

Guidelines for environmental life cycle assessment of cultivated meat

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Abstract

Purpose: Cultivated meat is produced by growing animal cells *in vitro* without using, or reducing the use of, animals for meat, poultry, or seafood production. Responsibly and consistently investigating the environmental impacts of cultivated meat is essential to provide reliable performance benchmarks and realistic comparisons with animal-based production systems. In this contribution, we provide technical, actionable guidelines for conducting life cycle assessments (LCAs) of cultivated meat and highlight further research needs for the field.

Methods: We assembled a global team of recognized and active scientists in cultivated meat LCA, livestock systems LCA, and ISO LCA standards to develop this set of guidelines using a workshop (in person and online) and online meetings, as well as asynchronous feedback, to reach consensus.

Results and discussion: These guidelines provide specifications throughout the four phases of LCA, from goal definition to the interpretation of LCA results. Data gaps, including the availability and quality of feed or food-grade culture media component inventories, are among the areas highlighted for further exploration.

Conclusion: We invite LCA practitioners to apply these guidelines when investigating cultivated meat systems to increase the consistency and reliability of environmental impact evaluations for these emerging products.

Keywords: cell-cultivated, cultured meat, cellular agriculture, environmental impact, sustainability, future food, food technology, controlled environment agriculture, alternative proteins

1. Introduction

Cultivated meat systems produce animal cells (e.g., muscle and fat cells from livestock, poultry, fish, and other animals) *in vitro* for food, eliminating the need for animal slaughter. These technologies have been touted as more

environmentally sustainable and ethical alternatives to conventional meat production. Since the publication of the first peer-reviewed life cycle assessment (LCA) of cultivated meat in 2011 (Tuomisto & Teixeira de Mattos, 2011), the field of cultivated meat LCA has grown; extant studies have focused on diverse products and employed a wide range of modeling choices, data quality, and assumptions that lead to uncertainty regarding cultivated meat systems' impacts (**Table 1**).

Due to the nascency of the cultivated meat industry, LCA practitioners encounter the following critical barriers in developing cultivated meat LCAs: 1) lack of clarity on which datasets to use to represent key inputs; 2) appropriate datasets for representing inputs that may not exist in databases; 3) easily accessible primary data (e.g., lab or bench scale) likely does not represent production-scale activities (thus, data quality limitations); 4) significant variations in inputs and model parameters across assumed scales (e.g., lab vs. commercial), timeframes (e.g., current vs. future projected), geographies, and technologies. Additionally, the choice of comparison products, byproduct handling, and boundaries of the analysis can significantly influence results, underscoring the need for harmonized guidelines. While the Good Food Institute has developed a helpful LCA primer for alternative protein companies, it does not provide detailed, technical guidance on data or modeling choices essential for LCA practitioners to assess the industry (Chapman & Murray, 2023).

With this contribution, we provide technical, methodological guidance to LCA practitioners working in the field of cultivated meat. To do this, we convened an expert working group of practitioners who have previous or current experience conducting LCAs of cultivated meat, expertise in LCAs of animal production systems, and/or expertise with ISO standards development. These guidelines are aimed at practitioners undertaking LCA studies of cultivated meat for research purposes or consultancy projects. In addition to supporting practitioners in design and implementation of cultivated meat LCAs, we also aim to advance transparency, facilitate replication, and enable cross-study comparisons for LCAs carried out following these guidelines. These guidelines adhere to the ISO standards for LCA and PEF guidelines where applicable (*ISO14040:2006*, 2006; *ISO14044:2006*, 2006; *Product Environmental Footprint Category Rules Guidance Version 6.3 — May 2018*, 2018).

2. Methods

To draft the guidance, the co-chairs organized a workshop at the 14th LCA Food Conference in Barcelona, Spain in September 2024. The invitation process began in April 2024 over email. All first and corresponding authors of previously published cultivated meat LCAs were invited. Additional experts, known to be working on cultivated meat LCAs, animal production systems LCA, or experienced with the ISO standards, were also invited. The workshop description was posted on the LCA Food conference website with a request to email the co-chairs for an invitation. Participants were added to the workshop list if they had prior or current involvement in cultivated meat LCAs and were not employed by an advocacy group or food company due to potential conflicts of interest.

Appendix Table 1 lists the participants, their expertise, sectors, and affiliations.

An initial outline of these guidelines was drafted by the co-chairs and their research groups in June 2024. One month prior to the workshop, participants were asked to review and comment on the draft guidance. Areas of the guidance with significant disagreement or uncertainty were selected for in-depth discussion at the workshop. The workshop was held in a hybrid format, with 22 participants attending in total, 14 in person and 8 virtual. Four participants were unable to attend the workshop but provided substantial feedback on the guidance both before and afterwards. All participants were subsequently invited to co-author this manuscript. The structure of the half-day workshop included two rounds of breakout sessions, organized by topic, each followed by a report-out and discussion amongst all workshop participants. Breakout groups used shared google slides to note key points raised for each topic, areas of agreement, and areas of disagreements, informing subsequent discussions with the whole workshop group. The workshop was recorded, and notes were taken by the co-chairs and their research groups.

Post-workshop, the co-chairs' research groups drafted a full version of this guidance that incorporated decisions from the workshop, added figures and tables, and drafted a harmonized list of flows for culture media to include in the supplementary materials (SM). The co-chairs and their research groups met several times to discuss and resolve different aspects. The complete draft of this guidance was then sent to all co-authors for three rounds of review, with the co-chairs' teams integrating edits between. During this period, one additional online meeting was held to come to consensus on a subset of issues identified during review. The resulting guidance from this process is provided in the results and discussion section below, organized by phases of LCA.

3. Results and Discussion

3.1 Goal and scope

This section includes guidance on goal definition and some essential aspects of scope, including product system definition, system boundaries, functional unit, and comparisons or comparative assertions. Guidance on allocation methods and impact assessment are included in subsequent separate sections, though initial handling of these topics should be covered in goal and scope. We refer practitioners to ISO 14044 for guidance on the remaining aspects of goal and scope. To increase the applicability of the guidance, in many cases we do not prescribe a course of action, but rather present available options and refer to existing additional guidance. At the same time, we hold that comparability across studies and the ability to replicate results from individual studies is paramount to advance the field. As such, in addition to the immediate guidance that follows for Goal and Scope, researchers should consult the [“Facilitating cross-study comparisons”](#) section when designing their study for guidance on calculating a standardized set of results for inclusion in supplementary documentation.

3.1.1 Goal statement and product system definition

The goal statement of a cultivated meat LCA should explain its intended application, purpose, intended audience, and whether the study is a comparative assessment. When the results of the study are intended to be communicated to an external audience, either business-to-business (B2B) or business-to-consumer (B2C), there are guidelines that should be followed. The guidelines vary based on the study’s impact scope, whether comparisons will be made with other products, and the nature of comparisons. Further details are in the “Comparisons and comparative assertions” section.

Goal statements for cultivated meat LCAs should also include the temporal positionality of the study. Temporal positionality addresses whether the analysis is of historical, recent past (often referred to as current), or future systems (Arvidsson et al., 2024). Practitioners should state whether their LCA is retrospective (historical, recent past) or prospective (future) (Arvidsson et al., 2024). For a prospective study, practitioners should specify the future time frame, either a specific year or a range. In the context of cultivated meat, such studies often account for future

technological advancements, previously termed “ex-ante” LCA. We adopt the terminology “prospective LCA” to align with guidance by Arvidsson and colleagues (Arvidsson et al., 2024).

