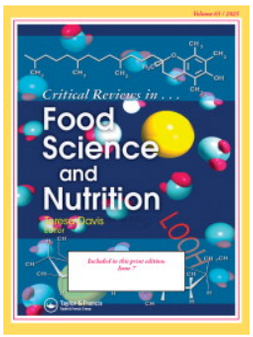

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REVIEW ARTICLE

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Reassessing the sustainability promise of cultured meat: a critical review with new data perspectives

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ABSTRACT

There are currently over 170 companies in the field of cultured meat (CM) which have attracted over US$3 Billion in investments since 2019. The CM industry owes much of this success to the many claims around environmental benefits and alleviating animal welfare concerns, while being equally nutritious and as acceptable as conventional meat. This review aims to provide a much needed discussion on the latest research findings concerning the nutritional and environmental sustainability of CM and provide an evidence-based discussion around some of the challenges that the industry faces today. Recent developments in the field have revealed that some of the sustainability claims of the CM industry are overly ambitious and not supported by evidence. Environmental assessments have revealed that CM production is highly energy intensive and its environmental footprint can only be improved if renewable energy sources are used. In terms of nutritional quality of CM, there are many unknowns and gaps in the knowledge that require investigation.

KEYWORDS

Cellular agriculture; cultivated meat; lab-grown meat; nutrition; sustainability

Introduction

The aim of the Paris Agreement was to restrict the rise in the average global temperature from preindustrial levels, with a primary target of keeping it "well below 2 °C" and striving for further efforts to cap the increase at 1.5 °C (Masson-Delmotte et al. 2022). The global food system contributes about 30% of the greenhouse gas emissions every year (Rosenzweig et al. 2020), with the meat sector accounting for about 15% of this impact (M. Clark et al. 2022). Food-related greenhouse gas emissions can originate from multiple sources such as deforestation, using fossil fuels in food processing and supply chains, using agricultural chemicals, and the enteric fermentation in ruminant livestock farming which produces methane (CH_4) (M. A. Clark et al. 2020). While animal products make up approximately 18% of the total calories and 37% of the protein in the average global diet, based on a widely cited study by Poore and Nemecek (2018), their environmental impacts are significantly greater when compared to non-animal products in diets.

However, the role of meat in the diet is more nuanced than simply global average greenhouse gas emissions, calories and protein. It is a dense and globally important source of many micronutrients (Smith et al. 2022), and average consumption ranges from <10 g to >100 g per capita per day in different global regions, with important implications for its local impact on diet and greenhouse gas emissions (Miller et al. 2022).

While dietary change away from animal-sourced foods has been recommended by many (Willett et al. 2019), it is important to note that dietary change is not the only solution for reducing food-related environmental impact. Other strategies such as increasing efficiency of the production systems and reducing wastage can also be effective in lowering such environmental pressure. In addition to these strategies, another emerging avenue to mitigate food-related environmental impact is the development of low-impact novel food products, which has garnered substantial attention and investment in recent years.

Cultured meat (CM), also known as lab-grown meat, cell-based meat, or cultured meat, is meat produced by laboratory-based cultivation of animal cells, rather than from whole animals. It involves taking a small sample of animal cells and then growing them in media that supplies essential nutrients for cell proliferation. Cultivated cells are kept in isolation in a controlled environment, such as a bioreactor, to grow into tissue that is then harvested and processed into meat products. While contemplated for many years, CM became a reality in 2013 with the production of the first

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cell-based burger at a cost of US$325,000 (Fountain 2013). Since then, there has been significant commercial investment in this technology and the first licensed products have reached the market (Carrington 2018). However, there remains a range of nutritional, environmental, technical, economic and consumer challenges if CM is to become a viable option for consumption at scale (Wood et al. 2023; Hocquette et al. 2025).

Cell lines for a wide variety of animal species have been created and grown in specialized media at laboratory scale, but moving to production scale has been challenging. The original concept of growing muscle cells in single cell suspensions and then inducing them to differentiate to form muscle fibers has shifted to the production of a cell paste, which is blended with plant-based material to form hybrid products like burgers, sausages and dumplings.

The downturn in the market for alternative meat products has also raised questions about the size of the market for CM and recent life cycle assessment (LCA) studies have demonstrated that CM will be an energy intensive industry (Risner et al. 2023; Sinke et al. 2023).

