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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

Ex-ante life cycle assessment of commercial-scale cultivated meat production in 2030

Pelle Sinke[1] · **Elliot Swartz**[2] · **Hermes Sanctorum**[3] · **Coen van der Giesen**[1] · **Ingrid Odegard**[1]

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Abstract

Purpose Cultivated meat (CM) is attracting increased attention as an environmentally sustainable and animal-friendly alternative to conventional meat. As the technology matures, more data are becoming available and uncertainties decline. The goal of this ex-ante life cycle assessment (LCA) was to provide an outlook of the environmental performance of commercial-scale CM production in 2030 and to compare this to conventional animal production in 2030, using recent and often primary data, combined with scenario analysis.

Methods This comparative attributional ex-ante LCA used the ReCiPe Midpoint impact assessment method. System boundaries were cradle-to-gate, and the functional unit was 1 kg of meat. Data were collected from over 15 companies active in CM production and its supply chain. Source data include lab-scale primary data from five CM producers, full-scale primary data from processes in comparable manufacturing fields, data from computational models, and data from published literature. Important data have been cross-checked with additional experts. Scenarios were used to represent the variation in data and to assess the influence of important choices such as energy mix. Ambitious benchmarks were made for conventional beef, pork, and chicken production systems, which include efficient intensive European animal agriculture and incorporate potential improvements for 2030.

Results and discussion CM is almost three times more efficient in turning crops into meat than chicken, the most efficient animal, and therefore agricultural land use is low. Nitrogen-related and air pollution emissions of CM are also lower because of this efficiency and because CM is produced in a contained system without manure. CM production is energy-intensive, and therefore the energy mix used for production and in its supply chain is important. Using renewable energy, the carbon footprint is lower than beef and pork and comparable to the ambitious benchmark of chicken. Greenhouse gas profiles are different, being mostly CO_2 for CM and more CH_4 and N_2O for conventional meats. Climate hotspots are energy used for maintaining temperature in reactors and for biotechnological production of culture medium ingredients.

Conclusions CM has the potential to have a lower environmental impact than ambitious conventional meat benchmarks, for most environmental indicators, most clearly agricultural land use, air pollution, and nitrogen-related emissions. The carbon footprint is substantially lower than that of beef. How it compares to chicken and pork depends on energy mixes. While CM production and its upstream supply chain are energy-intensive, using renewable energy can ensure that it is a sustainable alternative to all conventional meats.

Recommendations CM producers should optimize energy efficiency and source additional renewable energy, leverage supply chain collaborations to ensure sustainable feedstocks, and search for the environmental optimum of culture medium through combining low-impact ingredients and high-performance medium formulation. Governments should consider this emerging industry's increased renewable energy demand and the sustainability potential of freed-up agricultural land. Consumers should consider CM not as an extra option on the menu, but as a substitute to higher-impact products.

Keywords Cultivated meat · Cultured meat · Comparative LCA · Alternative proteins · Renewable energy · Culture medium · Carbon footprint · Land use

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Extended author information available on the last page of the article

1 Introduction

Cultivated meat (CM), also referred to as cultured or cell-based meat, is genuine animal meat or seafood produced by cultivating animal cells directly via modern biotechnological methods (Specht et al. 2018). CM is intended to be interchangeable in diets, competing in the marketplace on taste, nutrition, and other meat attributes. Currently, over 100 companies across the globe have been founded to bring CM to market; however, it has only been approved for sale in Singapore (GFI 2022).

CM is a sub-discipline of cellular agriculture, which broadly aims to substitute agricultural products derived primarily from animals, including meat, seafood, milk, materials such as leather and fur, and individual proteins such as collagen or heme. Plant-derived products such as cocoa, cotton, or palm oil can also be targeted through cellular agriculture approaches. The potential benefits of cellular agriculture lie in the removal of the animal or plant middle-man, coincident with a reduction in any negative externalities that contribute to climate change and environmental degradation, risk of antibiotic resistance and zoonotic disease, and animal welfare concerns (Stephens et al. 2018). Furthermore, having more control over the production process may lead to safer, more nutritious, and tastier products than their conventionally produced counterparts. Manufacturers of cellular agriculture products assume that these features will make them attractive to consumers and interchangeable in diets with little behavioral change required.

1.1 Food system impacts, global picture conventional animal agriculture, and footprints

Although animal products contribute around 18% of calories and 37% of protein to the average global diet, the impacts on the environment are disproportionately large compared to non-animal products in diets (Poore and Nemecek 2018). Estimates of global animal agriculture's contribution to environmental issues are as follows:

- Climate change: 16.5–19.4% contribution to total anthropogenic greenhouse gas emissions, making animal production by far the highest contributor within food system emissions, twice as large as plant-based sources (Crippa et al. 2021; Twine 2021; Xu et al. 2021). The contribution of ruminants to total animal agriculture emissions is significant due to their methane emissions, with enteric fermentation accounting for 27% of global anthropogenic methane emissions (Global Methane Initiative 2015; Grossi et al. 2019). Without interventions food system emissions alone could preclude Paris Agreement climate targets to limit warming at 1.5 °C by 2050 (Clark et al. 2020).
- Land use and land use change: 83% of global agricultural land use, including pastures and cropland for feed (Poore and Nemecek 2018), which in turn is the main driver for global land use change (Poore and Nemecek 2018; Pendrill et al. 2019; FAO 2022).
- Water use: 41% of green and blue water use combined, although contribution to blue water use is around 6% (Heinke et al. 2020).
- Nutrients: Over a third of anthropogenic nitrogen emissions (Uwizeye et al. 2020) and a dominant driver of disruption of natural nitrogen and phosphorus cycles (Garske and Ekardt 2021).
- Biodiversity loss: All of the impacts mentioned above are strong drivers for loss in biosphere integrity (Steffen et al. 2015). Current production of animal products has a disproportionately large effect on biodiversity loss compared to other food products (Benton et al. 2021).

Reducing the impact of meat production on the environment can be achieved by improving animal agriculture and reducing the amount of animal agriculture. Given that animal meat consumption is projected to rise by more than 70% by the year 2050, compared to 2010 (FAO 2011), cellular agriculture technologies that can ultimately reduce the amount of animal agriculture are of paramount importance, as any improvements to conventional animal agriculture may be offset by anticipated growth.

1.2 Impacts of CM and conventional meats

LCA studies up to date indicate that CM has the potential to have lower carbon footprint, land use, water use, and eutrophication effects than most conventional meats (Tuomisto and Teixeira de Mattos 2011; Tuomisto et al. 2014, 2022; Mattick et al. 2015). An overview of the main study characteristics and results is provided in Appendix A. For land use, the difference is most striking, mirroring that CM is a more efficient way of turning biotic resources into meat. Energy use of CM however is higher, and therefore generally CO_2-emissions are expected to be higher. Because animal production systems have greater emissions of strong greenhouse gasses (GHGs) such as methane (CH_4) and nitrous oxide (N_2O), and have higher land use change (LUC)-related emissions, aggregated climate change effects of CM are generally found to be lower than conventional meats. The most recent results for CM from Mattick et al. (2015) and Tuomisto et al. (2022) show that CM has the potential to have lower carbon footprints than global averages for all animal meats but will likely have higher carbon footprints than efficiently produced chicken (Poore and Nemecek 2018).

Because of the different GHG-emission profiles between CM and conventional meats, Lynch and Pierrehumbert (2019) modeled beef consumption scenarios over a time period of 1000 years, both conventional and CM beef. Their conclusion is that while "GWP100a" carbon footprints of CM may be lower than conventional beef, the overall long-term effect on climate change may be higher, because CO_2 from energy production in the CM system remains in the atmosphere a long time, while CH_4 from cows breaks down into biogenic CO_2. The study by Lynch and Pierrehumbert (2019) however did not account for decarbonization of the global energy mix. Only Tuomisto et al. (2022) accounted for the increase in available decarbonized energy and show that this can have significant influence on the results. Because of the different GHG emission profiles between CM and conventional meat, this is a crucial modeling choice and therefore should be included in scenarios. In this study, this was taken into account.

1.3 Ex-ante LCA, upscaling, and uncertainty

CM is being developed with the promise of being more sustainable. However, since the technology is still immature and mostly on lab- or pilot-scale, this promise cannot yet be tested on the (large) scale that will benefit most from economies of scale. In contrast the conventional meat production systems and supply chains are mature and efficiently organized. Comparing a technology that is lab- or pilot-scale to a mature technology that enjoys the high-efficiency benefits of economies of scale yields an unrealistic picture of how the new technology could perform. The difficulties in comparisons notwithstanding, providing a picture of the environmental impacts and hotspots of a future production system can aid decision-making for increased sustainability in the design stages of this system, when it is still relatively inexpensive to change course of development (Villares et al. 2017; Cucurachi et al. 2019). Performing an LCA before (ex-ante) a technology is fully developed can therefore provide highly useful insights to deliver on the promise of sustainability.

Tsoy et al. (2020) propose a framework for upscaling of three consecutive steps. These are projected technology scenario definition, preparation of a projected LCA flowchart, and projected data estimation. A few things should be considered when developing future scenarios (Pesonen et al. 2000). First, it is important to select a timeframe for the scenarios. Secondly, there is the option to develop probable or extreme scenarios. Experts can be used to determine or describe realistic probable scenarios and future conditions (Tsoy et al. 2020), while a bandwidth is created between optimistic and pessimistic development trajectories for extreme scenarios.

Heijungs and Huijbregts (2004) describe uncertainty as "the problem of using information that is unavailable, wrong, unreliable, or that show a certain degree of variability." A common challenge when conducting an ex-ante LCA is the lack of representative data for the system assessed which might introduce considerable uncertainty in the study (van der Giesen et al. 2020). Voglhuber-Slavinsky et al. (2022) proposed to explicitly acknowledge uncertainty and use different scenario's to address uncertainty. Where Tsoy et al. (2019) states that the performance of ex-ante LCA increasingly requires the involvement of stakeholders, the necessary assumptions in defining these scenarios are based on discussion with relevant stakeholders and "not on firm statements that are gratuitously presented as correct" (Ott et al. 2022). Similar to Ott et al. (2022), this study uses scenario and sensitivity analysis to deal with the encountered uncertainty. For further discussion of ex-ante LCA literature, see Appendix H.

2 Methods

2.1 Methods and materials

2.1.1 General method

This study was a comparative (ex-ante) attributional LCA following general guidelines (ISO14044). Various types of cultivated and conventionally produced meat were assessed and compared. The impact assessment methods used are ReCiPe 2016 Midpoint v1.1 (Hierarchist perspective) (Huijbregts et al. 2017) and cumulative energy demand (CED) (Frischknecht et al. 2007), with characterization factors adapted for lower heating values (LHV), as is included in the used Simapro version 9.2.0.2. Six indicators are included in the main paper in order to limit the number of figures. These are selected both based on perceived relevance to conventional meat and CM production systems and on robustness to minor changes in the LCA models. All ReCiPe 2016 indicators are reported in Appendix B, and the most important findings for these indicators are discussed in the main paper. Four indicators that are generally used in LCA of food products (Poore and Nemecek 2018) are included: carbon footprint (climate change), land use, blue water use, and terrestrial acidification. In addition, fine particulate matter (FPM) formation, CED, and feed conversion ratio (FCR) are included. FPM formation is relevant because this has significant effects on human health (Huijbregts et al. 2017) and both animal agriculture and industrial supply chains (such as in CM) have strong contributions to total emissions (Weagle et al. 2018; Wyer et al. 2022). FCR and CED are included because together they illustrate a fundamental difference between conventional meat and CM. CM is reportedly a more efficient way to convert feed into meat, without the need for growing the whole animal, but with added industrial energy to fulfill certain functions of living organisms. There are different approaches to the indicator CED, and as of yet, there is no harmonized methodology (Frischknecht et al. 2015). Acknowledging the different approaches to CED, it is useful as a screening indicator and presented alongside the carbon footprint in this study for improved interpretation (Huijbregts et al. 2006).