Key considerations for defining a cultivated meat product system include temporal positionality, technology maturity, and the classification of the product as intermediate or final. Technology maturity refers to whether the technology is at a low (early-stage), medium (mid-stage), or high (late-stage) maturity, commonly assessed using Technology Readiness Levels (TRL) and/or Manufacturing Readiness Level (MRL) (Kimmel, 2020; *Manufacturing Readiness Level (MRL) Deskbook*, 2020). To our knowledge, there is no guidance for assessing TRL or MRL for the cultivated meat field specifically, nor published TRLs or MRLs for cultivated meat technologies. However, as a biomanufacturing process, cultivated meat can be assessed using the BioMRL framework, where early-stage maturity corresponds to BioMRL 1-3, mid-stage corresponds to BioMRL 4-7, and late stage corresponds to BioMRL 8-10 (Smanski et al., 2022).

We follow Arvidsson and colleagues (2024) and recommend that for cultivated meat LCA studies, TRL or BioMRL should be specified if possible, and if not, technology maturity should be specified qualitatively (Arvidsson et al., 2024; van der Hulst et al., 2020). The purpose is to transparently indicate how well developed a technology is and to support interpretation of the study, given less certainty for low TRL and BioMRL technologies. In cultivated meat, technology maturity will vary by cell line, product type (e.g., ground product), and manufacturing systems used. Assessing the TRL or BioMRL of a technology is a significant task that requires subject matter expertise, time, and resources through Technology Readiness Assessment (TRA) or Manufacturing Readiness Assessment (MRA) (Smanski et al., 2022)). To advance the field and inform future LCAs, these assessments of cultivated meat technologies are necessary. Currently, based on our collective knowledge, the maturity of cultivated meat technologies likely ranges from early-stage (TRL 3 and BioMRL3) to mid-stage (BioMRL4-6) for the most advanced systems with marketed products (Watson, 2024).

MRLs and BioMRLs include descriptions of the experimental environments (i.e., laboratory, production-relevant, production-representative) (Smanski et al., 2022). While there is a correlation between these environments and production scale, the relevant scale for commercial readiness depends on the product system (Smanski et al., 2022).

If the scale of the system under study fits product demand and the technological and manufacturing capabilities of the product's production process at that scale are well developed, higher TRL and BioMRL can be justified. We have provided general guidance regarding correspondence between different production scales and potential BioMRLs that can be used as a starting point (**Table 2**). Practitioners should specify the scale of the product system by indicating production volume per batch and bioreactor size. This could either be actual production volume or simulated production volume, if the system is being modeled using process simulation software (e.g., for Techno-Economic Analysis (TEA)).

In addition to temporal positionality and technology maturity, defining a cultivated meat product system requires determining whether the system produces an *intermediate or final product*. We provide the following definitions to help identify the most appropriate classification for a study:

- *Final products*: These can be consumed directly or prepared in a kitchen (home, commercial, or otherwise) for consumption. Business-to-consumer (B2C) applications of cultivated meat LCA would focus on final products, including hybrid or blended products (i.e., cultivated and plant-based) and fully cultivated products. Final products may also be of interest in a business-to-business (B2B) context, for example when retailers calculate Scope 3 emissions.
- *Intermediate products*: These require additional manufacturing or processing before consumption or kitchen preparation (home, commercial, or otherwise) for consumption. They can be used as ingredients in a final product or undergo further processing to become a final product. For example, wet cell mass harvested from a proliferation bioreactor would not be directly prepared as a food product. Additional steps - at minimum, centrifugation and filtration - would be needed to create a final product. Intermediate product impact reporting is likely to only be valuable in a business-to-business (B2B) context.

When defining the product system and study scope, additional considerations for prospective LCAs of cultivated meat include technology selection, technology upscaling, scenario development, and stakeholder interactions. For general guidance on these aspects, refer to Arvidsson et al., 2024.

3.1.2 System boundaries

While a cradle-to-grave approach is the theoretical aspiration in life cycle assessment, data limitations in post-production stages can affect the accuracy of results. This is especially the case in agrifood LCAs where individual consumer behaviour varies (e.g., transport mode to/from retail or restaurant, storage, cooking mode and food waste). In such cases, cradle-to-gate system boundaries are often preferable. For cultivated meat LCAs, cradle-to-gate system boundaries should encompass *all phases* up to the stage where the final or intermediate product is ready to be utilized (i.e., leaving the production facility). For example, for an intermediate product, post-harvest processing such as centrifugation and filtration, would need to be included. For a final product, post-harvest processing, blending with plant-based or other compounds, and any additional manufacturing steps (e.g., 3D printing) would need to be included.

For comparative studies (e.g., cultivated meat compared to conventional meat or plant-based meat), it is crucial to harmonize system boundaries across products. Cradle-to-gate system boundaries are usually sufficient, as the downstream stages of distribution, retail and consumption may include minimal differences between the products. That said, there could be differences in shelf-life between cultivated meat and comparator products due to differences in production (i.e., sterile cultivation environment for cultivated meat). This is an important area of future research, and a potential limitation for practitioners to note when undertaking a cradle-to-gate study. Finally, in cradle-to-gate studies, the gate at which the system boundary ends must be clear. Comparisons of cultivated meat with alternatives (i.e., livestock meat, cultivated meat, and hybrid meat) should consider the “processing gate” as the earliest gate at which comparisons can be made (**Figure 1**).

Generally, LCAs of cultivated meat have excluded processes that were assumed to have minimal impact due to their minor mass inputs (e.g., growth factors) and other culture media ingredients. With increasing information available on culture media ingredient manufacturing, processes representing all media ingredients should be included in the system boundary, unless evidence shows that the impact of an ingredient is minor and cut-off can be applied.

Further guidance on this is provided in the “Life Cycle Inventory” section below. In addition, wastewater treatment, cell-line development, and post-processing phases should also be included when data are available.

According to European Commission's Product Environmental Footprint (PEF) guidelines, capital goods should be included into the system boundary only if evidence stating their relevance can be provided (*Annex 1 to 2 Product Environmental Footprint Method*, 2021). In Sinke et al. (2023), the production of the bioreactor had a minor contribution to cultivated meat carbon footprint in 2030; the contributions of capital goods to other impact categories is unknown. There is insufficient evidence available to know whether capital goods (including infrastructure) would have negligible impacts across all recommended impact categories (e.g., resource use, minerals and metals) for all systems. Therefore, it is recommended to include capital goods in LCAs of cultivated meat systems, focusing on production equipment, but allowing exclusion of infrastructure (e.g., buildings, R&D). Each study should include a list of capital goods modeled. For comparisons, capital goods should also be included in the inventory of all systems compared to ensure consistency of system boundaries, unless capital goods have been determined to have a negligible impact for the comparison systems.

3.1.3 Functional unit

As the general aim of cultivated meat is to offer and diversify meat alternatives, it is important to determine the basis on which meat alternatives in particular are compared. Cultivated meat, like other meat, contains water, fat, protein, and other nutrients, so the functional unit can be based on product mass or nutritional qualities. The aim and the target audience of the produced cultivated cells should be clearly established before defining the relevant functional unit, as this facilitates categorizing the cultivated cells as either intermediate or final products (see product system section).

Generally, a product mass- or servings-based functional unit is recommended for LCAs of cultivated meat, as each product is unique with its characteristics and the specifications needed in the market. In addition to product mass, LCA practitioners should report the dry matter content (required) and nutritional profile (if known) of the product(s). This allows the flexibility of considering alternative functional units when comparisons with other product systems are made. LCA practitioners are recommended to present sensitivity analyses with alternative functional units (e.g., that cover nutritional properties of the product(s)) to explore the robustness of results.

