Guidelines for environmental life cycle assessment of cultivated meat

Nicole Tichenor Blackstone, Anisiya Pavlova, Kirsten R. Trinidad, Amin Nikkhah, Pelle Sinke, Martin Heller, Joe Duncan-Duggal, Brad Ridoutt, Sergiy Smetana, Tamar Makov, Shira Shabtai, Ashley Green, Will Barnes, Ira Bhattarai, Shashank Goyal, Nicole Imholz, Tamar Meshulam, Cresha Gracy Nadar, Gregory A. Norris, Julian Quandt, Natalie Ronco, Hanna L. Tuomisto

Angaben zur Veröffentlichung / Publication details:

Tichenor Blackstone, Nicole, Anisiya Pavlova, Kirsten R. Trinidad, Amin Nikkhah, Pelle Sinke, Martin Heller, Joe Duncan-Duggal, et al. 2025. "Guidelines for environmental life cycle assessment of cultivated meat." *The International Journal of Life Cycle Assessment* 30 (12): 2943–63. https://doi.org/10.1007/s11367-025-02562-4.

The International Journal of Life Cycle Assessment (2025) 30:2943–2963
https://doi.org/10.1007/s11367-025-02562-4

LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

Guidelines for environmental life cycle assessment of cultivated meat

Nicole Tichenor Blackstone[1,2] · Anisiya Pavlova[3,4] · Kirsten R. Trinidad[2] · Amin Nikkhah[1] · Pelle Sinke[5] · Martin Heller[6] · Joe Duncan-Duggal[7] · Brad Ridoutt[8,9] · Sergiy Smetana[10,11] · Tamar Makov[12] · Shira Shabtai[12] · Ashley Green[13] · Will Barnes[14] · Ira Bhattarai[15] · Shashank Goyal[16] · Nicole Imholz[5] · Tamar Meshulam[12] · Cresha Gracy Nadar[17] · Gregory A. Norris[18] · Julian Quandt[19,20] · Natalie Ronco[21] · Hanna L. Tuomisto[3,4,15]

Received: 10 June 2025 / Accepted: 12 October 2025 / Published online: 3 December 2025

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). Even among more recent studies that include cradle-to-gate boundaries and fully cultivated (versus hybrid) products, comparisons of environmental impacts with meat have been mixed (Mattick et al. 2015; Tuomisto et al. 2022; Sinke et al. 2023; Risner et al. 2025). For example, three of four of these studies demonstrated lower global warming potential and blue water use, but higher energy use relative to beef at baseline or in scenario analyses (Mattick et al. 2015; Tuomisto et al. 2022; Sinke et al. 2023). The fourth study, which garnered significant media attention, however suggested that cultivated meat could have a much higher global warming potential than beef (Risner et al. 2025). This has led to public confusion regarding the environmental performance of cultivated meat and also debate among LCA practitioners about best practices for the field.

Due to the nascency of the cultivated meat industry, numerous assumptions need to be made in order to perform

Communicated by Matthias Finkbeiner.

Extended author information available on the last page of the article

Table 1 Summary of study designs and results for published cultivated meat LCAs. Updated from 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	1 kg cell biomass (cell type not defined)	1 kg ready to eat product	1 kg 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, carcinogenics, 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	12.31–1508.3.31.3

LCA. In particular, 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 and 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 disagreement, 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. 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. When drafts were sent for re-review, major comments were maintained in a new version of the document with answers from the co-chairs' research groups regarding how they were addressed, and the prior reviewed manuscript version was also included for reference. During this review period, one additional 90-minute online meeting was held to come to consensus on a subset of topics identified during review. This discussion was curated by the co-chairs with slides that included the topics where there was disagreement on what to recommend, a summary of the divergent viewpoints, and in some cases, a proposal for how to proceed. This call included negotiation between coauthors, facilitated by the co-chairs, with consensus achieved when the group visually and verbally agreed with the resulting recommendation. All coauthors reviewed the final manuscript in detail prior to submission, indicated that they approved with submission, and did not flag any recommendations with which they disagreed. 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 14,044 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). It is important to note that the use of the term prospective here does not entail a particular inventory modelling approach (i.e., attributional vs. consequential), despite the original definition of the term as consequential (Weidema et al., 2004).

