022) in addition to other similar products (Hoek et al., 2011). Furthermore, consumers' perceived benefits were generally driven by societal benefits (e.g., animal and environmental) while perceived barriers were often linked to their personal risks (e.g., naturalness, safety and health, trust, technology neophobia) (Bryant and Barnett, 2018; Chriki and Jean-François, 2020). Highlighting these benefits (Bryant and Dillard, 2019; Gómez-Luciano et al., 2019) by utilizing counter-messaging (targeting conventional meat production issues to promote cultured meat) (Baum et al., 2022) positively influence consumer acceptance. Terminology preference (e.g., "clean meat") might also play a role (Bryant and Barnett, 2020), though this was not found in earlier studies (Verbeke et al., 2021). Nevertheless, price and taste expectations and evaluations of cultured meat products will continue to play a dominant role in consumers' decision making, similar as for other alternative protein sources.

The conclusion to draw from this section is not surprising: dietary habits are notably sticky and difficult to alter, hence notably slow and incremental. Nevertheless, it is clear that further development of alternatives and increasing concerns for human and environmental health are altering the potential.

Future prospects for alternative protein development

This review has presented the three major domains of alternative protein development. The ways that disruptive technologies involving alternative protein may influence consumer behavior, trade, and international inequalities are described as well. The increase in meat consumption per capita is most striking in countries that have increased in wealth, and a substantial middle class desirous of markers of affluence, including animal sourced products. Consumer behavior and willingness-to-pay will be important for aligning the future development of alternative protein products to potential target markets. In the future advancement of the three alternatives to meat proteins will concentrate on safety, perceived healthiness, taste, price and nutritional benefits and/or greater environmental friendliness.

Although alternative proteins have elicited much interest on a global scale, much effort will be required at multiple stages along the food supply chain. To start with, global warming is already affecting the yields in Southern Europe, and for some crops reducing their nutrient content; it will also create an opportunity for production in Northern Europe, to the detriment of existing forests. Improvements in crop breeding will be required, to increase the number of varieties with increased levels of high-quality protein, for plant-based meat production, Similarly, the removal of off-flavors and improved sensory characteristics—particularly taste and texture –will be critical (Specht, 2022). To mimic the red to brown change in color while cooking, improvements in color indicators for plant-based meat are also essential, and changes such as these will in turn lead to higher consumer acceptance.

Facility layout and operation will be critical for the cultivated meat industry. Today, the global market in meat products is over $800 billion; to produce quantities sufficient to capture a portion of that necessitates substantial scaling up of current infrastructure (Statista, 2022). The production of cultivated meat products with texture and taste that closely resemble conventional chicken breasts, beefsteaks or fish filets will be challenging. Because these represent newly emerging technologies, winning over consumers will require educational information about cultivated meat (Specht, 2022). Focusing on perceived benefits (Verbeke et al., 2021), especially through leveraging problems of conventional meat production to build the case for cultured meat (Baum et al., 2022), appear to influence acceptance.

Microbial bioreactors will also require development for the adequate fermentation of animal proteins. These will include the development of new microbial strains that can perform tasks with greater precision and result in better taste, as will be the identification of new feedstocks that could be optimized for fossil fuel independent production pathways that are also not reliant upon crop production. Bioreactors could in the future be used to produce green industrial products that are not only petroleum independent, but in fact make use of greenhouse gases such as CO_2 and CH_4 for their feedstock, thus making them carbon negative in production (Järviö et al., 2021).

While cultivated meat and precision fermentation each require bioreactors for cell growth, animal cells proliferate much more slowly than microbes, and may generate growth-inhibiting catabolites such as ammonia during the incubation process (O'Neill et al., 2021). Since animal cells lack a cell wall, they are also more likely to be damaged. For animal cells, different types of culture are needed to recreate complex forms of meat, with bioreactor design and tailored media requirements being essential for this task (Ben-Arye and Levenberg, 2019). The total capital investment estimated today per kg for cultured meat using a perfusion bioreactor is $51 while a bioreactor with a fed-batch design have been determined at a total cost of $37. Consumers have demonstrated a willingness to pay for cultured meat at a cost limitation of $25 per kg. After further packaging, and distribution, a minimum of $50 per kg for cultured meat is estimated for supermarket settings, making advancements a significant challenge (Humbird, 2021).

In sum, multiple questions concerning practicality and cost emerge from the specifics of alternative production techniques and products. These questions point the way to intelligent choices of both research and funding.