3.1.4 Comparisons and comparative assertions

When the study goal includes supporting a public claim about a product, most often by a company or trade group for marketing purposes, this could either take the form of a comparison or a comparative assertion. A comparison can be made on the basis of a single impact category, such as a product carbon footprint. For comparisons, the guidance of ISO 14026:2017, “*Environmental labels and declarations — Principles, requirements and guidelines for communication of footprint information,*” should be followed. A comparative assertion, by contrast, is a claim of overall environmental superiority or equivalence, according to ISO 14050:2020. We refer the reader to ISO14040, ISO14044, and ISO 14050 for guidance on comparative assertions. Of particular note is that both comparisons and comparative assertions both require critical review in accordance with ISO 14071. For B2C studies, this review should be performed by a panel of interested parties. For B2B studies, it is possible to complete a critical review with only one reviewer, but this reviewer must have all of the required competencies for reviewers as laid out by ISO 14071. This should include subject-matter knowledge regarding cellular agriculture. PEF also includes helpful guidance on reviewer competencies to help guide practitioners (Fazio, 2016; *Product Environmental Footprint Category Rules Guidance Version 6.3 — May 2018*, 2018).

For both comparisons and comparative assertions, practitioners should explain why specific comparator or reference products are chosen, and whether this aligns with the scope of the cultivated product (i.e. scale, market, geography, temporal aspects). Practitioners should specify and justify whether a market-average (with indicated ranges of impacts) or state-of-the art comparator is chosen. All relevant life cycle stages must be included, and functional units should be the same across compared systems (*ISO 14026:2017(En)*, 2017; *ISO14040:2006*, 2006).. If a nutritional functional unit (nFU) is used for the study (see functional unit section), the market and target population for the comparator system(s) should be aligned. For prospective LCA, practitioners should indicate how the future comparator systems were chosen and whether future improvements are taken into account.

Comparisons across products with different technology or manufacturing maturity levels must be made cautiously. Cultivated meat technology presently ranges from early to mid-stage maturity, while comparisons are often made

with late-stage mature technologies (e.g., MRL or BioMRL 8-10) like large-scale food production systems (meat, poultry, seafood, or plant-based proteins). We recommend the following best practices:

- Lab and pilot-scale systems can be compared with more technologically mature systems for benchmarking, setting targets, and other activities that support green design
- Primary data from lab and pilot-scale systems can be used to inform commercial scale process simulation and techno-economic assessment (TEA) to support rigorous comparisons with more advanced technologies (e.g., to support a public claim). TEAs of cultivated meat were recently summarized by Goodwin and colleagues (2024). These engineering models of commercial scale production provide most of the flow data needed for an LCA, which would result in a simulated commercial scale LCA. For guidance on environmental TEA, practitioners should consult the newly developed ISO standard (*ISO/TS 14076:2025(En)*, 2025).

Our guidance regarding comparisons does not entirely align with the EU's Product Environmental Footprint (PEF) regulations. In PEF, comparisons are only allowed within a product group, which includes products that belong to the same Product Environmental Footprint Category Rules (PEFCRs). There is no PEFCR for cellular agriculture or cultivated meat products, and most comparisons that practitioners seek to make will be to other product groups, such as livestock meat, seafood, plant-based protein sources, insects, algae and microbial proteins.

3.2 Life Cycle Inventory

Practitioners commonly identify the collection of life cycle inventory (LCI) data as the most challenging aspect of an LCA. We outline the essential requirements for consistent and reliable LCI of cultivated meat and introduce a new decision tree practitioners can use in the LCI phase, while also addressing the key challenges associated with data collection.

3.2.1 Data Quality

The quality of data used in an LCI can substantially influence the uncertainty of life cycle impact assessment (LCIA) results. Ideally, when conducting an LCI for an existing product or service system, the highest quality is associated with primary data in the foreground system, and in the background system, data that is obtained from

suppliers. These options are often unavailable, and secondary data from literature and databases is utilized, which can have varying accuracy depending on the method chosen for LCI collection or generation (Fazio et al., 2020).

ISO recommends (or requires, in the case of comparative assertions) specifying data quality requirements (DQR) during Goal and Scope definition (ISO 14044:2006 4.2.3.6). These domains (e.g., time-related coverage, geographical coverage) are the framework for data quality assessment using either qualitative or semi-quantitative approaches. There are several methods to semi-quantitatively assess data quality, including but not limited to the International Reference Life Cycle Data System (ILCD), ecoinvent, and PEF. When using data from literature and databases, according to PEF method's data quality criteria, the two minimum requirements for a dataset to be compliant with the Environmental Footprint method are (I) completeness and (II) methodological appropriateness and consistency (*Product Environmental Footprint Category Rules Guidance Version 6.3 — May 2018*, 2018). Additionally, Weidema et al. (2013) developed a pedigree matrix for assessing the quality of data sources indicating their reliability, completeness, temporal correlation, geographical correlation, and further technological correlation with the product or system under assessment.

To our knowledge, there currently exists no data quality pedigree matrix tailored specifically for the LCI of emerging technologies. Cultivated meat studies should assess data quality at least qualitatively and ideally with a semi-quantitative, pedigree matrix type approach. When it comes to LCI of cultivated meat systems, at least the following factors should be taken into account when evaluating quality of secondary datasets:

- *Temporal representativeness*: Datasets must be the most current available for conventional LCA, and forward-looking for prospective LCA, i.e., using *premise* (PRospective EnvironMental Impact asSEment) library (see paragraph on electricity below). If the background system is modelled, it is crucial to avoid its temporal mismatch with the foreground system, unless it is not expected to considerably change from status quo (Arvidsson et al., 2018). When using prospective datasets, it is recommended to employ either predictive scenarios or scenario ranges, according to Arvidsson et al. (2018).
- *Technological representativeness*: Datasets should correspond to ingredients with food or feed purity levels, as utilizing technical or pharmaceutical purity level compounds can lead to inaccuracies in the energy requirements for manufacturing. That is, except for cases when pharmaceutical grade inputs may be

required for production (e.g., with particular cell types). Within any single study, it is essential to maintain consistency by using ingredients of the same grade and state the grade. Finally, in prospective studies, the ingredients used for scaled-up production of CM should be considered to be produced in large-scale manufacturing as well.

- *Geographical representativeness*: Correlation of the geographical location of the studied system with its LCI data is crucial in the estimation of midpoint environmental impact categories, such as land use, water scarcity, or biodiversity, and especially endpoint impact indicators, which are tied to a specific location. In the same way, the accuracy of the LCI data is tied to the geographical representativeness of the electricity mixes used in a specific area.

3.2.2 Cell Cultivation

Currently, the primary data from cultivated meat manufacturing plants is largely proprietary (Nikkhah et al., 2024), and secondary data for culture media ingredient production is also difficult to access, particularly if they are chemical and pharmaceutical ingredients (Abbate et al., 2024; Parvatker & Eckelman, 2019; Wernet et al., 2008, 2009, 2010, 2012). To inventory cell cultivation processes at the production facility, data may be measured if accessible (e.g., through power metering or monitoring) or sourced from reports provided by academic laboratories and companies, interviews, and surveys. Such data includes, for example, experimental data on cell yield, media inputs per unit of cell yield, use of electricity, heat and other materials.

Culture media contains numerous chemicals and synthesized organic compounds. Amino acids, glucose, vitamins, and minerals have been identified as the biggest contributors to most impact categories (Tuomisto, 2022). However, there is a lack of available LCI data for these components, and LCA practitioners often have to use proxies. Proxies in LCI lead to greater uncertainty of LCIA results, depending on the contribution of each ingredient to the total environmental impact of the product. A comprehensive list of best available inventory data used for culture media in published LCAs is provided in the Supplementary Material (SM). It should be used by practitioners as part of the inventory decision tree process (see “Decision Tree” section below). **Table 3** shows a summary of inventory data gaps for commercial scale, food- or feed-grade media components, which have been represented to date with proxies of varying data quality or omitted from analyses. While improving data quality across media components is

important, given published findings on the impacts of amino acids in basal media, recombinant proteins, and growth factors, these components should be prioritized for inventory development (Marinussen & Kool, 2010; Mattick et al., 2015; Trinidad et al., 2023). Plant-based hydrolysates have been identified as a potential replacement for synthetically produced amino acids in prior TEAs and LCAs (Humbird, 2021; Sinke et al., 2023); inventory data for commercial scale production of protein hydrolysates is also a critical need for the field.

