LCA of cultivated meat

Future projections for different scenarios

CE Delft

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LCA of cultivated meat

Future projections for different scenarios

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Content

Summary

In this prospective Life Cycle Assessment (LCA) study[1] of cultivated meat (CM, also sometimes referred to as cell-based meat, clean meat, cultured meat and in-vitro meat) we provide insight into the environmental impact of this product when produced at commercial scales. This is the first LCA study which uses primary data from multiple CM companies and from associated companies in the CM supply chain. Data collection efforts have been carried out among over 15 companies active in CM development and its supply chain, supplemented with cross-checks with independent experts. While uncertainties still exist due to the early stage of technology development, we believe this has resulted in a robust inventory with as much primary data as is currently possible.

Comparing future production systems in 2030

The results represent a production scenario for 2030, which reflects expected changes, both internally (e.g. the scaling up of CM production) and externally (e.g. share of sustainable sources in electricity mix). The final product being modelled is a ground-meat product, cultivated around 37°C, produced in a future commercial-scale facility. The results for this product are compared to an ambitious benchmark for conventional protein products, which was chosen to make sure conclusions with regard to the sustainability of CM would be as robust as possible. The ambitious benchmark should not be interpreted as a projection of global average meat consumption in 2030. Results are presented using the weighted ReCiPe single score (environmental single score) to represent the total environmental impact and the carbon footprint (CFP) measured in greenhouse gas equivalents (GHGe). For more context, global average carbon footprints are also shown for both the CFP and the environmental single score (ambitious benchmark adjusted for average carbon footprint).

Cultivated meat has the potential to be a highly sustainable meat product

CM is compared to ambitious benchmarks of traditional meats and meat alternatives. CM in the conventional energy scenario has a lower environmental single score and lower CFP than beef (also dairy beef), but a higher environmental single score than chicken, pork, and plant-based meat alternatives in the baseline scenario (Figure 1 and Figure 2). As can be seen in Figure 1, in case of a switch to sustainable energy, CM has a lower environmental single score than all meat products.

If the carbon footprint component in the environmental single score is adjusted to reflect the global average carbon footprint of meat products, conventional energy CM scores comparable to the adjusted single score for chicken, and lower than pork and beef. CM can compete on carbon footprint with the global average footprints for chicken and pork, if > 30% of energy use is sourced sustainably.

Compared to all meat products, both cultivated and conventional, the environmental single score and the carbon footprint of vegetable protein products is low. With a carbon footprint which is 2.5 to 4 times lower, and an environmental single score of over 3 and 7 times

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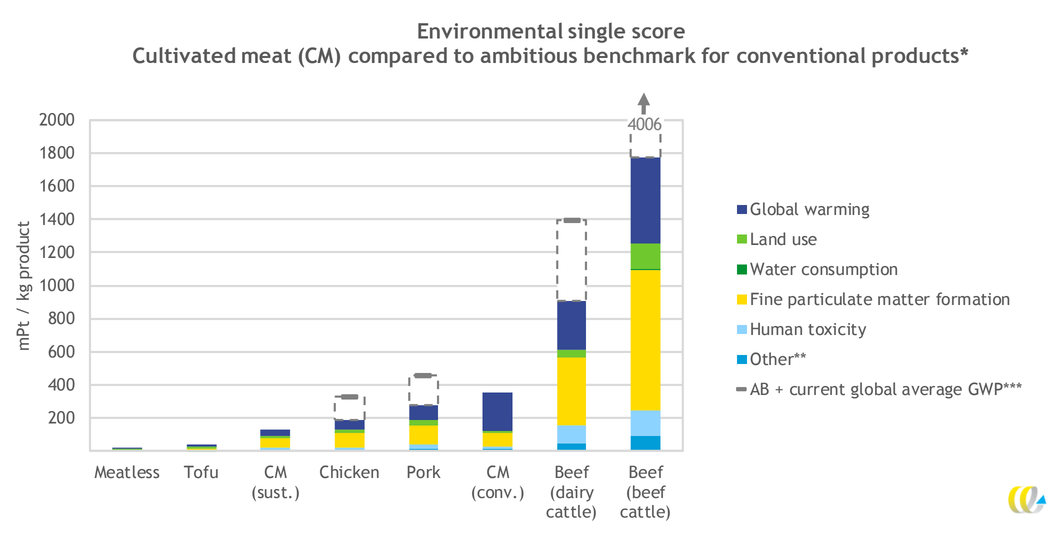
[1] Note: This report is one part of the combined Life Cycle Assessment (LCA) and Techno-Economic Assessment (TEA) project. For the TEA, see CE Delft (2021).

lower, cultivated meat is unlikely to be able to compete with vegetable protein products on these two indicators.

In livestock production, the total environmental impact is driven by a number of impacts: climate change, fine particulate matter formation (both direct from stables and feed crop production, as indirect from ammonia), land use and human toxicity. For CM, this is primarily driven by climate change impacts, and to a lesser extent fine particulate matter formation. This also means that switching to sustainable energy means lowering the impact of multiple environmental impact categories at once.

Figure 1 – Environmental impact (ReCiPe single score) of CM and conventional protein products (ambitious benchmark and ambitious benchmark adjusted for global average score on global warming)



* Intensive, West-European, circular agriculture with LUC-free soy.

** ‘Other’ includes 14 impact categories, among which other toxicity categories, acidification and resource depletion. A complete list can be found in Annex A.

*** Current global average carbon footprint taken from Poore and Nemecek (2018).

We have analysed the effects of a conventional energy scenario (global stated policies electricity mix for 2030 and heat from natural gas) and a sustainable scenario (solar and wind electricity and geothermal heat) in this study. Of course there are many other variations possible, with sustainability performance likely to fall somewhere between these scenarios, at least in the timeframe modelled in our study (2030). This largely depends on the geographical location and choices of the CM producer to either buy or produce certain types of electricity.

Most important drivers of impact: energy use and medium

The environmental impact of CM is largely driven by energy use; primarily electricity use during production itself, but also electricity and heat use in upstream production of medium. We therefore see that electricity use is the most important driver for the environmental single score impact of CM in a conventional energy scenario (see Figure 2).

After climate change, fine particulate matter formation contributes most to total impacts. Both are primarily driven by energy production and heavy industrial processes (mining and raw material processing) upstream in the globalised supply chains. If these processes take place in areas of high population density, the impacts can be significant. It is therefore important to have transparency in the supply chain.

Sensitivity analyses show that results are sensitive to medium quantity (driven by efficiency of conversion of medium into final product), lower maximum cell densities and cooling load required (for eliminating hotspots caused by metabolic heat). Process optimisation in these areas may result in significant environmental improvements.

Figure 2 – Environmental impact (ReCiPe single score) per kg CM, contribution analysis

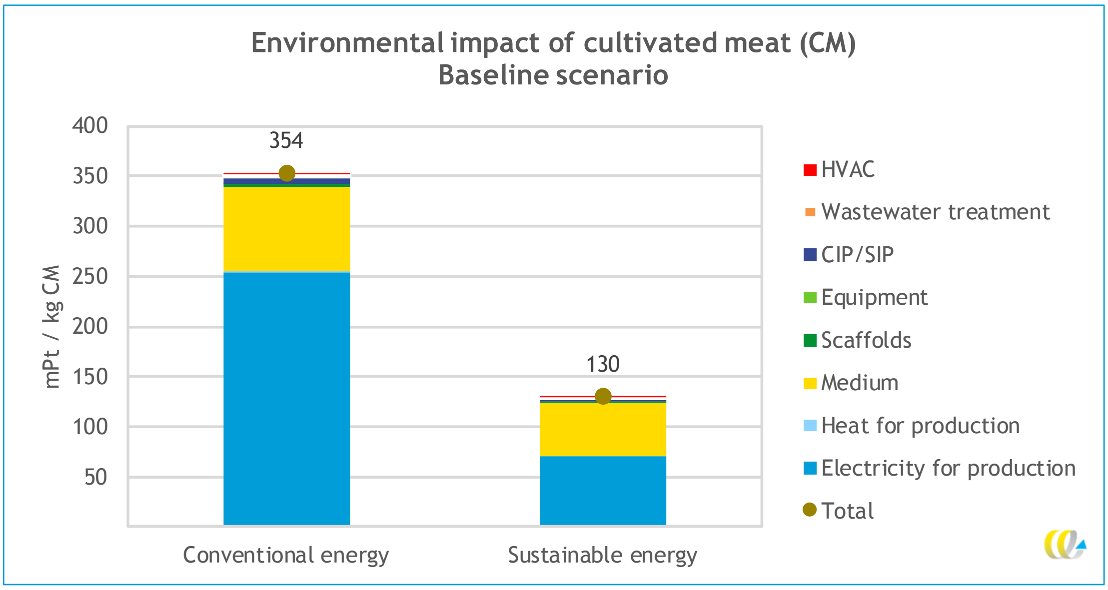
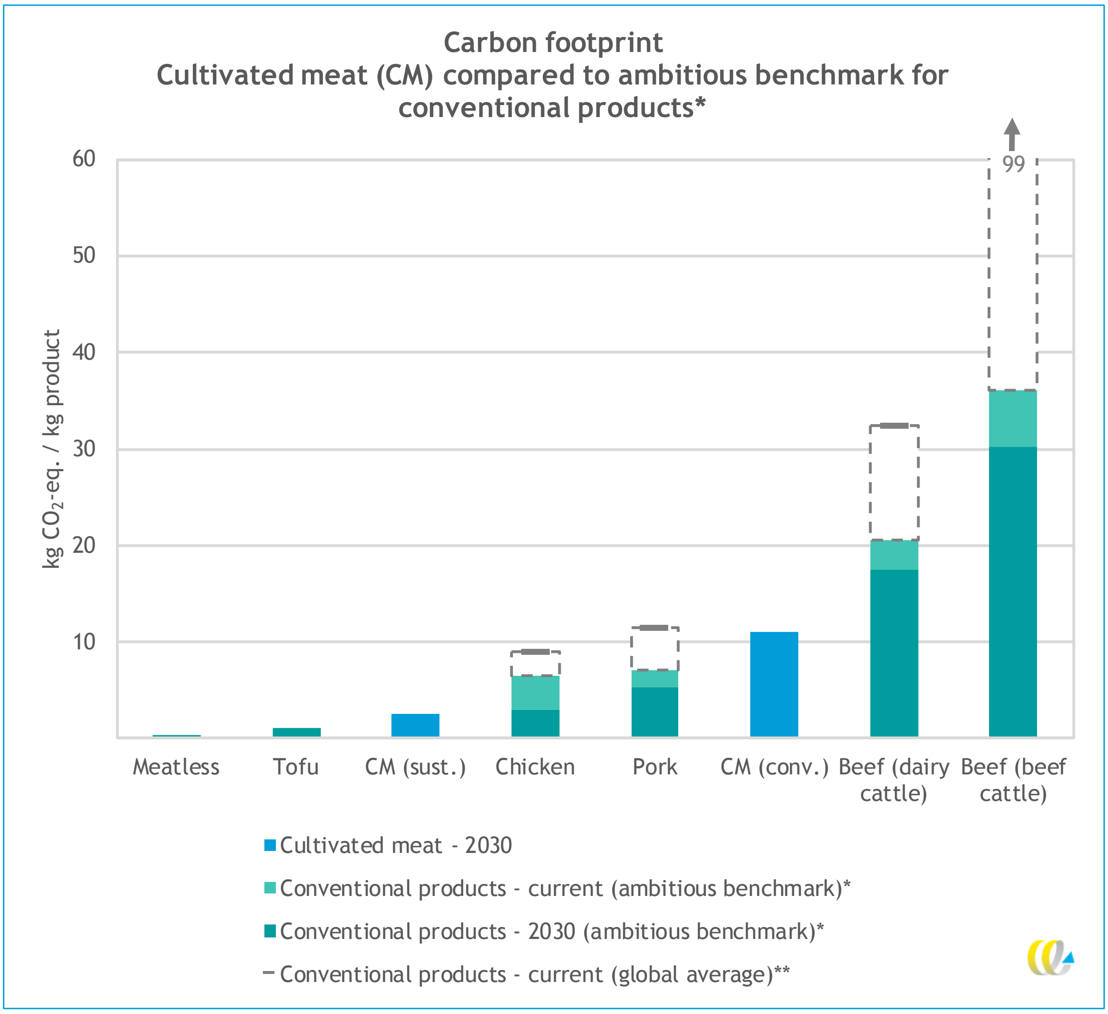


Figure 3 - Carbon footprint of CM and conventional protein products (ambitious benchmark + global average based on Poore and Nemecek 2018)



* Intensive, West-European, circular agriculture with LUC-free soy. The ‘current’ bar represents additional impacts of current production compared to the 2030 benchmark.

** Taken from Poore and Nemecek (2018).

In comparison to earlier studies (Tuomisto et al. 2014; Tuomisto and Teixeira de Mattos 2011; Mattick et al. 2015), the CFP of CM is higher in this study. This is mainly driven by the model assumption that cooling of the process takes place using active cooling. This also results in significantly higher industrial energy use than in aforementioned studies. We show however the potential benefits of using a more sustainable energy mix for production.

This study shows that CM has the potential to become a sustainable source of protein compared to most conventional meat products, and could even undercut all conventional animal meats in sustainable energy scenarios. Specific attention should thus be given towards sourcing of sustainable energy and optimising specific process characteristics regarding medium efficiency, maximum cell density and the balance of heating and cooling during proliferation.

Overlap LCA and TEA

At the same time this LCA was carried out, a techno-economic assessment (TEA) was also made (CE Delft 2021). Do conclusions overlap? Can measures to reduce environmental impact also lower costs, and vice versa? Four aspects stand out:

1. **Energy efficiency**: being more energy efficient reduces environmental impact and costs. There still are uncertainties regarding energy use for heating and cooling, and further research into e.g. energy efficient cooling and sustainable heat sources could help reduce both environmental impact and costs.
2. **Energy sources**: a switch to sustainable energy, especially electricity, substantially lowers the environmental impact. The most transparent and robust way to ensure *additional* sustainable electricity production, which actually lowers the national average environmental impact of electricity generation, is taking care of one's own sustainable electricity generation. If sustainable electricity is generated by the CM company on site, this could also mean a reduction in cost compared to either fossil or sustainable electricity purchased on the market.
3. **Medium use**: both increased medium efficiency and increasingly efficient production of ingredients can lower both costs and environmental impacts. Especially regarding certain functional ingredients: the results of the LCA and of the TEA both highlight certain specialty functional ingredients such as recombinant proteins in this regard. A reduction or a switch could mean reducing both impact and costs.
4. **Supply chain collaboration**: To reduce environmental impact and costs further, collaboration in the supply can help lower impact and costs of production of all required substances for CM production. Most notably this is important with regard to medium ingredients, but this reasoning can of course be extended to other inputs (e.g. scaffolds, filtration membranes) as well.

1 Introduction

Numerous innovative companies are currently exploring and developing methods to produce cultivated meat (CM, also sometimes referred to as cell-based meat, clean meat, cultured meat or in-vitro meat): animal cells cultivated in bioreactors, as opposed to on a farm. Conventional meat production is associated with high environmental impacts, e.g. in contribution to climate change, land use and land use change related to feed, and local air quality. Therefore, an alternative could potentially be very attractive from an environmental perspective. A prospective life cycle assessment (LCA) is the best way to explore the potential impact.