The FCR shows the amount of dry matter (dm) ingredients needed for the output of 1 kg of fresh meat (assumed dm content between 20 and 30% and protein content between 18 and 25%, see Appendix E). Differentiation is made for primary products, by-products, and biotic and mineral resources. The inputs are counted on a crop level. For example, to produce 1 kg of glucose, more than 1 kg (dm) of sugar crop is needed, because a sugar beet consists of more than glucose alone. The amount of ingredients needed for producing 1 kg of CM is therefore higher than the sum of the ingredients in the medium. Whether a by-product can be used as feed (for animals or CM) is an important sustainability characteristic of a feed regime. It is important to note here that soybean meal is also classified as a by-product in the frame used, although this is more a coproduct (Walker 2000). For CM, it is relatively uncertain to what extent by-products can be used as feed, and therefore only the soy hydrolysate is assumed to be derived from soybean meal.

2.1.2 Data collection and handling

Primary data were collected from over 15 companies and research institutes, both active in CM production and in the CM supply chain, supplemented by literature and theoretical modeling. For an overview of the organizations that provided data, see Appendix C. Important primary data points and ranges were checked by independent experts and/or by mass and energy balancing. Appendix D provides an overview of the foreground data used, the data quality (representativeness), number of sources used. and whether an independent cross-check has been made. Datasets from individual organizations are confidential, but derived parameters and scenarios are included in the appendix. This study uses sensitivity and scenario analyses to treat uncertainty and variability in the dataset. For upscaling we considered the framework presented in Tsoy et al. (2020). We defined scenarios (with the help of questionnaires and conversations with stakeholders), prepared an LCA flowchart of what an average future facility might look like (Figs. 1 and 2), and created the data inventory. Data handling for upscaling is discussed in Sect. 2.3 when applicable.

Data collection took place over the period 2019–2022. In preliminary conversations with the organizations, a probable timeline for commercial-scale CM production was established, resulting in the target year 2030 and a facility size of 10 ktonne/year. This is not to imply that CM products will be cost-competitive with conventional meat by that time but that some products such as minced meat could be produced and sold at ktonne scales. Subsequently, data were requested from the organizations for their current situation and expectations for 2030, including technology improvements. The latter data points were cross-checked and used as much as possible. If only current data were available, future expectations were either extrapolated with the help of experts or used as-is. Clear outliers were removed from the dataset. For important and variable data, such as culture media composition and quantity used, and energy mixes, various scenarios were developed, and a baseline model was created with representative values from the dataset (see Sect. 2.3). These values were determined based on data spread, for example, mean, mode, or geometric mean. The baseline model is not representative of any single cell type or technology, and the values can therefore not be interpreted as such.

For CM production, data has been collected and modeled in as much detail as possible, but since there are still unknowns (and unknown unknowns), data gaps cannot be avoided. To balance this, conservative estimates were used and extreme, worst-case scenarios were included.

Data from both land and aquatic animal cell cultures were collected. CM production for these different species follows similar practices. However, there are important differences related to heating and cooling demand, where aquatic cells in many cases require lower temperatures for growth and are more tolerant to fluctuations in temperature (Krueger et al. 2019). Therefore, the worst case is used (land animals, cultivated around 37 °C). These study results are not directly representative of aquatic CM products, but they can help shed light on general hotspots when taking these differences into consideration during the interpretation of the results. The differences in culture medium use efficiency between land and aquatic species have not yet been robustly assessed.

Data handling for conventional meat production is discussed in paragraph 2.3.4.

2.1.3 Background data, software, and allocation procedures

Background data were taken from Ecoinvent 3.7.1. (system model: allocation, cut-off by classification) (Wernet et al. 2016) and Agri-Footprint 5.0 (system model: economic allocation) (van Paassen et al. 2019). The software used is Simapro 9.2.0.2. Allocation was done using economic principles, as the available data best suited this form of allocation, and it is in line with the Ecoinvent database methodology (Wernet et al. 2016). Although it is regularly done in LCA research, one should be aware of potential problems when combining two datasets from different sources, such as Agri-Footprint and Ecoinvent. Problems could be differences

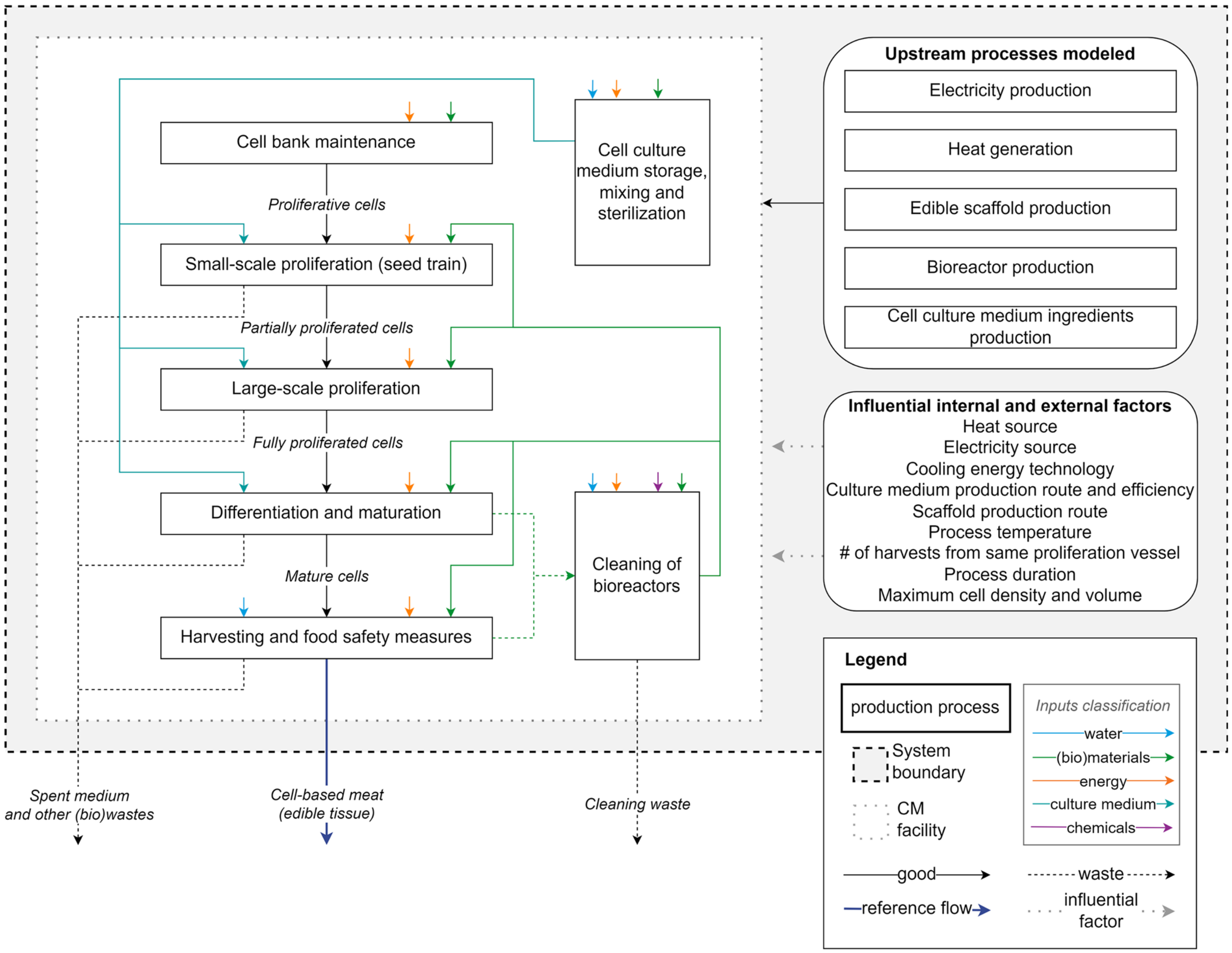

Fig. 1 Simplified LCA flowchart of cultivated meat (CM) production

in methodologies and modeling, selection criteria for data, and different naming of environmental interventions (emissions and extractions) which can cause problems in impact assessment. Agri-Footprint has indicated specifically to this point that modeling of field emissions is mostly done using similar methodologies as Ecoinvent, and the software developer of SimaPro, PRé, has ensured that environmental interventions have been mapped to be compatible with ReCiPe for both databases (Blonk Sustainability n.d.). Additionally, we have ensured consistency by using main inputs from agro-food supply chains from Agri-Footprint and using transport, energy, synthetic chemicals, and other materials from Ecoinvent. In order to make the datasets used consistent with the 2030 time horizon used in the study, we have created foreground processes for the most important inputs (including energy mixes for 2030, which is also used as an input into other foreground processes). Further data handling is described in Sect. 2.3. Adapting background databases in order to be representative of 2030 was not feasible. This may cause a slight overestimation of environmental impacts throughout all LCA models presented in this study (both CM and conventional meats), assuming globally technologies only become more sustainable over time.

2.2 Goal and scope

2.2.1 Goal

The goal of this study was to compare commercial-scale CM production in 2030 to conventional meat production to gain insights into the comparative environmental impacts of different meats and identify hotspots in CM production. Scenarios and sensitivity analyses were used to further explore the effects of developments internal and external to the CM product system on the comparison and hotspots.