Conclusion

This review has addressed possible futures for alternative proteins, with a view toward alleviating the current climate crisis and avoiding injustice in the transition to a more sustainable food system. Though research into and development of animal protein replacements has produced an explosion of innovation, dietary habits are notably sticky and difficult to alter, hence notably slow and incremental.

Different technologies have been reviewed with their attendant products. Technological limitations and safety issues along the production chain suggest that cultivated meat and insect protein offer attractive prospects but will likely advance slowly for some time. From the current consumer perspective, plant-based proteins are preferred, although there are challenges for product development throughout the chain. Fermented foods will gain more attention in the coming years as they provide desired flavor and textures. For all of these elements of a new food system to be successful, both public and private funding will need priority tags and informed choices, but with ramifying benefits. Reducing the financial investment necessary to produce plant-based meat and thus decreasing costs would render plant-based meat production more viable in less affluent countries, contributing to enhancement of global justice and environmental sustainability. Success in expanding production and use of alternative proteins will involve an amalgamation of specific solutions – not a silver bullet—and changes in attitudes about production and consumption of food discussed in this essay.

Author contributions

KH: Conceptualization, Methodology, Investigation, Writing—original draft preparation, Writing—review & Editing. HD: Investigation, Writing—review & Editing; FP-C: Investigation, Writing—review & Editing; RH: Investigation, Writing—review & Editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Aimutis, W. R. (2022). Plant-based proteins: the good, bad, and ugly. *Annu. Rev. Food Sci. Technol.* 13, 1–17. doi: 10.1146/annurev-food-092221-041723

Allied Market Research (2022). Available online at: https://www.alliedmarketresearch.com/press-release/protein-supplement-market.html (accessed April 3, 2022).

Andreassen, R. C., Rønning, S. B., Solberg, N. T., Grønlien, K. G., Kristoffersen, K. A., Høst, V., et al. (2022). Production of food-grade microcarriers based on by-products from the food industry to facilitate the expansion of bovine skeletal muscle satellite cells for cultured meat production. *Biomaterials* 286, 121602. doi: 10.1016/j.biomaterials.2022.121602

Ardoin, R., and Prinyawiwatkul, W. (2021). Consumer perceptions of insect consumption: a review of western research since 2015. *Int. J. Food Sci. Technol.* 56, 4942–4958. doi: 10.1111/ijfs.15167

Aschemann-Witzel, J., Gantriis, R. F., Fraga, P., and Perez-Cueto, F. J. A. (2021). Plant-based food and protein trend from a business perspective: markets, consumers, and the challenges and opportunities in the future. *Crit. Rev. Food Sci. Nutr.* 61, 3119–3128. doi: 10.1080/10408398.2020.1793730

Barennes, H., Phimmasane, M., and Rajaonarivo, C. (2015).Insect consumption to address undernutrition, a national survey on the prevalence of insect consumption among adults and vendors in Laos. *PLoS ONE* 10, e0136458. doi: 10.1371/journal.pone.0136458

Baum, C. M., Verbeke, W., and De Steur, H. (2022). Turning your weakness into my strength: how counter-messaging on conventional meat influences acceptance of cultured meat. *Food Quality Pref.* 97, 104485. doi: 10.1016/j.foodqual.2021.104485

Bechtold, M. L., Brown, P. M., Escuro, A., Grenda, B., Johnston, T., Kozeniecki, M., et al. (2022). When is enteral nutrition indicated? *J. Parenter. Enteral Nutr.* 46, 1470–1496. doi: 10.1002/jpen.2364

Bekker, G. A., Tobi, H., and Fischer, A. R. (2017). Meet meat: an explorative study on meat and cultured meat as seen by Chinese, Ethiopians and Dutch. *Appetite* 114, 82–92. doi: 10.1016/j.appet.2017.03.009

Ben-Arye, T., and Levenberg, S. (2019). Tissue engineering for clean meat production. *Front. Sustain. Food Syst.* 3:46. doi: 10.3389/fsufs.2019.00046

Bentzinger, C. F., von Maltzahn, J., and Rudnicki, M. A. (2010). Extrinsic regulation of satellite cell specification. *Stem Cell Res. Ther.* 1, 27. doi: 10.1186/scrt27

Bhat, Z. F., Kumar, S., and Bhat, H. F. (2017). *In vitro* meat: a future animal-free harvest. *Crit. Rev. Food Sci. Nutr.* 57, 782–789. doi: 10.1080/10408398.2014.924899

Bryant, C., and Barnett, J. (2018). Consumer acceptance of cultured meat: a systematic review. *Meat Sci.* 143, 8–17. doi: 10.1016/j.meatsci.2018.04.008