3.2.3 Electricity

According to PEF, when assessing existing or planned production of a particular producer, supplier-specific electricity mixes should be used if available (*Annex 1 to 2 Product Environmental Footprint Method*, 2021). This market-based method of electricity accounting applies only to countries, where there is a system of reporting renewable energy purchases (certificates of the guarantee of origin), e.g., in EU member states and economic areas (WRI, 2015). In cases where the production is located in a country with renewable energy purchase tracking, but there is no primary data on sources of consumed electricity, we recommend using country-specific residual mixes. Residual mixes represent energy sources that exclude those claimed by the guarantees of origin and help avoid double counting of the same electricity consumption (Association of Issuing Bodies, 2023). For some countries, the residual mixes are known, and, for example, for European countries (EU-27, Serbia, Switzerland, Norway, and Iceland) are available for LCA modelling in ecoinvent. In all the other cases, we recommend using a location-based approach to electricity accounting, i.e., an average electricity mix of a country.

For prospective LCA studies, it is recommended that projected electricity mixes correspond to the anticipated years of late-scale production (Abbate et al., 2024; Sacchi et al., 2022). For reference, the *premise* database developed by Sacchi et al. (2022) provides reliable projections of various electricity mixes for prospective LCAs extending to the year 2060. Python library *premise*, a tool that links the ecoinvent inventories with future socio-economic scenarios provided by integrated assessment models (IAM) such as REMIND (REgional Model of Investment and Development) and IMAGE (Integrated Model to Assess the Global Environment), is open-source and can be used with different software (Sacchi et al., 2022).

If there is no information on what voltage electricity mix is used in the product system, we recommend following this approximation and applying same logic to each specific case: 1) the medium voltage grid is applicable to most cases of food manufacturing plants, including large-scale CM production, as well as laboratory scale production, since they are usually located in university campuses; 2) if the use phase is modelled, the low voltage grid would be more suitable for residential areas.

3.2.4 Transportation

In order to adequately consider transportation of raw materials to ingredient manufacturing and from ingredient manufacturing to the cultivated meat production system, it is advised to use market activities (e.g., fromecoinvent), or if not available - estimate the transportation from suppliers to the factory in accordance with section 7.14.2 of PEFCR recommendations (*Product Environmental Footprint Category Rules Guidance Version 6.3 — May 2018*, 2018).

3.2.5 Cleaning, sterilization, and wastewater treatment

Bioreactor clean-in-place and sterilize-in-place processes (CIP/SIP) are necessary for multi-use vessels to abate potential contamination issues from adventitious agents and ensure product safety (*Cultivated Meat Bioprocess Design | Deep Dive | GFI*, 2021). Therefore, CIP/SIP should be included within the system boundary of CM LCAs if reusable systems (i.e. stainless steel reactors) are employed (Djislav et al., 2021). CIP focuses on the internal cleaning of bioreactors and associated piping without disassembly and proper procedures are dependent on the application in which the bioreactor is being used and the reactor type (Moerman et al., 2014). Detergent and rinse cycles are satisfactory for cultivated meat production processes as the cell culture media is not as complex as those used for microbial or fungal fermentation (Chisti & Moo-Young, 1994). Practitioners can use the CIP inventory process described in Tuomisto et al. (2022). Pre-clean and post-clean rinse water flows should be purified and modeled using ultrapure water or water that is processed using reverse osmosis. Volumes of water may be set at 25% of the overall volume of the reactor, in alignment with Sinke et al. (2023). The SIP inventory can follow that of Tuomisto et al. (2022) in which steam at 121.5°C is used for sterilization.

Treatment of wastewater from cultivated meat facilities should be included in the system boundary. Wastewater treatment has previously been modeled using wastewater treatment from vegetable processing as a proxy (Sinke et al., 2023) or using heat or chemical treatment prior to drain disposal (Tuomisto et al., 2022). Because wastewater may have high amounts of ammonia, lactate, and other metabolites via spent media, it is critical that appropriate treatment systems are modeled to avoid underestimating burdens. Methods for tofu wastewater treatment can be used as a proxy, as this wastewater is also protein- and sugar-rich. Coagulation–flocculation process followed by a membrane separation (macro-, nano-, and ultrafiltration and reverse osmosis) are established and studied methods of tofu wastewater purification (Albi & Kartohardjono, 2020; Sabarudin & Kartohardjono, 2020; Purnawan et al., 2021). Similarly, flocculation followed by ultrafiltration and reverse osmosis has been used in the treatment of wastewater from microbial protein production (Järviö et al., 2021). Wastewater from microbial protein production is generally rich in nutrients and organic matter (Albi & Kartohardjono, 2020; Sabarudin & Kartohardjono, 2020). The LCI for different effluent treatment methods can be, for instance adopted from Soleimani et al. (2025), where an approach for modular LCA of wastewater was developed, with the modules of best available technologies being suggested in a decision tree, depending on the characteristics of the treated effluents (Soleimani et al., 2025). CIP/SIP processes demand additional energy, chemicals, and water, generating wastewater, making their inclusion in the LCI essential to fully capture the environmental footprint.

3.2.6 Decision Tree

Considering the challenges listed above, we have created a decision tree (**Figure 2**) to assist LCA practitioners and improve the efficiency of LCI data collection for cultivated meat systems. This tool is applicable to most unit processes in cultivated meat production and is based on the decision tree for scaling-up novel technologies by Tsoy et al. (2020) and the hierarchy of chemical LCI generation methods, developed by Parvatker and Eckelman (2019). Depending on the circumstances, the decision tree offers varying LCI collection and generation methods and examples from peer-reviewed LCA studies (**Table 4**).

3.3 Allocation methods

Allocation choices in cultivated meat LCA pertain to the production of the inputs, cultivated meat production processes, and the production of livestock and plant-based products used for comparison. In all cases, allocation

should be avoided if it is possible to divide the unit processes in sub-processes and collect the inputs and outputs related to sub-processes as recommended in ISO 14044 as the first priority (ISO, 2006). The second option in the ISO 14044 allocation hierarchy to expand the product system to include the additional functions related to the co-products is not recommended here as this method is seen as a consequential LCA approach. As the second step, the ISO 14044 allocation hierarchy guides to allocate based on physical relationship between the inputs and outputs. However, this option is rarely feasible, for instance, in agricultural processes where the whole crop needs to be produced to get the grain seeds. Therefore, we recommended using economic allocation, as it reflects the drivers of the production process. For instance, mass based allocation might assign the highest proportion of the impacts to a low value by-product instead of the main product.

Economic allocation should be applied to the production of inputs for cultivated meat processes (e.g., energy, culture medium ingredients, and materials). Challenges include proprietary processes and prices, and non-existent production processes for future studies. To derive prices/costs where they do not exist, it is ideal to do a techno-economic analysis (TEA) and use cost of production as a proxy for market price. Another option is to assume the price of the ingredient is equal to one with a similar function on the market. If no information exists to make a price assumption, practitioners should make their best assumption and justify it, while including alternatives in a sensitivity analysis. To support more robust economic allocation, future research could establish databases with average prices for co-products valid for specified periods (e.g., 5 years); such databases would be useful to reduce variability due to fluctuations in price.

Cultivated meat production may have multiple products. Two examples include co-metabolites from the cells or utilization of spent media, where it may be possible to extract valuable substances from the media or the leftover media may be possible to use as fertilizer. The recommendation for retrospective studies and prospective studies are as follows:

- *Retrospective studies:* Model systems as they are at baseline. For example, if media is not recycled, the study should reflect that. Scenarios can be used to explore alternative designs for extracting valuable substances from the spent media. Economic allocation shall be applied to the co-products. If prices are not available, the prices of the products that the co-products are replacing can be used as a proxy.