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.

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 (Smanki et al. 2022)

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

According to ISO 1440, system boundary is a "set of criteria specifying which unit processes are part of a product system" (ISO, 2006a). 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 behavior 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 (Fig. 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 criteria 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 a quantified performance-basis on which meat alternatives in particular are compared (i.e., the functional unit). 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).

According to the ILCD Handbook, the functional unit should be described by answering to the following questions: what, how much, how well, and for how long (ILCD Handbook: General guide for Life Cycle Assessment - Detailed guidance, 2010). Most of the published LCA papers of cultivated meat answer the first two questions by defining the functional unit as 1–1000 kg of cultivated meat. The question about "how well" is rarely addressed. A nutritional functional unit could be an option to be used, but the full nutritional content of cultivated meat is generally not available for LCA practitioners. How long –question is not relevant for food products as food can only be eaten once. For this aspect, the shelf-life of the product could be considered but currently there is no evidence whether cultivated meat would have any longer shelf-life compared to conventionally produced meat. A longer shelf-life could be taken into account by assuming less wasted products along the life cycle of the product if the system boundaries of the study extend to retail or consumption. 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 (i.e., moisture free) 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 Comparative assertions

When the study goal includes supporting a public claim about the overall environmental superiority or equivalence of a product by a company or trade group for marketing purposes, this is a comparative assertion according to ISO 14044. Importantly, a comparative assertion is different than a comparison, which can be made on the basis of a single impact category, such as a product carbon footprint (see ISO 14026:2017, "*Environmental labels and declarations — Principles*, *requirements and guidelines for communication of footprint information*,"). Making a comparative assertion requires meeting several criteria (see Supplementary Material 1 (SM 1), including impact assessment with "a sufficiently comprehensive set of category indicators" (ISO 14044) and critical review in accordance with ISO 14071. For B2C studies, critical 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