Bryant, C., and Barnett, J. (2020). Consumer acceptance of cultured meat: an updated review (2018–2020). *Appl. Sci.* 10, 5201. doi: 10.3390/app10155201

Bryant, C., and Dillard, C. (2019). The impact of framing on acceptance of cultured meat. *Front. Nutr.* 6, 103. doi: 10.3389/fnut.2019.00103

Bueno-Díaz, C., Biserni, C., Martín-Pedraza, L., de Las Heras, M., Blanco, C., Vázquez-Cortés, S., et al. (2021). Seed storage proteins, 2s albumin and 11s globulin, associated to severe allergic reactions after flaxseed intake. *J. Investig. Allergol. Clin. Immunol.* 4, 713. doi: 10.18176/jiaci.0713

Chai, B. C., van der Voort, J. R., Grofelnik, K., Eliasdottir, H. G., Klöss, I., Perez-Cueto, F. J. A., et al. (2019). Which diet has the least environmental impact on our planet? A systematic review of vegan, vegetarian and omnivorous diets. *Sustainability* 11, 4110. doi: 10.3390/su11154110

Cherta-Murillo, A., and Frost, G. S. (2021). The association of mycoprotein-based food consumption with diet quality, energy intake and non-communicable diseases' risk in the UK adult population using the national diet and nutrition survey (NDNS) years 2008/2009-2016/2017: a cross-sectional study. *Br. J. Nutr.* 17, 1–10. doi: 10.1017/S000711452100218X

Chriki, S., and Jean-François, H. (2020). The myth of cultured meat: a review. *Front. Nutr.* 7, 7. doi: 10.3389/fnut.2020.00007

Ciani, M., Lippolis, A., Fava, F., Rodolfi, L., and Niccolai, A. (2021). Microbes: food for the future. *Foods* 10, 971. doi: 10.3390/foods10050971

da Silva Lucas, A. J., de Oliveira, L. M., Da Rocha, M., and Prentice, C. (2020). Edible insects: an alternative of nutritional, functional and bioactive compounds. *Food Chem.* 311, 126022. doi: 10.1016/j.foodchem.2019.126022

Dagevos, H. (2021). A literature review of consumer research on edible insects: Recent evidence and new vistas from 2019 studies. *J. Insects Food Feed* 7, 249–259. doi: 10.3920/JIFF2020.0052

De Boer, J., and Aiking, H. (2011). On the merits of plant-based proteins for global food security: marrying macro and micro perspectives. *Ecol. Econ.* 70, 1259–1265. doi: 10.1016/j.ecolecon.2011.03.001

de Castro, R. J. S., Ohara, A., dos Santos Aguilar, J. G., and Domingues, M. A. F. (2018). Nutritional, functional and biological properties of insect proteins: Processes for obtaining, consumption and future challenges. *Trends Food Sci. Technol.* 76, 82–89. doi: 10.1016/j.tifs.2018.04.006

de-Magistris, T., Pascucci, S., and Mitsopoulos, D. (2015). Paying to see a bug on my food: how regulations and information can hamper radical innovations in the European Union. *Br. Food J.* 117, 1777–1792. doi: 10.1108/BFJ-06-2014-0222

Derbyshire, E. J. (2017). Flexitarian diets and health: a review of the evidence-based literature. *Front Nutr.* 3, 55. doi: 10.3389/fnut.2016.00055

Dickstein, J., Dutkiewicz, J., and Guha-Majumdar, J. (2022). Veganism as left praxis. *Capitalism Nat. Soc.* 33, 56–75. doi: 10.1080/10455752.2020.1837895

Domokos-Szabolcsy, É., Yavuz, S. R., Picoli, E., Fári, M. G., Kovács, Z., Tóth, C., et al. (2023). Green biomass-based protein for sustainable feed and food supply: an overview of current and future prospective. *Life* 13, 307. doi: 10.3390/life13020307

Eat Just Inc (2020). *Gets Approval in Singapore for Lab-Grown Chicken.* Available online at: https://www.foodsafetynews.com/2020/12/eat-just-inc-gets-approval-in-singapore-for-lab-grown-chicken/ (accessed December 13, 2020).

Eckl, M. R., and Biesbroek, S., Van't Veer, P., and Geleijnse, J. M. (2021). Replacement of meat with non-meat protein sources: a review of the drivers and inhibitors in developed countries. *Nutrients* 13, 3602. doi: 10.3390/nu13103602

Faber, I., Castellanos-Feijoó, N. A., Van de Sompel, L., Davydova, A., and Perez-Cueto, F. J. A. (2020). Attitudes and knowledge towards plant-based diets of young adults across four European countries. Exploratory survey. *Appetite* 145, 104498. doi: 10.1016/j.appet.2019.104498

FAO (2021). *Looking at Edible Insects From a Food Safety Perspective. Challenges and Opportunities for the Sector*. Rome: FAO.