- *Prospective studies:* At baseline, 100% of burdens should be allocated to cultivated meat because whether co-products will be produced (and their economic values) is uncertain. Scenarios can be used to explore creation of co-products from, for example, waste media (e.g., lactate recovery).

In cases when cultivated meat is compared with livestock meat or other alternatives, economic allocation is preferable to use also for the comparator products. However, if LCA results based on economic allocation are not available, it is also possible to use other allocation methods for the comparator products. System expansion can be used as a sensitivity analysis to compare whether avoiding allocation changes the conclusions of the study.

3.4 Life cycle impact assessment

3.4.1 Impact assessment methods and impact categories

Several impact assessment methodologies have been developed for LCAs based on ISO 14040 and 14044 standards. Of the seven peer-reviewed cultivated meat LCAs published, each study utilizes a different life cycle impact assessment method or methods (**Table 1**). We do not recommend a specific LCIA method for all cultivated meat LCAs, though the Environmental Footprint method was strongly considered. Although there is currently an ongoing global LCIA harmonization effort being coordinated through UNEP, at the time of writing, the Global Life Cycle Assessment method (GLAM) launched is unavailable in LCA software packages (*GLAM - Life Cycle Initiative*, 2024). While the LCIA method(s) chosen are at the practitioner’s discretion, practitioners should review the “Facilitating cross-study comparisons” section for guidance on publishing standardized LCIA results to advance the field.

Table 1 summarizes the impact categories included in peer-reviewed cultivated meat LCA literature. While many impact categories were assessed at midpoint, climate change, water consumption, land use, and energy use impacts were reported across most studies. These categories align with those generally used in LCAs of food products (see Poore and Nemecek, 2018). Climate change, water consumption (ideally water scarcity, if production locations are known), land use, and energy demand are recommended as the minimum set of impact categories for cultivated meat LCAs. Given the role that agriculture plays in water quality impairment through nitrogen and phosphorus flows and air quality impairment through ammonia emissions, eutrophication potential and particulate matter formation impact categories are recommended to be included in addition to the minimum set (Bouwman et al.,

2013). Practitioners should report as many additional impact categories as is feasible, ideally the full suite of categories used in their LCIA methods.

In the case of climate change, in addition to reporting impact category results (i.e., CO₂ equivalent emissions), disaggregated greenhouse gas inventories should be included and reported separately to enable the reader to recalculate emissions using different climate change metrics. This is particularly material for studies that compare cultivated meat with ruminant products, given differences in the lifetime of methane and carbon dioxide (Allen et al., 2018). Especially in these comparative studies, the importance of different greenhouse gases can be discussed and a sensitivity assessment using different climate change indicators can be included.

For water, water use impacts are represented quite differently across LCIA methods. In ReCiPe, the water consumption impact category is uncharacterized inventory results (i.e., 1 m³ of withdrawal = 1 m³ of water consumption impact), whereas the AWARE method for water use impact is scarcity-weighted (i.e., 1 m³ of withdrawal in a scarce basin has a greater impact than 1 m³ withdrawn in a water-rich basin). While water scarcity is a more useful measure of impact than water consumption, estimating scarcity-weighted water use requires a thorough understanding of the production geographies for major processes throughout the supply chain. For cultivated meat, inventory data is scarce, often proxied, or simulated; it may not be feasible to accurately locate production of key inputs. Thus, water scarcity is ideal to include but not required at this time.

It is important to note that the recommended LCIA methods are not specifically designed for prospective studies. Impact assessment is by and large not tailored to estimate the potential impacts of future product systems at this point in time. Examples can be found for only a small number of impact categories (Arvidsson et al., 2024) — this is an area for future research.

3.4.2 Facilitating cross-study comparisons

In these guidelines, we attempt to balance needs and constraints that will vary across LCAs. To advance the field, we urge LCA practitioners to publish their inventories, which should include material and energy flows for unit processes, along with the datasets, literature sources, or other methods employed in LCI generation. Because this

may not be possible due to proprietary data, practitioners should *at least* include LCIA results for the cultivated meat system(s) under study using the following specifications to facilitate recalculation of results for cross-study comparisons. Practitioners should report LCIA results for the cultivated meat system(s) using ReCiPe 2016 Midpoint and cumulative energy demand (CED) with the following system boundary: cradle-to-manufacturing gate (i.e., processing gate represented in **Figure 1**, or an earlier gate if an intermediate product), without packaging, including capital goods, and disclosing dry matter percentage for the product. These can be published as supplementary materials if ReCiPe and CED are not the primary LCIA methods for the study. Finally, in addition to reporting impact assessment results for climate change (i.e., CO₂ equivalent emissions), practitioners should include and report disaggregated greenhouse gas inventories separately to enable recalculation of emissions using different climate change metrics.

3.5 Presentation and interpretation of results

Life cycle stage-specific results should be shown for all impact categories. The life cycle stages can vary depending on the system design. At a minimum, results should be shown separately for production of media, proliferation, and differentiation stages if possible. For comparability between published studies, it should be possible to recalculate results at the preferred system boundary (e.g., separate grouping of impacts related to packaging). Because losses and wastes in the supply chain induce additional impacts in upstream stages, these contributions should be quantified explicitly to enable recalculation of results for different system boundaries. For example, a cradle-to-grave study that includes wastes should include the percent contribution of waste/loss at each life cycle stage so that a cradle-to-gate boundary could be recalculated.

3.5.1 Managing and treating uncertainty

Addressing the uncertainty associated with LCA results requires multiple approaches. Uncertainty assessment should indicate the range of confident results based on the uncertainty of underlying input data in LCA models. Sensitivity analyses generally aim to assess whether study design and methodological choices (e.g., assumptions, boundary conditions) could influence the general high level conclusions from an LCA study.

Quantitative uncertainty assessment should be used when uncertainties for individual parameters in the LCA model are quantifiable (i.e., mean or median and standard deviation are available). The predominant method of quantitative uncertainty assessment used in LCA is Monte Carlo Simulation (MCS), which is available in major LCA softwares. MCS uses input parameter uncertainties to propagate a distribution of results for each impact category, rather than providing a point estimate of results. Based on available guidance, if MCS is used, practitioners should use 100 to 1,000 iterations (Heijungs, 2020; Mendoza Beltran et al., 2018). The ideal number of runs will be study dependent, and a more accurate approach would be to stop MCS when the coefficient of variance of the output distribution stabilizes; this would require repeated simulations at increasing numbers of runs to determine when this occurs and may not be feasible for most practitioners. It is important to note that there does not exist standardized guidance on uncertainty assessment in LCA generally at the time of writing. There is continued debate on the value and applications of MCS in the field, much less in future-oriented LCAs (Heijungs, 2020).

In line with the ISO standards, all cultivated meat LCAs should include sensitivity analyses. In addition to allocation and functional unit decisions, key parameters subject to sensitivity analysis in cultivated meat LCAs include: energy sources (e.g., electricity grid mix), growth media and feedstocks (use efficiency, ingredients, proxy choice, cut off criteria, improved production practices for prospective studies using retrospective databases), and waste management. For electricity grid mixes, practitioners can take different approaches depending on goal and scope. For example, for a country-specific study, different regions within the country could be used (see Trinidad and Ashizawa, 2023); for a global study, different countries that represent diverse grid types could be used (see Sinke et al., 2023). For media ingredients, it is recommended to conduct sensitivity analyses with ingredients or groups of ingredients (e.g., a set of amino acids) that are represented with proxies, especially if they are hotspots in the baseline analysis. Additionally, complex (undefined) media components, such as hydrolysates, that exhibit batch to batch variation should be subject to sensitivity analysis. The magnitude of variation may be unknown, in which case, it is sufficient to list this as a limitation and area of future research.