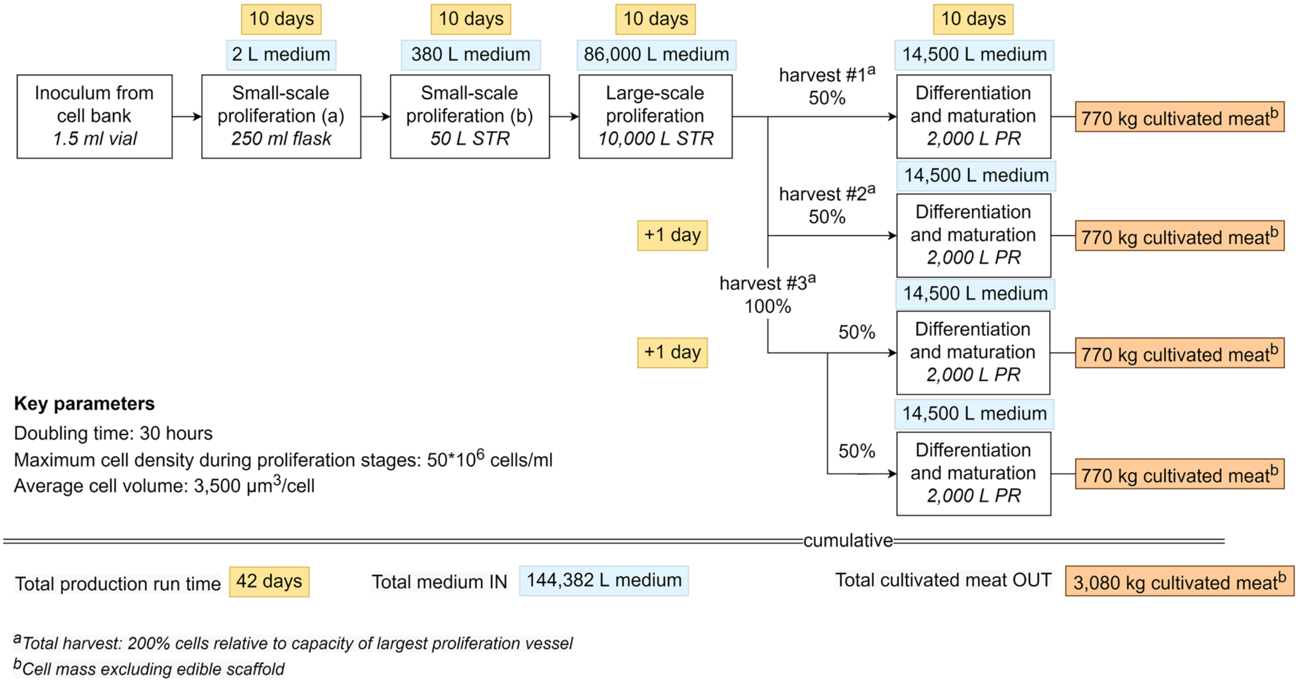

Fig. 2 Design of 1 semi-continuous production line with 3 harvests from the largest proliferation vessel

2.2.2 Scope, system boundaries, and flowchart

System boundaries were cradle-to-gate, excluding packaging (as we assume this to be identical for all products). In the case of CM, this means after harvesting but before leaving the facility. For conventional meat, this means at the slaughterhouse gate. All upstream production processes and transport were included in the scope. All impacts associated with the product system up to the economy-environment boundary were included (resource extraction, land use, or physical emissions). Buildings were excluded for both conventional meats and CM. For CM, bioreactors and culture medium storage and mixing tanks were included, as these are inherent to this different technology for meat production, and actually can be considered the replacement of the animal's body in the CM product system.

The CM system flowchart is provided in Fig. 1.

2.2.3 Functional unit

The functional unit was 1 kg of land animal meat produced in 2030. Meat types compared were CM, beef (beef herd), beef (dairy herd), pork, and chicken. The CM cell type was non-specific, cultivated around 37 °C. CM was produced using a 10% edible scaffold. To make a conservative comparison, the reference product for conventional meats was 1 kg of meat, and for CM is 1.1 kg product, which includes 1 kg meat cells and 0.1 kg edible scaffold. The average (macro)nutritional composition of the meats under study is provided in Appendix E.

2.3 Product systems under study and baseline scenario data

2.3.1 CM facility and production line design

A CM production facility producing 10 ktonne per year was modeled. The general product system is shown in Fig. 1. Production lines in the facility operate in parallel and on staggered schedules. One production line is shown in Fig. 2. Its design was based on Specht (2020) and was adapted in some aspects based on input from CM companies, such as the size of the largest proliferation vessel.

Data collection and handling are described in Sect. 2.1.2. The baseline model parameters are provided in Appendix D. Scenarios and sensitivity analyses were performed to account for variation and other types of uncertainty.

The baseline production process is semi-continuous with three harvests from the largest proliferation vessel (see Fig. 2). The same cell culture medium was assumed to be used throughout the process. Cell proliferation takes place in a seed train until the largest stirred-tank reactor (STR) (working volume 10,000 L) is filled to maximum cell density. At this point, 50% of the cells are harvested, culture medium replenished, and cells further proliferate until maximum cell density is reached. As cell doubling is exponential, most cell production takes place in this last phase of proliferation. A targeted feeding regime allows ingredients to be balanced, and water is expended and recycled throughout the process. There are three intermediate harvests, in total resulting in 200% of cells, relative to the maximum number of cells in the largest proliferation reactor (50% + 50% + 100%). Harvested cells are seeded onto edible scaffolds for further differentiation and maturation, which occurs in 4 perfusion reactors (PR, working volume 2000 L) operating in parallel. Conservatively, it was assumed that no further cell growth takes place in this phase even though some data suggest mass increase during differentiation can be more than 100% (Tuomisto et al. 2022). Additional equipment included were medium storage and mixing tanks, a cell banking system, and centrifuges.

After each production run (12 days for the 10,000 L STR and 10 days for the PR), the reactors are cleaned using a clean-in-place and steam-in-place (CIP/SIP) system. The total production run time from cell vial to final harvest from the PR is 42 days. For 10 kton/year production, it was assumed that the facility needs around 130 production lines to be operating in parallel on a staggered production schedule, which includes accounting for 15–20% downtime for cleaning and maintenance.

2.3.2 Process parameters

The main parameters regarding the cell culture process and system design are provided in Appendix D.

2.3.3 Material and energy inputs and their scenarios

For an overview of the sources, data quality, amount of data points, and whether there has been an independent cross-check of the data, see Appendix D. The most important data choices and assumptions are discussed below.

Culture medium Data about culture medium use were provided by nearly all CM producers involved in this study. Data was asked for both the current situation and 10 years from now (see Appendix D for more information about data collection for culture medium). How lab-scale measured medium efficiency relates to upscaled performances is uncertain. Some indicated that medium efficiency will go down with larger scales, and some indicated that there is no reason to think this will change much or that technology development will counter any negative effects. The proposed high medium scenario amply covers the maximum efficiency decrease mentioned, compared to the baseline (mid) medium scenario (−20%).

Data were aggregated to the ingredient group level to ensure confidentiality. Variation in the dataset indicated different process characteristics and expectations of developments. For the “low-medium” scenario, data assumptions for enhanced catabolism cell types from Humbird (2021) were used as an additional data source for amino acid and sugar consumption. Lower amino acid and sugar quantities were received from CM companies but could not be verified by independent experts and were excluded from this study. Three scenarios were developed, including two extreme scenarios reflecting the upper and lower data boundary, in addition to a probable baseline scenario. The baseline scenario values for the ingredient groups were based on the mean of the dataset, in some cases adjusted up- or downward if most data points were clustered around a certain value or if conversation with experts suggested some data points were more robust than others. The scenarios are shown in Table 1. The values correspond to the amount of medium ingredients needed for the production of 1 kg of meat. Compared to standard DMEM/F12, the medium formulations in this study contain relatively high amounts of amino acids. This could be explained by the fact that when hydrolysates are used as a (partial) source of amino acids, current evidence shows that more of them are needed than when single amino acids are used, because the composition is not defined and not optimal. Despite this, CM companies are likely to make this tradeoff due to cost (Humbird 2021) and environmental impact (Tuomisto et al. 2022) savings that can be expected with the use of hydrolysates.

The ingredients modeled were feed- or food-grade, with the exception of the recombinant proteins, for which only pharma grade data was available. The medium is sterilized using heat and microfiltration (for heat-sensitive substances). Pharma-grade microfiltration cartridges were modeled based on confidential company data.

The main energy, carbon, and nitrogen sources for CM are glucose and amino acids. Glucose is supplied as conventional food-grade maize glucose. Seventy-five percent of amino acids are supplied from soy hydrolysate, and the remaining 25% are single product amino acids from either microbial or chemical production. The soy used is assumed to be deforestation-free, just as for the animal feed in this study. Involved organizations indicated that it is plausible that hydrolysates can be used to supply amino acids in the culture medium, as long as the composition is well defined to enable targeted supplements (Ho et al. 2021). Additionally, soy was selected based on primary data, as it has an essential amino acid profile that roughly matches that of the popular basal medium formulation DMEM/F12 (Humbird 2021). L-Glutamine is the most abundant amino acid supplemented to the culture medium and is produced microbially. L-Glutamine is not available in Agri-Footprint, and therefore an average of three microbially produced feed-grade amino acids (lysine, threonine, and methionine) is used as a proxy (Marinussen and Kool 2010). If only single amino acids were used instead of hydrolysates, it is possible that less amino acids would be needed than when using hydrolysates.

Table 1 Culture medium scenarios (total in g ingredients per kg of cultivated meat cells, therefore excluding any scaffolding material)

Components	Low-medium scenario (g)	Baseline scenario (g)	High-medium scenario (g)	Main ingredients
Amino acids (total), of which:	200	283	400	L-glutamine, L-Arginine hydrochloride, multitude of other amino acids
Amino acids from hydrolysate	*150*	*212*	*300*	
Amino acids from conventional production	*50*	*71*	*100*	
Sugars (total), of which:	320	400	500	Glucose, pyruvate
Sugars: Glucose	*319*	*398*	*396*	
Sugars: Pyruvate	*1*	*2*	*4*	
Recombinant proteins	0.2	3	50	Albumin (dominant in the mid- and high medium scenarios), insulin, transferrin
Salts	100	224	500	Sodium chloride, sodium bicarbonate
Buffering agent	2	26	350	HEPES
Vitamins	0.2	2	20	i-Inositol, Choline chloride
Growth factors	<< 1	<< 1	<< 1	
Water	20,000	44,721	100,000	Ultrapure water
Total (g)	21,142	46,342	102,620	
Total (L)	21	47	103	

Recombinant proteins have important functions in the medium, mainly as growth factors that play a broad role in the control of various cellular pathways or as proteins that can transport and deliver nutrients and other macromolecules. It was assumed that these proteins are produced recombinantly using microbial fermentation, but little environmental data are available in the public literature. In this study, confidential company data is used for albumin, transferrin, and insulin-like growth factor (IGF). These substances are used in different concentrations in the medium, of which albumin has by far the highest concentration (if used) and IGF the lowest. Regarding albumin, companies have widely differing opinions as to what concentration is needed, or whether this will be included at all, and therefore the scenarios reflect this, with albumin present in both the mid- and high-medium scenarios. IGF production is currently at the smallest scale and has the highest environmental impact and therefore was used as a proxy for growth factors, for which production will likely be at small scales for a long time.

The pH buffering system used is largely bicarbonate in the low- and mid-medium scenarios. HEPES is used as an additional buffer, as this is currently widely used. In the low-medium scenario, HEPES is strongly reduced. HEPES is a zwitterionic sulfonic acid (C-ring with 4C and 2 N), and therefore naphthalene sulfonic acid, also zwitterionic, is selected as a proxy.

Edible scaffold Most companies indicated that differentiation will take place on an edible scaffold. Some options for this are hydrogels, electrospun collagen mesh, and textured vegetable protein (TVP), which in that order increasingly support textured final products (Bomkamp et al. 2022; Wollschlaeger et al. 2022; Seah et al. 2022). As the final product in this study was a minced-meat-like product, a starch hydrogel scaffold is modeled, based on De Marco et al. (2017).