FAO (2022). *The Future of Food and Agriculture – Drivers and Triggers for Transformation. The Future of Food and Agriculture, no. 3.* Rome: FAO.

Fegan, N., and Jenson, I. (2018). The role of meat in foodborne disease: is there a coming revolution in risk assessment and management? *Meat Sci.* 144, 22–29. doi: 10.1016/j.meatsci.2018.04.018

Franceković, P., García-Torralba, L., Sakoulogeorga, E., Vučković, T., and Perez-Cueto, F. J. A. (2021). How do consumers perceive cultured meat in Croatia, Greece, and Spain? *Nutrients* 13, 1284. doi: 10.3390/nu13041284

Gao, B., Hu, X., Xue, H., Li, R., Liu, H., Han, T., et al. (2022). Isolation and screening of umami peptides from preserved egg yolk by nano-HPLC-MS/MS and molecular docking. *Food Chem.* 377, 131996. doi: 10.1016/j.foodchem.2021.131996

GFI.org (2022). Available online at: https://gfi.org/science/the-science-of-cultivated-meat/deep-dive-cultivated-meat-scaffolding/

Girón-Calle, J., Vioque, J., Pedroche, J., Alaiz, M., Yust, M. M., Megías, C., et al. (2008). Chickpea protein hydrolysate as a substitute for serum in cell culture. *Cytotechnology* 57, 263–272. doi: 10.1007/s10616-008-9170-z

Gómez-Luciano, C. A., De Aguiar, D., Vriesekoop, L. K., and Urbano, F. B. (2019). Consumers' willingness to purchase three alternatives to meat proteins in the United Kingdom, Spain, Brazil and the Dominican Republic. *Food Quality Pref.* 78, 103732. doi: 10.1016/j.foodqual.2019.103732

González, N., Marquès, M., Nadal, M., and Domingo, J. L. (2020). Meat consumption: which are the current global risks? A review of recent (2010–2020) evidences. *Food Res. Int.* 137, 109341. doi: 10.1016/j.foodres.2020.109341

Grosshagauer, S., Kraemer, K., and Somoza, V. (2020). The true value of spirulina. *J. Agric. Food Chem.* 68, 4109–4115. doi: 10.1021/acs.jafc.9b08251

Hall, F., Johnson, P. E., and Liceaga, A. (2018). Effect of enzymatic hydrolysis on bioactive properties and allergenicity of cricket (*Gryllodes sigillatus*) protein. *Food Chem.* 262, 39–47. doi: 10.1016/j.foodchem.2018.04.058

Hanga, M. P., Ali, J., Moutsatsou, P., de la Raga, F. A., Hewitt, C. J., Nienow, A., and Wall, I. (2020). Bioprocess development for scalable production of cultivated meat. *Biotechnol. Bioeng.* 117, 3029–3039. doi: 10.1002/bit.27469

Hartmann, C., and Siegrist, M. (2017). Consumer perception and behaviour regarding sustainable protein consumption: a systematic review. *Trends Food Sci. Technol.* 61, 11–25. doi: 10.1016/j.tifs.2016.12.006

Hielkema, M. H., and Lund, T. B. (2021). Reducing meat consumption in meat-loving Denmark: exploring willingness, behavior, barriers and drivers. *Food Quality Pref.* 93, 104257. doi: 10.1016/j.foodqual.2021.104257

Hoek, A. C., Luning, P. A., Weijzen, P., Engels, W., and Kok, F. J., Graaf, d. e., et al. C. (2011). Replacement of meat-by-meat substitutes. A survey on person- and product related factors in consumer acceptance. *Appetite* 56, 662–673. doi: 10.1016/j.appet.2011.02.001

Hopkins, I., Farahnaky, A., Gill, H., Danaher, J., and Newman, L. P. (2023). Food neophobia and its association with dietary choices and willingness to eat insects. *Front. Nutr.* 10, 1150789. doi: 10.3389/fnut.2023.1150789

Humbird, D. (2021). Scale-up economics for cultured meat. *Biotechnol. Bioeng.* 118, 3239–3250. doi: 10.1002/bit.27848

Iannuzzi, E., Sisto, R., and Nigro, C. (2019). The willingness to consume insect-based food: an empirical research on Italian consumers. *Agric. Econ.* 65, 454–462. doi: 10.17221/87/2019

Jarosz, L. (2011). Defining world hunger: scale and neoliberal ideology in international food security policy discourse. *Food Culture Soc.* 14, 117–139. doi: 10.2752/175174411X12810842291308

Järviö, N., Maljanen, N. L., Kobayashi, Y., Ryynänen, T., and Tuomisto, H. L. (2021). An attributional life cycle assessment of microbial protein production: a case study on using hydrogen-oxidizing bacteria. *Sci. Total Environ.* 776, 145764. doi: 10.1016/j.scitotenv.2021.145764

Jongema, Y. (2022). (2017). *List of Edible Insects of the World*. Wageningen, The Netherlands: Wageningen University.