Motivated by the ongoing CM discussion and the appearance of recent novel research in this area, this review outlines and discusses the technical, regulatory, environmental, nutritional and broader sustainability challenges presently facing CM, with the intention of generating productive discussions on the role of CM in the future of the global food system.

Scalability and technical challenges

The major technical challenge with CM is to scale up manufacturing from bench scale to thousands of liters, at a cost that will allow the products to compete with conventional meat products (Wood et al. 2023). In the biotechnology industry, the maximum scale of cell culture for monoclonal antibody production is around 20,000 L (E. A. Specht et al. 2018) and the industry has had decades to optimize the cell lines, growth media and bioreactor designs. For CM the major costs are culture media, capital costs for both equipment and facilities and operating costs (Wood et al. 2023).

However, CM production at scale will require long continuous sterile culture periods, as any contaminating bacteria or fungi would quickly overgrow the mammalian or avian cells, which have a doubling time of around 24 h (FAO and WHO 2023). On the contrary, some companies have suggested that CM will not need to use the sophisticated clean rooms that the pharmaceutical industry uses with filtered air, positive pressure rooms and specialized clean surfaces, which are required to maintain sterile working conditions. It should also be noted that the use of antibiotics in the media, a common practice to control bacteria growth in non-foods, will not be allowed with a food product (FAO and WHO 2023).

In various parts of the cell production cycle, bovine serum (BS) is used to promote cell viability and growth. However, many CM companies aim to remove BS as it is clearly desirable from a marketing perspective to claim that no animals were slaughtered as part of the manufacturing process. BS is also expensive, so the use of serum free media is likely to be standard practice for CM (Chen et al. 2022). However, the serum free alternatives available on the market have shown suboptimal performance and may not be compatible with all cell lines (Kolkmann et al. 2020). The final volume of media required to produce a kilogram of CM is unknown, however it is likely to be over 20 L/kg, with reports of the yield of cells being in the range of 3–6 g/L of media (Sinke et al. 2023). Therefore, cost of the culture media, which is currently viewed as one of the major cost for production of CM (Garrison, Biermacher, and Brorsen 2022), will need to be less than US$1/L to manage costs.

The overall cost breakdown for CM has been estimated by modeling future production systems in two previous publications: Garrison, Biermacher, and Brorsen (2022) and Humbird (2021). These studies estimated the best case scenario for CM production at US$63/kg (Garrison et al. 2022) and US$25/kg (Humbird 2021), both assuming optimistic technology advancements.

Garrison et al. (2022) argued that facility costs are likely to be the major component of cost due to depreciation on capital, followed by culture media and operating expenses. In a report commissioned by the Good Food Institute (GFI), they estimated that the cost of production would need to be reduced over 1000-fold to be competitive (Sinke et al. 2023).

The scalability and technical challenges facing CM are significant. It is as yet unclear when a viable, cost-effective alternative to BS will be available; nor is the extent to which pharmaceutical (and more expensive) practices will need to be adopted to maintain product quality. These challenges come with significant associated costs, which leave the production of CM far from competitive with conventional meat production for the foreseeable future.

Regulatory challenges and labeling

The first CM product available to the public was approved by the Singaporean authorities in 2020 (Ives 2020), but it has taken over three years for a second product to be approved. There are now five products approved in three countries, with the USA and Israel also granting approvals (Table 1). The major issue for regulatory authorities in reviewing these new types of food products is safety for human consumption (Post et al. 2020; Guan et al. 2021). However, a joint FAO/WHO (FAO and WHO 2023) report concluded that while there were over 50 potential health risks associated with CM, the overall risk was not greater

Table 1. Registered CM products at the time of writing.

Country	Company	Registration date	Product
Singapore	Good Meat	December 2020	Chicken-hybrid 70/30
USA	Good Meat	July 2023	Chicken
USA	Upside Foods	June 2023	Chicken fillet
Israel	Aleph Farms	January 2024	Beef-thin-cut steak
Singapore	Vow	April 2024	Japanese quail
Hong Kong[a]	Vow	November 2024	Japanese quail

[a]Special Administrative Region of China.

than that seen with conventional meat products (FAO and WHO 2023).