In prospective LCAs, where quantified uncertainty metrics may be unreliable or infeasible to generate, scenarios and sensitivity analyses can be combined and used as an approach to test the robustness of results. For the development of scenarios, practitioners should explain what approach to scenario development is taken, and why,

e.g. probable or extreme scenarios (see Tsoy et al. 2020). If time and resources allow, practitioners should also consider including stakeholders to be able to develop robust and practical scenarios (Ott et al., 2023; Tsoy et al., 2020). Ultimately, for proper prospective analyses that include a change in technology maturity (i.e., ex-ante) there is a need for forward-looking background databases (van der Giesen et al., 2020). Newer LCA platforms, such as Brightway, include tools to prospectively project background datasets (*Brightway LCA Software Framework — Brightway Documentation*, n.d.). If prospective databases are not available, this poses additional uncertainty, which can be partially treated by sensitivity analysis on improved production of key parts of the supply chain (e.g., inputs).

4 Conclusion

LCAs are particularly complex for emerging technologies like cultivated meat, where much of the science remains under development or proprietary. The guidance generated here by an international expert working group will support practitioners in conducting high quality, more transparent and comparable LCAs of cultivated meat to advance the field. Much work remains to fill inventory data gaps, particularly for culture media components such as recombinant proteins, growth factors, amino acids, and protein hydrolysates. Filling these gaps will require continued collaboration with industry and an openness to pool and share data. Additionally, further research that advances prospective LCA methods generally - from inventory databases to impact assessment methods - is also needed to advance cultivated meat LCA. Overall, these guidelines are a much needed starting point, and best practice should continue to evolve. Continued collaboration between researchers and industry across novel foods and animal agriculture systems will be needed.

Declarations

Competing interests

Nicole Tichenor Blackstone, Anisiya Pavlova, Kirsten R Trinidad, Amin Nikkhah, Sergiy Smetana, Ashley Green, Ira Bhattarai, Tamar Meshulam, Cresha Gracy Nadar, Julian Quandt, and Natalie Ronco have no competing interests to declare.

Pelle Sinke and Nicole Imholz are consultants to various companies and NGOs active in the field of cultivated meat and conventional animal farming.

Martin Heller has offered consultancy and performed environmental impact assessments for companies throughout the food and agriculture sector, including cultivated products and conventional livestock products.

Joe Duncan-Duggal has completed environmental impact assessments on behalf of a range of private sector food businesses throughout the food system. This has included both organisations producing alternative and animal protein products, as well as those serving food containing either or both.

Brad Ridoutt has undertaken food systems research related to environmental issues for a variety of private sector organizations and Australian government agencies. This has included Dairy Australia and Meat and Livestock Australia.

Tamar Makov has offered consultancy and performed environmental impact assessments for cellular agriculture companies including cultivated products.

Will Barnes is working on an LCA of cultivated meat as part of a CASE funded PhD studentship with a cellular agriculture company partner.

Shashank Goyal is working on a EU funded project 'FEASTS - Fostering European Cellular Agriculture for Sustainable Transition Solutions.

Greg Norris is working on an LCA of cultivated meat for a private company. He first completed a scoping LCA, and is now working on an in-depth LCA.

Data availability

Best available inventory datasets for commercial scale culture media are listed in the Supplementary Material. Valid licenses may be required to inventory datasets, depending on the database listed and their terms.

Author contributions

Conceptualization: Nicole Tichenor Blackstone, Amin Nikkhah, Hanna Tuomisto; **Methodology:** Nicole Tichenor Blackstone, Hanna Tuomisto; **Data collection (culture media inventory):** Kirsten Trinidad, Amin Nikkhah, Anisiya Pavlova, Martin Heller, Pelle Sinke; **Original draft preparation:** Nicole Tichenor Blackstone, Anisiya Pavlova, Amin Nikkhah, Hanna Tuomisto, Kirsten Trinidad. All authors edited and approved of the final manuscript.

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Tables

Appendix Table 1. List of co-authors and affiliations.

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Joe Duncan-Duggal	Chief Scientific Officer	Foodsteps	Number 22 Mount Ephraim, Tunbridge Wells, England, TN4 8AS	LCA of cellular agriculture, LCA of animal production systems, ISO standards
Brad Ridoutt	Principal Research Scientist	1) Agriculture and Food, Commonwealth Scientific and Industrial Research Organisation (CSIRO) 2) Department of Agricultural Economics, University of the Free State	1) Clayton South, Melbourne, VIC 3169, Australia 2) Bloemfontein 9300, South Africa	ISO standards, LCA of animal production systems
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Julian Quandt	Senior Consultant / Doctoral Researcher	1) corsus-corporate sustainability GmbH 2) Augsburg University	1) Großneumarkt 50, 20459 Hamburg, Germany 2) Universitätsstraße 2, 86159 Augsburg, Germany	LCA of animal production systems, ISO standards, LCA of cellular agriculture
Natalie Ronco	Undergraduate student	Pembroke College, University of Cambridge	Trumpington St, Cambridge CB2 1RF, United Kingdom	LCA of cellular agriculture

Table 1. Summary of study designs and results for published cultivated meat LCAs (Rodríguez Escobar et al., 2021; Scharf et al., 2020)

	(Tuomisto & Teixeira de Mattos, 2011)	(Smetana et al., 2015)	(Mattick et al., 2015)	(Kim et al., 2022)	(Tuomisto et al., 2022)	(Sinke et al., 2023)	(Risner et al., 2025)
Locations	Spain, US, Thailand	Global	US	US	United Kingdom	Global	Global
Functional Unit	1kg cell biomass (cell type not defined)	1kg ready to eat product	1kg CHO cell biomass	1 kg novel burger (blended product with cells and plants)	1 kg C2C12 cells with 7 days differentiation period	1 kg of high protein CM product	1 kg of CM (wet basis)
Nutrient composition	30% dry matter, 19% protein	None disclosed	17% dry matter, 7% protein content	None disclosed	30% dry matter, 20% protein	20-30% dry matter, 18-25% protein of total weight, 0-12% other	30% dry matter content (70% protein, 15% lipids, 10% carbohydrates, 5% nucleic acids)
System boundaries	Cradle-to-gate	Cradle-to-plate	Cradle-to-factory gate	Cradle-to-factory gate	Cradle-to-factory gate	Cradle-to-factory gate	Cradle-to-factory gate
LCI principle	Attributional	Attributional	Attributional	Attributional	Attributional	Attributional	Attributional

Cell type	Stem cells from animal embryo	Stem cells from animal embryo	Chinese hamster ovary (CHO) cells	“Bovine muscle and fat”	Mouse skeletal muscle cells (C2C12)	“Meat cells”	Chinese hamster ovary (CHO) cells
Feed Source	Cyanobacteria hydrolysate	Cyanobacteria hydrolysate	Serum free medium supplemented with soy hydrolysate	Serum-containing media (formulation undisclosed)	Serum-supplemented media and serum free media	Biomass converted to glucose, 75% amino acids from soy hydrolysate, 25% from microbial/chem prod	Essential 8 (E8)/Beefy-9) (B9) growth media, corn (glucose)
Bioreactor Type	Cylinder stirred tank	Cylinder stirred tank	Stirred tank (prof, diff)	Undisclosed	Hollow fiber (prolif and diff)	Stirred-tank (prolif), perfusion with scaffolds (diff)	Stirred Tank
Production Time	60 days	60 days	5 days proliferation, 3 days differentiation	Undisclosed	23 days (16 prolif, 7 days diff)	42 days	Undisclosed
LCIA Method	GWP: IPCC 2006, Energy use: Primary energy, Land use: land occupation, Water use: Water Footprint Network	ReCiPe V1.08, IMPACT 2002+	Cumulative energy demand (CED), eco footprint, CML ‘01	CML-IA, Cumulative Energy Demand (CED), ReCiPe 2016 Midpoint (E)	ReCiPe Midpoint 2016 (H) Method, Cumulative Energy Demand (CED)	ReCiPe Midpoint 2016 v1.1, Cumulative Energy Demand (CED)	Tool for Reduction and Assessment of Chemicals and other Environmental Impacts (TRACI) 2.1
Impact Categories	Energy use, GHG emissions, land use, water use	Land use, global warming, energy, water use, depletion of resources, ecotoxicity, acidification	Global warming, eutrophication potential, land use	GHG emissions, energy use (aggregated renewable and non), land use, water use	Full suite of categories reported from above LCIA methods	Full suite of categories reported from above LCIA method	Smog, acidification, respiratory effects, non carcinogenic, ecotoxicity, global warming potential, carcinogenic, eutrophication, fossil fuel depletion