Kawai, M., Okiyama, A., and Ueda, Y. (2002). Taste enhancements between various amino acids and IMP. *Chem. Senses* 27, 739–745. doi: 10.1093/chemse/27.8.739

Kornher, L., and Schellhorn, M. (2019). Disgusting or innovative-consumer willingness to pay for insect based burger patties in Germany. *Sustainability* 11, 1878. doi: 10.3390/su11071878

Kumar, P., Sharma, N., Sharma, S., Mehta, N., Verma, A. K., Chemmalar, S., et al. (2021). In-vitro meat: a promising solution for sustainability of meat sector. *J. Anim. Sci. Technol.* 63, 693–724. doi: 10.5187/jast.2021.e85

Lee, H. J., Kim, D. W., Kim, C., Ryu, H. D., Chung, E. G., Kim, K., et al. (2021). Concentrations and risk assessments of antibiotics in an urban-rural complex watershed with intensive livestock farming. *Int. J. Environ. Res. Pub. Health* 18, 10797. doi: 10.3390/ijerph182010797

Lee, K. Y., Loh, H. X., and Wan, A. C. (2022). Systems for muscle cell differentiation: from bioengineering to future food. *Micromachines* 13, 71. doi: 10.3390/mi13010071

Lee, S. Y., Lee, D. Y., Jeong, J. W., Kim, J. H., Yun, S. H., Mariano, E. J., et al. (2023). Current technologies, regulation, and future perspective of animal product analogs - A review. *Anim Biosci*. 36, 1465–1487. doi: 10.5713/ab.23.0029

Leggett, S., and Lambert, T. (2022). Food and power in early medieval England: a lack of (isotopic) enrichment. *Anglo-Saxon England* 24, 1–34. doi: 10.1017/S0263675122000072

Li, X., and Siddique, K. H. (2018). *Future Smart Food. Rediscovering Hidden Treasures of Neglected and Underutilized Species for Zero Hunger in Asia, Bangkok*. Rome: FAO.

Li, Z., Zhou, Y., Li, T., Zhang, J., and Tian, H. (2022). Stimuli-responsive hydrogels: fabrication and biomedical applications. *View* 3, 20200112. doi: 10.1002/VIW.20200112

Lima, M., Costa, R., Rodrigues, I., Lameiras, J., and Botelho, G. A. (2022). Narrative review of alternative protein sources: highlights on meat, fish, egg and dairy analogues. *Foods* 11, 2053. doi: 10.3390/foods11142053

Lombardi, A., Vecchio, R., Borrello, M., and Caracciolo, F. (2019). Willingness to pay for insect-based food: the role of information and carrier. *Food Q. Pref.* 72, 177–187. doi: 10.1016/j.foodqual.2018.10.001

Lusk, J., and Norwood, F. (2009). Some economic benefits and costs of vegetarianism. *Agric. Res. Econ. Rev*. 38, 109–124. doi: 10.1017/S1068280500003142

Micha, R., Wallace, S. K., and Mozaffarian, D. (2010). Red and processed meat consumption and risk of incident coronary heart disease, stroke, and diabetes mellitus: a systematic review and meta-analysis. *Circulation* 121, 2271–2283. doi: 10.1161/CIRCULATIONAHA.109.924977

Mouritsen, O. G., and Styrbæk, K. (2021). Design and 'umamification'of vegetable dishes for sustainable eating. *Int. J. Food Desig.* 5, 9–42. doi: 10.1386/ijfd_00008_1

Nakagawa, S., and Hart, C. (2019). Where's the beef? How masculinity exacerbates gender disparities in health behaviors. *Socius Sociol. Res. Dyn. World* 5, 237802311983180. doi: 10.1177/2378023119831801

O'Neill, E. N., Cosenza, Z. A., Baar, K., and Block, D. E. (2021). Considerations for the development of cost-effective cell culture media for cultivated meat production. *Compr Rev Food Sci Food Saf.* 20, 686–709. doi: 10.1111/1541-4337.12678