Energy Two energy mixes were modeled for this study. The conventional energy mix was based on a global average stated policies scenario for 2030 in the World Energy Outlook (IEA 2019) (for composition see Appendix D), and heat is generated using natural gas (European market mix for industrial heat production from Ecoinvent). The sustainable energy mix was based on on-shore wind and solar PV electricity (both 50%) and heat from geothermal sources. Three energy scenarios were defined, using the energy mixes as an input into different parts of the model, delineated by scope 1, 2, and 3 as defined in the Greenhouse Gas Protocol (GHG Protocol 2011):

- Ambitious Benchmark 2030: Renewable energy for scope 1, 2, and 3 (scope 3 modeling only for culture medium ingredients, scaffold, filters, and water purification)
- Renewable scope 1 and 2: Renewable energy for scope 1 and 2 (at the facility), average mix for scope 3 (upstream)
- Global average energy: Global average energy mix for scope 1, 2, and 3*

Energy demand for the CM facility and upstream materials and ingredients production was based on primary data (upstream materials) and computational models for similar large-scale cell culture processes, using the assumptions and process parameters provided in Appendix D. The energy use was estimated for one production line as under study here (Fig. 2), and this was multiplied by the amount of production lines present at the facility. See Appendix D for further information about data collection, assumptions, and handling for facility energy use. For the upstream materials production, we asked for expected energy use at production scales that the producers expected to attain in 2030. The energy use differs per ingredient, as, for example, the technology and production scales for albumin are already more advanced than for growth factors, which will be expected to stay at small scales for a long time due to more limited demand. Therefore, implicitly, expected status of technology and market size is also included for some upstream products.

Water use Water is used in the process for cell culture medium, CIP, and washing after harvesting. For cell culture medium water use, see Table 1. For the CIP/SIP step, every cleaning cycle consumes 25%v of the bioreactor working volumes. The meat is washed after harvesting, for which 2 L water per kg of meat was assumed. All water was modeled as ultrapure water, for which production was modeled based on confidential primary data. Internal water recycling was included and assumed to be at 75% efficiency, as is demonstrated in full-scale (algal) cell cultures (Yang et al. 2011; Wang et al. 2012).

Cleaning (CIP/SIP) Energy and water use for equipment cleaning and sterilization is reported above. Additionally, an alkaline cleaning agent (NaOH) is used in the CIP step at a concentration of 0.05% v/v.

Wastewater Waste metabolites produced were calculated, based on mass balancing of inputs and outputs and including the metabolism of C and N sources (see Appendix D) (Mattick et al. 2015). Wastewater could be treated on- or off-site, and valuable substances could be separated, reused, or sold as feedstock to third parties, potentially resulting in an overall reduced environmental burden. For this study, wastewater treatment is modeled (proxy: from potato starch production), and no recycling of medium components except water was assumed. While companies indicated that this is an objective, with the provided data, it was not possible to calculate environmental tradeoffs with regard to increased energy use and using recycling-grade (ultra)filtration filters.

Equipment Production of bioreactors and storage and mixing tanks for culture medium was modeled (see Appendix D). Assumptions for calculations for steel and glass wool insulation were based on Tuomisto et al. (2014), with added 10% mass for piping, heat exchangers, and maintenance in all equipment. Additional PVC tubing and electronic control panels were included. The average lifetime of equipment was 20 years, with materials recycled at end-of-life.

2.3.4 Conventional meat production and determination of ambitious benchmarks

In this study, we include ambitious benchmarks for meats from intensive, Western European animal agriculture. Ambitious benchmarks were used to ensure that no unfair advantage is given to CM. CM is often presented as an environmental solution, but in order for that to be true on a product level, it needs to be able to compete environmentally with conventional meat products from efficient and sustainable production systems. The comparison made in this study shows minimum expected benefits from CM. Current global average production of conventional meat has 2x – 4 × higher footprints than the ambitious benchmarks (Poore and Nemecek 2018).

The ambitious benchmarks for conventional meats are based on LCA models from Agri-Footprint LCA database (van Paassen et al. 2019), which represent intensive, efficient production systems located in the Netherlands (chicken, pork, dairy cattle) and Ireland (beef cattle). These models are extended with technological and supply chain improvements. History learns that adoption of sustainability innovations in (animal) agriculture systems is challenging and actual effects on sustainability are uncertain (OECD 2001). Additionally, there seems to be an increasing demand for products with higher animal welfare standards (Scherer et al. 2019), which make certain innovations that could decrease product carbon footprints unlikely (e.g., slaughtering at younger ages or keeping livestock fully indoors to capture methane). The ambitious benchmarks focus on a selection of improvements that are proven to be feasible and are likely to be implemented at larger scales by 2030. This does not mean that these are expected to disseminate widely or globally, but there is a high likelihood that these kinds of production systems will exist.

The improvements included for the ambitious benchmarks are the following (see Appendix F for substantiation):

- Reduced methane emissions from cattle (− 15%) through the use of enzymes
- Reduced ammonia emissions from cattle (− 5.4%) through increased outdoor grazing
- Renewable energy at farm and feed facilities
- No LUC and associated GHG emissions related to soybean production

Beef produced in grazing systems on marginal lands was excluded from the comparison. It should be acknowledged that animal production systems can be very different and are

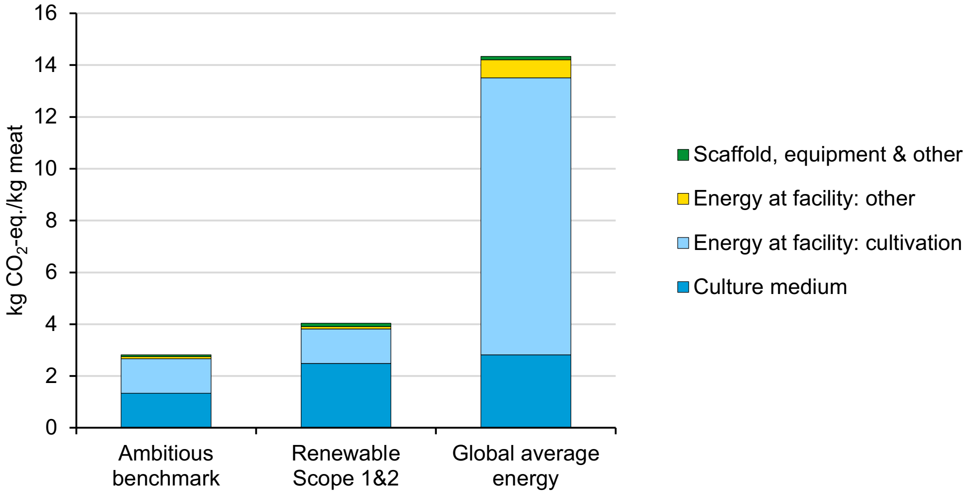

Fig. 3 Carbon footprint of cultivated meat in 2030, baseline scenario with different energy mixes

often interlinked. This adds complexity to an LCA, among others with regard to allocation and land use comparisons. For example, meat from dairy systems (cows, calves, and bulls) provides more than half of global cattle meat (Vellinga et al. 2010). This meat has a lower impact because most of the emissions are allocated to the milk produced in this system. Meat from dairy systems was also included in the comparison.

The ambitious benchmark of CM consists of the baseline scenario with renewable energy for scope 1, 2, and partially scope 3. All scenarios for CM also include LUC-free soy for soy hydrolysate.

2.4 Sensitivity analyses

There are many process parameters that influence the environmental impact and could be further optimized by CM companies. In this study, six sensitivity analyses were performed for key process parameters that were found variable in the primary data collected or that were identified in earlier model iterations as influential for the environmental performance of the process (or both):

(A) Cell culture medium composition and efficiency
(B) Maximum cell density
(C) Production run time
(D) Cell volume
(E) Amount of harvests from the largest proliferation vessel
(F) Partially passive cooling

These parameters influence, among others, the number of bioreactors and production runs, culture medium quantity used, and energy and water demand. For the medium scenarios, see Table 1. For elaboration on the influence on process dynamics and parameters used for the other sensitivity analyses, see Appendix G.

3 Results

3.1 Carbon footprints and greenhouse gas profiles

The carbon footprint results for the baseline production scenario are shown in Fig. 3. The baseline scenario is described in Sect. 2.3. Results are shown for different energy mixes, which are repeated here for clarity (for further info, see Sect. 2.3):

- Ambitious benchmark: Renewable energy for scope 1, 2, and 3*
- Renewable scope 1 and 2: Renewable energy for scope 1 and 2 (at the facility), average mix for scope 3 (upstream)
- Global average energy: Global average energy mix for scope 1, 2, and 3

**Scope 3 modeling: only for culture medium ingredients, scaffold, filters, and water purification*

The carbon footprint of cultivated meat is sensitive to selection of energy mix. In the global average energy scenario, the carbon footprint is over 14 kg CO_2-eq./kg meat, while the ambitious benchmark has a carbon footprint of less than 3 kg CO_2-eq./kg meat. In the renewable scope 1 and 2 scenario, the carbon footprint is around 4 kg CO_2-eq./kg meat. The hotspot analysis shows that the carbon footprint is mainly driven by energy use at the facility (scope 1 and 2) and energy use in production of medium ingredients. Depending on what electricity mix is used, and in which scopes, either facility energy use or medium ingredient production is the main hotspot.

Energy use at the facility is mainly driven by energy use of the heat exchanger (cooling energy, ~ 75%), followed by heating the culture medium (~ 10%), aeration, agitation, CIP/SIP, and HVAC (all < 5%, see Appendix D). While different estimates show slightly different hotspots regarding this

Table 2 Comparison of carbon footprint and greenhouse gas emission profiles of CM and conventional meats

Meat	**System**	**Total**	**Contribution of GHG to carbon footprint**[b]					**Source**
		kg CO_2-eq	***CO_2***	***CH_4***	***N_2O***	***dLUC***	***Other***	
Cultivated meat 2030 Baseline model + energy scenarios	2030 ambitious benchmark	2.8	84%	10%	5%	0%	1%	This study
	Renewable scope 1 and 2	4.0	86%	9%	4%	0%	1%	This study
	Global average energy	14.3	91%	7%	2%	0%	0%	This study
Cultivated meat 2030 Sensitivity analyses best and worst case	Sensitivity analysis best case 2030 ambitious benchmark + passive cooling	2.2	83%	10%	6%	0%	1%	This study
	Sensitivity analysis worst case Global average energy + high medium scenario	24.8	90%	8%	2%	0%	0%	This study
Chicken	2030 ambitious benchmark	2.7	58%	9%	21%	13%	0%	This study
	Current ambitious benchmark	6.0	34%	4%	9%	52%	0%	Agri-Footprint 5.0
	2018 global average	9.0	n.a	n.a	n.a	n.a	n.a	Poore and Nemecek (2018)
Pork	2030 ambitious benchmark	5.1	35%	31%	23%	11%	0%	This study
	Current ambitious benchmark	6.9	34%	23%	17%	26%	0%	Agri-Footprint 5.0
	2018 global average	11.4	n.a	n.a	n.a	n.a	n.a	Poore and Nemecek (2018)
Beef (dairy cattle)	2030 ambitious benchmark	8.8	16%	54%	27%	2%	0%	This study
	Current ambitious benchmark	11.0	18%	49%	22%	11%	0%	Agri-Footprint 5.0
	2018 global average	32.4	n.a	n.a	n.a	n.a	n.a	Poore and Nemecek (2018)
Beef (beef cattle)	2030 ambitious benchmark	34.9	16%	46%	37%	1%	0%	This study
	Current ambitious benchmark	39.8	17%	46%	32%	5%	0%	Agri-Footprint 5.0
	2018 global average	98.6	n.a	n.a	n.a	n.a	n.a	Poore and Nemecek (2018)

[a] Scope 3 processes that use renewable energy are the (bio)chemical production of medium ingredients (not the agricultural feedstock production), scaffolds, and microfiltration filters

[b] Percentages may not add up to 100% due to rounding

energy use, it is clear that in-facility energy demand is high and current models indicate that cooling energy is one of the main contributors to be expected. The carbon footprint of the culture medium is mainly driven by production of amino acids from microbial or chemical production (29–37%, depending on the energy mix during production), followed by recombinant proteins (8–29%), glucose (22–29%), and soy hydrolysate (12–16%). In the high-medium scenario, albumin and HEPES both contribute significantly as they are used in higher concentrations and have a high associated footprint. On a per kg ingredient basis, the recombinant proteins have the highest carbon footprint by far, followed by amino acids from microbial or chemical production. These are energy-intensive biochemical processes that are currently mostly not produced at large scales (except for some amino acids commonly used as food and feed additives), and therefore do not enjoy the benefits of economies of scale. The data for these processes is also rather uncertain, but it seems clear that most currently used (fermentation) technologies have high energy use for some time to come, until the industry is fully mature.