1.1 A life cycle assessment based on the latest company data

Several studies on the environmental impact of CM have been done, but there are still large uncertainties surrounding the results (for an overview, see Scharf et al. 2019). The results so far suggest that whether CM compares favourably to its conventional counterpart, largely depends on the type of conventional meat CM is compared to. Most studies suggest cell-based beef may become more environmentally friendly than conventional beef, since the latter has a high associated environmental impact. For chicken meat and pork, it is less clear how cell-based meat compares to conventional counterparts. So far, none of the studies assessing the environmental impact of CM have used primary data from multiple CM manufacturers or and from associated companies in the supply chain. Acknowledging that CM is still in development and many significant challenges exist (see e.g. Stephens et al. 2018), our life cycle assessment (LCA) uses the latest data and understanding to give the currently best possible insight into the expected environmental impact of CM when production is scaled up to commercial scales in the future.

The goal of our assessment is to get a better idea of how CM compares environmentally to different types of conventional meat, for different environmental indicators. Furthermore, the contribution of different parts of the process will be of specific interest, and how a potential range in certain inputs and outputs influences the environmental outcome.

Because the CM process is still in development, there is a degree of uncertainty regarding the results. Where possible we have included ranges and interpretation of such ranges and the uncertainties. Therefore, the results presented here should not be interpreted as ‘the truth’, but rather as a good indication and a basis to assess impact of internal and external factors, and the possibilities and focus areas for further improvement of the CM process in the future.

1.2 Clients, partners and roles

This study was commissioned by GAIA and The Good Food Institute (clients). While expertise from both organisations was relevant in the research process, CE Delft was independent in carrying out the research, and data from (CM and other) companies was not shared with the clients. Over fifteen companies (both CM developing companies and companies active in the supply chain) were involved in this project to provide data, for modelling and cross-checks. A full list of main data partners is included in Chapter 2.

1.3 Reading guide

In Chapter 2 we describe the methodology used and the process followed for data inventory and data sources. Because much of the data gathered is confidential, this report does not include a full data inventory (a summary is given in Annex A). In Chapter 3 we describe the results; we dive into the weighted score (the ReCiPe single score (Annex A), which includes eighteen environmental impact categories), and the carbon footprint of CM. We also make a comparison to conventional products. In the comparison, additional to the ReCiPe single score and the carbon footprint, we highlight the results for land use, water use and particulate matter formation. Furthermore, in Chapter 3 we elaborate on certain parts of the production process with sensitivity analyses (underlying data and assumption in Annex C). In Chapter 4 we interpret results and draw conclusions.

2 Methodology and inventory

In this chapter we elaborate on the methodology used to assess the environmental impact of cultivated meat (CM) and the process of data inventory.

2.1 Goal and scope

This study is a comparative ex-ante life cycle assessment (LCA) of cultivated meat, with a comparison to conventional protein products, both meat- and plant-based. The goal of this study is to gain insight into the environmental impact of CM, into the contribution of different processes to the impact and compare the impact to conventional protein products (meat and plant-based alternatives).

As CM is still in development, we model a future commercial scale production facility which reflects expected changes, both internally (the scaling up of CM production) and externally (e.g. share of sustainable sources in electricity mix).

In this LCA we look at cultivated meat production from cradle to facility gate. This means that all process inputs and outputs up to the meat leaving the facility are considered. This includes resource extraction, energy production that is needed to produce the cultivated meat, from all parts of the production process (including nutrition medium and production equipment) and transport between processes. For the conventional meat products and plant-based alternatives this means we look at all inputs into the agricultural processes (e.g. fertilizer and land used for feed production), transport of feed to the animal farm, emissions at the animal farm, including emissions for energy use, transport to a slaughterhouse and slaughtering.

We present the environmental impact for a non-specific type of CM. The baseline scenario considers a CM product of a meat product, cultivated around 37°C. Water-based animals can often be grown at lower temperatures, but this temperature-range is currently out of scope, as are comparisons to conventional seafood. Other model inputs, besides energy demand, are based on inventory data from both land-based and water-based animals. Because of data confidentiality, no division into different types of meat (e.g. beef, chicken) is possible at the moment, as the number of data sources per type of cultivated meat is limited. Presenting results per type, if possible (because of data availability), would therefore for some types mean presenting results for a specific company, which we do not do in this report. Therefore, the results do not represent the impact of a specific product developed by a specific CM company, and may not be interpreted as such. CM companies can use the results to gain insight into factors that may contribute (significantly) to their impact, or extract recommendations for focus areas for future exploration within their product development and for product improvement.

2.2 Functional unit

The functional unit of this study is: the production of 1 kg of high-protein product (i.e. CM, conventional meat or a plant-based meat alternative that is eaten for its high protein content)[2].

Composition and structures of different protein products may vary (slightly), e.g. in terms of water, protein and carbohydrate content, or in texture and mouth-feel.
The compositions of the CM product modelled, as well as of conventional meat products and alternatives are presented in Table 1. For CM, the final product is determined to be a ground-meat type product that has had ten days of differentiation and maturation.
This yields a product that is slightly texturized, but needs further processing into final products. This further processing into final products is out of scope, for CM as well as for conventional meat products (which often undergo further processing as well).

Table 1 - Composition of different protein products[3]

Product	Water	Protein	Carbohydrates	Other
	% of total weight			
CM	70-80	18-25	0	0-12
Beef	74	23	0	3
Pork	72	22	2	4
Chicken	74	23	0	3
Tofu	78	11	1	10
Meatless (wheat-based)[4]	50-80	10-25	1-5	10-25

2.3 Inventory

To ensure a robust model and robust results, we contacted over fifteen companies that (aim to) have a role in the CM supply chain for environmental data. These main data suppliers and their expertise to the data inventory are listed in Table 2.

Table 2 - Partnering companies and institute, and their contribution to the data inventory for the LCA

Company or institute	Expertise
A*star	Cultivated meat research institute (Avian)
Aleph Farms	Cultivated meat production (Bovine)
Avant Meats	Cultivated meat production (Fish)
Mosa Meat	Cultivated meat production (Bovine)
Shiok Meats	Cultivated meat production (Crustacean)

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[2] In the case of CM this means 1 kg of meat cells. The impact of any scaffolding material is added to the total environmental impact, but is not counted as mass for the functional unit. In this study this means that 1 kg of CM actually is 1.1 kg of 'CM-product', including 0.1 kg of edible plant-based scaffolding material. This is done in order to avoid underestimations of the environmental impact of CM because of low-impact scaffolding material skewing final results.

[3] https://nevo-online.rivm.nl/

[4] Meatless is a brand of texturized meat replacement products (high protein content). Various product types, among which the one mentioned here, are included in the Agri-Footprint LCA database. For more info: https://www.meatless.nl/. Exact composition is unknown to us, composition was based on summary of typical meat analog ingredients taken from Egbert and Borders (2006).

Company or institute	Expertise
Wild Type	Cultivated meat production (Fish)
Akron Biotech	Recombinant proteins, scaffolds, cell banking systems
Black & Veatch	Consulting engineering and design-build services
Buhler	Extrusion and feed pre-mix
Cell-trainer Biotech	Consulting engineering
Evides	Water production and treatment
Merck[5]	Cell culture media and other process related products (e.g. equipment and filters)
OSPIN	Bioreactors and tissue chambers for cell expansion and differentiation
Richcore	Recombinant proteins
Warner Advisors	Consulting engineering

Inventory data was shared confidentially. Therefore, this report does not include an extensive data inventory, but only ranges, averages and median or mode values, depending on the nature of the data. In Annexes A and C the inventory data we can share are summarized.

2.3.1 Inventory data: quality

Gathering inventory data from multiple (CM and other) companies allowed us to do cross-checks, make mass and energy balances and make a robust model. The inventory included both inquiry into the current situation, and a projection of future potential. These projections were cross-checked, and discussed with the relevant experts (from supply chain companies and research organisations). For some future projections publicly available data were used, for example for the expected global average electricity mix in 2030 (see Section 2.3.2).

A generic inventory questionnaire was sent to CM companies twice, to which most companies also responded twice. All supply chain companies listed in Table 1 were contacted with general questions, after which specific aspects of the production process were discussed further with certain experts. In general, important variables such as volume, cell density, production time, quantity of medium, medium composition, were based on the input of ~five to fifteen companies (CM and non-CM based on topic). Specific values, such as inputs for waste water treatment, energy use have mostly been determined based on the expert judgement, cross-checked by other independent experts and/or literature.
In Annex A full inventory list (not quantified) and an assessment of data quality is given.

2.3.2 Inventory data: future scenarios

As the model is based on a (hypothetical) production situation in 2030, some changes in influential internal and external factors are assessed and used for the model. An example of an external factor is the electricity mix. For the baseline scenario we have adopted two different electricity mixes:
- a conventional energy mix, in which electricity is generated based on a global average stated policies scenario for 2030 in the World Energy Outlook (IEA 2019) (for composition see Table 13 in Annex A) and heat is generated using natural gas;
- a sustainable energy mix, in which electricity is generated using on-shore wind turbines and solar PV panels (both 50%), and heat used is geothermal.

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[5] Merck KGaA, Darmstadt, Germany. https://www.emdgroup.com/en/research/innovation-center/innovation-fields/cultured-meat.html

These two 2030 energy mixes were used for the CM production process itself and for the medium production process. For electricity use further downstream, e.g. production of bioreactors and auxiliaries, current electricity mixes were used. This means the environmental footprint could be lower if electricity use is sustainably sourced throughout the supply chain.

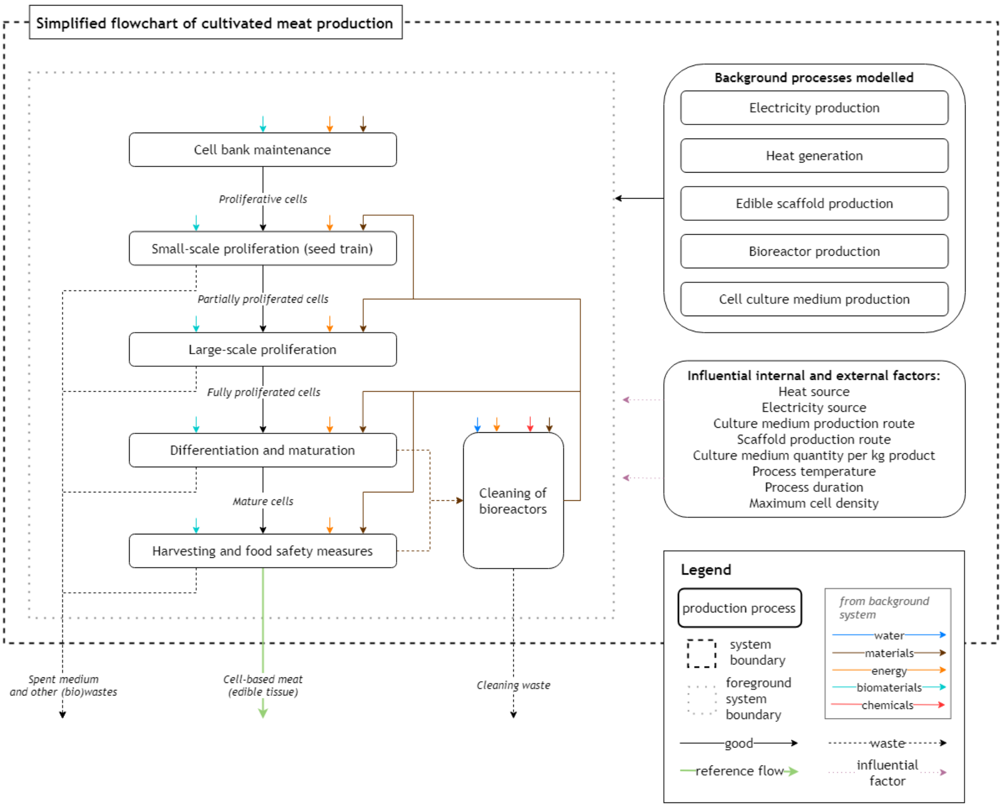
For production processes upstream, we have selected state-of-the art production processes as much as possible in the Ecoinvent database (Wernet et al. 2016). This usually means that production data is from >2005 and from industrialised countries. For some products in the upstream supply chain, there are no industrial-scale production facilities yet. In these situations, together with the companies and independent experts we have estimated increases in efficiency and expected effects of economies of scale, based on comparable effects observed in the sector. If this was not possible, we have assumed current best practice to be representative of 2030 production.

The availability and quality of data inevitably introduce uncertainties into the model, therefore we have assessed different scenarios and sensitivity analyses to estimate to which extent (ranges in) different factors influence results (see Section 2.4.3 and Section 3.3).

2.4 System and system boundaries

Figure 4 shows a simplified flowchart of the CM production process. Vials with inoculum of cell lines are stored in a cell bank. To start production, a vial is taken and the cells are multiplied in a series of bioreactors of increasing volume in a process called the seed train (small-scale proliferation). Finally the cells are moved to the largest proliferation vessel, where they multiply until maximum cell density is reached. At this point, a percentage of the total cells is removed from the proliferation reactor and seeded onto a scaffold in a perfusion reactor for differentiation and maturation. At the end of the process, the cells are harvested from the perfusion reactor and prepared for further processing by washing and centrifuging.

Figure 4 - Simplified flow chart of cultivated meat (CM) production



2.4.1 Main parameters for model (baseline scenario)

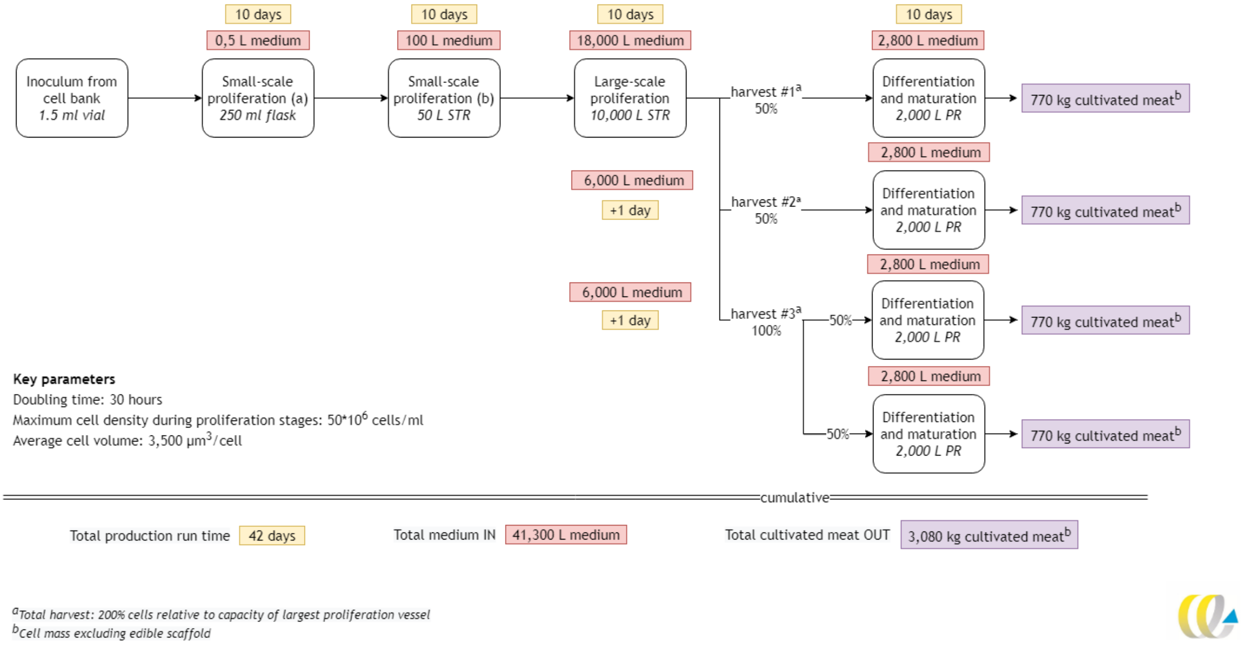
We modelled production of CM for a future situation, in which production is scaled up to a production unit of 10 kton per year. The theoretical baseline production line is described below and in Figure 5. This design of the production process is based on Specht (2020), adapted in some aspects for the purposes of this study.