Onwezen, M. C., Bouwman, E. P., and Reinders, M. J. (2021). A systematic review on consumer acceptance of alternative proteins: pulses, algae, insects, plant-based meat alternatives, and cultured meat. *Appetite* 159, 105058. doi: 10.1016/j.appet.2020.105058

Onwezen, M. C., Verain, M. C. D., and Dagevos, H. (2022). Social norms support the protein transition: the relevance of social norms to explain increased acceptance of alternative protein burgers over 5 years. *Foods* 11, 3413. doi: 10.3390/foods11213413

O'Riordan, K., Fotopoulou, A., and Stephens, N. (2017). The first bite: imaginaries, promotional publics and the laboratory grown burger. *Pub. Understanding Sci.* 26, 148–163. doi: 10.1177/0963662516639001

Paarlberg, R. (2009). *Starved for Science: How Biotechnology is Being Kept Out of Africa.* Boston, MA: Harvard University Press.

Palmieri, N., and Nervo, C. (2023). Consumers' attitudes towards sustainable alternative protein sources: comparing seaweed, insects and jellyfish in Italy. *Food Q. Pref.* 104, 104735. doi: 10.1016/j.foodqual.2022.104735

Pandey, S., and Ritz, C. (2021). An application of the theory of planned behaviour to predict intention to consume plant-based yogurt alternatives. *Foods* 10, 148. doi: 10.3390/foods10010148

Parlasca, M., Knößlsdorfer, I., Alemayehu, G., and Doyle, R. (2023). How and why animal welfare concerns evolve in developing countries. *Anim. Front*. 13, 26–33. doi: 10.1093/af/vfac082

Parodi, A., Leip, A., De Boer, I. J. M., Slegers, P. M., Ziegler, F., Temme, E. H. (2018). The potential of future foods for sustainable and healthy diets. *Nat. Sustain.* 1, 782–789. doi: 10.1038/s41893-018-0189-7

Paterson, S., Gómez-Cortés, P., de la Fuente, M. A., and Hernández-Ledesma, B. (2023). Bioactivity and digestibility of microalgae tetraselmis sp. and nannochloropsis sp. as basis of their potential as novel functional foods. *Nutrients* 15, 477. doi: 10.3390/nu15020477

Perez-Cueto, F. J. (2020). Sustainability, health and consumer insights for plant-based food innovation. *Int. J. Food Design* 2, 139–148. doi: 10.1386/ijfd_00017_3

Pérez-Cueto, F. J., Aschemann-Witzel, J., Shankar, B., Brambila-Macias, J., and Bech-Larsen, T. (2012). Assessment of evaluations made to healthy eating policies in Europe: a review within the EATWELL Project. *Pub. Health Nutr*. 15, 1489–1496. doi: 10.1017/S1368980011003107

Pérez-Cueto, F. J., Verbeke, W., de Barcellos, M. D., Kehagia, O., Chryssochoidis, G., Scholderer, J., et al. (2010). Food-related lifestyles and their association to obesity in five European countries. *Appetite* 54, 156–162. doi: 10.1016/j.appet.2009.10.001

Perignon, M., and Darmon, N. (2022). Advantages and limitations of the methodological approaches used to study dietary shifts towards improved nutrition and sustainability. *Nutr. Rev*. 80, 579–597. doi: 10.1093/nutrit/nuab091

Pieniak, Z., Pérez-Cueto, F., and Verbeke, W. (2009). Association of overweight and obesity with interest in healthy eating, subjective health and perceived risk of chronic diseases in three European countries. *Appetite* 53, 399–406. doi: 10.1016/j.appet.2009.08.009

Pikaar, I., Matassa, S., Bodirsky, B. L., Weindl, I., Humpen?der, F., Rabaey, K. (2018). Decoupling livestock from land use through industrial feed production pathways. *Environ. Sci. Technol.* 52, 7351–7359. doi: 10.1021/acs.est.8b00216

Pohjolainen, P., Vinnari, M., and Jokinen, P. (2015). Consumers' perceived barriers to following a plant-based diet. *Br. Food J.* 117, 1150–1167. doi: 10.1108/BFJ-09-2013-0252

Poma, G., Cuykx, M., Amato, E., Calaprice, C., Focant, J. F., Covaci, A., et al. (2017). Evaluation of hazardous chemicals in edible insects and insect-based food intended for human consumption. *Food Chem. Toxicol.* 100, 70–79. doi: 10.1016/j.fct.2016.12.006

Poore, J., and Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science* 360, 987–992. doi: 10.1126/science.aaq0216

Post, M. J. (2013). Cultured beef: medical technology to produce food. *J. Sci. Food Agric*. 94, 1039–1104. doi: 10.1002/jsfa.6474

Quorn Press Release (2020). Available online at: https://www.quorn.co.uk/company/press/quorn-unveils-carbon-footprint-labelling-of-its-products-and-calls-on-other#:~:text=In%202018%20alone%2C%20Quorn%20Foods,90%25%20lower%20than%20beef1 (accessed April 10, 2020).