The production of the scaffold has a minor contribution but is also only used at small mass percentages (10% of the final product) and is made from relatively low-impact materials. Other (minor) drivers for the carbon footprint are CIP/SIP and recycling of water. Equipment has a relatively low contribution to the carbon footprint, at the lifetimes assumed in the baseline scenario (20 years).

Compared to conventional meat, the greenhouse gas emissions profile is different. In CM production, the main contributor is CO_2, directly or indirectly from energy consumption (also production of raw materials and upstream industrial processes). In conventional meats, this is more CH_4 and N_2O (Table 2).

3.2 Comparison of ambitious benchmarks

Figure 4 shows the comparison of the ambitious benchmarks of cultivated and conventional meats for 2030, for a selection of environmental impacts. Other environmental indicators are included in Appendix B. CM has a carbon footprint comparable to chicken and lower than pork and beef. Beef from beef cattle has the highest environmental impact for most indicators. This is largely driven by the production of the strong greenhouse gas methane, in addition to the relatively

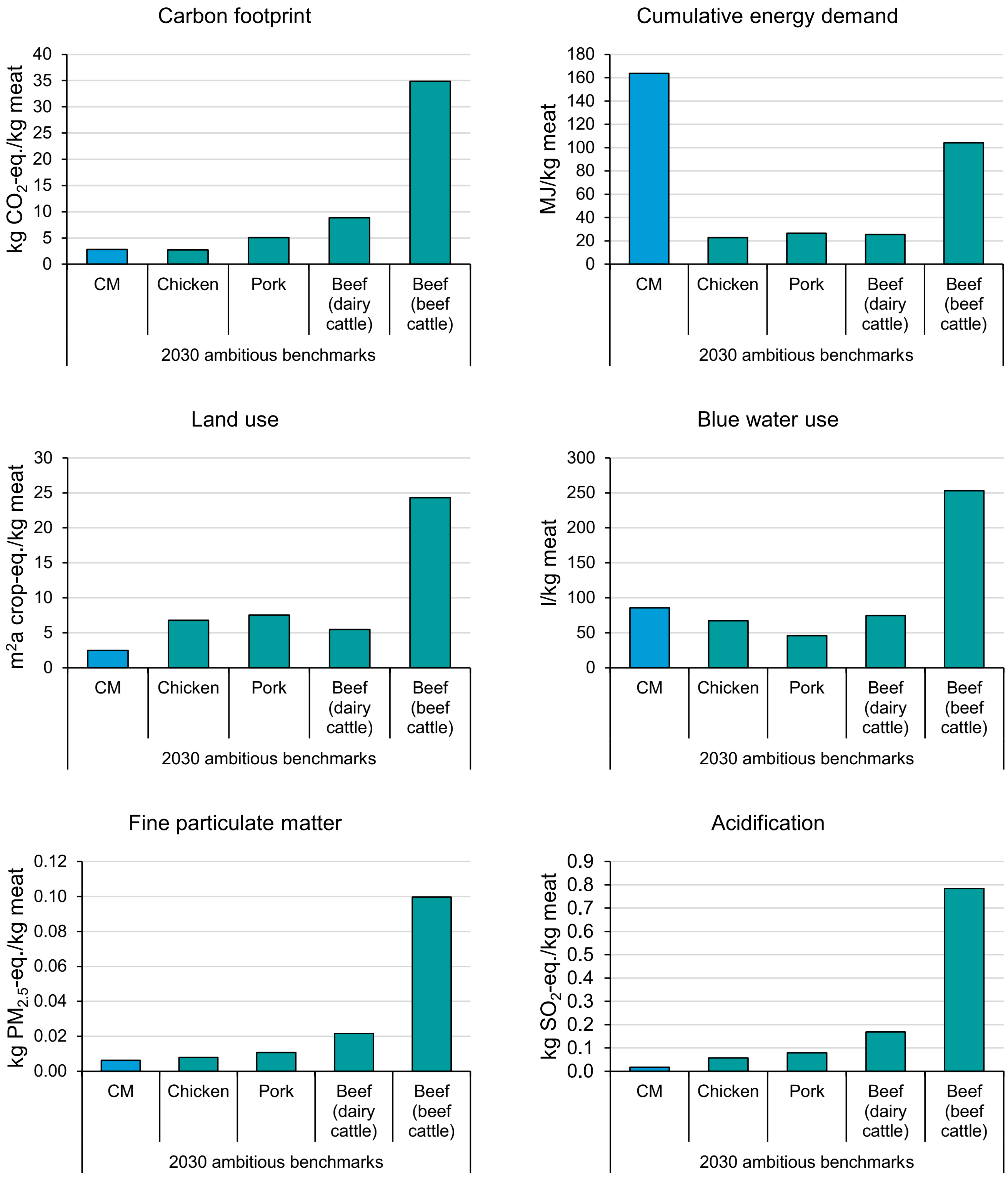

Fig. 4 Comparison of ambitious benchmarks of cultivated meat and conventional meats for 2030

high feed conversion ratio (see Table 3), due to which a lot of land and agricultural inputs are needed.

Cumulative energy demand is higher than in most conventional meat systems, and this is driven by energy use within the facility (> 70%), followed by energy use for (bio)

Table 3 Feed conversion ratio (FCR) of the ambitious benchmarks, dm in:fresh meat out

Resource type	Description	Cultivated meat	Chicken[a]	Pork[a]	Beef (dairy cattle)[a]	Beef (beef cattle)[a]
Biotic	Primary feed	0.8	1.5	3.1	3.7	4.6
	By-product feed	0.2	1.3	1.5	2.1	1.1
	Grass				7.5	31.6
Mineral	Salts and other	0.2				
Total biotic + mineral (incl. grass)		1.3	2.8	4.6	13.4	37.3
Total biotic + mineral (excl. grass)		1.3	2.8	4.6	5.8	5.7
Total biotic (excl. grass)		1.0	2.8	4.6	5.8	5.7

[a] Intensive, Western European production

chemical production of medium ingredients (~ 25%). If this energy comes from renewable sources, it can be largely decoupled from the carbon footprint, as is seen in this comparison of ambitious benchmarks.

Land use for CM is lower than for all conventional meats, which is a robust conclusion that is explained by the more efficient conversion of crops into final product, and therefore lower agricultural land use. Land occupied for renewable energy production (solar and wind) contributes around 10–20% to total land use, highlighting a tradeoff in land use for CM, but overall the reduced land use for crops far outweighs the increased land use for renewable energy production.

Blue water use (surface and groundwater) in CM production is higher for chicken, pork, and beef from dairy cattle, and lower for beef from beef cattle. This result is sensitive to internal water recycling at the facility (in this ambitious benchmark, the recycling percentage is 75%). Around half of the water use is at the facility itself (mostly for use in culture media), and half in the supply chain, mainly for the (bio) chemical production of medium ingredients and in the production of the renewable energy materials and infrastructure.

Fine particulate matter and acidification results for CM are lower than those of all conventional meats, and these results are relatively insensitive to changes in the model. The main reason for this is that ammonia emissions for CM are lower than in the animal systems, because there is no manure and CM needs less crops and therefore less fertilizer. Whereas ammonia is the dominant driver for fine particulate matter and acidification for the conventional meat systems, sulfur dioxide and NOx are the main drivers in the CM system. These are linked to the industrial upstream processes, mainly the production of chemicals for medium ingredient production and the mining and processing of materials for the renewable energy infrastructure.

Other impact categories are provided in Appendix B, some of which are discussed here. Marine eutrophication shows similarities to acidification results, because nitrogen-related emissions (importantly ammonia) are dominant in both indicators. Freshwater eutrophication results are potentially relatively high for CM (higher than for chicken and pork) but are sensitive to the configuration of wastewater treatment processes and upstream industrial chemical processes and their treatment and therefore also relatively uncertain. Real-world measurements should provide a better idea of what type of wastewater treatment is needed. Toxicity impact categories show variation. While for the water-related toxicity impact categories conventional meat production has higher scores, terrestrial ecotoxicity and human non-carcinogenic toxicity are potentially indicators where CM performs worse than conventional meat. Similar to freshwater eutrophication, this is due to upstream production of raw materials for the industrialized and energy-intensive supply chain, highlighting the need for transparent supply chains and responsible sourcing.

The feed conversion ratio (FCR) for the ambitious benchmarks is shown in Table 3. CM feed conversion ratio is lower than all conventional meats, which means it is a more efficient way of turning crops into meat. This explains why the agricultural land use of CM is low compared to conventional meats. The low FCR is also linked to the relatively high energy use in CM production, as part of the energy needed by animals to keep their biological processes going are now supplied via external (electrical or other) energy.

When looking at the biotic FCR, CM is almost three times more efficient than chicken, which has the most efficient feed conversion of the conventional meats. Mineral feed use for CM is relatively high, while for conventional animal production, this is negligible. In CM production, this mainly concerns direct use of salts in the culture medium and indirect use for microbial production of the amino acids and recombinant proteins. Conventional animals have a relatively large share of by-products in their feed, compared to CM. However, as the FCR for CM is lower, primary feed use is still lowest for CM, almost twice as low as for chicken.

3.3 Sensitivity analyses

The dataset used showed variation in some aspects, highlighting the different approaches to producing CM and the uncertainties at this stage of technology development. To account for this, sensitivity analyses were made, for which

Table 4 Sensitivity analyses for CM production

Scenario	Carbon footprint (CO_2-eq./kg meat)					
	2030 ambitious benchmark		Renewable scope 1 and 2		Global average energy	
Baseline scenario (reference)	2.8	ref.	4.0	ref.	14.3	**ref.**
A1: Shorter production run time (−25%: 32 days, 3 harvests)	2.6	−7%	3.7	−8%	13.6	−5%
A2: Longer production run time (+25%: 52 days, 3 harvests)	3.0	6%	4.3	7%	15.0	4%
B1: Higher cell density (x1.4: 7.1E7 cells/ml)	2.8	−1%	4.0	−1%	14.0	−2%
B2: Lower cell density (× 10: 5E6 cells/ml)	3.9	37%	5.3	30%	20.9	46%
C1: Larger cell volume (5000 μm^3)	2.8	−1%	4.0	−1%	14.1	−2%
C2: Smaller cell volume (500 μm^3)	3.6	27%	5.0	23%	18.8	31%
D1: Low medium (more efficient medium usage, removal of albumin, largely reduced HEPES use)	2.3	−17%	2.9	−28%	12.9	−10%
D2: High medium (less efficient medium usage, full use of albumin and HEPES)	5.0	78%	13.8	241%	24.8	73%
E1: More harvests from proliferation vessel (5 harvests)	2.5	−10%	3.8	−7%	12.2	−15%
E2: Less harvests from proliferation vessel (1 harvest—batch process)	3.6	28%	4.8	20%	20.4	43%
E3: More harvests from proliferation vessel (10 harvest—going towards continuous process)	2.3	−18%	3.5	−13%	10.4	−28%
F1: Smart cooling (active + passive, 50% electricity reduction for cooling)	2.2	−21%	3.4	−15%	9.6	−33%

the carbon footprint results are shown in Table 4. Full ReCiPe indicator results and further description of the scenarios are provided in Appendix G.