The input data for the model is based on company data, as described in Section 2.3.
The baseline parameters for the model are reported in Annex A. The baseline parameters are based on representative averages, or in some cases median or mode, values (depending on the spread). It is important to note that the values used in this study do not represent any single production system and the values can therefore not be interpreted as being fully representative for the product system of any of the companies involved in providing data.

For a few parameters, variation in company data causes large uncertainties in final results, and therefore sensitivity analyses were performed (see Section 2.4.3 for elaboration).

The process (schematically shown in Figure 1) is semi-continuous with three intermediate harvests. Proliferating occurs until the largest stirred-tank reactor (STR) volume (working volume 10,000 L) is filled, at which point 50% of the cells are harvested, the medium is refilled, and cells again proliferate until maximum density is reached. This repeats a total of three times, in total ensuring 200% (relative to the largest proliferation reactor: 50% + 50% + 100%) of cells are harvested. Harvested cells are seeded onto scaffolds in perfusion reactors (PR). This production line has a total of 4 PRs (working volume 2,000 L, each containing 50% of the harvest) installed in parallel[6]. After each production run (for the 10,000 L STR this is twelve days, for each of the PR this is ten days) the reactors are cleaned using a clean-in-place and steam-in-place (CIP/SIP) system. The total production time from cell vial to harvest is 42 days. Around 130 of these production lines are assumed to be operating in parallel to meet the demands of 10 kton annually set forth in the study.

Figure 5 – Baseline production line, semi-continuous with three intermediate harvests



2.4.2 Conventional protein products

In this assessment, we compare the results for CM with conventional protein products. In Table 3 the conventional protein products which are used in the comparison are listed, as well as the basis (database and process) for the assessment of their impacts.

We note an important aspect related to system boundaries of the intensive animal production systems. For pork and chicken, manure application in agriculture and corresponding emissions are not included in the model. In circular agriculture, with an intensity (number of farms) that fit the local and regional environmental boundaries, manure is considered a valuable resource. Emissions in the agricultural phase are allocated to the agricultural product for which the manure is used as a fertilizer. It is important to note that the value of manure depends on the local situation; in regions with a nitrogen surplus, manure becomes a waste stream, as is the case in the Netherlands. For beef (cattle and dairy) manure application is included in the model, for which an extensive system is assumed where all manure is used on grassland within the system boundaries of the farm.

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[6] The perfusion systems modelled in this study do not yet exist and the cultivated meat industry will have to innovate over the next decade to develop cost-effective perfusion systems tailored for meat production. Areas of focus may include automated, adaptive control of feeding and perfusion rates that limit the formation of nutrient and oxygen gradients, incorporation of scaffolding, and automated media recycling and cell harvesting systems.

We also included two vegetable protein products: tofu and meatless. First, because vegetable protein products are also alternatives to meat when looking for more sustainable sources of protein. Second, because products like meatless can, similarly to CM, be used in hybrid products (with conventional meat or CM). There are therefore included to show a more complete picture.

Changes in production systems, which may have an effect on environmental impact, are possible. To make sure we include such changes, and present a fair comparison to CM, a number of changes were made to the conventional processes to present an ambitious 2030 benchmark. These changes are not meant to be interpreted as a projection.

Box 1 – Rationale ambitious benchmark conventional products and system perspective

We chose an ambitious benchmark to make sure that no unfair advantage is given to CM; if CM is presented as an environmental solution, it needs to be able to compete environmentally with the conventional meat products which have a relatively low environmental impact. This also means that the potential environmental benefits of CM shown here, are minimum benefits; compared to 'global average production' environmental benefits are larger.

The footprints for conventional products presented here are not meant as a projection, certainly not of global average footprints. In our opinion they represent the low end (footprint-wise) of optimized intensive production in 2030 in West-European countries, in case of a circular agricultural system.

Important to note here is that not all sustainability issues are included in LCA, some of which are particularly interesting when considering animal products; e.g. soil health, odour and animal welfare. We also stress that looking at environmental impact of products is not the only indicator of sustainability of this sector. Also, the local situation, and the intensity of the system (number of producers in an area) is important; emissions of particulate matter, odour, acidification and eutrophication are more of a problem in areas with higher population, with higher background concentrations of these emissions and therefore also in areas with numerous producers generating these emissions.

Methane emission from enteric fermentation contributes significantly to the carbon footprint of beef products. Food additives have been developed that claim a reduction of methane emissions from enteric fermentation, of up to 30%[7]. To our knowledge, these claims are not yet robustly substantiated in field tests and literature, and therefore we have modelled a reduction of 15%, with an addition to feed of 1.5 grams of enzymes per day. Electricity and heat used for production of these enzymes is modelled as sustainable.

For pork and chicken (and to a much lesser extent beef) the inclusion of e.g. soy products contributes significantly to the carbon footprint and to loss of biodiversity, through land use change (LUC). For soy, **certification of LUC-free soy** has been around for a while[8].
For all feedstuffs, it was therefore assumed possible that LUC associated with soy will be zero in 2030 (both in m^2a and in kg CO_2).
Energy (electricity and heat) is used in numerous processes throughout the meat (and meat alternatives) production chains. In the comparison with CM, it was assumed that all electricity and heat is from a similar source (same environmental impact) as in the **sustainable energy** scenario for CM.

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[7] https://www.dsm.com/corporate/solutions/climate-energy/minimizing-methane-from-cattle.html#:~:text=Just%20a%20quarter%20teaspoon%20of,the%20cow's%20normal%20digestive%20system

[8] The Round Table on Responsible Soy was founded in 2006. https://responsiblesoy.org/sobre-la-rtrs?lang=en

For cattle (beef and dairy), emission of ammonia (NH_3) contributes substantially to the environmental single score result. With additional outdoor grazing, ammonia emissions can be reduced. **Outdoor grazing** is already included, for example for dairy cattle based on the average grazing in the Netherlands. The ammonia emissions modelled for Ireland (beef) are a little higher. For both, 50% of the difference between the Dutch average and the required amount for organic production, in hours of outdoor grazing per year, was included as a potential reduction of ammonia emissions (based on Hoving et al. (2014)). This translates to a reduction of ammonia emissions by 5.4%.

The changes presented here results in an environmental single score which is 6% (beef), 11% (pork), and 25% (chicken) lower, and a carbon footprint which is 15% (beef), 26% (pork) and 53% (chicken) lower for the 2030 benchmark.

Table 3 - Choice for ambitious benchmark for conventional products (intensive, West-European, circular agriculture, LUC-free soy), their source for the impact assessment, and the adjustments made to reflect changes in production systems in 2030

Product	Based on database and process	Adjusted for
Beef (beef cattle)	Agri-footprint: Beef meat, fresh, from beef cattle, at slaughterhouse, PEF compliant/IE Economic	– Methane emissions from enteric fermentation: -15%, additional input: enzymes. – Additional outdoor grazing resulting in ~5.4% lower NH_3 emissions. – Sustainable energy (electricity and heat) at farm and in feed compound production and soybean production.
Beef (dairy cattle)	Agri-footprint: Beef meat, fresh, from dairy cattle, at slaughterhouse, PEF compliant/NL Economic	– Methane emissions from enteric fermentation: -15%, additional input: enzymes. – Additional outdoor grazing resulting in ~5.4% lower NH_3 emissions. – Sustainable energy (electricity and heat) at farm and in feed compound production and soybean production.
Pork	Agri-footprint: Pig meat, fresh, at slaughterhouse/NL Economic	– No LUC or associated GHG emissions related to soy in feed. – Sustainable energy (electricity and heat) at farm and in feed compound production and soybean production.
Chicken	Agri-footprint: Chicken meat, fresh, at slaughterhouse/NL Economic	– No LUC or associated GHG emissions related to soy in feed. – Sustainable energy (electricity and heat) at farm and in feed compound production and soybean production.
Tofu	Ecoinvent: Tofu [CA-QC]| production | Cut-off	– No LUC or associated GHG emissions related to soy. – Sustainable energy (electricity and heat) at production facility and for soybean production.
Meatless (wheat-based)	Agri-footprint: Meatless, hydrated (wet), wheat based, at plant/NL Economic	– Sustainable energy (electricity and heat) at production facility.

2.4.3 Sensitivity analyses

As the technology is still under development and companies pursue different final products for a range of species, there is a lot of uncertainty in the results. While the production process generally is the same across these companies, details may vary. The baseline scenario is based on average, or sometimes median, values derived from the questionnaires. Where variation in influential parameters was observed, sensitivity analyses were conducted in order to provide insight into the different process designs. Companies can compare the results of the baseline scenario with those of the sensitivity analysis in order to estimate the environmental profile of their own production process.

The sensitivity analyses performed are the following:

- **Production run time:** Can be longer or shorter depending on doubling time (during proliferation stages) and the desired level of maturity of the cells in the final product.
- **Maximum cell density:** During proliferation stages the cell density can be higher or lower depending on e.g. cell type or reactor type.
- **Cell volume**: The cell volume can be smaller or larger, depending on species type and cell type.
- **Efficiency of medium use**: Ingredients can be used more or less efficiently, influencing both inputs (amount of nutrients needed) and waste output.

The variation of model parameters for these scenarios is described in Annex C. The results are reported in Section 3.3.

An important difference between companies that is assumed not to lead to significant differences in results is the difference between water-based and land-based species. In this study it was not possible to reliably quantify the implications for the environmental profile. The topic is however discussed qualitatively below.

2.4.4 Process temperature and difference between water-based and land-based species

There are a few important differences related to heating and cooling demand in cell cultivation of land-based and water-based species. First, the temperature at which the process has to be maintained is lower for water-based species (15-30°C) than for land-based species (around 37°C) (Krueger et al. 2019). Second, the acceptable temperature range is generally larger for water-based species than for land-based species, meaning they are less sensitive to overheating and to the formation of temperature hot spots in the reactor. Third, metabolic processes may differ significantly, resulting in different energy expenditure dynamics and variation in metabolic heat produced.

Based on our data it was not possible to sufficiently determine differences in metabolic heat produced. The aforementioned differences suggest that water-based species production systems have a lower energy demand, both from lower heating demand and lower cooling demand. Further analysis with more specific process data will have to shed more light on this topic.

2.5 LCA method

There are two types of LCA assessment: attributional and consequential. In an attributional analysis one assesses the impact of realisation of the functional unit and does not consider (environmental) impacts on the overall economy if the product or service under assessment would replace the current situation. In a consequential assessment, such considerations are taken into account. This increases the number of variables and the uncertainty of results. In this study an attributional approach was chosen, because we are looking at a product under development, which already has its own internal and external variables and uncertainties. Furthermore, because an important part of the promise of CM is the potential reduction in environmental impact, it is important to start with a clear and transparent assessment of that impact.

2.5.1 Software, databases and impact assessment method

The LCA was modelled in the LCA software SimaPro. The LCA database Ecoinvent 3 (Wernet et al. 2016), version 3.6 (allocation cut-off by classification), was used for most background processes in the CM model. For some of the biobased ingredients in the medium (maize solubles and soy), the conventional products and the plant-based alternatives the Agri-footprint database (Durlinger et al. 2017) was used (version 4.0, economic allocation). The impact assessment method used is ReCiPe World H/A. The ReCiPe method is described in more detail in Annex A.

2.5.2 Environmental impact categories

Food products (or bio-based products in general) are associated with a wide range of environmental impacts. Not only an impact on climate change, but also e.g. land use, particulate matter formation and water use. Because an important part of the CM production process is medium production, based on bio-based ingredients, assessing a set of impact categories is also important when assessing CM. Therefore, we look at the ReCiPe single score, which includes the eighteen impact categories listed in Table 4. We call this the ‘environmental single score’ throughout the report. This way we make sure that we have insight into potential shifting of burdens (from one category to the other). The results on these impact categories reflect potential impacts. For most of these categories, actual impacts depend on the local or regional situation, except for global warming. Therefore, for CM companies who want to minimize their impacts for future production locations, assessing the local situation is important (e.g. is this a water scarce region?), and implementing procurement criteria (e.g. sustainable/no-LUC soy and sustainable energy).

Table 4 – Impact categories, and corresponding units, included in ReCiPe method

Impact category	Unit
Global Warming	kg CO_2-eq.
Stratospheric ozone depletion	kg CFC11-eq.
Ionizing radiation	kBq Co-60-eq.
Ozone formation, Human health	kg NO_x-eq.
Fine particulate matter formation	kg $PM_{2.5}$-eq.
Ozone formation, Terrestrial ecosystems	kg NO_x-eq.
Terrestrial acidification	kg SO_2-eq.
Freshwater eutrophication	kg P-eq.
Marine eutrophication	kg N-eq.
Terrestrial ecotoxicity	kg 1,4-DCB-eq.
Freshwater ecotoxicity	kg 1,4-DCB-eq.
Marine ecotoxicity	kg 1,4-DCB-eq.
Human carcinogenic toxicity	kg 1,4-DCB-eq.
Human non-carcinogenic toxicity	kg 1,4-DCB-eq.
Land use	m^2a crop-eq.
Mineral resource scarcity	kg Cu-eq.
Fossil resource scarcity	kg oil-eq.
Water consumption	m^3

3 Results and interpretation

In this chapter we present the LCA results. We first focus on the CM production system in Section 3.1: we start with the impact on the ReCiPe (environmental) single score in Section 3.1.1, then elaborate on the carbon footprint in Section 3.1.2. In Section 3.2 we focus on a comparison between CM and different protein products, again zooming into environmental single score results (Section 3.2.1) and the carbon footprint (Section 3.2.2). Furthermore, we show the results for three additional impact categories: particulate matter formation, land use and water use. In Section 3.3 we present sensitivity analyses in which we explore a range of potentially influential parameters on the environmental performance of CM.