Range of reported results for GWP (kg CO2-eq)	1.9 - 2.2	23.9 - 24.6	3.0 - 25.0	1.93 - 4.09	4.9 - 25.2	2.2 - 24.8	12.31-1508.3
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Table 2: General correspondence between technology readiness and production scale for cultivated meat applications

Correspondences		Production scale		
		Lab	Pilot	Commercial
Good Food Institute typology ¹		R&D and bench scale	Pre-pilot and pilot	Industrial and commodity
	Bioreactor size (L)	< 25	25 - 999	1,000+
	Output per production cycle (kg)	< 10	10 - 999	1,000+
Generalized technology maturity ²		BioMRL 1-3, TRL 1-3 ³	BioMRL 4-6	BioMRL 7-10
Example study		Retrospective LCA by Trinidad and Ashizawa et al., 2023	Prospective LCA by Tuomisto et al., 2022	Prospective LCA by Sinke et al., 2023

¹ Harsini and Swartz 2024

² Establishing a TRL or BioMRL is a significant task requiring a Technology Readiness Assessment (TRA) or Manufacturing Readiness Assessment (MRA) (Smanski et al., 2022). This table provides a general correspondence between scale and technology maturity, can be used by LCA practitioners as a starting point and should not be substituted for a TRA or MRA.

³ Range of TRLs is provided for lab scale due to the close correlation between TRL and BioMRL at early stages of readiness (Smanski et al. 2022).

Table 3. Media ingredients with inventory proxies or no data for commercial scale, food/feed grade components.

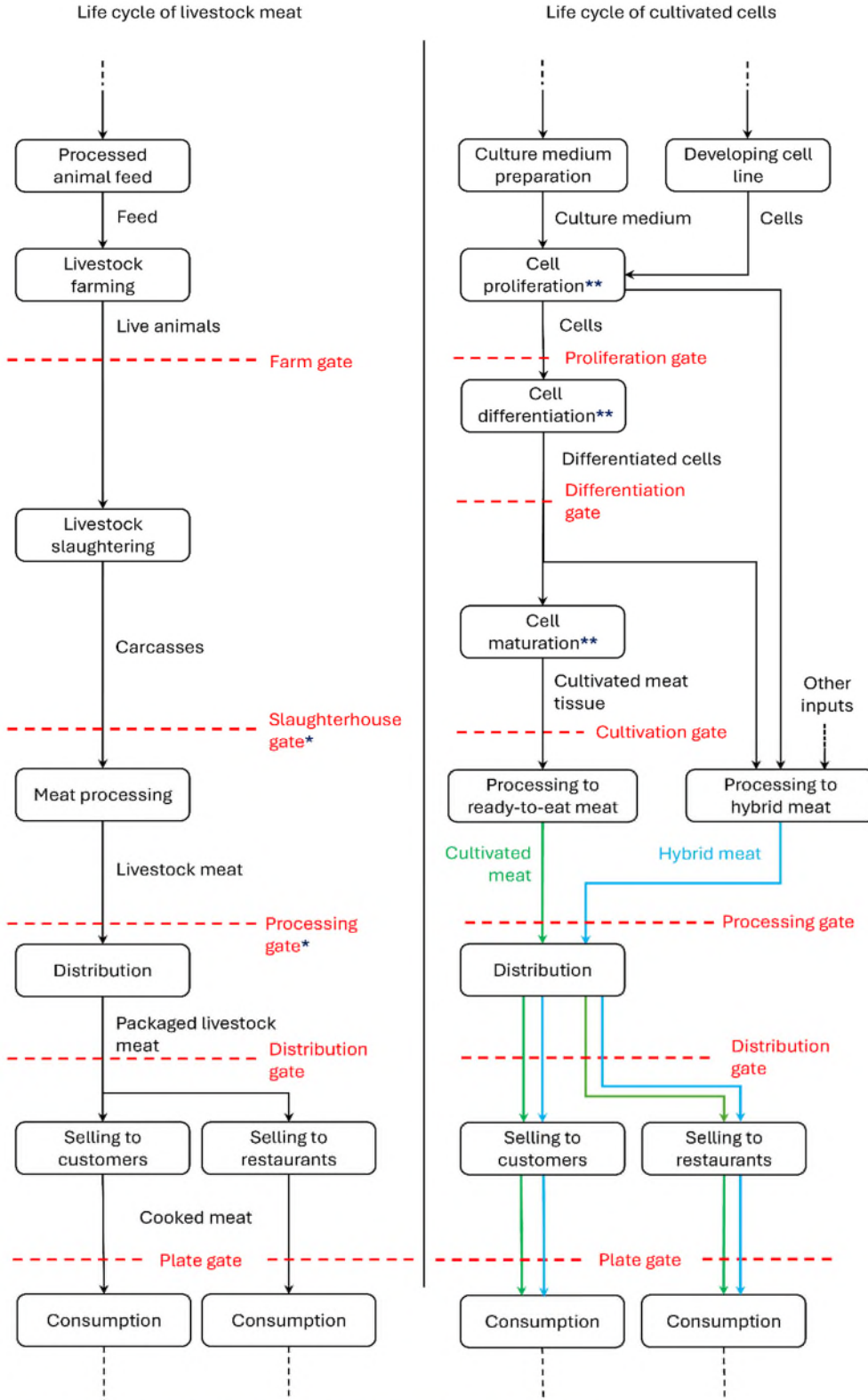
Category	Ingredient currently represented with a proxy or no data available
Amino acids	Alanine, asparagine, aspartic acid, cysteine, cystine, phenylalanine, proline, serine, tyrosine
Vitamins and minerals	Biotin, choline chloride, d-calcium pantothenate, folic acid (B9), i-inositol, niacinamide (B3), pyridoxal hydrochloride, pyridoxine hydrochloride, riboflavin (B2), thiamine hydrochloride, vitamin B12

Fatty acids	Arachidonic acid, cholesterol, linoleic acid, linolenic acid, lipoic acid, myristic acid, oleic acid, palmitic acid, phosphatidylcholine, stearic acid, and thioctic acid
Inorganic salts	Ammonium metavanadate, copper chloride, cupric sulfate, ferric citrate, ferric nitrate, magnesium chloride, molybdic acid (ammonium), nickel chloride, sodium metasilicate, sodium selenite, stannous chloride, zinc sulfate heptahydrate
Recombinant proteins and growth factors	Albumin, Fibroblast growth factor-2 (FGF2-G3), IGF-1, Insulin, Neuregulin 1, Transforming growth factor beta-3 (TGFβ1), Transferrin

Table 4. LCI collection and generation methods recommended for cultivated meat LCA (to be used alongside Figure 2).