The most promising routes for lowering the carbon footprint of CM production are applying smart cooling (combining and optimizing passive and active cooling), increasing the amount of harvests from the largest proliferation vessel (moving towards continuous production), improving medium efficiency (especially optimizing use of recombinant proteins, amino acids, and pH buffer system), and shortening overall production time. These improvements lead to a reduced energy demand, either in the upstream supply chain or during production.

Conversely, energy demand and thereby the carbon footprint are increased by inefficient medium use, less harvests (moving towards batch processes), and attaining lower maximum cell densities or working with smaller cells (at constant cell densities).

4 Discussion

4.1 Comparison of cultivated and conventional meats

CM and conventional meat are fundamentally different technologies for producing the same product: meat. Compared to conventional meats, CM is produced in a closed environment that enables higher degrees of control. This comes at the expense of requiring more energy but with the advantage of requiring different and less feed. It is therefore not surprising that the environmental profiles of CM and conventional meats are different. This study includes the latest estimates from industry and experts. While many uncertainties still exist, public and private research and commercial developments are accelerating, and environmental data is coming available at a fast pace. The use of scenarios informs the high-level conclusions that can already be drawn at this stage of technology development.

More efficient feed use for CM translates itself directly into lower agricultural land use and good performance on other environmental indicators that are strongly linked to crop production. Indirectly, it also causes CM to have higher energy use, because part of the energy (calories) used for biological processes in animals (such as maintaining body temperature) is replaced by electricity and heat. The important distinction between those two types of energy is that electricity and heat can be produced sustainably, while the sustainability improvement potential for animal feed is more limited and less scalable.

The controlled environment, direct metabolism, and absence of manure in CM production ensure limited emissions from the production process itself. Importantly, ammonia and the strong greenhouse gasses methane and nitrous oxide are avoided or can be mitigated during wastewater treatment or spent media recycling, the latter of which was not yet included in this study. This is in contrast to conventional meat production, where these emissions are harder to mitigate, because these are inherent to biological processes that happen in a less controlled environment. CM therefore performs relatively well on environmental indicators that are strongly linked to ammonia, such as acidification, fine particulate matter formation, and marine eutrophication. For climate change, the sustainability potential of CM is high, because it is mostly CO_2 driving its carbon footprint, and this emission can be reduced by using decarbonized technologies like renewable energy. As the global energy system continues to decarbonize, the average footprint of CM will continue to decline more strongly than that of conventional meats. Methane and nitrous oxide emissions in conventional meat production are more difficult to reduce (Eckard et al. 2010; Höglund-Isaksson and Gómez-Sanabria 2020). If renewable energy is used, the carbon footprint of CM can be low and comparable to chicken, but if this is not the case, its carbon footprint may be higher than pork. With high certainty, the carbon footprint of CM will be lower than beef from beef cattle.

The bioreactor-based production of CM and the biochemical production of medium ingredients in the upstream supply chain have a few important characteristics. Besides the aforementioned high energy use, there is also relatively high blue water use (surface- and groundwater) and mineral resource use. Blue water use in industrial bioprocessing technologies is high. While conventional meats are known for high water use, the majority of this is green water (rainwater), which is easily replenishable. Looking at blue water use alone, CM scores higher than chicken, pork and beef from dairy cattle, when 75% water is recycled at the facility. Further reduction of the blue water footprint of CM is possible through further increasing recycling at the facility (which is in theory well possible within a controlled environment (Yang et al. 2011; Wang et al. 2012), and efforts in the supply chain, for example by reducing water use for production of culture medium ingredients. Mineral resource use in CM production in feed is mostly due to salts in the culture medium and upstream microbial production processes of medium ingredients. These salts have relatively low associated impacts per kg, but the amounts add up when used in significant amounts. Recycling of salts was not considered in this LCA but could be an important avenue for improving total resource use and associated environmental indicators. The bioreactors and other equipment needed for CM production use substantial amounts of steel and other materials. However, this does not come up as a hotspot in the carbon footprint, as the operational impacts (of energy and resources) dwarf the impacts of the bioreactors over their lifetime (assumed to be 20 years in this study).

Implicit in the comparison of CM and conventional meats is that the products are equal, or in LCA terminology, the function is the same. CM uses the same biological processes to produce the same meat cells; therefore, its function is arguably the same as conventional meats. However, there are more ways to look at the function of foods within an LCA framework, for example, by taking a diet- or product-based perspective or by focusing on specific nutritional quality (McAuliffe et al. 2020). As health effects and consumer perception and behavior cannot yet be studied in relation to CM, these factors cannot yet be considered. Another factor influencing the functional unit is the inclusion of the (edible) scaffold in the final product. While potentially optional for some CM products, scaffolding materials permit cell adherence and mimic the extracellular matrix of the cells, which can allow for greater control over the final product's texture. Many options for scaffolding material exist (Seah et al. 2022). In this study, the scaffolding material was not considered meat, and therefore (conservatively) the reference product of CM is actually ~ 1.1 kg of final product, including 1 kg meat cells and ~ 0.1 kg scaffolding material. If the nutritional quality and consumer perception of the product including scaffold are comparable to meat, this correction to the functional unit arguably does not need to be made.

Some effects that are relevant when comparing two fundamentally different technologies were not captured in this LCA. Examples of topics often mentioned in relation to alternative proteins such as CM are animal welfare, ecosystem functions of livestock systems, biodiversity and ecosystem impacts (especially in aquatic environments), zoonotic disease and antimicrobial resistance risk, odor and other aspects affecting quality of living, food security and food sovereignty, the resilience of and distribution of power in supply chains, and consumer perception and behavior. These are not captured in an LCA but arguably part of a broader definition of sustainability, and therefore there are attempts to include these within the LCA framework (for animal welfare, see, e.g., Scherer et al. 2018). Also, a greater debate about the role of animals in the agricultural and food systems is inadequately captured by using a product-based comparison. An example is the function of animals to produce food on marginal lands or in high-quality recycling of waste streams. There is a lot of variation in the environmental impacts or values that meat production systems have, both for conventional meats and CM. By zooming in on ambitious benchmarks, this variation is ignored. This study therefore provides a relevant dataset for the greater discussion on CM, specifically regarding its product environmental footprint, but many other factors are important and should be considered.

4.2 Insights from 10 years of cultivated meat LCAs

A little over 10 years ago, Tuomisto and Teixeira de Mattos (2011) published the first LCA of CM. That study was followed by Tuomisto et al. (2014) and Mattick et al. (2015), and the results from those early studies were incorporated in additional assessments by Smetana et al. (2015, 2018) and Lynch and Pierrehumbert (2019). The most recent addition is an LCA based on experimental bench-scale data from Tuomisto et al. (2022). A comparison of these studies, including study design and main environmental indicators, are presented in Appendix A and compared to this study. Over the years, insights have progressed, uncertainties have decreased, and environmental benefits and hotspots have become clearer. In all studies, biotic resource use is relatively low compared to conventional meats, but there is variation in the type of feedstocks used and the extent to which hydrolysates can be incorporated. These factors can significantly influence environmental performance. In this study, the effects of more sustainable feedstocks were not included, but previous assessments, such as those that modeled hydrolysates from cyanobacteria (Tuomisto and Teixeira de Mattos 2011; Tuomisto et al. 2014), show that there may be opportunities here. The controlled environment and efficient resource use of CM show sustainability potential with regard to direct farm/facility-level emissions and associated disruption of nutrient cycles, which are serious and hard to mitigate environmental concerns in conventional animal agriculture. Estimates of energy use have increased over the years, highlighting the relative uncertainty in this regard and the importance of decarbonizing the energy sources. As energy estimates are shown to be uncertain, in this study, a conservative approach has been taken, in which importantly the cooling load is supplied by active cooling. It may well be that energy use at large scales is lower than the current estimate, as is shown by the sensitivity analysis on smart cooling.

4.3 Environmental hotspots in cultivated meat production and technology development

The main environmental hotspots of CM production are the facility energy use and culture medium ingredient production, in which energy use also plays an important role. The impacts of CM can therefore be greatly reduced by using renewable energy in both the facility (scope 1 and 2) and the supply chain, mainly for production of medium ingredients.

4.3.1 Energy

Facility energy use is directly within the influence of the CM producers. As far as possible, energy efficiency should be optimized. In this study, a conservative estimate of energy use is taken, mainly regarding the need for a large active cooling load, which accounts for ~ 75% of energy use. The need for the cooling load as modeled here is uncertain. In comparison, Tuomisto et al. (2022) model lower facility energy demand (according to our calculations 2.8–9.6 kWh/kg meat cells, compared to 22.3 kWh/kg meat cells in the baseline scenario in this study). As this study and Tuomisto et al. (2022) assess different bioreactor systems (a combination of STRs and perfusion reactors and a hollow fiber bioreactor, respectively), different production scales (commercial and bench-scale, respectively) have different process characteristics; these numbers cannot directly be compared, and therefore these differences cannot easily be explained. An important reason could be that the approach used to calculate facility energy demand in this study differs from previous studies (Mattick et al. 2015; Tuomisto et al. 2022) in the sense that data from computational models of similar processes at large scales were used, instead of using thermodynamic calculations for specific processes at the cell level. This results in higher estimates for overall energy use in this study and specifically for necessary cooling load. It is therefore a conservative approach. It is also possible that there are differences in heating and cooling efficiency due to differences in bioreactor sizes, overall water volumes, cooling jacket design, and vessel geometry. The topic of heating and cooling balance is an area of ongoing research and development in the field, because large-scale empirical data for CM production does not exist yet. While small-scale cultures generally do not produce much heat, heat dynamics may change at larger scales, resulting in temperature hotspots that need to be cooled quickly (Li et al. 2020). The demand for heating and cooling will depend on multiple factors such as reactor design, cell densities, oxygen uptake rates (OUR), and glucose consumption. Further modeling of real-world pilot CM processes, and preferably experimental data, is needed to provide more accurate estimates of heating and cooling demand at scale.

Environmental impacts of cooling could also be mitigated by applying partially passive cooling. Whether this is possible will depend on the environmental conditions of the facility location and ambient temperatures. The most universally applicable cooling systems are based on active cooling, using vapor-compression refrigeration or cooling water, both of which ultimately reject their heat to the ambient air. The economic optimum temperature differential in the cooling system will be around 10 °C. The production process considered in this study has to be kept around 37 °C, so the cooling fluid will have a maximum temperature of around 27 °C. Another 10 °C temperature differential is required to reject the heat to the ambient air. Roughly speaking, there are four options for cooling, ranging from active to fully passive cooling, that are suitable for different ambient temperatures:

- Using a refrigeration cycle, for ambient temperatures up to 27 °C
- Using cooling water and an evaporating cooling tower, for ambient temperatures up to 22 °C
- Using cooling water and an air fin cooler with mechanical air circulation, for ambient temperatures up to 17 °C
- Using cooling water and an air fin cooler without mechanical air circulation, for ambient temperatures up to 12 °C

Depending on year-round ambient temperature conditions, there will be a need for active or passive cooling, or likely a combination of both, as many locations on Earth have strong seasonal temperature fluctuations. In the baseline scenario, year-round use of the refrigeration cycle was assumed as this is suitable for any location at any time, but this is a conservative approach.