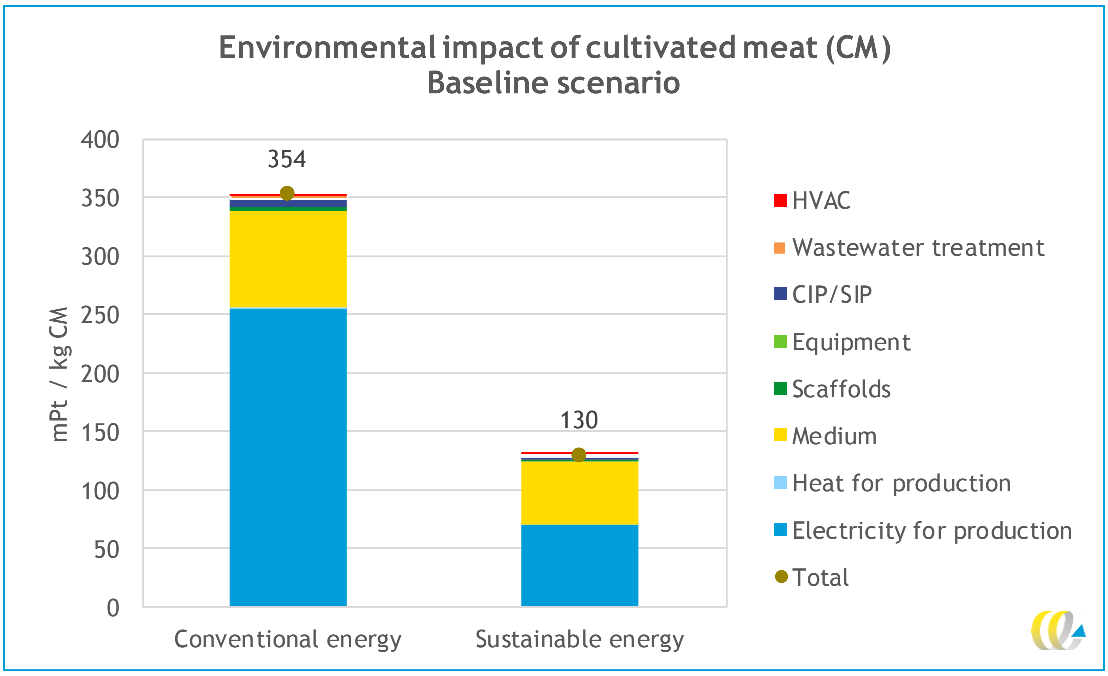
3.1 Cultivated meat production system – baseline scenario

In this section we explore the results of the baseline scenario (see Annex B for key parameters); commercial scale production of CM in 2030. In each figure, results of CM production with a conventional energy mix (global average stated policies scenario for 2030 (IEA 2019) and sustainable energy mix are presented (see Section 2.3).

3.1.1 Environmental single score results

In Figure 6 the environmental impact, in environmental single score (ReCiPe), is presented, both for the scenario in which conventional energy is used and the scenario in which sustainable energy is used. In the conventional energy system, the main drivers for environmental impact are electricity use during production, and medium production.
The energy production system offers a large reduction in environmental footprint compared to the conventional energy production system. For the sustainable energy scenario, electricity and medium production have roughly the same impact.

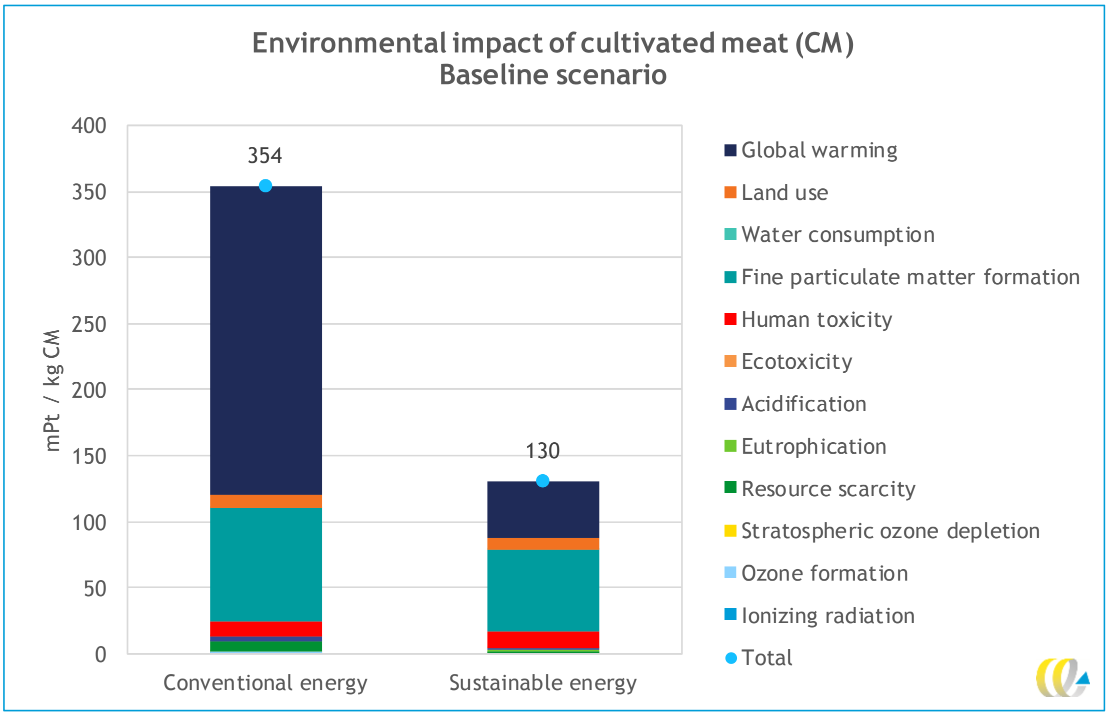
Figure 6 - Environmental impact (ReCiPe single score) per kg CM, contribution analysis processes



In Figure 7, the contribution of the different impact categories (e.g. climate change, land use) is presented for both the conventional energy scenario and the sustainable energy scenario. The main contributors to environmental single score impacts are climate change and fine particulate matter formation, followed human toxicity and land use. Impacts of fine particulate matter formation are highly dependent on geographical characteristics. If these processes take place in areas of high population density, the impacts can be significant.

The main drivers for the carbon footprint are discussed in Section 3.1.2. The main driver for fine particulate matter formation is electricity generation in the conventional energy scenario. In the sustainable energy scenario the drivers are raw material mining and processing for energy infrastructure and the production of feedstock ingredients (such as soybeans and maize) for medium ingredient production. Human toxicity impacts are primarily driven by mining and raw material processing for electricity production and infrastructure in both systems, followed by fertilizer and pesticide use in medium feedstock production. Eventually, most of these impacts can be traced back to heavy industrial processes (mining, raw material processing or other energy-intensive activities) far upstream in the globalised supply chains.

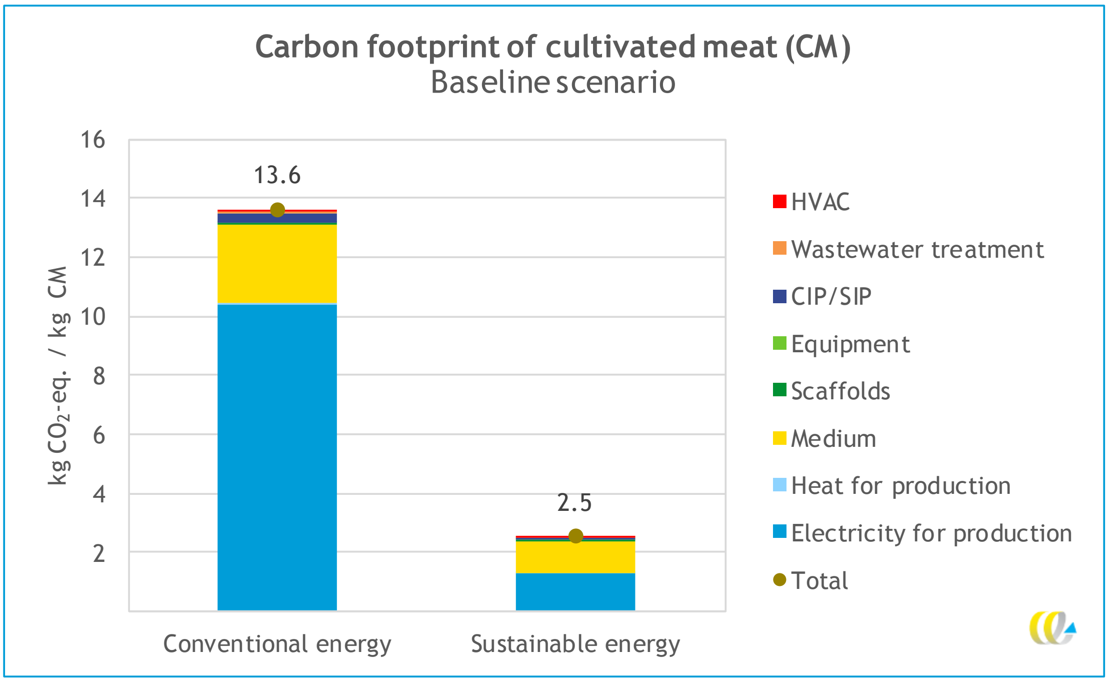
Figure 7 - Environmental impact (ReCiPe single score) for CM, contribution analysis impact categories



3.1.2 Climate change

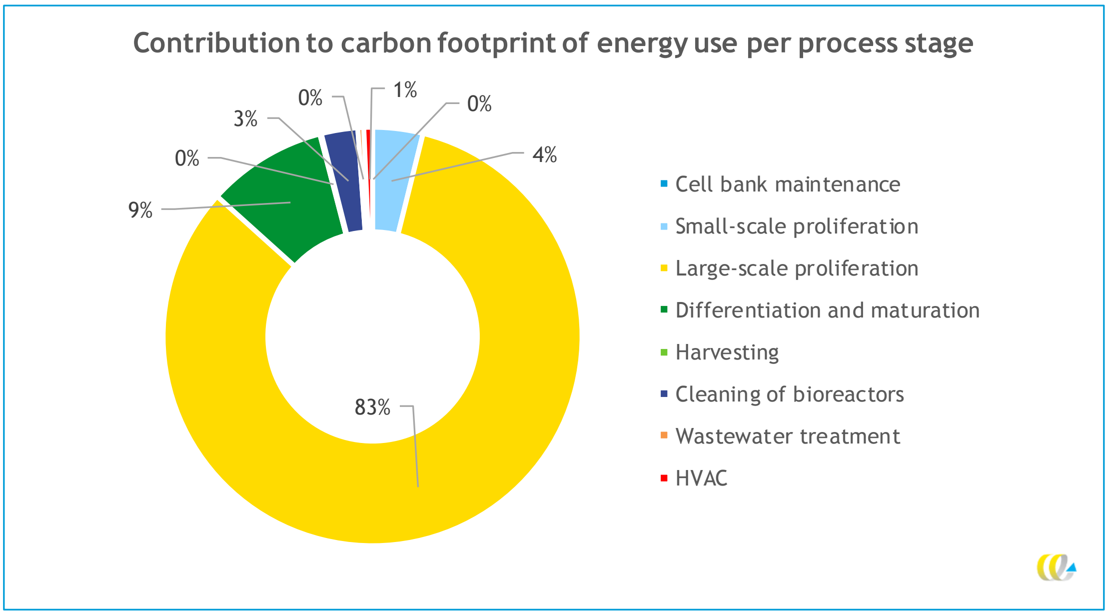
Figure 8 presents the carbon footprint of 1 kg of CM production. In the conventional energy scenario, this carbon footprint is ~14 kg CO_2-eq./kg CM. In the sustainable energy scenario, this drops to ~2 kg CO_2-eq./kg CM meat. The main driver for the carbon footprint in the conventional energy scenario is electricity use during production, followed by the production of medium ingredients. A significant reduction in carbon footprint can be achieved by decarbonising the energy mix. In the (upstream) production of medium, reductions that can be achieved by decarbonisation are smaller because a part of the carbon footprint there is caused by the agricultural production of the feedstock and chemicals used during production of the medium ingredients, which rely on heavy industrial processes, that are harder to decarbonise. Scaffolds (assumed in this study to be in the form of a hydrogel), equipment, wastewater treatment and HVAC of the facility make up a relatively minor part of the carbon footprint (total of < 2%).

Figure 8 - Carbon footprint of CM



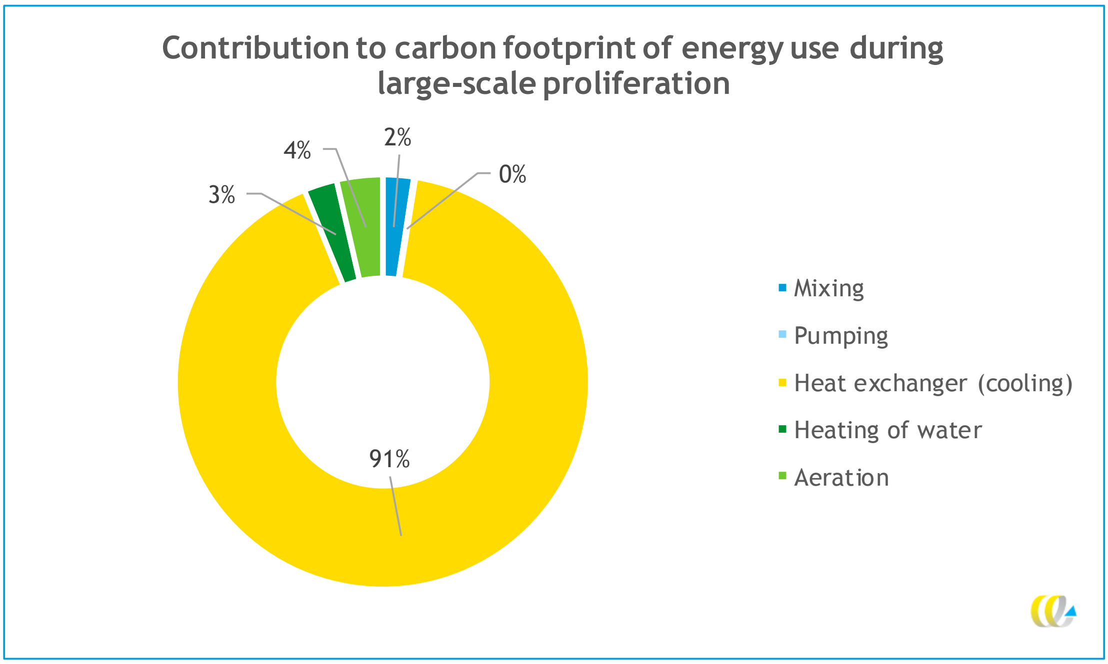
Zooming into the carbon footprint of energy use during production, the main driver is large-scale proliferation, followed by differentiation and maturation, as shown in Figure 9.

Figure 9 - Electricity use per process stage, % of total



During large-scale proliferation, the main driver for electricity use is the heat exchanger (94%) delivering a cooling load to the bioreactor to avoid overheating (Figure 10). In this study, we have assumed that active cooling of the cooling fluid is necessary. This is a different assumption from Mattick et al. (2015), where cooling was modelled using ambient temperature cooling water. This assumption has a large influence on the results.
While metabolic heat production of animal cell cultures is lower than for e.g. bacteria, especially at low cell densities, the cultures are sensitive to overheating. Therefore our current model design incorporates a stand-by cooling load for cooling down rapidly, mitigating heat inhomogeneity, or eliminating temperature hotspots. This especially seems to become more important for large-scale cultures (Li et al. 2020). How much heating or cooling large-scale cell cultures need is highly dependent on various factors, such as cell densities, oxygen uptake rates (OUR), glucose consumption and type and volume of the bioreactors.