LCI collection and generation method	Description	Examples
Use primary data or datasets	These include manufacturer facility data , environmental product declarations (EPD), company sustainability publications, LCI databases (e.g. ecoinvent, Sphera’s LCA Database, etc.), or an industry-specific database shared by an industry association. These sources, however, have their own limitations, e.g. the data can represent another geographical area, be outdated, or lack transparency, and this should be reflected in the data quality assessment of the LCA study (Parvatker & Eckelman, 2019). At the time of publication, there is no association for cultivated meat producers, however collecting a transparent and reliable industry inventory database would significantly help improve the quality of cultivated meat LCA papers.	(Parvatker & Eckelman, 2019)
Process simulation	This method allows modeling a hypothetical scaleup of a lab- or pilot-scale production, with the software estimating the material and energy flows required for an industrial level chemical production (Parvatker & Eckelman, 2019; Tsoy et al., 2020). There is a range of open-source and commercial options for process simulation software. Process simulation is a step in TEA, so TEA software and outputs can be used. This method requires knowledge of the specific technology and chemical engineering, and can be otherwise quite time and resource consuming.	(Parvatker & Eckelman, 2019)
Manual process design calculations	Processes can be modeled without special software, when there is not enough process data for simulation, but sufficient “to parametrize design equations with mass and energy balances to provide material and energy requirements and process emissions”, according to Parvatker & Eckelman (2019). Piccino et al. (2016) developed a framework for scaling up laboratory-level processes to an industrial level of chemical production.	(Parvatker & Eckelman, 2019; Piccino et al., 2016; Wernet et al., 2012)

<p>Model the process based on stoichiometric reactions</p>	<p>This method is used to create an approximate LCI for known chemical reactions, when there is no process data available. This method is useful for biochemical and chemical ingredient process modeling. Stoichiometric reactions provide information on the amount of reactants (input) and reaction products (output of the product under assessment, coproducts, and emissions-byproducts), but lack data on subsequent steps of separation, energy use, waste generation, and other real life conditions of industrial chemical production (Parvatker & Eckelman, 2019). Furthermore, stoichiometric ratios are usually not representative of amounts of reactants used in industrial chemical production (Parvatker & Eckelman, 2019). However, the simplicity of the execution requirements made it the most commonly used method for chemical LCI generation, e.g. it is widely used in ecoinvent datasets, together with average data for chemical reaction for energy (steam, natural gas, and electricity), water and infrastructure use (activity 'chemical factory, organics'). Wernet et al. (2012), cited in the chemical inventory sources in ecoinvent, provides approximations on typical chemical production conditions, such as 95% reaction yield, 2MJ energy used in the form of steam and 0.333 kWh of electricity, according to (Hischier et al., 2005). Additionally, air emissions of volatile chemicals are assumed as 0.2% of the input, and wastewater is estimated to reduce 90% in organic material during treatment (Köhler et al., 2007).</p>	<p>(Parvatker & Eckelman, 2019)</p>
<p>Molecular structure models (MSM)</p>	<p>MSM derives information on material and energy required for production of a chemical solely based on its molecular structure. This method is applicable to chemical ingredients used for cultivated meat manufacturing. It is advised to use MSM only in cases where the impact of the component contributes less than 5% to the total impact (Wernet et al., 2012).</p>	<p>(Parvatker & Eckelman, 2019; Wernet et al., 2008, 2009, 2010, 2012)</p>
<p>Use a proxy</p>	<p>A proxy is a process that mostly resembles the unit process technologically and has LCI data available. A proxy LCI is far from ideal and has to be replaced with a more accurate LCI generation method whenever possible, but it is still considered better than omitting the unit process entirely (Parvatker & Eckelman, 2019).</p>	<p>(Parvatker & Eckelman, 2019)</p>
<p>Use the data from Culture Media Harmonized List of Flows (SM)</p>	<p>A culture media harmonized list of flows was developed in order to aid cultivated meat LCA practitioners, collecting inventories from peer-reviewed studies available at the time of publication. It provides a review of ingredients of culture media and flows used in those studies to represent each ingredient flow and provides detailed information on dataset names if databases were used (e.g. ecoinvent, Agribalyse) or literature sources if the inventory was modelled based on those. It should be noted that most of the ingredients in these LCA papers were modelled using proxies.</p>	<p>This study, refer to SM</p>



*Slaughtering and processing phases can happen in the same facility
 **Post-processes occur i.e., cleaning of facility equipment

Fig 1. Overview of the partial life cycles of livestock meat and cultivated cells. Red dashed lines refer to the boundary gate following each stage.

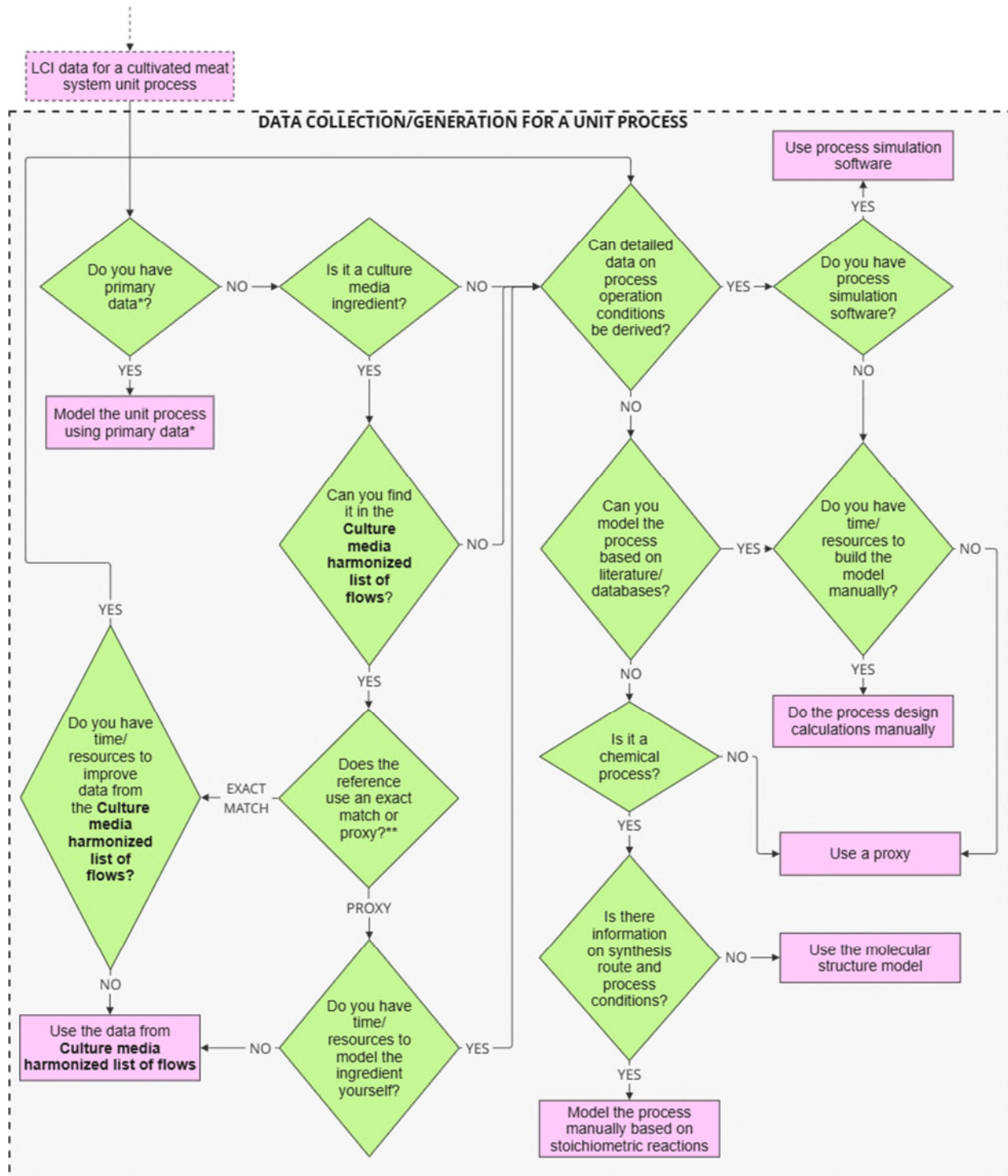


Fig. 2. A decision tree to support LCA practitioners in LCI collection for cultivated meat systems.

* Here, primary data refers to manufacturer’s data or datasets listed in Table 4.

**Find this information in the Culture Media Harmonized List of Flows (SM): compare the flow name with the flow used in the corresponding referenced paper.