It is expected that additional approvals will be granted in Australia/New Zealand, Korea, China and Canada in the coming years, however the lengthy and costly regulatory processes are a concern for this new food sector (Guan et al. 2021). In Europe the path to registration for CM will be difficult as strict legislations, such as authorizing and labeling genetically engineered products, are in place (see Post et al. 2020 for an overview of the European regulatory system).

Labeling of CM has been controversial, with Italy, France and the states of Florida, Arizona and Alabama in the USA moving to ban these products due to concerns around the use of the term "meat" (Nowell 2024). With the majority of CM products being hybrid products, meaning that cultured cells are blended with plant-based material in the final product, there will also be a question around what percentage of cultured cells will determine use of the term "meat" on the label.

While these challenges are more surmountable than the technical and scalability challenges, they should be expected to delay or prevent the commercial availability of CM in many parts of the world.

Environmental impact of cultured meat production

The environmental impact of food production and supply is under justified examination, due to the food system's major role in environmental harms (Poore and Nemecek 2018; Willett et al. 2019). Thus, any new technology in the food system must be considered on its environmental impact, as well as its other qualities such as contribution to human nutrition and cost. The environmental impact associated with the production and consumption of foodstuffs can be quantified using life cycle assessment (LCA). There are six peer-reviewed LCA studies on CM to date, and one pre-print (not yet peer-reviewed). These studies are listed in Table 2.

The first LCA of CM was published by Tuomisto et al. in 2011, followed by another study by the same researchers Tuomisto, Ellis, and Haastrup (2015) and a third study by Mattick et al. (2015), all conducted before the establishment of the first CM companies. Further studies have emerged since, some able to utilize commercial or pilot scale data for greater accuracy (although this data is confidential, reducing the transparency of the study) (Sinke et al. 2023). The scope of environmental impact indicators covered in these studies is broad: climate change, energy use, land use, and water use are the most common, but others extent to additional aspects of environmental pollution and impacts on human health. A list of various environmental impact indicators used in each study is available in Table 2.

It should be noted that most studies (in line with common practice in the LCA literature) did not consider the environmental impact associated with building facilities or the downstream processes such as packaging, thus the results of these studies should be seen as indicative of process-only impacts (World Resources Institute & World Business Council for Sustainable Development 2011).

Based on these studies, the most notable environmental impacts of CM are the energy requirements and the greenhouse gas emissions (which are largely a result of energy demand), with water use also of concern in some studies (Tuomisto and Teixeira de Mattos 2011; Mattick et al. 2015). A comparison of footprints calculated in each study is shown in Figure 1 for selected impacts; a more complete comparison can be found in the Supplementary Material of Sinke et al. (2023).

A clear upwards trend is notable in the footprint estimates over time (Figure 1), with the estimated greenhouse gas emissions and energy use per kg of CM rising notably in more recent publications, for which increased understanding of and availability of data on CM production was available. Studies have also become generally more comprehensive in their analysis of the production process and in their sensitivity analyses on the influence of key parameters, such as energy grid generation profile, final titer, protein yield from sugar, on final footprints, which accounts for the greater variation between upper and lower estimates in more recent studies. As calculated by Poore and Nemecek (2018), the footprints of conventionally produced meat also vary substantially between production systems.

Care must be taken when comparing estimates, both between CM and conventionally produced meat, and between CM estimates themselves as these estimates can vary based on the underlying data used and the assumptions made. The

Table 2. Summary of life cycle assessment (LCA) studies conducted on cultured meat (CM) production. *Denotes the study that is only available as a pre-print, not yet peer-reviewed.

Authors (year)	System boundaries	Functional unit	Environmental indicators
Tuomisto and Teixeira de Mattos (2011)	Cradle to facility gate	1000 kg CM	Energy use, climate change, land use, and water use
Tuomisto, Ellis, and Haastrup (2015)	Cradle to facility gate	1000 kg CM	Energy use, climate change, land use, and water use
Mattick et al. (2015)	Cradle to facility gate	1 kg Chinese hamster ovary biomass	Energy use, global warming potential, eutrophication potential, and land use
Smetana et al. (2015)	Cradle to plate	1 kg ready to eat meat	Energy use, climate change, eutrophication
Tuomisto, Allan, and Ellis (2022)	Cradle to facility gate	1 kg of CM	Cumulative energy demand, water consumption, terrestrial acidification, global warming potential, ozone formation, land use, freshwater eutrophication, fossil resource scarcity, and fine particulate matter formation
*Risner et al. (2023)	Cradle to facility gate	1 kg of CM	Smog, acidification, respiratory effects, non carcinogenic, ecotoxicity, global warming potential, ozone depletion, carcinogenics, eutrophication fossil fuel depletion
Sinke et al. (2023)	Cradle to facility gate	1 kg of CM	Energy use, climate change, land use, water use, particulate matter, terrestrial acidification, freshwater eutrophication, ozone formation, fossil resource scarcity, cumulative energy demand, feed conversion ratio, greenhouse gas emission profile