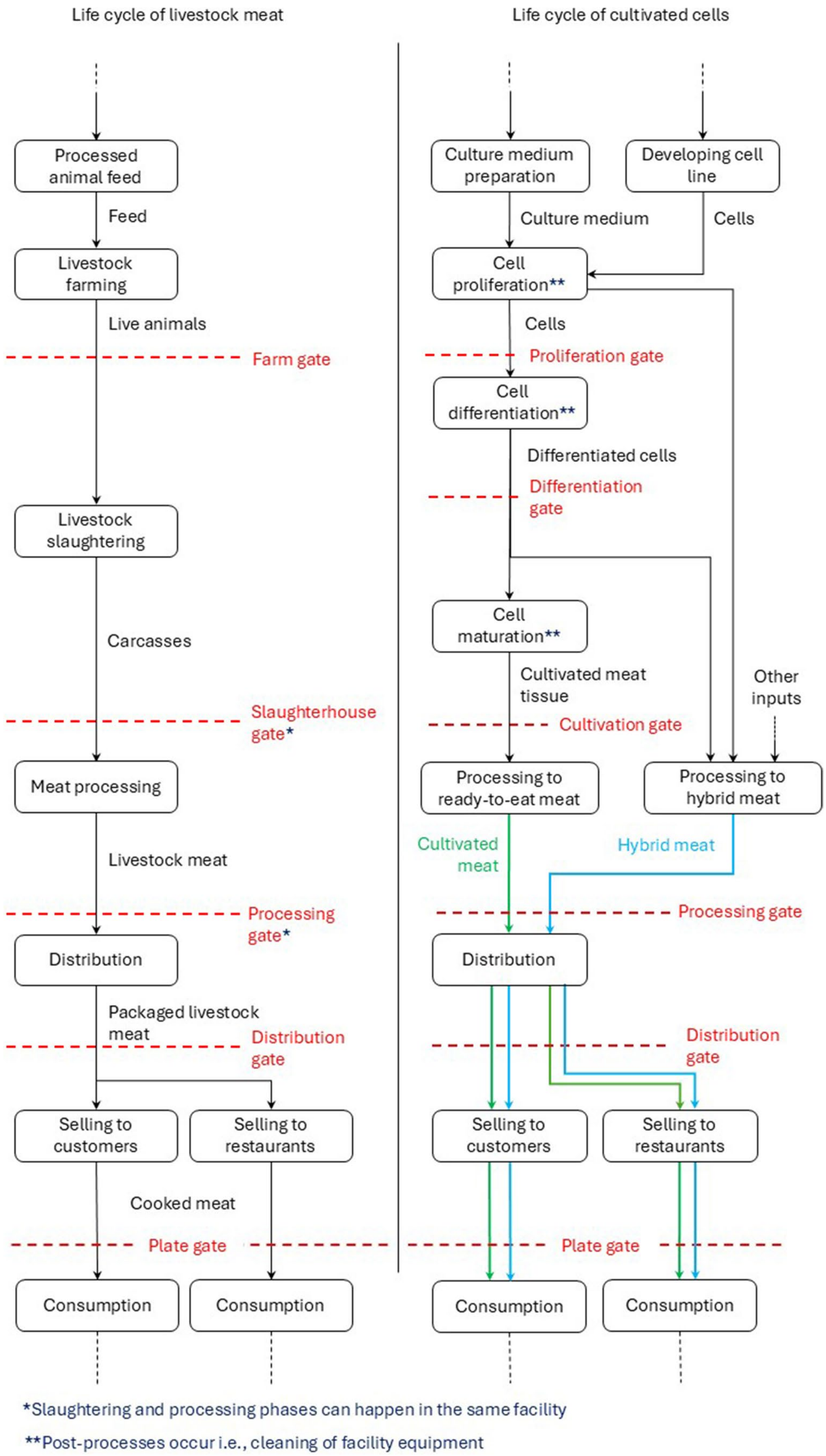

Fig. 1 Overview of the partial life cycles of livestock meat and cultivated cells. Red dashed lines refer to the boundary gate following each stage

help guide practitioners (Fazio 2016; *Product Environmental Footprint Category Rules Guidance Version 6.3 — May 2018*, 2018).

For 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.

Comparing products with different technology or manufacturing maturity levels must be done 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 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) (ILCD Handbook: General guide for Life Cycle Assessment - Detailed guidance, 2010), Ecoinvent-pedigree (Weidema et al. 2013), and PEF (Damiani et al. 2022). 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, in the Ecoinvent-pedigree method, 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. Therefore, our recommendation is to assess data quality at least qualitatively against the study's own data quality goals, which can be designed and set beforehand. It is recommended to describe in detail the quality of data regarding generally recognized dataset quality factors (temporal, technological, and geographical representativeness, reliability, completeness, and methodological appropriateness and consistency) (Weidema et al. 2013; PEF), While all data quality factors are important and should be included, the following aspects of temporal, technological, and geographical representativeness should be taken into account for CM LCA specifically:

- *Temporal representativeness*: Datasets must be the most current available for conventional LCA, and forward-looking for prospective LCA, e.g., 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).
- *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.

For prospective studies, inventory development must account for technological development, reflecting an anticipated rate of change over a specific timeframe according to a set of well-justified assumptions. These sets of assumptions describing the system at a future time are known as "future scenarios" and should ideally be developed using established methods, such as those found in the field of foresight (Bisinella et al. 2021). In prospective LCAs, scenarios and inventory are best developed in tandem, following an iterative, transparent process such as Scenario-based Inventory Modelling for Prospective LCA (SIMPL), which is suitable for "small-scale" prospective LCA of emerging technologies like cultivated meat (Langkau et al. 2023). This process informs both foreground and background inventory development and can help improve the temporal, technological, and geographical data quality factors discussed above.

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 and 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 et al., 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 Supplementary Material 2 (*SM 2*). 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 and 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.