The cooling electricity demand can be reduced by optimizing the cooling system to the geographical location. The sensitivity analysis on smart cooling (cutting down the electricity demand by 50%) shows that this can have a significant effect on the carbon footprint (−33% in the global average energy scenario and −21% in the ambitious benchmark scenario). This could be extended to the biochemical production processes in the upstream supply chain, but this was not considered in this study. Also not considered in this study is that the carbon footprint of electricity will on average be lower when active cooling load is most needed, as this is when ambient temperatures are highest and there is more solar electricity available. This has a damping effect on the carbon footprint of products that use a lot of cooling energy. Cooling system design will always be strongly related to location-specific opportunities. Cold-water sources (e.g., oceans or rivers) or residual heat from industry (for absorption cooling) might be viable options, but this depends on geographical, legal, and economic context.

Whatever the exact assumptions for facility energy demand, it is clear that energy sourcing is an important lever for sustainability. Lower energy use results in lower carbon footprints and the conservative energy assumptions in this study therefore possibly result in conservative carbon footprints estimates. CM companies should look for suitable locations where renewable energy, especially electricity, is abundant. There is evidence that this is already occurring in the CM industry.

CM is a new and potentially large sector with substantial energy demand, and thus its role in the energy transition must be considered. On the one hand, it may increase pressure on an energy transition that is already experiencing difficulty meeting global climate goals (Gielen et al. 2021). On the other hand, it is potentially disruptive to the food system, providing meat with a significantly smaller land footprint, which provides opportunities to use this land for additional carbon storage or renewable energy production while reducing deforestation pressure. Additional studies are needed to further understand this carbon opportunity cost, and robust policies will be needed to realize these opportunities.

4.3.2 Culture medium

Culture medium ingredient production is the second environmental hotspot, which becomes important (even dominant) when renewable energy is used for the facility. These impacts are mostly driven by the energy-intensive production of recombinant proteins and single amino acids produced microbially or chemically, followed by glucose, soy hydrolysate, and HEPES (if used). When albumin is used in the medium, this dwarfs the impact of the other ingredients, as it is needed in up to 100,000 times higher concentrations than growth factors. The estimated carbon footprint of microbially produced amino acids is 5x – 10 × higher than amino acids from hydrolysates. If production with hydrolysates is not realized, and companies continue to rely on single amino acids, the impacts of culture medium are likely to be higher, even though less amino acids would be needed as the medium would be fully defined. This is illustrated in Tuomisto et al. (2022), where the amino acids are the dominant driver for the life cycle carbon footprint of CM. The industries supplying the recombinant proteins and amino acids necessary for CM production are not yet always at scale, and therefore this study uses ex-ante estimates for these products for a large part. Currently, these ingredients come from the pharma sector, where price pressure is low, and therefore energy efficiency is not the main priority. As the CM industry matures, the recombinant protein and amino acid industries will also mature and be incentivized towards more sustainable practices given the importance of scope 3 emissions. A dialogue between the CM companies and their suppliers is needed to implement these practices, guided by LCAs that model medium composition and efficiency changes. The majority of recombinant proteins are currently supplied by microbial fermentation; however, other methods such as expression in plants, insects, or cell-free systems may offer advantageous sustainability characteristics (Tripathi and Shrivastava 2019; GFI 2021). Fermentation using filamentous fungi currently looks highly promising from an environmental perspective (Järviö et al. 2021). Future research is needed to clarify the most suitable production platforms that balance quality, cost, sustainability, and other factors that may be important for regulation and consumer acceptance.

The exact composition and efficiency of the culture medium show variation between technologies and cell types (O'Neill et al. 2022). In this study, the various medium scenarios reflect realistic future scenarios, to current knowledge, but not per se the absolute upper or lower bounds of medium efficiency. Lower numbers than those modeled in the low-medium scenario have been reported, but could not be generalized across products and technologies at this point, and were therefore not included. Future research and experimental data will have to provide additional insights on this topic.

It is uncertain to what extent CM lends itself to converting waste- or by-products into edible meat. This could be an avenue through which the footprint of culture medium can be reduced. For example, it is possible that the glucose, both for direct use in the culture medium and for indirect use for biochemical fermentation processes in the supply chain, can be sourced from waste- or by-products such as lignocellulosic biomass. Conventional animal production lends itself well to the conversion of by-products into meat, but the currently optimized production systems, including the ambitious benchmarks in this study, are not representative of such a system, and there are limits to the scale of global animal production when increasing the amount of by-products (Mottet et al. 2017). Also, the ambiguous terminology around waste-, co-, and by-products casts confusion on the debate, most clearly seen in the discussion regarding soybean meal. Perhaps more useful indicators focus on the percentage that is “human-edible” in an ingredient, which in the case of soybean meal is 80% (Wilkinson 2011), or on the share of land that could otherwise be used for human-edible food production (van Zanten et al. 2016).

Offsetting the environmental impact of the culture medium could also be accomplished by harvesting co-products from a CM process. This is not considered in this study because of lacking data regarding separation, capture, and recycling at scale, but Tuomisto et al. (2022) show that this could have significant effects on overall system performance. This is an interesting area for future research. It is estimated that under baseline assumptions ~ 3200 tonnes of lactate, 16 tonnes of ammonia, and 1 tonne of alanine will be produced as waste in a year of operation in this model facility (Appendix D). Capture and recycling of these co-products are possible and could valorize them as inputs into downstream applications for bioplastics, fertilizers, or other feedstocks (Nahmias and Wissotsky 2021). The environmental benefits of this could be substantial. For example, the carbon footprint of biobased lactic acid ranges from 1.6 (Morão and de Bie 2019) to 11 kg CO_2-eq./kg (Parajuli et al. 2017), depending on the feedstock and production process. Avoided production of virgin lactic acid production could be partially counted as a reduction in the impacts of CM production. Additional studies are needed to understand the techno-economics of such recycling approaches as well as potential sustainability tradeoffs if recycling systems require high amounts of energy to operate.

4.3.3 Other technological innovations

In order to realize the production system as modeled in this study, technological innovations are needed. Importantly, this relates to the bioreactor platforms. Perfusion systems modeled in this study are not yet available for meat production. Cost-effective systems will have to be developed over the next decade. Important characteristics relate to automated feeding (e.g., nutrients and oxygen), perfusion and removal of unwanted substances (e.g., ammonia and lactate), and incorporation of scaffolding. At the facility scale, these relate to harvesting of cells and recycling of nutrients and other medium ingredients. In this study, only water recycling was included (at 75% efficiency). When recycling solid ingredients, additional separation steps are needed, which can be costly and will likely have a tradeoff with added energy and material use. Future research will have to shed light on these costs and environmental tradeoffs.

4.3.4 Product development and targeted diet substitution

It is important to see the potential of CM in the context of diets. From an environmental perspective, the largest gains are by substituting the highest impact conventional meat products by CM on the plate of the consumer, being beef from beef cattle. Of course other factors besides those captured in an LCA play a role and regional context matters, but the message is that CM can be seen as a tool to reduce the downsides of current global demand for conventional animal products. In this sense, it can be an attractive part of a mix of sustainable protein sources in a healthy diet, which also includes increased amounts of fully plant-based options, still the most direct way to consume proteins while having the lowest associated impacts (Poore and Nemecek 2018). Lastly, hybrid products (partly plant-based, partly CM) can be made to increase the amount of sustainable proteins in diets while also optimizing for efficiency, sustainability, and costs.

5 Conclusions

CM has the potential to be a sustainable source of animal protein. How it compares to conventional meats depends on various factors, most importantly the sources of energy used for the facility and the production of medium ingredients. When fully renewable energy is used in these areas, its carbon footprint can compete with ambitious benchmarks of chicken and is lower than that of the other conventional meats. Land use of CM is significantly lower than all conventional meats, resulting from the more efficient conversion of crops into meat. When CM replaces conventional meats in diets, this means that land is freed up. This land could be used to mitigate climate change, support biodiversity, or provide other societal and environmental benefits, but robust policies are needed to realize this.

CM companies should invest in strong supply chain collaborations to drive down the carbon footprint in all parts of the supply chain. Strong climate goals can be set and realized by continuously conducting LCAs to support decision-making and guide technology development.

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Author contribution Pelle Sinke (PS), Ingrid Odegard (IO), Elliot Swartz (ES), and Hermes Sanctorum (HS) contributed to the study conception. PS and IO made the study design. Contacts with data partners were established via the authors and the extended network of the Good Food Institute. Material preparation was performed by PS and IO and reviewed by ES. Data collection and analysis were performed by PS and IO. Interpretation of modeling results was performed by PS, IO, ES, and HS. Design of follow-up questions was performed by PS, IO, ES, and Coen van der Giesen (CG). The first draft of the manuscript was written by PS and reviewed by ES, HS, and CG. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability Most data generated or analyzed during this study are included in this published article and its supplementary materials. In some cases, these are aggregated data, summarized as averages or scenarios, in order to account for variation and to ensure data confidentiality. In a few cases, confidential company data that could not be aggregated are used. In these cases, it is mentioned in-text that confidential data are used and these are not included in the article or supplementary materials.

Declarations

Conflict of interest Elliot Swartz works at the Good Food Institute. Hermes Sanctorum works as a private consultant for GAIA. Pelle Sinke, Ingrid Odegard, and Coen van der Giesen work at CE Delft.