Reipurth, M. F. S., Hørby, L., Gregersen, C. G., Bonke, A., and Perez Cueto, F. J. A. (2019). Barriers and facilitators towards adopting a more plant-based diet in a sample of Danish consumers. *Food Q. Pref.* 73, 288–292. doi: 10.1016/j.foodqual.2018.10.012

Rubio, N. R., Xiang, N., and Kaplan, D.L. (2020). Plant-based and cell-based approaches to meat production. *Nat. Commun.* 11, 6276. doi: 10.1038/s41467-020-20061-y

Satija, A., Malik, V., Rimm, E. B., Sacks, F., Willett, W., and Hu, F. B. (2019). Changes in intake of plant-based diets and weight change: results from 3 prospective cohort studies. *The Am. J. Clin. Nutr.* 110, 574–582. doi: 10.1093/ajcn/nqz049

Schosler, H., de Boer, J., Boersema, J. J., and Aiking, H. (2015). Meat and masculinity among young Chinese, Turkish and Dutch adults in the Netherlands. *Appetite* 89, 152–159.

Scieszka, S., and Klewicka, E. (2019). Algae in food: a general review. *Crit. Rev. Food Sci. Nutr.* 59, 3538–3547. doi: 10.1080/10408398.2018.1496319

Seah, J. S. H., Singh, S., Tan, L. P., and Choudhury, D. (2022). Scaffolds for the manufacture of cultured meat. *Crit. Rev. Biotechnol.* 42, 311–323. doi: 10.1080/07388551.2021.1931803

Sexton, A. E., Lorimer, J., and Garnett, T. (2019). Framing the future of food: the contested promises of alternative proteins. *Environ. Plan. E Nat. Space* 2, 47–72. doi: 10.1177/2514848619827009

Sievert, K., Lawrence, M., Parker, C., and Baker, P. (2021). Understanding the political challenge of red and processed meat reduction for healthy and sustainable food systems: a narrative review of the literature. *Int. J. Health Policy Manag.* 10, 793–808. doi: 10.34172/ijhpm.2020.238

Slade, P. (2018). If you build it, will they eat it? Consumer preferences for plant-based and cultured meat burgers. *Appetite* 125, 428–437. doi: 10.1016/j.appet.2018.02.030

Smart Protein (2021). *What Consumers Want: A Survey on European consumer Attitudes Towards Plant-Based Foods, With a Focus on Flexitarians', European Union's Horizon 2020 Research and Innovation Programme (No 862957).* Available online at: https://smartproteinproject.eu/wp-content/uploads/FINAL_Pan-EU-consumer-survey_Overall-Report-.pdf (accessed November 12, 2021).

Specht, L. (2022). *Good Food Intitute.org.* Available online at: https://gfi.org/science (accessed April 3, 2022).

Spectre, M. (2011). *Test Tube Burgers, The New Yorker*. Available online at: https://www.newyorker.com/magazine/2011/05/23/test-tube-burgers (accessed May 23, 2011).

Statista (2022). Available online at: https://www.statista.com/topics/4880/global-meat-industry/ (accessed April 3, 2022).

Stephens, N., Sexton, A. E., and Driessen, C. (2019). Making sense of making meat: key moments in the first 20 years of tissue engineering muscle to make food. *Front. Sust. Food Syst.* 3, 45. doi: 10.3389/fsufs.2019.00045

Stevens, G. A., Beal, T., Mbuya, M. N. N., Luo, H., Neufeld, L. M., and Global Micronutrient Deficiencies Research Group (2022). Micronutrient deficiencies among preschool-aged children and women of reproductive age worldwide: a pooled analysis of individual-level data from population-representative surveys. *Lancet Glob. Health* 10, e1590–e1599. doi: 10.1016/S2214-109X(22)00367-9

Storz, M. A. (2022). What makes a plant-based diet? A review of current concepts and proposal for a standardized plant-based dietary intervention checklist. *Eur. J. Clin. Nutr.* 76, 789–800. doi: 10.1038/s41430-021-01023-z