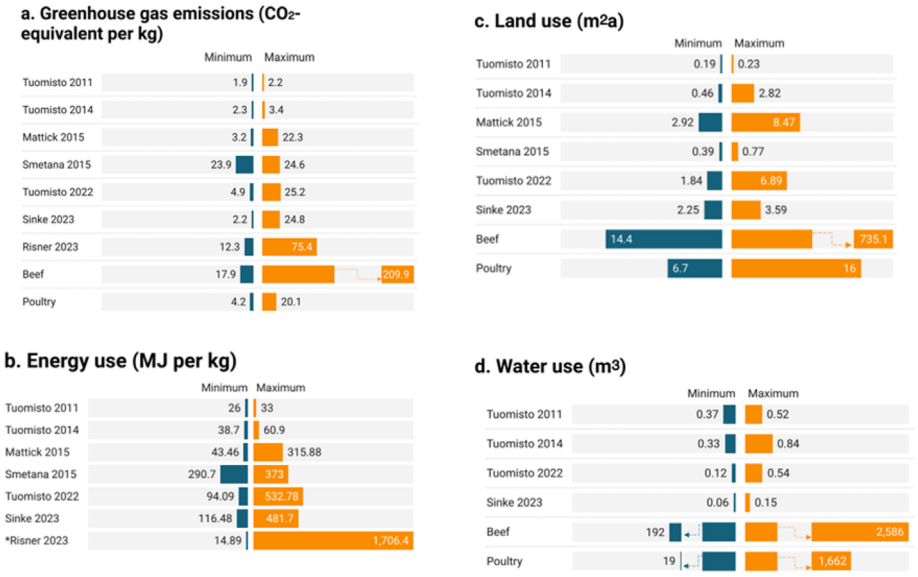

Figure 1. Implications of cultured meat production for (a) greenhouse gas emissions (CO_2-equivalent per kg), (b) energy use (MJ per kg), (c) land use (m^2a), and (d) water use (m^3) as calculated by existing life cycle assessment publications displayed in each graph. For each study, a minimum (best-case scenario) and a maximum (worst-case scenario) value are shown. Data for conventional beef and poultry were adapted from Poore and Nemecek (2018) (does not apply to energy use). *Denotes the study that is only available as a pre-print, not yet peer-reviewed. Dashed arrows represent a break in the graph.

functional unit for each study was standardized here to 1 kg of meat after being harvested at facilities prior to being packaged or processed, except in Smetana et al. (2015) where the functional unit represents the end product at the point of consumption. It should be noted that the uniform functional units used in these studies do not imply equivalence between these products. For example, the nutritional profile of poultry meat and beef is quite distinct, in terms of protein content, protein composition, and digestibility, as well as the micronutrient composition, which is almost certainly also true for CM (see next section). Studies also differed in whether the footprint was calculated at point of production or point of consumption (post cooking). Many techniques exist for conducting nutritional LCA, as discussed in a recent FAO report (McLaren et al. 2021), such as the integration of single nutrients or nutrient metrics into the functional unit. The correct approach must be determined by the circumstances of the comparison: if protein powders are being compared, then comparing on the basis of digestible protein may be sufficient, whereas if two complex foods with diverse nutritional contributions to the diet are compared, a more comprehensive nutritional metric would be necessary. The comparison of CM with conventional meat on a mass basis is acceptable, provided the limitations of this functional unit are acknowledged.