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

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 (Sotos, 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* is an open source 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) (Sacchi et al. 2022). *Premise* is also available as ScenarioLink plugin in an open source LCA software Activity Browser (AB), which is built on software package Brightway2 written in python (Steubing et al. 2020; *Brightway LCA Software Framework — Brightway Documentation*). Using both *premise* and AB equires valid ecoinvent license and login credentials, which may be not available if the ecoinvent license comes in a package with a commercial LCA software. Practitioners should consult the documentation for *premise* and their LCA software for further information.

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., from ecoinvent), or if not available - estimate the transportation from suppliers to the factory in accordance with Sect. 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 (Djisalov et al. 2021). Similarly, treatment of wastewater from cultivated meat facilities should be included in the system boundary. The technology of all processes involved in CM production is likely to progress with time and developing future scenarios for auxiliary systems using methods such as SIMPL, described above is ideal (Langkau et al. 2023). However, this can be challenging due to time- and resource-related constraints. If needed, practitioners can model the best available technology at the time of study for cleaning, sterilization, and water treatment, together with future oriented background datasets. The following information on and examples of CIP/SIP and wastewater treatment modeling can be useful for CM LCA practitioners.

CIP focuses on the internal cleaning of bioreactors and associated piping without disassembly. 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 tendency to form biofilms or exhibit filamentous growth is lower compared to microbial or fungal fermentation (Chisti and Moo-Young, 1994). For 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 and Kartohardjono 2020; Sabarudin and 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 and Kartohardjono 2020; Sabarudin and 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 (Fig. 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 14,044 as the first priority (*ISO*, 2006). The second option in the ISO 14,044 hierarchy to expand the product system and include the additional functions related to the co-products is not recommended here, as this method is seen as a consequential LCA approach. That said, views in favor of using substitution in ALCA have been presented; we refer practitioners to Provost-Savard and Majeau-Bettez (2024) for further reading.

If allocation is needed, Step 2 of the ISO 14,044 hierarchy indicates that allocation should reflect "the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system." ISO 14,044 was amended in 2020 to provide additional clarification about physical causality allocation:

> "Physical allocation can be applied when a physical, i.e., causal, relationship can be identified between the inputs, outputs and co-products of the multifunctional process. Such a relationship exists when the amounts of the co-products can be independently varied. How the amounts of inputs and outputs (emissions and waste) change following such a variation can be used to allocate the inputs and outputs to the varied co-product." (ISO 14044:2006, Amendment 2).

In agri-food systems, it is often not possible to independently vary the amounts of co-products; this makes physical causality allocation infeasible in many cases. For this and other reasons, biophysical allocation as applied to some agrifood systems has been subject to critique (Mackenzie et al. 2017). No biophysical causality methods presently exist for cultivated meat, and there are significant barriers to their development. For example, metabolic processes are not well understood for cell lines used in cultivated meat production. Even if ISO-compliant physical causality allocation factors could be developed, it is important to consider the implications of doing so. Amendment 2 of ISO 14,044 (Part D.3.3.), states that "for co-products with significantly different economic values, physical allocation