Takeda, K. F., Yazawa, A., Yamaguchi, Y., and Koizumi, N. (2023). Comparison of public attitudes toward five alternative proteins in Japan. *Food Q. Pref.* 105, 104787. doi: 10.1016/j.foodqual.2022.104787

Tangyu, M., Muller, J., and Bolten, C. J. (2019). Fermentation of plant-based milk alternatives for improved flavour and nutritional value. *Appl. Microbiol. Biotechnol.* 103, 9263–9275. doi: 10.1007/s00253-019-10175-9

Tilman, D., and Clark, M. (2014). Global diets link environmental sustainability and human health. *Nature* 515, 518–522. doi: 10.1038/nature13959

Tuomisto, H. L. (2019). The eco-friendly burger: Could cultured meat improve the environmental sustainability of meat products? *EMBO Rep*. 20, e47395. doi: 10.15252/embr.201847395

Vaidyanathan, G. (2021). What humanity should eat to stay healthy and save the planet. *Nature* 600, 22–25. doi: 10.1038/d41586-021-03565-5

Vallverdú-Queralt, A., de Alvarenga, J. F., Estruch, R., and Lamuela-Raventos, R. M. (2013). Bioactive compounds present in the Mediterranean sofrito. *Food Chem*. 141, 3365–3372. doi: 10.1016/j.foodchem.2013.06.032

van der Valk, J., Bieback, K., Buta, C., Cochrane, B., Dirks, W. G., Fu, J., et al. (2018). Fetal bovine serum (FBS): past - present - future. *ALTEX* 35, 99–118. doi: 10.14573/altex.1705101

Van Huis, A. (2013). Potential of insects as food and feed in assuring food security. *Ann. Rev. Entomol.* 58, 563–583. doi: 10.1146/annurev-ento-120811-153704

Verbeke, W., Hung, Y., and Baum, C. M. H. (2021). The power of initial perceived barriers versus motives shaping consumers' willingness to eat cultured meat as a substitute for conventional meat. *Livestock Sci.* 253, 104705. doi: 10.1016/j.livsci.2021.104705

Verbeke, W., Pérez-Cueto, F. J., and Grunert, K. G. (2011). To eat or not to eat pork, how frequently and how varied? Insights from the quantitative Q-PorkChains consumer survey in four European countries. *Meat Sci*. 88, 619–626. doi: 10.1016/j.meatsci.2011.02.016

Vermeir, I., Weijters, B., Houwer, D., e., Geuens, J., Slabbinck, M. and Spruyt, H. et al. (2020). Environmentally sustainable food consumption: a review and research agenda from a goal-directed perspective. *Front. Psychol.* 11, 1603. doi: 10.3389/fpsyg.2020.01603

Verstraete, W., Yanuka-Golub, K., Driesen, N., and De Vrieze, J. (2022). Engineering microbial technologies for environmental sustainability: choices to make. *Microb Biotechnol.* (2022) 15:215–227. doi: 10.1111/1751-7915.13986

Walsh, E. A., Diako, C., Smith, D. M., and Ross, C. F. (2020). Influence of storage time and elevated ripening temperature on the chemical and sensory properties of white Cheddar cheese. *J. Food Sci.* 85, 268–278. doi: 10.1111/1750-3841.14998

Wang, W., Huang, Y., Zhao, W., Dong, H., Yang, J., Bai, W., et al. (2022). Identification and comparison of umami-peptides in commercially available dry-cured Spanish mackerels (*Scomberomorus niphonius*). *Food Chem*. 380, 132175. doi: 10.1016/j.foodchem.2022.132175

Warner, R. (2019). Review: analysis of the processes ad drivers for cellular meat production. *Animal* 13, 3041–3058. doi: 10.1017/S1751731119001897

Wendin, K. M., and Nyberg, M. E. (2021). Factors influencing consumer perception and acceptability of insect-based foods. *Cur. Opin. Food Sci.* 40, 67–71. doi: 10.1016/j.cofs.2021.01.007

Willet, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. *EAT Lancet* 393, 447–492. doi: 10.1016/S0140-6736(18)31788-4

Wolk, A. (2017). Potential health hazards of eating red meat. *J. Int. Med*. 281, 106–122. doi: 10.1111/joim.12543

World Health Organization (2022). Available online at: https://www.who.int/publications/m/item/the-state-of-food-security-and-nutrition-in-the-world-2021 (accessed April 3, 2022).

Yao, T., and Asayama, Y. (2017). Animal-cell culture media: history, characteristics, and current issues. *Reprod. Med. Biol*. 16, 99–117. doi: 10.1002/rmb2.12024