For the environmental impacts beyond energy use, greenhouse gas emissions, and water use, generally publications find that CM has a lower footprint than conventionally produced meat. It is also important to consider the tradeoffs between different impact categories. Smetana et al. (2015) provided an aggregated score across multiple categories, which found CM to have the poorest performance compared to conventional meat, plant proteins, and other novel protein technologies. However, comparisons across multiple categories are subjective, and it is likely more valuable to consider categories individually, and on a local basis. For example, of the existing studies only Tuomisto, Ellis, and Haastrup (2014) considered water scarcity, which can be a more meaningful metric than total water use as it captures the local availability of water (Boulay et al. 2018) and has been applied in prospective LCA of other novel food products (Behm et al. 2022). Locality can also be useful for understanding transport emissions and local energy generation profiles.

All studies cited the challenges of uncertainty in the data used, due to emerging nature of CM. These uncertainties were addressed via sensitivity analyses, and also provide avenues for the potential improvement of CM footprints. The most commonly highlighted were a shift to renewable energy, greatly reducing the carbon footprint of the CM process by decarbonizing the electricity source, and improvements to the sourcing of culture media. These potential improvements are captured in the lower estimates of footprints in each publication (Figure 1).

Since there are no large-scale CM facilities, all the environmental assessments available to date are based on projections and assumptions, hence often referred to as anticipatory LCAs. A challenge inherently involved in such assessments is to keep the balance between representation of the current state of affairs and predicting how the future commercial process may diverge. Greater availability of data on commercial CM production would greatly improve the quality of CM LCA, but this only appears likely if research is at least partially publicly funded (Zimmermann et al. 2022).

Nutritional challenges facing the cultured meat industry

A key tenet in the CM industry is the potential for their products to deliver a nutrient profile comparable to that of

conventional meat (Fraeye et al. 2020). However, little is known about the nutritional characteristics of CM and to the best of author's knowledge, there is no publicly available nutritional profile for such products.

What is evident though is that the nutritional composition of CM will not inherently be identical to the conventional products without fortification. For example, vitamin B12, which is known to be predominantly found in meat and dairy (Obeid et al. 2019), will not be present in the CM products unless added to the culture medium or to the final CM product. This is since vitamin B12 is synthesized by the microorganisms present in the digestive tract of the animals and then translocated to the muscle tissues (Fraeye et al. 2020). A vitamin of microbial origin cannot naturally occur in the microbe-free conditions suitable for growing mammalian cells and must be added to the culture media as an individual ingredient. It should be noted that B12 is usually added to the growing media due to its role in enhancing cell proliferation (L. Specht 2019), not necessarily for its nutritional benefit. This raises the question of how efficiently the cultivated cells will uptake B12, the optimum B12 concentration in the media and the degree to which the absorbed B12 will be bioavailable to consumers. Similarly, suitability of CM as a fortification vehicle must be evaluated if CM is to be enriched with B12 after harvest.

In addition, CM products are commonly derived from fibroblasts, because these tissues require minimal inputs to grow, hence are optimal for CM production (Pasitka et al. 2023). However, a fibroblast-based product would be devoid of fatty acids due to the absence of other cell types. Some fatty acids are known to possess health benefits (Pereira and Vicente 2013) as well as improving sensory attributes of meat (Starowicz, Kubara Poznar, and Zieliński 2022). For CM to contain fatty acids, the presence of fat cells or adipocytes is necessary. Such cells need to be cultivated independent of the muscle cells and then added to the CM product. It has also been suggested that muscle fiber and fat cells can be co-cultured when adult skeletal muscle stem cells known as satellite cells are being used (Rasmussen et al. 2024). Alternatively, plant-based fatty acids might be utilized in hybrid CM products (Fraeye et al. 2020). Such products are expected to have different nutritional characteristics depending on the formulation and the biochemical attributes of each ingredient, thus deviating from the nutritional profile of conventional meat.

Another important aspect in assessing nutritional value of CM is protein quality. Although CM is assumed to mimic animal-derived protein, the protein quality of these products has not yet been thoroughly studied. So far, the only study that has considered protein quality in CM is by Smetana et al. (2015), in which the authors assumed a Protein Digestibility Corrected Amino Acid Score (PDCAAS) of 0.92 for cultivated beef, matching that of conventional beef (Hoffman and Falvo 2004). This is a fair assumption in the absence of specific data, however protein quality scores such as PDCAAS and Digestible Indispensable Amino Acid Score (DIAAS) are typically determined through laboratory-based, animal and/or clinical assessments of protein sources to evaluate their amino acid composition and digestibility (Adhikari et al. 2022). Depending on the protein content derived from cultivated cells, cell lines used, culture media composition and any other changes made through processing, quality of various types of CM may vary as a source of protein.