Figure 10 - Electricity use for large-scale proliferation, % for different parts of the process



3.2 Comparison to conventional products

In this section we compare results for CM with results of our ambitious benchmark for conventional products; intensive, West-European, circular agriculture with LUC-free soy, see Section 2.4.2 for full elaboration. For more context, results for the environmental single score are also shown adjusted for the global average carbon footprint (based on Poore and Nemecek 2018). Results for the carbon footprint are also shown for the current global average footprint (Supplementary Materials to Poore and Nemecek 2018).

3.2.1 Environmental single score results

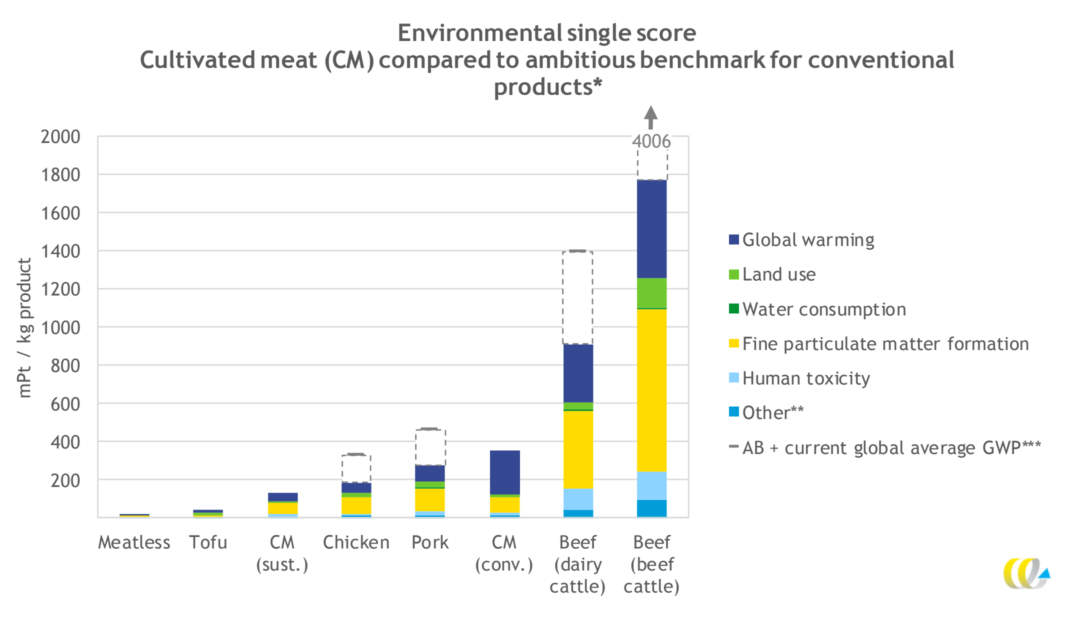
Looking at the environmental single score results (Figure 11), in all cases CM compares favourably to beef meat from both specialised beef cattle and dairy cows. Compared to beef meat from dairy cows, the difference is smaller, due to a large part of the environmental impact being allocated to milk production.

Differences between CM and chicken or pork are smaller, and highly dependent on the energy mix selected for CM production, as the energy mix is an important driver for both climate change and fine particulate matter formation. While pork and chicken have lower carbon footprints than CM in the conventional energy scenario, land use and fine particulate matter formation contribute to a greater extent to the impact of animal production systems. In case of a sustainable energy scenario for CM, it scores lower than both chicken and pork on the environmental single score.

In Figure 11 results for the environmental single score adjusted for the global average carbon footprint of these products is also shown, in grey. Adjustments for other environmental impact categories could not be done, due to differences in methodology. As can be seen in the figure, conventional energy CM scores comparable to the adjusted single score for chicken, and lower than pork and beef.

In all cases, CM has a higher environmental footprint than plant-based alternatives tofu and wheat-based meatless (a textured plant-based product). This is due to the relatively high environmental impacts of upstream industrial processes and energy-intensive production in the CM supply chain.

Figure 11 - Environmental impact (ReCiPe single score) of CM and conventional protein products (ambitious benchmark and ambitious benchmark adjusted for global average score on global warming)



* Intensive, West-European, circular agriculture with LUC-free soy.

** 'Other' includes 14 impact categories, among which other toxicity categories, acidification and resource depletion. A complete list can be found in Annex A.

*** Current global average carbon footprint taken from Poore and Nemecek (2018). All other impact category scores are identical to the ambitious benchmark.

Table 5 shows the environmental impact for CM in a sustainable energy scenario set to 100% (third column). In the second column, the contribution of the impact category to the total environmental single score of CM from the sustainable energy system is shown, showing the relative importance of different environmental impact categories. Fine particulate matter formation (47%), global warming (33%), human toxicity (10%) and land use (6%) contribute most to the environmental single score of CM in a sustainable energy scenario.

Table 5 - Impact of protein products (ReCiPe single score - ambitious benchmark) relative to CM - sustainable energy, for different impact categories

Impact category	% of single score of CM (sust.)	CM (sust.)	CM (conv.)	Beef (beef cattle)	Beef (dairy cattle)	Pork	Chicken	Tofu	Meatless
Fine particulate matter formation	47%	100%	140%	1,400%	671%	197%	142%	20%	10%
Global warming	33%	100%	539%	1,198%	694%	209%	121%	38%	17%
Human toxicity*	10%	100%	94%	1,191%	880%	187%	98%	11%	16%
Land use	6%	100%	109%	1,892%	526%	361%	274%	107%	12%
Other**	4%	100%	262%	1,830%	843%	259%	165%	26%	30%

* CM (conv.) has a lower human toxicity score than CM (sust.) due to relatively high toxic emissions during mining and raw material processing in the supply chains of wind and solar PV energy.

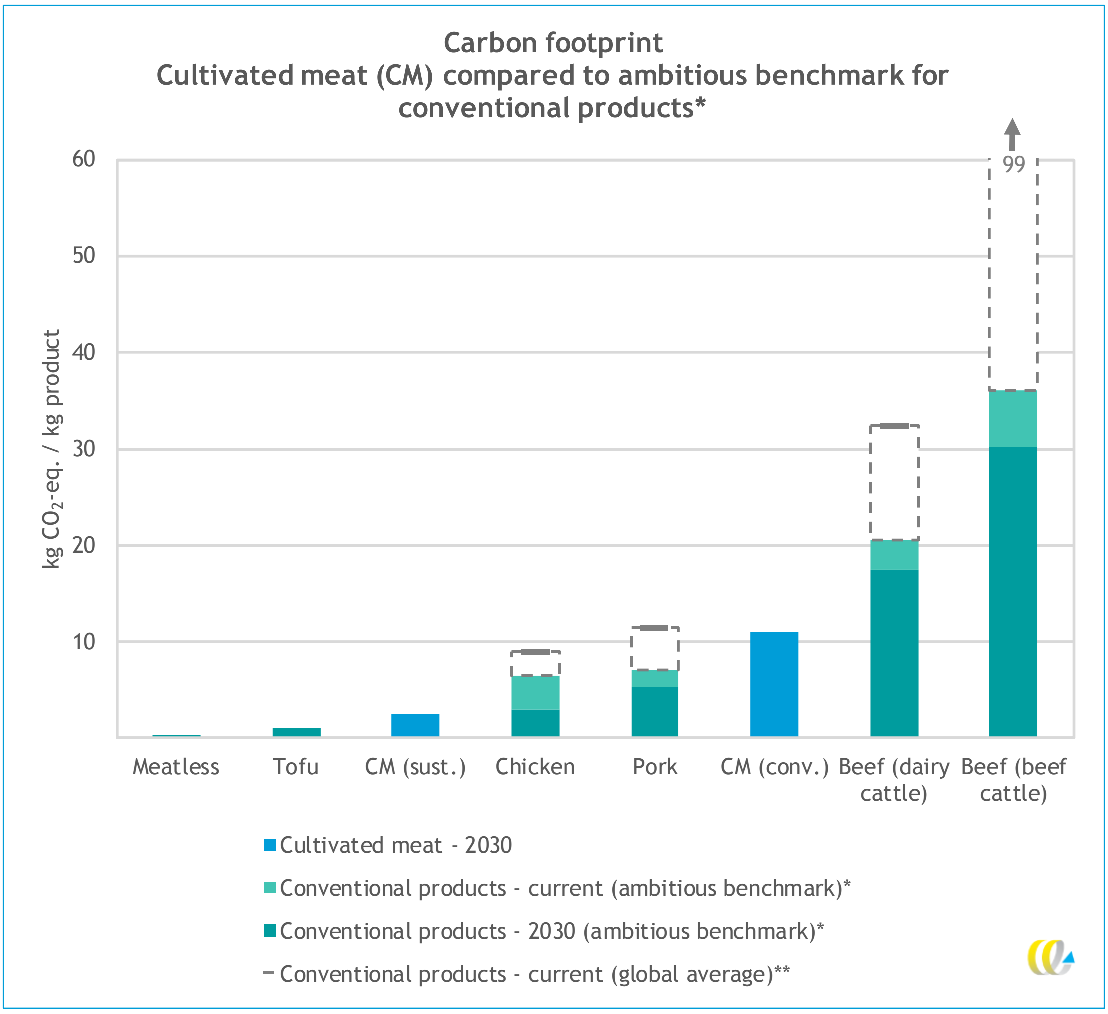
** 'Other' includes 14 impact categories, among which other toxicity categories, acidification and resource depletion. A complete list can be found in Annex A.

The production of CM in a sustainable energy scenario compares favourably to beef, pork and chicken meat and CM in a conventional energy scenario on all relevant impact categories. The plant-based alternatives compare favourably to CM on all impact categories, except in the case of land use impacts of tofu, for which CM scores better in the sustainable energy scenario.

3.2.2 Climate change

In comparison to other protein-rich products, the carbon footprint of CM production falls in the spectrum between beef cattle meat and plant-based meat alternatives. Depending on the grade of decarbonisation of energy production, it compares either favourably or unfavourably to chicken and pork meat. This is shown in Figure 12. In Section 2.4.2, Table 3, the adjustments made to the current ambitious benchmark, to achieve the 2030 ambitious benchmark, are elaborated on. Most importantly, a shift tot sustainable energy is made throughout the supply chain and LUC-free soy is used in the feed mixes.

Figure 12 - Carbon footprint of CM and conventional protein products (ambitious benchmark + global average based on Poore and Nemecek 2018)



* Intensive, West-European, circular agriculture with LUC-free soy. The 'current' bar represents additional impacts of current production compared to the 2030 benchmark.

** Taken from Poore and Nemecek (2018).

As stated in Chapter 2 on methodology and inventory, the basis for the comparison chosen here is ambitious. The carbon footprints of meat products vary wildly on a global level. As Poore and Nemecek present (Poore and Nemecek 2018), the ninetieth percentile GHG emissions of beef (90% of results fall within this range) are 105 kg CO_2-eq. per 100 grams of protein. As the researchers assume a protein content of 20%, that translates to a carbon footprint of ~210 kg CO_2-eq. per kg beef (beef cattle), which is almost seven times the footprint of beef cattle in our ambitious benchmark. The mean carbon footprints presented by Poore and Nemecek are (per kg of meat[9]): around 100 kg CO_2-eq. for beef cattle, almost 40 kg CO_2-eq. for lamb and mutton, around 30 kg CO_2-eq. for dairy cattle, a little over 14 kg CO_2-eq. for pig meat and around 11 for poultry meat (Poore and Nemecek 2018). For all meat categories, the low end of the carbon footprints presented by Poore and Nemecek is

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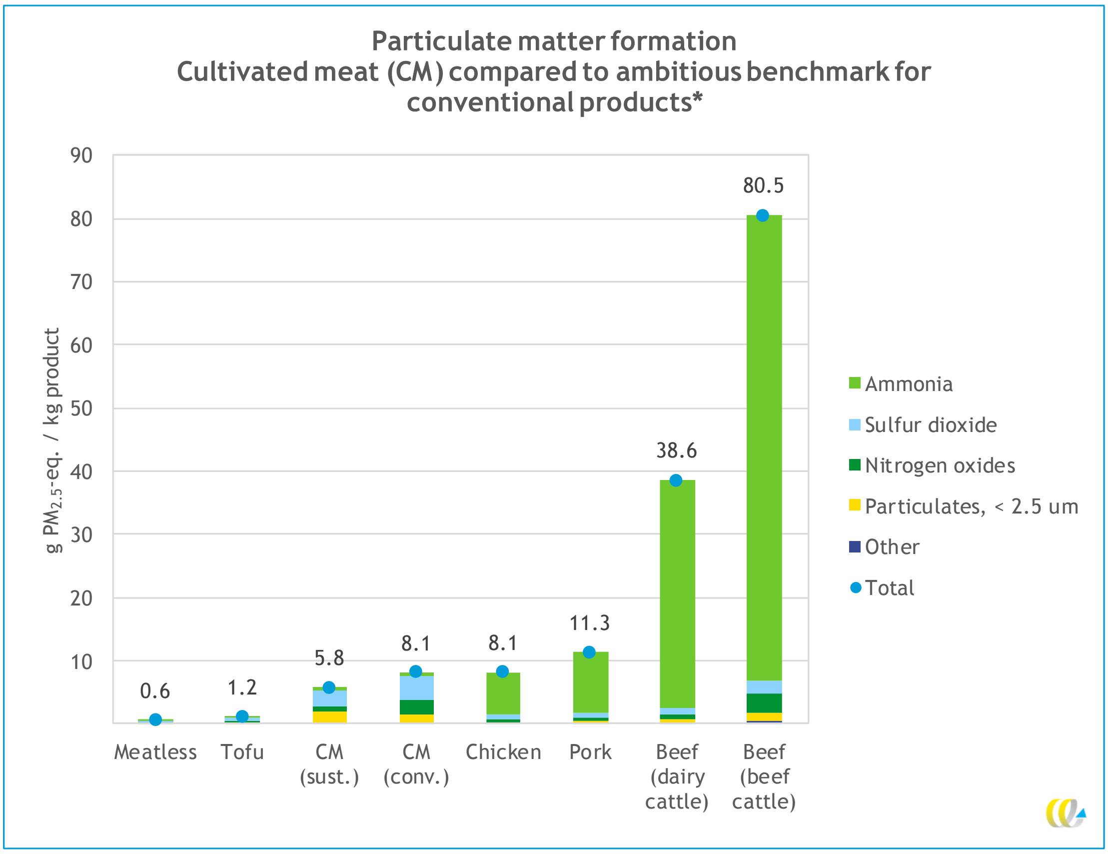
[9] Per 100 grams of protein: around 50 kg CO_2-eq. for beef cattle, 19 kg CO_2-eq. for lamb and mutton, 15 kg CO_2-eq. for dairy cattle, little over 7 kg CO_2-eq. for pig meat and 5,5 for poultry meat (Poore and Nemecek 2018).

still higher than the carbon footprints we present in our ambitious benchmark, which illustrates the level of ambition we set for the comparison. It also corroborates the conclusion that CM, even with non-renewable energy, has a lower carbon footprint than beef (cattle or dairy). And furthermore, that CM can compete on carbon footprint with the global average footprints for chicken and pork presented by Poore and Nemecek, if > 30% of energy use is sourced sustainably.