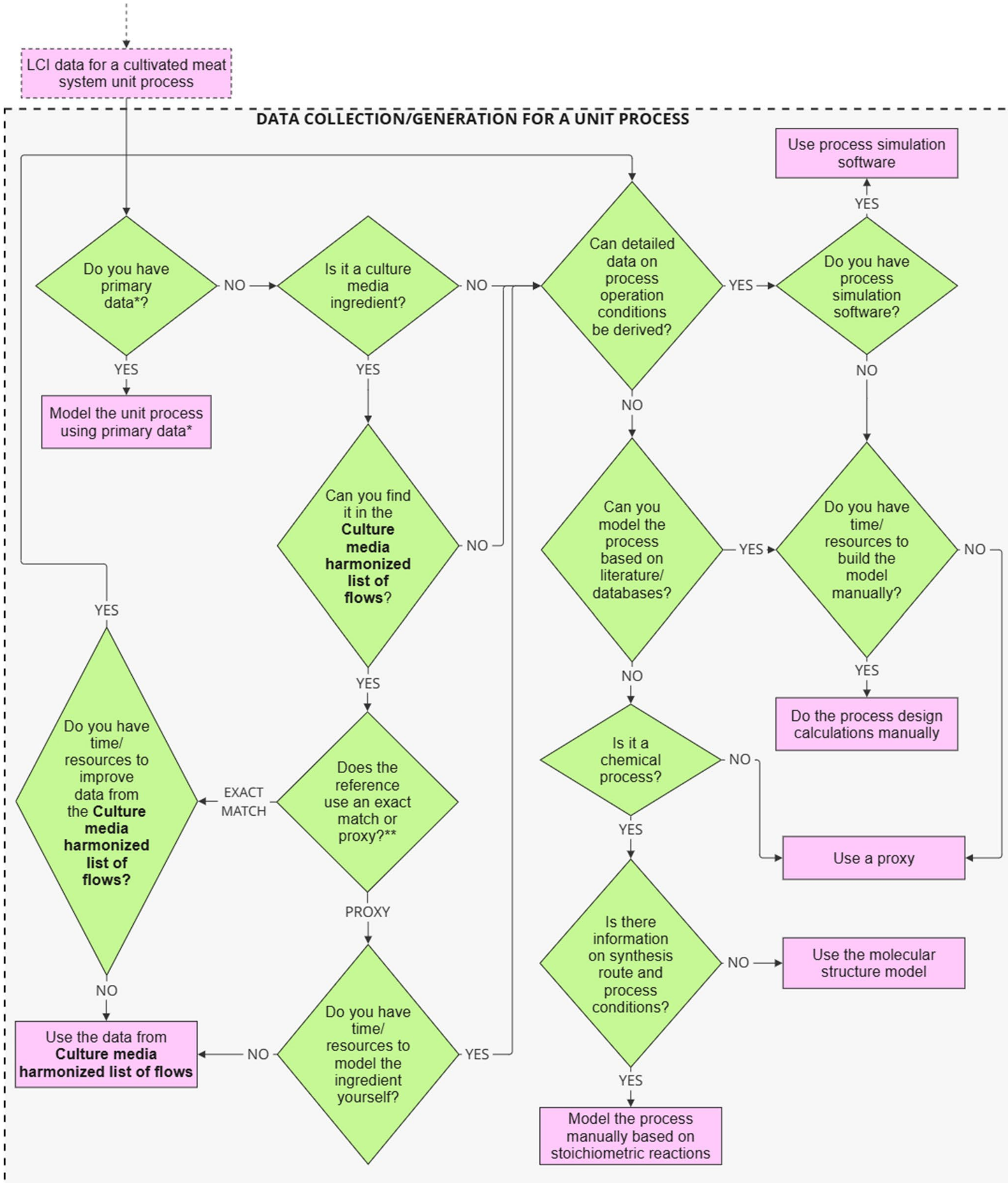

Fig. 2 A decision tree to support LCA practitioners in LCI collection for cultivated meat systems * Here, primary data refers to manufacturer's data or datasets listed in Table 4 **Find this information in the Culture Media Harmonized List of Flows (*SM*): compare the flow name with the flow used in the corresponding referenced paper

Table 4 LCI collection and generation methods recommended for cultivated meat LCA (to be used alongside Fig. 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 and 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 and 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 and 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 and 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 and Eckelman (2019). Piccino et al. (2016) developed a framework for scaling up laboratory-level processes to an industrial level of chemical production.	(Parvatker and Eckelman 2019; Piccinno et al. 2016; Wernet et al. 2012)
Model the process based on stoichiometric reactions	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 and Eckelman 2019). Furthermore, stoichiometric ratios are usually not representative of amounts of reactants used in industrial chemical production (Parvatker and 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, 2 MJ 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).	(Parvatker and Eckelman 2019)
Molecular structure models (MSM)	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).	(Parvatker and Eckelman 2019; Wernet et al. 2008, 2009, 2010, 2012)
Use a proxy	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 and Eckelman 2019).	(Parvatker and Eckelman 2019)
Use the data from Culture Media Harmonized List of Flows (*SM*)	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.	This study, refer to SM

does not always properly reflect the intention to operate the process" and can "lead to interpretations that are disconnected with business reality." This is true for many agriculture and food products and certainly would be for cultivated meat, if coproducts are produced.