On the other hand, postmortem biochemical changes can significantly affect digestibility of animal-derived proteins (Kim et al. 2020). Upon slaughter, muscles in a farm animal undergo a complex biochemical transformation into meat. These changes are influenced by the architecture and integrity of the skeletal muscle cell, as well as by various events that modify these proteins and their interactions. Notably, processes such as protein degradation and oxidation play crucial roles in altering both the proteins themselves and the tenderness of the resulting meat. The intracellular environment emerges as a significant factor governing these processes. As a result, the biochemical nature of meat is vastly different from the pre-slaughter muscle tissues (Huff Lonergan, Zhang, and Lonergan 2010). It is fair to expect that, in the absence of such processes and in isolation from other tissues, the cultivated muscle tissues will behave differently. Whether this will be a positive, negative, or neutral change for the nutritional quality of the product is unclear (Kim et al. 2020). Further research is required to better understand the quality of CM as a source of protein and to establish its protein quality metrics such as DIAAS and PDCAAS, which will only be possible with the participation of CM companies to supply product for analysis.

How does CM fit into sustainable diets?

Sustainable healthy diets are "dietary patterns that promote all dimensions of individuals' health and well-being; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable" (FAO and WHO 2019). Thus, CM must be an affordable, acceptable, nutritious, and have a modest environmental impact if it is to fit into future diets. Examining CM across this range of factors is challenging given the limited data currently available, but has been attempted through diet modeling.

To understand how novel foods, including CM, fit into the future sustainable diets, Mazac et al. (2022), conducted a dietary optimization study using a linear programming approach. Linear programming is a mathematical method used in many dietary optimization studies where researchers aim to find the best combination of foods to satisfy one or more goals such as reducing environmental impact or achieving dietary nutrient adequacy (Wilson et al. 2013). In this study, nine novel food products including ovalbumin, mycoprotein, microbial protein, microalgae, kelp, insect meal, cultured milk, CM and cloudberry culture, were examined for inclusion in diets optimized for global warming potential (GWP), land use and water use, while fulfilling nutrient adequacy. Their results showed that in the absence of animal-sourced foods, out of all nine novel food products tested, insect meals and cultured milk were the foods

predominantly selected in optimized diets. The largest contribution of CM was reported when optimizing for water use and even then it was selected in very small quantities (0.10 g/day). When insect meal, cultured milk and all animal sourced foods were removed, CM was selected at 29 g/day, under a water use reduction scenario. It is important to note that the underlying environmental data in Mazac et al. (2022) study was adapted from Tuomisto, Allan, and Ellis (2022) with some modifications. As elaborated in "Environmental impact of cultured meat production" section of this review, system boundaries in Tuomisto, Allan, and Ellis (2022) did not cover the environmental impacts of building the facilities and the stainless steel equipment. Additionally, the underlying nutrition data was obtained from the USDA Food Data Central database assuming that the nutritional profile of CM matches that of conventional ground beef. Such assumption is arguable, as discussed in "Nutritional challenges facing the cultured meat industry" section of this review.

Even subject to these caveats, which likely positively impacted the likelihood of CM selection in optimized diets, their contribution to these diets was small. This is reflective of the nutritional profile and environmental credentials of CM being poorly competitive with those of the other novel foods trialed. To our knowledge the study by Mazac et al. (2022) is the only study on the role of CM in sustainable diets to date, and it omits many of the aspects of sustainable diets (such as affordability and acceptability), it highlights the importance of a holistic view of the place of CM in the global food system: from production through to consumption.

Sensory challenges and consumers' acceptability

If the technical hurdles of scaling up CM production are surmounted, the market success of CM will still rely on consumer willingness to integrate these products into their diets. Several studies have previously reviewed consumers acceptance of CM (C. Bryant and Barnett 2018; To et al. 2024) in different parts of the world including Germany (Weinrich, Strack, and Neugebauer 2020), Italy (Mancini and Antonioli 2019), United Kingdom, Spain, Brazil and the Dominican Republic (Gómez-Luciano et al. 2019).