3.2.3 Other impact categories: land, water and fine particulate matter

In this section we highlight three additional impact categories: particulate matter formation, land use and water use. Figure 13 shows the results for particulate matter formation for the two CM scenario's and conventional meat and vegetable protein products. Three things stand out. First, the difference in emission contributing most to the score: for meat products this is ammonia, for CM it is a mix of sulphur dioxide, particulates and nitrogen oxide (which are mainly related to energy use in the background processes). Second, CM results are lower for the sustainable energy scenario, and lower or equal for the conventional energy scenario. Third, while CM scores relatively good compared to pork, possibly good compared to chicken, and definitely good compared to beef, the vegetable protein sources score much better still.

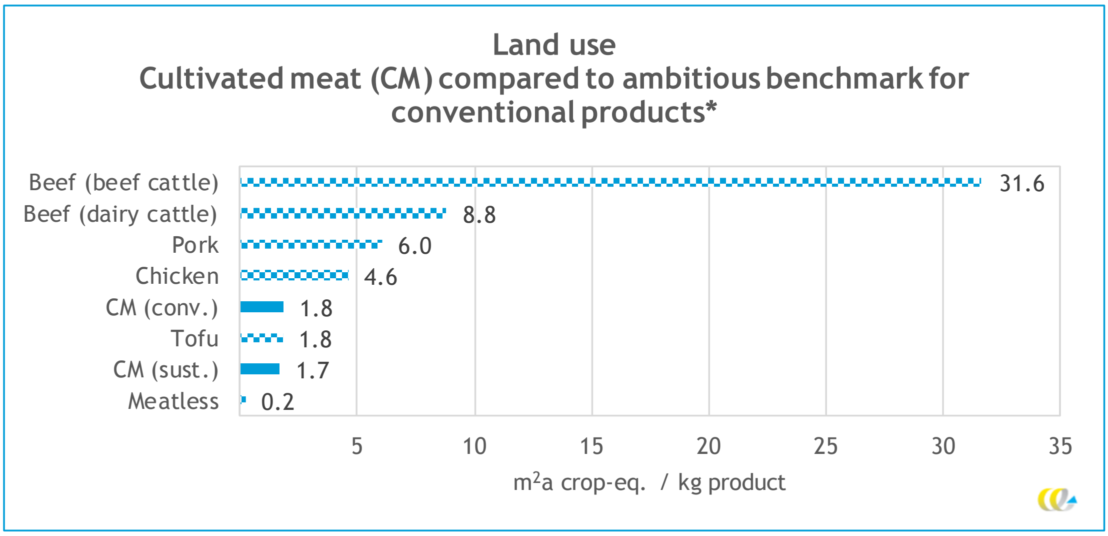
Figure 13 – Comparison of CM to conventional products (ambitious benchmark) of particulate matter formation



* Intensive, West-European, circular agriculture with LUC-free soy.

In Figure 14 and Figure 15 land use and water use (blue water) of cultivated meat and the conventional products are presented. When we look at land use, CM scores much better than all meat products, and comparable to tofu.

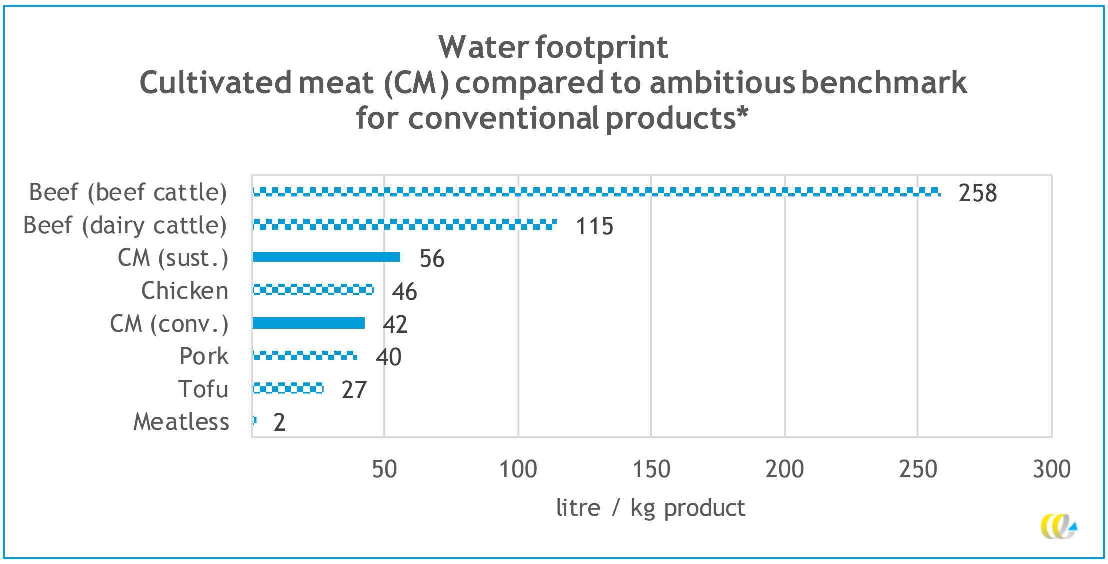
Figure 14 - Land use of CM and conventional products (ambitious benchmark)



* Intensive, West-European, circular agriculture with LUC-free soy.

For the assessment on water use, it is important to note that this assessment only included blue water, which contributes to scarcity (not green water (rain) which does not).
The methods to assess the impact of water use in LCA are in development, especially when it comes to including scarcity, but are unfortunately far from perfect. Because scarcity depends on location, we present water use here and note that the effects of water use differ substantially from region to region, depending on scarcity. When we look at the results for water use, shown in Figure 15, CM, chicken and pork have similar scores, which are much lower than those for beef. What stands out though, it that for CM the result for a sustainable energy scenario is higher than the result for a conventional energy scenario. The additional water use for sustainable energy can be traced back to the production of electronics-grade silicon in the model (solar cells). While this is a water-intensive process, a study by Lohrmann et al. (2019) concluded that water use per MWh is drastically lower for PV, compared to coal and nuclear energy. Therefore, these results are probably in part based on out-dated inventories of the supply chain, and we therefore recommend using these results as a guideline.

Figure 15 - Water use (blue water) of CM and conventional products (ambitious benchmark)



* Intensive, West-European, circular agriculture with LUC-free soy.

3.2.4 Feed conversion

For inputs (e.g. soy, maize), CM will be dependent on conventional agriculture. Looking at the ‘feed conversion ratio’ (total input per output) helps understand how this dependence for CM is compared to conventional protein products. In Table 6 the inputs (quantities) in terms of feed and other resources are listed for CM and the conventional protein products.

CM is highly efficient in terms of resource utilisation, compared to all animal products and especially compared to beef. As compared to the conventional products, CM does have chemical inputs, mainly chemicals used for amino acid and recombinant protein production. Some of these are fully consumed, but some of these are not consumed and could theoretically be recycled in the downstream supply chain. Since this is currently hard to quantify, we choose to adopt a conservative approach and assume all inputs are consumed, and add the amounts of the chemicals to the conventional ‘feed’ inputs.

With similar agricultural practices for feed production as for input production for CM, a lower feed conversion most likely translates into lower land use, lower water use, lower pesticide use. For all products, more sustainable sourcing can help reduce the environmental impact of inputs.

For beef, the total as presented in Table 6 excludes grass (fresh and silage), which are mentioned separately in the table. This value for grass can be even higher, for animals with longer lifetimes. From a carbon footprint and biodiversity perspective it is undesirable to have land use change from grass land to crop land. Because the feed conversion ratio for CM is much lower than for beef, a switch from beef to CM is an unlikely driver of land use change, especially because in intensive production systems (basis here) the number of cows per hectare is maximized. With a lower number of cows per hectare (as is common in extensive systems) grasslands can be maintained, while at the same time meat production could remain the same by switching to CM.

Table 6 - Indication of inputs quantities (feed and resources) for 1 kg of product

Meat type	Feed (excl. grass)	By-products	Grass (fresh and silage)	Organic chemi-cals	In-organic chemi-cals	Total - kg in per kg out (excl. grass)	Remarks
Cultivated meat*	0.3	0.4		0.1	0.1	0.8	Assuming 75% amino acids from soy hydrolysate and 25% amino acids from conventional (microbial and chemical) production. Feed is biomass converted to glucose. By-products are soybean meal and maize solubles. Organic chemicals mainly methanol. Inorganic chemicals acids, ammonium carbonate and ammonia
Beef (beef cattle)	4.6	1.1	129.3			5.7	Feed is mostly barley, maize and soybeans. By-products mostly rapeseed meal.
Beef (dairy cattle)	9.8	2.9	24.2			12.7	Economic allocation applied for milk products. Feed is mostly maize silage and maize grains. By-products mostly rapeseed meal. soybean meal, palm kernel expeller and sugar beet pulp.
Pork	3.1	1.5				4.6	Feed is mostly wheat and barley grains. By-products rapeseed meal and soybean meal.
Chicken	1.5	1.3				2.8	Feed is mostly maize and wheat grains. By-products soybean meal and rapeseed meal.
Tofu*	0.4					0.4	Soybeans
Meatless* (wheat-based)	0.2					0.2	Wheat

* The feed conversion ratio is <1 because of the difference in water content between input and output.

3.3 Sensitivity analyses

Several sensitivity analyses have been carried out, on:

- A: Production run time;
  - A1: Shorter production run time (-25%: 32 days, 3 harvests).
  - A2: Longer production run time (+25%: 52 days, 3 harvests).
- B: Maximum cell density during proliferation stages;
  - B1: Higher cell density (x4: 2E8 cells/ml).
  - B2: Lower cell density (x10: 5E6 cells/ml).
- C: Cell volume;
  - C1: Smaller cell volume (500 μm^3).

  - C2: Larger cell volume (5,000 μm^3).
- D: Medium composition and quantity used per kg of cultivated meat;
  - D1: Low medium (more efficient medium usage).
  - D2: High medium (less efficient medium usage).

The basis for variation of the parameters are described in Section 2.4.3 and associated implications for model inputs are described in Annex C. Elaboration on medium compositions assumed for the scenarios and the contribution of ingredients to total environmental impact of medium is also described in Annex C.

The results of these sensitivity analyses are summarized in Table 7. Also shown in the table is the deviation from the baseline scenario (in percentages). As can been seen, for certain process parameters a variation does not influence the results significantly; production run time, a higher cell density and a larger cell volume. Others, however, do influence the results substantially, most notably high medium, lower cell density and smaller cell volume. For companies focussing on reducing the environmental footprints, these aspects of the production process are particularly important to take into consideration.

What is important to note, is how the results from these sensitivity analyses influence the comparison made to conventional protein products. When we look at the environmental single score, the highest value we report (599 mPt per kg CM, for the conventional energy system) is still substantially lower than the environmental single score results for beef (both dairy (909 mPt/kg) and cattle (1,775 mPt/ kg)). Compared to pork (278 mPt/kg) and chicken (184 mPt/kg), the results for the sustainable energy scenario (188-235 mPt/ kg) show a result in the same range.

When we look at the carbon footprint, scenario B2, C1 and D2 can increase the footprint to a higher footprint than beef from dairy cattle in a conventional energy scenario. If we look at a sustainable energy scenario, again, compared to pork (5.3 kg CO_2-eq./kg) and chicken (3.1 kg CO_2-eq./kg), the results are in that range (3.5-4.5 kg CO_2-eq./kg).

Table 7 - Results sensitivity analyses in environmental single score and carbon footprint per kg of product

Scenario	Environmental single score (mPt)				CFP (CO_2-eq.)			
	Conventional energy		Sustainable energy		Conventional energy		Sustainable energy	
Baseline scenario (mid medium)[a]	354	*ref.*	130	*ref.*	13.6	*ref.*	2.5	*ref.*
A1: Shorter production run time (-25%: 32 days, 3 harvests)	343	-3%	128	-2%	13.1	-4%	2.4	-5%
A2: Longer production run time (+25%: 52 days, 3 harvests)	369	+4%	138	+6%	14.1	+4%	2.6	+5%
B1: Higher cell density (x4: 2E8 cells/ml)	348	-2%	131	0%	13.2	-3%	2.5	-1%
B2: Lower cell density (x10: 5E6 cells/ml)	498	+29%	188	+31%	20.7	+34%	3.8	+33%
C1: Smaller cell volume (500 μm^3)	498	+29%	188	+31%	18.9	+28%	3.5	+28%
C2: Larger cell volume (5,000 μm^3)	350	-1%	131	0%	13.4	-1%	2.5	-1%
D1: Low medium (more efficient medium usage)	313	-13%	111	-17%	12.1	-12%	2.1	-21%
D2: High medium (less efficient medium usage)	599	+41%	235	+44%	22.6	+40%	4.5	+44%

[a] Reference scenario for comparison to sensitivity analyses results.

4 Conclusions and discussion

This prospective Life Cycle Assessment study of cultivated meat is the first LCA study which uses primary data from multiple CM companies and from associated companies in the CM supply chain. In this LCA we look at meat production from cradle to facility gate.
We present the environmental impact for a non-specific type of CM. The baseline scenario considers a CM product cultivated at around 37°C. As CM is still in development, we modelled a future commercial scale production facility which reflects expected changes, both internally (the scaling up of CM production) and externally (e.g. share of sustainable sources in electricity mix).

The results do not represent the impact of a specific product developed by a specific CM company, and may not be interpreted as such. CM companies can use the results to gain insight into factors that may contribute (significantly) to their impact, or extract recommendations for focus areas for future exploration within their product development and for product improvement.

4.1 Conclusions and discussion

The results show that:
- CM can compete with all conventional meat environmentally, and scores much better than beef. This conclusion is based on comparison with our ambitious benchmark for conventional products, and therefore quite robust. When producers switch to sustainable energy, CM becomes the most environmentally friendly option for meat production.
- The most important drivers of the environmental impact of CM are processing energy, medium quantity and medium composition. For all these drivers an important option for improvement is a switch sustainable energy.
- Potential variability regarding quantity of medium used, residence time of cells in the reactors, maximum cell density and process temperature are unlikely to influence these conclusions.

These conclusions are elaborated on hereafter.

CM can compete with all conventional meats environmentally (and scores much better than beef); with sustainable energy CM becomes the most environmentally attractive meat product

We compare the environmental impact of CM to conventional products, using both the ReCiPe (environmental) single score and carbon footprint. We chose an ambitious benchmark: conventional meat with a relatively low environmental impact (compared to the global average).