References

Benton T, Bieg C, Harwatt H et al (2021) Food system impacts on biodiversity loss: three levers for food system transformation in support of nature. Compassion in World Farming (CIWF)

Blonk Sustainability (n.d.) In: Frequently Asked Questions about Agri-footprint. https://blonksustainability.nl/tools/agri-footprint/faq. Accessed 30 Sep 2022

Bomkamp C, Skaalure SC, Fernando GF et al (2022) Scaffolding biomaterials for 3D cultivated meat: prospects and challenges. Adv Sci 9:e2102908

Clark MA, Domingo NGG, Colgan K et al (2020) Global food system emissions could preclude achieving the 1.5° and 2 °C climate change targets. Science 370:705–708

Crippa M, Solazzo E, Guizzardi D et al (2021) Food systems are responsible for a third of global anthropogenic GHG emissions. Nat Food 2:198–209

Cucurachi S, Scherer L, Guinée J, Tukker A (2019) Life cycle assessment of food systems. One Earth 1:292–297

De Marco I, Riemma S, Iannone R (2017) LCA of aerogel production using supercritical gel drying: from bench scale to industrial scale. Chem Eng Trans 57:241–246

Eckard RJ, Grainger C, de Klein CAM (2010) Options for the abatement of methane and nitrous oxide from ruminant production: a review. Livest Sci 130:47–56

FAO (2011) World Livestock 2011 - Livestock in food security. FAO, Rome

FAO (2022) FRA 2020 remote sensing survey. FAO

Frischknecht R, Jungbluth N, Althaus H-J et al (2007) Implementation of life cycle impact assessment methods. Data v2.0 (2007). Ecoinvent report No. 3. Ecoinvent Centre

Frischknecht R, Wyss F, Büsser Knöpfel S et al (2015) Cumulative energy demand in LCA: the energy harvested approach. Int J Life Cycle Assess 20:957–969

Garske B, Ekardt F (2021) Economic policy instruments for sustainable phosphorus management: taking into account climate and biodiversity targets. Environ Sci Eur 33:1–20

GFI (2021) 2021 State of the Industry Report: fermentation - meat, seafood, eggs and dairy. The Good Food Institute (GFI)

GFI (2022) 2021 State of the Industry Report: cultivated meat. The Good Food Institute (GFI)

GHG Protocol (2011) Product life cycle accounting and reporting standard. World Business Council for Sustainable Development (WBCSD) and the World Resources Institute (WRI)

Gielen D, Gorini R, Leme R et al (2021) World Energy Transitions Outlook: 1.5 °C pathway. International Renewable Energy Agency (IRENA)

Global Methane Initiative (2015) Global methane emissions and mitigation opportunities. Global Methane Initiative

Grossi G, Goglio P, Vitali A, Williams AG (2019) Livestock and climate change: impact of livestock on climate and mitigation strategies. Anim Front 9:69–76

Heijungs R, Huijbregts MAJ (2004) A review of approaches to treat uncertainty in LCA. In: International Congress on Environmental Modelling and Software. Brigham Young University: BYU Scholars Archive, p 197

Heinke J, Lannerstad M, Gerten D et al (2020) Water use in global livestock production—opportunities and constraints for increasing water productivity. Water Resour Res 56. https://doi.org/10.1029/2019WR026995

Ho YY, Lu HK, Lim ZFS et al (2021) Applications and analysis of hydrolysates in animal cell culture. Bioresour Bioprocess 8:93

Höglund-Isaksson, Gómez-Sanabria (2020) Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe–results from the GAINS model. Environ Toxicol Water Qual. https://doi.org/10.1088/2515-7620/ab7457/meta

Huijbregts MAJ, Rombouts LJA, Hellweg S et al (2006) Is cumulative fossil energy demand a useful indicator for the environmental performance of products? Environ Sci Technol 40:641–648

Huijbregts MAJ, Steinmann ZJN, Elshout PMF et al (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 22:138–147

Humbird D (2021) Scale-up economics for cultured meat. Biotechnol Bioeng 118:3239–3250

IEA (2019) World Energy Outlook 2019. https://www.iea.org/reports/world-energy-outlook-2019. Accessed 10 Aug 2020

Järviö N, Parviainen T, Maljanen N-L et al (2021) Ovalbumin production using Trichoderma reesei culture and low-carbon energy could mitigate the environmental impacts of chicken-egg-derived ovalbumin. Nature Food 2:1005–1013

Krueger K, Rubio N, Datar I, Stachura D (2019) Cell-based fish: a novel approach to seafood production and an opportunity for cellular agriculture. Front Sustain Food Syst 3:43

Li X, Zhang G, Zhao X et al (2020) A conceptual air-lift reactor design for large scale animal cell cultivation in the context of in vitro meat production. Chem Eng Sci 211:115269

Lynch J, Pierrehumbert R (2019) Climate impacts of cultured meat and beef cattle. Front Sustain Food Syst 3. https://doi.org/10.3389/fsufs.2019.00005

Marinussen M, Kool A (2010) Environmental impacts of synthetic amino acid production. Netherlands: Blonk Milieu Advies BV

Mattick CS, Landis AE, Allenby BR, Genovese NJ (2015) Anticipatory life cycle analysis of in vitro biomass cultivation for cultured meat production in the United States. Environ Sci Technol 49:11941–11949

McAuliffe GA, Takahashi T, Lee MRF (2020) Applications of nutritional functional units in commodity-level life cycle assessment (LCA) of agri-food systems. Int J Life Cycle Assess 25:208–221

Morão A, de Bie F (2019) Life cycle impact assessment of polylactic acid (PLA) produced from sugarcane in Thailand. J Polym Environ 27:2523–2539

Mottet A, de Haan C, Falcucci A et al (2017) Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. Glob Food Sec 14:1–8

Nahmias Y, Wissotsky G (2021) Methods and devices for filtering cell culture media. World Patent

O'Neill EN, Ansel JC, Kwong GA et al (2022) Spent media analysis suggests cultivated meat media will require species and cell type optimization. NPJ Sci Food 6:46

OECD (2001) Adoption of technologies for sustainable farming systems: Wageningen Workshop Proceedings. 149

Ott D, Goyal S, Reuss R et al (2022) LCA as decision support tool in the food and feed sector: evidence from R&D case studies. Environ Syst Decisions. https://doi.org/10.1007/s10669-022-09874-y

Parajuli R, Knudsen MT, Birkved M et al (2017) Environmental impacts of producing bioethanol and biobased lactic acid from standalone and integrated biorefineries using a consequential and an attributional life cycle assessment approach. Sci Total Environ 598:497–512

Pendrill F, Persson UM, Godar J et al (2019) Agricultural and forestry trade drives large share of tropical deforestation emissions. Glob Environ Chang 56:1–10

Pesonen H-L, Ekvall T, Fleischer G et al (2000) Framework for scenario development in LCA. Int J Life Cycle Assess 5:21

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

Scherer L, Tomasik B, Rueda O, Pfister S (2018) Framework for integrating animal welfare into life cycle sustainability assessment. Int J Life Cycle Assess 23:1476–1490

Scherer L, Behrens P, Tukker A (2019) Opportunity for a dietary win-win-win in nutrition, environment, and animal welfare. One Earth 1:349–360

Seah JSH, Singh S, Tan LP, Choudhury D (2022) Scaffolds for the manufacture of cultured meat. Crit Rev Biotechnol 42:311–323

Smetana S, Aganovic K, Irmscher S, Heinz V (2018) Agri-food waste streams utilization for development of more sustainable food substitutes. In: Benetto E, Gericke K, Guiton M (eds) Designing Sustainable Technologies, Products and Policies: From Science to Innovation. Springer International Publishing, Cham, pp 145–155

Smetana S, Mathys A, Knoch A, Heinz V (2015) Meat alternatives: life cycle assessment of most known meat substitutes. Int J Life Cycle Assess 20:1254–1267

Specht EA, Welch DR, Clayton EMR, Lagally CD (2018) Opportunities for applying biomedical production and manufacturing methods to the development of the clean meat industry. Biochem Eng J 132:161–168

Specht L (2020) An analysis of culture medium costs and production volumes for cultivated meat. The Good Food Institute

Steffen W, Richardson K, Rockström J et al (2015) Sustainability. Planetary boundaries: guiding human development on a changing planet. Science 347:1259855

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

Tripathi NK, Shrivastava A (2019) Recent developments in bioprocessing of recombinant proteins: expression hosts and process development. Front Bioeng Biotechnol 7:420

Tsoy N, Prado V, Wypkema A, Quist J (2019) Anticipatory life cycle assessment of sol-gel derived anti-reflective coating for greenhouse glass. J Clean Prod 221:365–376

Tsoy N, Steubing B, van der Giesen C, Guinée J (2020) Upscaling methods used in ex ante life cycle assessment of emerging technologies: a review. Int J Life Cycle Assess 25:1680–1692

Tuomisto HL, Allan SJ, Ellis MJ (2022) Prospective life cycle assessment of a bioprocess design for cultured meat production in hollow fiber bioreactors. Sci Total Environ 851:158051

Tuomisto HL, Teixeira de Mattos MJ (2011) Environmental impacts of cultured meat production. Environ Sci Technol 45:6117–6123

Tuomisto HL, Ellis MJ, Haastrup P (2014) Environmental impacts of cultured meat: alternative production scenarios. In: Schenck R, Huizenga D (eds) Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-food Sector. ACLCA

Twine R (2021) Emissions from animal agriculture—16.5% is the new minimum figure. Sustain Sci Pract Policy 13:6276

Uwizeye A, de Boer IJM, Opio CI et al (2020) Nitrogen emissions along global livestock supply chains. Nat Food 1:437–446

van der Giesen C, Cucurachi S, Guinée J et al (2020) A critical view on the current application of LCA for new technologies and recommendations for improved practice. J Clean Prod 259:120904

van Paassen M, Braconi N, Kuling L et al (2019) Agri-footprint 5.0

van Zanten HHE, Mollenhorst H, Klootwijk CW et al (2016) Global food supply: land use efficiency of livestock systems. Int J Life Cycle Assess 21:747–758

Vellinga T, Gerber P, Opio C (2010) Greenhouse gas emissions from the global livestock sector - methodology for a life cycle assessment. Wageningen University and Research Centre (WUR)

Villares M, Işıldar A, van der Giesen C, Guinée J (2017) Does ex ante application enhance the usefulness of LCA? A case study on an emerging technology for metal recovery from e-waste. Int J Life Cycle Assess 22:1618–1633

Voglhuber-Slavinsky A, Zicari A, Smetana S et al (2022) Setting life cycle assessment (LCA) in a future-oriented context: the combination of qualitative scenarios and LCA in the agri-food sector. Eur J Futur Res 10:15

Walker P (2000) Food residuals: waste product, by-product, or co-product, food waste to animal feed. In: Westendorf M (ed) Food Waste to Animal Feed. Iowa State University Press, Ames, pp 17–30

Wang Y, Liu W, Bao J (2012) Repeated batch fermentation with water recycling and cell separation for microbial lipid production. Front Chem Sci Eng 6:453–460

Weagle CL, Snider G, Li C et al (2018) Global sources of fine particulate matter: interpretation of PM2.5 chemical composition observed by SPARTAN using a global chemical transport model. Environ Sci Technol 52:11670–11681

Wernet G, Bauer C, Steubing B et al (2016) The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21:1218–1230

Wilkinson JM (2011) Re-defining efficiency of feed use by livestock. Animal 5:1014–1022

Wollschlaeger JO, Maatz R, Albrecht FB et al (2022) Scaffolds for cultured meat on the basis of polysaccharide hydrogels enriched with plant-based proteins. Gels 8. https://doi.org/10.3390/gels8020094

Wyer KE, Kelleghan DB, Blanes-Vidal V et al (2022) Ammonia emissions from agriculture and their contribution to fine particulate matter: a review of implications for human health. J Environ Manage 323:116285

Xu X, Sharma P, Shu S et al (2021) Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. Nature Food 2:724–732

Yang J, Xu M, Zhang X et al (2011) Life-cycle analysis on biodiesel production from microalgae: water footprint and nutrients balance. Bioresour Technol 102:159–165

Authors and Affiliations

Pelle Sinke[1] · **Elliot Swartz**[2] · **Hermes Sanctorum**[3] · **Coen van der Giesen**[1] · **Ingrid Odegard**[1]

✉ Pelle Sinke
sinke@ce.nl

[1] LCA Department - Food Chains Team, CE Delft, Oude Delft 180, Delft 2611 HH, the Netherlands

[2] Science & Technology Department, The Good Food Institute (GFI), 1380 Monroe St. NW #229, Washington, DC 20010, USA

[3] GAIA, Hopstraat 43, 1000 Brussels, Belgium