Many of the plant-based meat alternative companies such as Impossible Foods and Beyond Meat provide consumers with sustainability messages around the environmental and animal welfare benefits of their products (Beyond Meat 2022; Impossible Foods 2024). The CM industry appears to be adopting a similar strategy (Upside Foods 2024; Aleph Farms 2024). However, as stated in a systematic review on consumers' acceptance of CM by C. Bryant and Barnett (2018), there is limited evidence supporting the effectiveness of environmental awareness and providing sustainability messages on consumers' acceptance of CM. One of the few studies that have investigated the impact of receiving information about the sustainability of farm-raised beef versus plant-based and CM alternatives was conducted by Van Loo, Caputo, and Lusk (2020), targeting the US market. In this study, participants were given information about the technology and the environmental footprint associated with producing farm-raised beef, CM and plant-based patties prior to making a decision to adopt them in their diet. They reported that offering information about the environmental and animal welfare advantages could attract slightly more consumers to the market for CM.

In another study, the impact of different names for CM on consumers' acceptance was examined by C. J. Bryant and Barnett (2019). Their findings indicated that consumers were more receptive to CM when it was presented as "clean meat" or "animal free meat" in contrast to being labeled as "cultured meat" or "lab-grown meat."

A New Zealand study showed that acceptability of CM is affected by cultural differences, gender and country of residence. 592 New Zealanders were surveyed to investigate their perception of CM and their potential engagement with such products. It was revealed that in general male consumers who were better informed about CM had a higher tendency toward potential engagement with CM. Therefore it was suggested that increasing consumer awareness will play an important role in promoting engagement with CM (Giezenaar et al. 2023).

It must be highlighted that existing sensory studies on CM have notable limitations. As stated in a recent review by To et al. (2024), most available studies in this area have not used an actual CM product. Out of three studies that have used actual CM products (Rolland, Markus, and Post 2020; Pasitka et al. 2023; Lee et al. 2022), one did not recruit human participants and only used analytical instruments to measure liking (Lee et al. 2022). Considering the novelty of this research area, there is ample opportunity for future studies to explore factors influencing consumer preferences and how these preferences change over time, as well as how these preferences convert to purchasing decisions.

Conclusions and future prospects

The next few years will be a critical time for the CM sector with more licensed products entering the market, while the funding available to these companies has recently contracted (GFI 2024). CM is also just one option among many alternative protein products that are entering the market (Wood and Tavan 2022). It is unlikely that any company will achieve a dominant position through intellectual property, as most patents are process patents which are hard to protect, so the development of key brands and reductions in the cost of manufacturing will be important. It seems likely there will be a consolidation in the number of companies as some run out of funds or are acquired. While Singapore was the first country to issue a license for a CM product in 2020, there has been minimal activity in this country since then and companies are moving to focus on the larger consumer markets in the USA and other parts of Asia.

With sustainability being a major driver for the development of CM, there will likely be more focus on beef and lamb products due to the greater carbon footprint of producing ruminant meat compared to other meats. However,

our understanding of the CM industry's environmental impact will remain limited until the industry has scaled up.

The challenge of being highly energy-intensive remains, placing pressure on the need for renewable energy sources. Waste management and environmental pollution associated with CM should also be considered in future research efforts. Consideration is being given to how spent media might be recycled for use as fertilizer for crops (Myers et al. 2023).

Even though the main function of food is delivering nutrients to the human body, the nutritional quality of CM is unclear. Publicly available data on the nutritional profile of these products does not exist and we do not yet know whether CM will match conventional meat nutritionally. Even if the nutritional profile of CM were to match that of conventional meat on a gram-for-gram basis, the bioavailability of nutrients may not necessarily be equivalent. Such questions deserve further research, but appear unlikely in the near future due to the lack of CM products available for analysis.

The economic sustainability of the CM industry has not been proven yet, regardless of whether reaching price parity is the aim of CM producers. The cost of production of chicken meat is also the cheapest of all the traditional meats and therefore will be the hardest to compete with on price, again suggesting a move to higher value meats will be in the best interests of CM companies.

The need for a food system that is more sustainable across environmental, economic, and human dimensions is clear. It is still too early to determine the role that CM should play in this system, but the current challenges imply that several great changes - technological, regulatory, environmentally, nutritionally, and in the mind of consumers – will be necessary before CM can achieve global integration.

Disclosure statement

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