Despite being the least preferred tier in the ISO hierarchy, most practitioners utilize economic value allocation (Kyttä et al. 2022; Pelletier et al., 2015). Economic allocation is likely the most feasible option for cultivated meat LCAs, given the lack of data to support biophysical allocation. Economic allocation can 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 that employ economic allocation 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 if it is uncertain whether an output will have economic value in the future (i.e., designated as co-product or by-product). Scenarios can be used to explore creation of co-products from, for example, waste media (e.g., lactate recovery). If the system design includes co-products, economic allocation shall be used as explained for retrospective studies.

Regardless of the allocation method applied, the reasoning behind the allocation method should be clearly stated, including the limits this choice puts on interpretation. Additionally, any allocation decisions should be subject to sensitivity analysis. These comparisons can provide additional information to support decision making.

In cases when cultivated meat is compared with livestock meat or other alternatives, allocation methods should match across products. However, if results based on identical allocation methods are not available, it is also possible to use other allocation methods for the comparator products, which must be paired with sensitivity analyses. 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 14,040 and 14,044 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. ISO 14,044 requires the inclusion of all relevant impacts, with any exclusions clearly justified (ISO, 2006b). As a starting point, practitioners should include *at minimum* climate change, water consumption (ideally water scarcity, if production locations are known), land use, and energy demand in cultivated meat LCA, based on our expert consensus and alignment with impact categories generally used for agri-food systems (See Poore and Nemecek 2018) 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 that are relevant to their particular application and 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. We recognize that datasets may be provided to LCA practitioners under non-disclosure agreements (NDA). While individual datasets may not be disclosable (e.g., due to trade secret recipes for culture media), there are large variations in the level of detail that can provided by life cycle inventories to enable replication. Having a transparent inventory is a prerequisite for academic publishing and a critical strategy to help advance the field. While it is ideal to report inventory data at the level of unit processes, ISO 14044:2006 permits aggregation that is consistent with the goal of the study and explained in the goal and scope phase (Sect. 4.3.3.3). Another strategy is to provide system level inventories for trade secret processes, also known as “system processes” in commercial LCA software, which provide the cradle-to-gate elementary flow inputs and outputs for said process. We urge practitioners working with industry clients to design agreements that enable publication of inventories in any possible form that allows replication.

Practitioners should also 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 Fig. 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 software. 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 could 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.