Our assessment shows that even with conventional energy (global average stated policy scenario in 2030), CM has a lower environmental single score and a lower carbon footprint than beef (cattle and dairy). In order to attain lower scores than pork and chicken, a (partial) switch to sustainable energy is necessary (95 and 76% respectively to have a carbon footprint and environmental single score equal to chicken). If the carbon footprint component in the environmental single score is adjusted to reflect the global average carbon footprint of meat products, conventional energy CM scores comparable to the adjusted single score for chicken, and lower than pork and beef. CM can compete on carbon footprint with the global average footprints for chicken and pork, if > 30% of energy use is sourced sustainably. As this is relatively easy to achieve technologically, we strongly recommend CM companies to source energy sustainably, to achieve a relatively quick win in reducing the footprint.

Compared to all meat products, both cultivated and conventional, the environmental single score and the carbon footprint of vegetable protein products is low. With a carbon footprint which is 2.5 to 4 times lower, and an environmental single score of over three and seven times lower, cultivated meat is unlikely to be able to compete with vegetable protein products on these two indicators.

We also assessed the impact on three important impact categories: particulate matter formation, land use and water use. When we look at particulate matter formation, CM results are lower than meat products for the sustainable energy scenario, and lower or equal for the conventional energy scenario. Especially the difference between beef and CM is particularly high (well over four to almost fourteen times higher for conventional beef). For land use, CM is comparable to tofu, with a footprint of around 1.8 m^2, substantially lower than chicken (4.6), pork (6.0) and beef (8.8-31.6). For water use, CM is comparable to chicken and pork, with a footprint of around 42 m^3, substantially lower than beef (115-258 m^3).

Important drivers of the environmental impact of CM

Switching from a global average stated policy scenario for electricity in 2030 to sustainable energy lowers the environment impact of CM by 60% for the single score and 80% for the carbon footprint. In this assessment this energy switch is applied to the **energy use** in the CM production process and in medium production. This also means that a (global) switch to sustainable energy will lower the impact further, as the environmental impact of energy use in all other background processes (e.g. production of bioreactors) will be reduced.
This effect is larger for CM than for conventional animal products, as the carbon footprint of CM is defined by energy use, while in the animal production systems also emissions of CH_4 and N_2O from enteric fermentation and manure handling contribute significantly.

As CM companies are still developing, the estimates for the amount of **medium** required and the composition of medium ingredients vary. It is important to consider the medium composition, since some ingredients contribute far more to the overall environmental impact than others. Especially albumin has a relatively large environmental footprint compared to other ingredients, and should therefore be minimised when possible. In our LCA, potential recycling (internally or externally) of medium is not taken into account.
If this would be possible it would help reduce the environmental footprint in multiple ways; a reduction of (natural) resource use, lower energy use for medium production and finally lower amounts of waste water.

This study shows that the **cooling load** required is highly influential on the environmental performance of production. However, heating and cooling dynamics in large-scale cell cultures remain difficult to predict, as it depends on a wide range of factors such as type of production and bioreactors used, internal reactor heat dynamics, maximum cell densities, and metabolic heat production for the specific cells used. At low densities, the culture will almost certainly require some heating as the cell metabolism does not produce enough heat for maintaining the temperature. For certain process designs there could be an optimum where little cooling and heating is needed. Further research, and especially trial experiments on pilot scale, will hopefully shed more light on this topic in the coming years.

Sensitivity analyses do not influence the conclusions

For certain process parameters a variation does not influence the results significantly; production run time, a higher cell density and a larger cell volume. Others influence the results substantially, most notably high medium use, lower cell density and smaller cell volume. When comparing the results of the sensitivity analyses to those for conventional products, the highest value we report for CM (599 mPt per kg CM, for the conventional energy system) is still substantially lower than the environmental single score results for beef (both dairy (909 mPt/kg) and cattle (1,775 mPt/kg)). Compared to pork (278 mPt/kg) and chicken (184 mPt/kg), the results for the sustainable energy scenario (188-235 mPt/kg CM) show a result in the same range.

When we look at the carbon footprint, three scenarios can increase the footprint to a higher footprint than beef from dairy cattle in a conventional energy scenario. If we look at a sustainable energy scenario, again, compared to pork (5.3 kg CO_2-eq./kg) and chicken (3.1 kg CO_2-eq./kg), the results are in that range (3.5-4.5 kg CO_2-eq./kg).

These results confirm that CM can compete with conventional products environmentally. A switch to sustainable energy in the production process (of both CM and the medium) makes CM the most environmentally attractive meat option.

Overlap LCA and TEA

At the same time this LCA was carried out, a techno-economic assessment (TEA) was also made (CE Delft, 2020). Do conclusions overlap? Can measures to reduce environmental impact also lower costs, and vice versa? Four aspects stand out:

1. **Energy efficiency**: being more energy efficient reduces environmental impact and costs. There still are uncertainties regarding energy use for heating and cooling, and further research into e.g. energy efficient cooling and sustainable heat sources could help reduce both environmental impact and costs.
2. **Energy sources**: a switch to sustainable energy, especially electricity, substantially lowers the environmental impact. The most transparent and robust way to ensure *additional* sustainable electricity production, which actually lowers the national average environmental impact of electricity generation, is taking care of one’s own sustainable electricity generation. If sustainable electricity is generated by the CM company on site, this could also mean a reduction in cost compared to either fossil or sustainable electricity purchased on the market.
3. **Medium use**: both increased medium efficiency and increasingly efficient production of ingredients can lower both costs and environmental impacts. Especially regarding certain functional ingredients: the results of the LCA and of the TEA both highlight certain specialty functional ingredients such as recombinant proteins in this regard. A reduction or a switch could mean reducing both impact and costs.
4. **Supply chain collaboration**: To reduce environmental impact and costs further, collaboration in the supply can help lower impact and costs of production of all required substances for CM production. Most notably this is important with regard to medium ingredients, but this reasoning can of course be extended to other inputs (e.g. scaffolds, filtration membranes) as well.

4.2 Recommendations

To minimize the environmental footprint of CM products we advise companies to:
- Lab phase: experiment with medium composition, and try to reduce or eliminate ingredients with a relatively large impact, such as albumin.
- Pilot phase: experiment with medium quantity, medium recycling, and energy use for heating and cooling.
- Full scale: incorporate sustainable procurement by sourcing sustainable energy and inputs, and optimize heating and cooling load.
- Focus on high cell density and high cell volume as these aspects of the production process can influence the environmental footprint significantly.

We encourage researchers to take pay particular attention to these aspects in (LCA) future studies.

4.3 A process under development: uncertainties and limitations

The results presented here are not meant to be used as a projection of the impact of products in development by specific CM companies. This study presents results which provide the sector with insights into CM's drivers of environmental impact.

In Table 8 the carbon footprint and the energy use modelled in this study is compared to results presented in other LCA's. The publications of Lynch and Pierrehumbert (2019) and Smetana et al. (2015; 2018) have been excluded since they build upon the results and data from the studies mentioned in Table 8 and furthermore make different methodological choices regarding impact assessment method and system boundaries respectively.
For further breakdown of previous studies, we refer to a recent gap analysis by Scharf et al. (2019). As expected, the carbon footprint for production (with a conventional energy mix) is higher than reported in other studies; the inventory in our LCA is more complete, the inputs and outputs specified in greater detail and, most importantly, a conservative approach to cooling load calculation was chosen to make sure the environmental impact was not underestimated.

Table 8 - Comparison of carbon footprint and energy use to results presented in other LCA's

	CFP (kg CO_2-eq./kg product)	**Energy use (MJ/kg product)**
This study (Best case/worst case sensitivity analysis)	2.5-13.5 (2.1-22.6)	147-264 (124-445)
Mattick et al. (2015) (Best case/worst case sensitivity analysis)	7.5 (3.2-22.3)	106 (44-316)
Tuomisto et al. (2014)	2.3-4.4	35-61
Tuomisto and Teixeira de Mattos (2011)	1.9-2.2	25-32

This research has resulted in a robust inventory with as much primary data as is currently possible, even though uncertainties exist due to the early stage of technology development. Data collection efforts have been carried out among over fifteen companies active in CM development and its supply chain, supplemented with cross-checks by independent experts. The effect of changes in the most uncertain issues were studied in sensitivity analyses.
A current limitation is that a breakdown to results for different meat types has not been done, to assure confidentiality of data. As development of CM is ongoing, research into the environmental footprint, by the developing companies and scientists, should therefore also be ongoing, and updates in the production process should be incorporated in future LCA's.

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A ReCiPe

This annex gives an introduction to the ReCiPe methodology which is used as the method for the LCA conducted in this study.

The ReCiPe methodology is developed for the Dutch government and is used for many LCA-studies in the Netherlands. The ReCiPe methodology translates a long list of primary results in easier to interpret indicators. With this method the environmental effects can be shown on two different levels:

Midpoints: problem-oriented environmental effects, such as climate change and acidification. In the ReCiPe methodology there are seventeen midpoints. The midpoint-level is a direct translation from substance/emission to environmental effect. The midpoint-level gives an insight into the different environmental effects and is characterized by a high level of transparency. The damage caused is not shown in this category, for this end the three endpoints (Level 2) are more useful.

Endpoints: impact-oriented environmental effects, the effects on nature, effect on humans and effect on resources. In the ReCiPe methodology the seventeen midpoints are categorized into three endpoints. At the endpoint-level the environmental effects are normalized and recalculated towards damage into three endpoint categories:
- damage to human health;
- damage to ecosystems;
- damage to resource availability.

Table 9 - Environmental effect categories, units and weighting according to ReCiPe 2016

Midpoints	Unit	Endpoints	Single Score
Global warming	kg CO_2-eq.	Human Health (DALY)	mPt
Stratospheric ozone depletion	kg CFC11-eq.		
Ionizing radiation	kBq Co-60-eq.		
Ozone formation. Human health	kg NO_x-eq.		
Fine particulate matter formation	kg $PM_{2.5}$-eq.		
Human carcinogenic toxicity	kg 1,4-DCB e		
Human non-carcinogenic toxicity	kg 1,4-DCB e		
Water consumption	m^3		
Global warming	kg CO_2-eq.	Ecosystems (species. year)	
Ozone formation. Terrestrial ecosystems	kg NO_x-eq.		
Terrestrial acidification	kg SO_2-eq.		
Freshwater eutrophication	kg P eq.		
Terrestrial ecotoxicity	kg 1,4-DCB e		
Freshwater ecotoxicity	kg 1,4-DCB e		
Marine ecotoxicity	kg 1,4-DCB e		
Land use	m^2a crop eq.		
Water consumption	m^3		
Mineral resource scarcity	kg Cu eq.	Resources ($)	
Fossil resource scarcity	kg oil eq.		

Source: (*ReCiPe 2016 : A harmonized life cycle impact assessment method at midpoint and endpoint level* 2016).

B Inventory and data quality

The data quality assessment classification is explained in Table 10. Table 11 shows the main model design parameters with information on sources and data quality. Table 12 shows the main model inputs with information on sources and data quality. Quantitative data on model inputs is confidential and therefore not included. Table 13 shows the conventional electricity mix modelled for this study. Table 14 shows the energy consumption modelled in the baseline model.

Table 10 - Data quality assessment classification

Data quality assessment classification	
0	No data available at this moment
1	Primary data from representative process and scale
2	Primary data from representative process with extrapolation for scale
3	Primary data from similar process and scale
4	Secondary data from literature
5	Estimate or calculation based on expert judgement

Table 11 - Main model design parameters values, sources and data quality

Main model parameters	Value	Source	Data quality	# of data points used	Independent cross-check
Annual production of commercial facility in 2030	10 kton	CM and supply chain companies	5	12	No
Species and cell type	Various species, assuming non-GMO cell lines	CM companies	1	7	Yes
Type of production	Semi-continuous production with 3 intermediate harvests	Literature, confirmed by bioprocessing companies	4	1	Yes
Size of largest proliferation vessel	10,000 L	CM and supply chain companies estimate (median)	5	7	Yes
Size and amount of bioreactors at facility	107 x 50 L STR, 130 x 10,000 L STR; 430 x 2,000 L PR	Calculated, based on production line presented in Specht (2020) and project-specific parameters	4/5	-	Yes
Doubling time	30 hours	Conservative round-up from Specht (2020): 28 days. Range validated by companies.	4/2	1	Yes
Duration of production from inoculum to harvest	42 days (30 days for ~25 doublings + 2 days for additional harvests + 10 days of differentiation and maturation)	Specht (2020), cross-check by bioprocessing companies	4	1	Yes
Maximum cell density	$50*10^6$ cells/ml	CM and supply chain companies (median)	2	7	Yes
Avg. cell volume	3,500 μm^3/cell	CM companies (median)	1	4	Yes
Density of meat	881 kg/m^3	Specht (2020)	4	N.a.	No

Table 12 - Main model inputs, sources and data quality

Main model inputs and their production	Source	Data quality	# of data points used	Independent cross-check
Energy use for production (heating, cooling, mixing, aeration, pumping)	Calculations by bioprocess engineers with extrapolations by CE Delft	5	1	Yes
Energy use for cleaning (CIP/SIP)	Calculations by bioprocess engineers with extrapolations by CE Delft	3	1	No
Energy use for HVAC	Calculations by engineers	4	1	No
Energy production	Ecoinvent LCA database, modelled after global stated policies scenario in World Energy Outlook 2030 (IEA 2019)	1	N.a.	N.a.
Purified water use for CM production (quantity))	CM and bioprocess engineering companies	2 (for medium-related water use) and 3 (for cleaning related water use)	2	Yes
Purified water production	Water companies	1	1	No
Medium use	CM and supply chain companies	2	6	Yes
Medium recycling rate	CM and supply chain companies	0 (no consensus)	6	Yes
Medium composition	CM and supply chain companies	2	7	Yes
Medium ingredient production	See below			
Hydrolysate	(Colantoni et al. 2017) EDIT: Soy LUC set to 0 (as is done for conventional products)	4	1	No
Amino acids	Data from (Marinussen and Kool 2010), Mattick (2014), Mattick et al. (2015). Amino acids modelled: - L-Glutamine - L-Threonine - L-Lysine - D,L-Methionine	4	1	No
Recombinant proteins	Amino acid production data from (Marinussen and Kool 2010), Mattick (2014), Mattick et al. (2015) used as basis. Water and electricity use adapted for recombinant protein fermentation with data from 2 producing companies.	2	3	Yes

Main model inputs and their production	Source	Data quality	# of data points used	Independent cross-check
Other medium ingredients	Ecoinvent and Agri-footprint LCA databases	1	N.a.	N.a.
Transport of medium ingredients	Based on standard Ecoinvent values for global markets	1	N.a.	N.a.
Scaffold use	CM and supply chain companies	5	8 companies (total) of which 3 with future estimate of quantity of scaffold used	No
Scaffold production	See below			
Hydrogel	De Marco et al. (2017)	4	1	No
Electrospinning	Supply chain companies	2	2	Yes
Bioreactor use	Size from CM and supplying companies, amount calculated	See above	See above	Yes
Bioreactor production	Tuomisto et al. (2014) and industry experts within CE Delft	4	2	Yes
Storage and mixing tanks use	Calculated	5	1	No
Storage and mixing tanks production	Industry experts within CE Delft	4	1	No
Filters for filtration use	Supplying companies	2	1	Yes
Filters for filtration production	Supplying companies	1	1	No

Table 13 - Energy mix for 2030, stated policy scenario, global average (IEA 2019)