Appendix

Table 5 List of co-authors and affiliations

Name	Title/Role	Affiliation(s)	Affiliation address(es), including country	Expertise
Nicole Tichenor Blackstone	Assistant Professor	1) Friedman School of Nutrition Science and Policy, Tufts University 2) Department of Biomedical Engineering, Tufts University	1) 150 Harrison Ave Boston, Massachusetts, USA 2) 4 Colby St Medford, Massachusetts, USA	LCA of cellular agriculture, LCA of animal production systems, ISO standards
Anisiya Pavlova	Doctoral Researcher	1) Future Sustainable Food Systems – Research Group, Department of Agricultural Sciences, Faculty of Agriculture and Forestry 2) Helsinki Institute of Sustainability Science (HELSUS)	1) P.O. Box 27, 00014 University of Helsinki, Helsinki, Finland 2) P.O. Box 4, 00014 University of Helsinki, Helsinki, Finland	LCA of retail products (pharmaceuticals, food supplements, and health & beauty products), LCI databases, LCA of cellular agriculture, ISO standards
Kirsten R Trinidad	Doctoral Researcher	Department of Biomedical Engineering, Tufts University	4 Colby St Medford, Massachusetts, USA	LCA of cellular agriculture
Amin Nikkhah	Research Assistant Professor	Friedman School of Nutrition Science and Policy, Tufts University	150 Harrison Ave Boston, Massachusetts, USA	LCA of cellular agriculture
Pelle Sinke	Senior Researcher/Consultant	LCA Department – Food Chains Team, CE Delft	Oude Delft 180, Delft 2611 HH, the Netherlands	LCA of cellular agriculture, LCA of animal production systems, ISO standards
Martin Heller	Senior Consultant	Merieux NutriSciences|Blonk	1250 24th St. NW, Suite 8107, Washington DC, 20,037 USA	LCA of cellular agriculture, LCA of animal production systems, ISO standards
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
Sergiy Smetana	Head of Department/Professor	1) German Institute of Food Technologies (DIL e.V.) 2) Institute of Food Quality and Food Safety, University of Veterinary Medicine Hannover, Foundation	1) Prof.-von-Klitzing-Str. 7, 49610 Quakenbrück, Germany 2) Bischofsholer Damm 15, 30173, Hannover, Germany	LCA of cellular agriculture, LCA of animal production systems, ISO standards
Tamar Makov	Associate Professor of Sustainable Innovation	Management Department, Ben-Gurion University of the Negev	P.O.B. 653, 8,410,501 Beer-Sheva, Israel	LCA of cellular agriculture
Ashley Green	PostDoctoral Researcher	ETH Zurich, Sustainable Food Processing Laboratory	Schmelzbergstrasse 9 8092 Zürich Switzerland	LCA of animal production systems, LCA of cellular agriculture
Will Barnes	Doctoral Researcher	Department of Life Sciences/Institute of Biological, Rural and Environmental Sciences (IBERS)	Aberystwyth University, Ceredigion, United Kingdom	LCA of cellular agriculture
Ira Bhattarai	Doctoral Researcher	Natural Resources Institute Finland (Luke)	Tietotie 4, 31,600 Jokioinen, Finland	LCA of animal production systems, LCA biodiversity footprint, LCA of cellular agriculture
Shashank Goyal	LCA Consultant	EurA AG	Krämpferstraße 2, 99,084 Erfurt, Germany	LCA of cellular agriculture

Table 5 (continued)

Name	Title/Role	Affiliation(s)	Affiliation address(es), including country	Expertise
Nicole Imholz	Senior Researcher/Consultant	LCA Department – Food Chains Team, CE Delft	Oude Delft 180, Delft 2611 HH, the Netherlands	LCA of cellular agriculture, LCA of animal production systems, ISO standards
Tamar Meshulam	Doctoral Researcher	Management Department, Ben-Gurion University of the Negev	P.O.B. 653, 8,410,501 Beer-Sheva, Israel	LCA of cellular agriculture
Shira Shabtai	PhD Candidate	Management Department, Ben-Gurion University of the Negev	P.O.B. 653, 8,410,501 Beer-Sheva, Israel	LCA of cellular agriculture
Cresha Gracy Nadar	Postdoctoral researcher	Queensland Alliance for Agriculture and Food Innovation, The University of Queensland	St. Lucia 4072, QLD, Australia	LCA of cellular agriculture
Greg Norris	Director, SHINE@MIT	Sustainability and Health Initiative for NetPositive Enterprise (SHINE)	Massachusetts Institute of Technology, Cambridge, MA 02139, United States of America	LCA of animal production systems, ISO standards, LCA of cellular agriculture
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

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-025-02562-4.

Acknowledgements The authors would like to gratefully acknowledge the Towards Sustainability Foundation for supporting the expert workshop. Open access publication and NTB, AN, and KT were supported by the Agriculture and Food Research Initiative (AFRI) Sustainable Agricultural Systems program, grant no. 2021-699012-35978 from the United States Department of Agriculture (USDA) National Institute of Food and Agriculture. AP and HT were supported by the Moonshot Research and Development Program for Agriculture, Forestry and Fisheries (Cabinet Office, Government of Japan) - grant No. JPJ009237.

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.

Data availability Information on ISO 14044:2006 requirements addressed in this study can be found in Supplementary Material 1 (SM 1). Best available inventory datasets for commercial scale culture media are listed in Supplementary Material 2. Valid licenses may be required to inventory datasets, depending on the database listed and their terms.

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.