Source	Share
Coal	29%
Gas	24%
Oil	3%
Nuclear	9%
Hydro	15%
Wind	9%
Solar	9%
Other renewable	3%

Table 14 - Modelled energy demand for 1 year of operation (baseline scenario)

Process	Quantity (kWh)
Electricity for aeration, agitation, pumping and heat exchanger during small-scale proliferation, large-scale proliferation and differentiation and maturation; centrifugation and pumping washing water during harvesting and as part of food safety measures; pumping during cleaning; HVAC; pumping (medium mixing and sterilization	2,17E+08
Heat for initial heating of medium during small-scale proliferation, large-scale proliferation and differentiation and maturation and cleaning; HVAC	1,08E+07

C Sensitivity analyses

Model inputs

Table 15 – Parameters and the relative change in parameters for the different sensitivity analyses

Parameters changed	Baseline scenario (mid medium)	A1: Shorter production run time (-25%: 32 days, 3 harvests)	A2: Longer production run time (+25%:52 days, 3 harvests)	B1: Higher cell density (x4: 2E8 cells/ml)	B2: Lower cell density (x10: 5E6 cells/ml)[a]	C1: Smaller cell volume (500 µm^3)[a]	C2: Larger cell volume (5,000 µm^3)	D1: Low medium[e]	D2: High medium[e]
Amount of production runs[a]	100%	100%	100%	25%	1,000%	700%	70%	100%	100%
Amount of bioreactors (50 L STR)	100%	79%	121%	25%	1,000%	700%	70%	100%	100%
Amount of bioreactors (10,000 L STR)	100%	85%	115%	25%	992%	692%	69%	100%	100%
Amount of bioreactors (2,000 L PR)	100%	79%	121%	100%	100%	100%	100%	100%	100%
Amount of storage and mixing tanks (60,000 L)	100%	100%	100%	100%	760%	760%	100%	100%	118%
Electricity for small-scale proliferation (total)[b]	100%	99%	101%	99%	126%	118%	99%	100%	100%
Heat for small-scale proliferation (total)[c]	100%	100%	100%	100%	1,010%	1119%	100%	51%	356%
Electricity for large-scale proliferation (total)[b]	100%	99%	101%	99%	123%	116%	99%	100%	100%
Heat for large-scale proliferation (total)[c]	100%	100%	100%	100%	1,007%	979%	100%	67%	271%
Electricity for differentiation and maturation (total)[b]	100%	75%	125%	100%	100%	100%	100%	100%	100%

Parameters changed	**Baseline scenario (mid medium)**	**A1: Shorter production run time (-25%: 32 days, 3 harvests)**	**A2: Longer production run time (+25%:52 days, 3 harvests)**	**B1: Higher cell density (x4: 2E8 cells/ml)**	**B2: Lower cell density (x10: 5E6 cells/ml)[a]**	**C1: Smaller cell volume (500 µm^3)[a]**	**C2: Larger cell volume (5,000 µm^3)**	**D1: Low medium[e]**	**D2: High medium[e]**
Heat for differentiation and maturation (total)[c]	100%	75%	125%	100%	101%	100%	100%	39%	418%
Electricity for cleaning (pumping)	100%	100%	100%	25%	1000%	700%	70%	100%	100%
Heat for cleaning (heating water)	100%	100%	100%	25%	923%	649%	73%	100%	100%
Electricity for medium mixing and sterilisation (kWh)	100%	100%	100%	100%	760%	760%	100%	59%	311%
Electricity for HVAC (total)[d]	100%	100%	150%	100%	850%	650%	100%	100%	150%
Heat for HVAC (total)[d]	100%	100%	150%	100%	850%	650%	100%	100%	150%
Water for cleaning	100%	100%	100%	26%	631%	454%	82%	100%	100%
Medium (small-scale proliferation)[e]	100%	100%	100%	100%	100%	100%	100%	see Table 16	see Table 16
Medium (large scale proliferation)[e]	100%	100%	100%	100%	100%	100%	100%		
Medium (differentiation and maturation)[e]	100%	75%	125%	100%	100%	100%	100%		

[a] *One production run consists of a train of proliferation reactors of increasing volume and 4 perfusion reactors (see Section 2.4.1). Depending on the potential staggering of production runs this is more or less proportional to the total amount of reactors needed for the facility.*

[b] *Electricity for the various production stages includes all aspects that are powered by electricity: Pumping, mixing, aeration and cooling in a heat exchanger.*

[c] *Heat for the various production stages is the heat needed for initial heating of the medium.*

[d] *HVAC includes all heating, cooling and ventilation needed to maintain ISO8 (cleanroom) environment in the production area.*

[e] *All scenarios except low and high medium assume the baseline medium quantities. For the low and high medium scenarios, see* Table 16.

Production run time

The production run time depends on the doubling time (for proliferation stages) and on the desired maturity of cells in the final product (for differentiation and maturation). Based on primary data we have decided to vary the total production run time with -25% and +25%. This does not necessarily cover all data received, but we feel that this does provide a solid basis for companies to interpret the results in comparison to their own specific process design.

For a shorter proliferation time, the cell doubling time is reduced from 30 to 22,5 days, and for a longer proliferation time increased from 30 to 37,5 days.

Shorter residence time in the reactors reduces overall energy demand, lowers medium demand during differentiation and maturation (we assume a linear relation) and results in a smaller amount of reactors needed to produce the same amount of CM. Longer residence time effects these aspects reversely. We assume medium use in proliferation stages is not affected, as the same amount of cells has to be produced, thus demanding the same amount of ingredients.

Maximum cell density

Maximum cell density during proliferation stages is a parameter for which many companies are optimising. This is highly dependent on the adopted product system and bioreactor types. In this study, we have adopted a median maximum cell density as expected to be achieved by CM companies in commercial-scale production. In the stirred-tank reactor (STR) system that we model, it may be feasible to increase cell densities by a factor 4 (to $20*10^7$ cells/ml, the higher density scenario), but not much more, according to experts in the field. It is plausible that certain large-scale production systems will not manage to operate at the cell densities that we model in the baseline scenario, and therefore factor 10 lower densities ($10*10^6$ cells/ml, the lower density scenario) is also modelled. In other reactor systems, cell densities up to 10^9 cells/ml are currently already feasible, albeit not yet at very large scales (Allan et al. 2019). However, limitations regarding metabolite formation and oxygen availability can be expected in those situations.

Higher cell densities would mean that more meat cells can be grown in a reactor of the same volume. It affects the energy demand for heating and cooling, as cultures with higher cell densities need less heating and more cooling, and cultures with lower cell densities need more heating and less cooling (per unit of volume). It is assumed that the total cooling load needed remains unchanged. Lower cell densities means that more water has to be added to the growing medium in order to fill up the reactors, and more reactors are needed in total to produce the same amount of CM, with subsequent more energy and water used for cleaning. Changes in cell density during proliferation stages have no effect on assumed cell density during differentiation and maturation.

Cell volume

Average cell volume differs per species type and cell type. For example, fat cells are much larger than muscle cells, and within the different types of muscle cells there is large variation. Also, small animals tend to have smaller cells than large animals. As the companies involved in this study produce a range of species and cell types, we used an average cell volume for the baseline scenario and determined smaller cell volume (500 μm^3) and larger cell volume (5,000 μm^3) on primary data collected and literature.

The effects of smaller and larger cell volume are similar to that of lower and higher cell densities, respectively, as total cell mass harvested from one unit of volume decreases accordingly.

Medium

Table 16 shows the medium compositions for the baseline, low- and high-medium scenarios. The quantities have been based on a combination of primary data (mostly, both from CM-producing companies and companies active in the supply chain) and literature.
The values for the baseline scenario are based on the geometric mean of the obtained values, as this corresponded best with the distribution of values we received. The exception is water use, for which the low-medium scenario was adapted for the process design we maintain; at the cell densities modelled in this study, the primary data for water use were too low to fill up the reactors to working capacity.

Table 16 – Medium composition: baseline scenario, low medium scenario and high medium scenario (total per kg of cultivated meat)

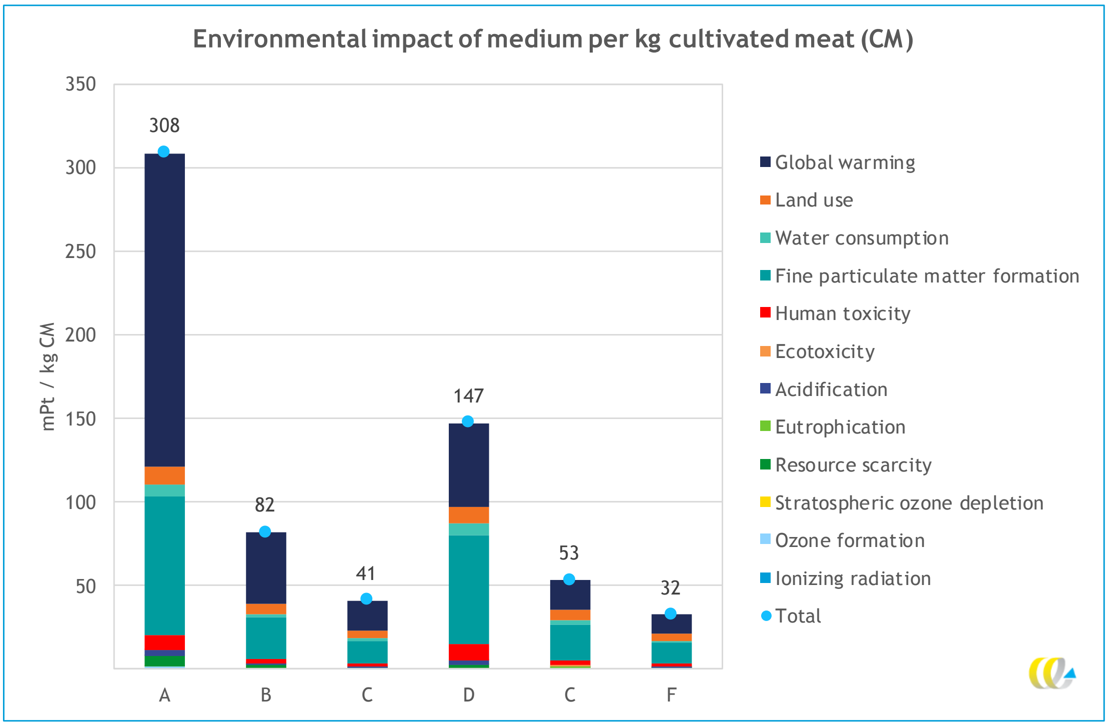
Components	**Baseline scenario (g)**	**Low-medium scenario (g)**	**High-medium scenario (g)**	**Main ingredients**
Amino acids (total), of which:	316	250	400	L-glutamine, L-Arginine hydrochloride
Amino acids from hydrolysate	*237*	*186*	*300*	
Amino acids from conventional production	*79*	*63*	*100*	
Sugars (total), of which:	78	15	400	Glucose, pyruvate
Sugars: Glucose	*76*	*14*	*396*	
Sugars: Pyruvate	*2*	*1*	*4*	
Recombinant proteins	7	1	50	Albumin (mainly), insulin, transferrin
Salts	80	40	160	Sodium chloride
Buffering agent	32	10	100	HEPES
Vitamins	2	0	20	i-Inositol, Choline chloride
Growth factors	<<1	<<1	<<1	
Water	12,649	7,500	40,000	Ultrapure water
Total (g)	13,164	7,816	41,130	
Total (L)	13	8	42	

Note: Approximate (rounded) values; values may not add up.

Figure 16 shows the environmental impact, and Figure 17 shows the carbon footprint of medium per kg CM, showing the importance of increasing medium efficiency in the process. The main driver for the differences in environmental single score is the amount of recombinant proteins needed for CM production. This follows logically from the fact that recombinant protein production has a relatively high demand for feedstock, energy, water and chemicals. To a lesser extent this also applies to microbial or synthetic amino acid production. On a per kg basis, hydrolysate has a significantly lower environmental impact than microbially or synthetically produced amino acids, because it is a relatively efficient process and therefore the impact is in large part determined by the feedstock (in this study soybean meal).

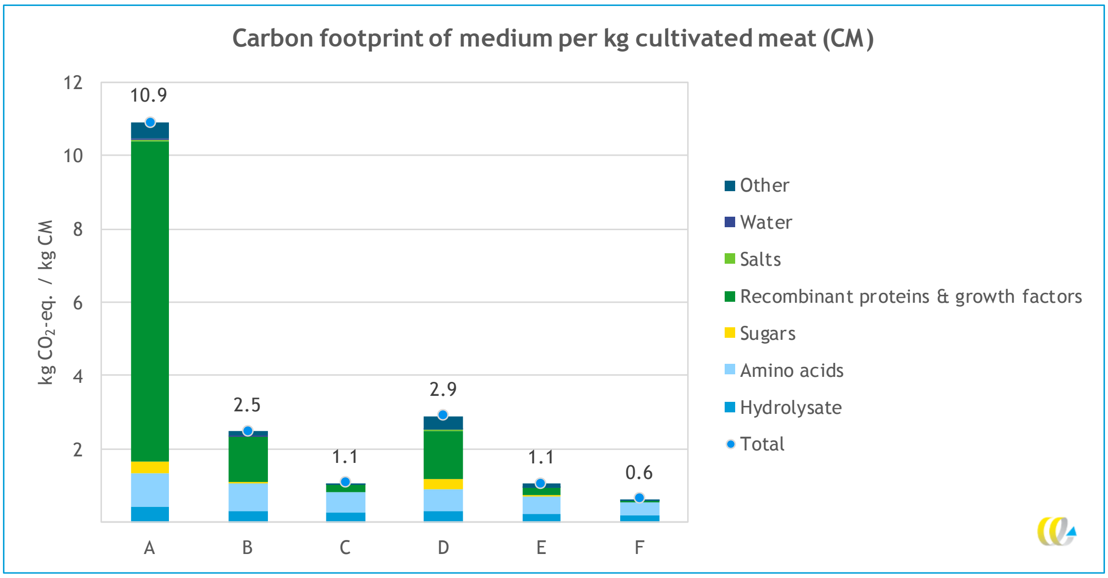
Especially regarding albumin and a few other proteins we have received varying data, as production scales are still relatively small and different expectations for future improvement exist. Due to the relatively high environmental footprint of recombinant proteins, only small variations will have large influence on results. Companies could focus on reducing the amount of recombinant proteins in their production process, or find alternatives with a lower environmental impact. An interesting production route for albumin could be to extract it from plants. However, no environmental data could be located for this and therefore this study assumes recombinant albumin production through fermentation.

Figure 16 - Environmental impact of medium use for 1 kg of CM



A: Conventional energy - medium high
B: Conventional energy - medium mid
C: Conventional energy - medium low
D: Sustainable energy - medium high
E: Sustainable energy - medium mid
F: Sustainable energy - medium low

Figure 17 - Carbon footprint of medium, per kg of CM produced - contribution analysis of different medium ingredients



A: Conventional energy - medium high
B: Conventional energy - medium mid
C: Conventional energy - medium low
D: Sustainable energy - medium high
E: Sustainable energy - medium mid
F: Sustainable energy - medium low