References

Abbate E, Garmendia Aguirre I, Bracalente G, Mancini L, Tosches D, Rasmussen K, Bennett MJ, Rauscher H, Sala S (2024) Safe and sustainable by design chemicals and materials—methodological guidance. Luxembourg: Publications Office of the European Union, 2024

Albi LS, Kartohardjono S (2020) The combined process of coagulation-flocculation and membrane separations to treat wastewater from Tofu industry. AIP Conf Proc 030010. https://doi.org/10.1063/5.0003027

Allen MR, Shine KP, Fuglestvedt JS, Millar RJ, Cain M, Frame DJ, Macey AH (2018) A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. Npj Clim Atmos Sci 1(1):1–8. https://doi.org/10.1038/s41612-018-0026-8

Annex 1 to 2 Product environmental footprint method (2021). https://environment.ec.europa.eu/document/download/680503dc-5a19-4f6a-bb92-84d9bfc8f312_en?filename=Annexes%201%20to%202.pdf

Arvidsson R, Tillman A-M, Sandén BA, Janssen M, Nordelöf A, Kushnir D, Molander S (2018) Environmental assessment of emerging technologies: recommendations for prospective LCA. J Ind Ecol 22(6):1286–1294. https://doi.org/10.1111/jiec.12690

Arvidsson R, Svanström M, Sandén BA, Thonemann N, Steubing B, Cucurachi S (2024) Terminology for future-oriented life cycle assessment: review and recommendations. Int J Life Cycle Assess 29(4):607–613. https://doi.org/10.1007/s11367-023-02265-8

Bisinella V, Christensen TH, Astrup TF (2021) Future scenarios and life cycle assessment: systematic review and recommendations. Int J Life Cycle Assess 26(11):2143–2170. https://doi.org/10.1007/s11367-021-01954-6

Bodies A (2023) of I. European residual mixes 2020

Bouwman L, Goldewijk KK, Van Der Hoek KW, Beusen AHW, Van Vuuren DP, Willems J, Rufino MC, Stehfest E (2013) Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. Proc Natl Acad Sci U S A 110(52):20882–20887. https://doi.org/10.1073/pnas.1012878108

Brightway LCA (n.d.) Software framework—brightway documentation. Retrieved December 16, 2024 from https://docs.brightway.dev/en/latest/

Chapman T, Murray S (2023) Life-cycle-assessment-lca-guide-for-alternative-protein-manufacturers.pdf. https://gfi.org/wp-content/uploads/2023/01/Life-Cycle-Assessment-LCA-Guide-for-Alternative-Protein-Manufacturers.pdf

Chisti Y, Moo-Young M (1994) Clean-in-place systems for industrial bioreactors: design, validation and operation. J Ind Microbiol 13(4):201–207. https://doi.org/10.1007/BF01569748

Cultivated meat bioprocess design \textbar Deep dive \textbar GFI (2021) https://gfi.org/science/the-science-of-cultivated-meat/deep-dive-cultivated-meat-bioprocess-design/

Damiani M, Ferrara N, Ardente F (2022) Understanding Product Environmental Footprint and Organisation Environmental Footprint methods. Publications Office of the European Union. https://doi.org/10.2760/11564

Djisalov M, Knežić T, Podunavac I, Živojević K, Radonic V, Knežević NŽ, Bobrinetskiy I, Gadjanski I (2021) Cultivating multidisciplinarity: manufacturing and sensing challenges in cultured meat production. Biology 10(3):204. https://doi.org/10.3390/biology10030204

European Commission (2010) Joint research centre. Institute for environment and sustainability. International reference life cycle data system (ILCD) handbook:general guide for life cycle assessment: detailed guidance. Publications Office. https://data.europa.eu/doi/https://doi.org/10.2788/38479

Fazio S (2016) Review schemes and reviewers' selection criteria in the life cycle data network framework, and at global level. https://doi.org/10.2788/578476

Fazio S, Zampori L, De Schryver A, Kusche O, Thellier L, Diaconu E (2020) Guide for EF compliant data sets. Publications Office. https://doi.org/10.2760/537292

GLAM - Life cycle initiative. (2024) https://www.lifecycleinitiative.org/category/glam/

Goodwin CM, Aimutis WR, Shirwaiker RA (2024) A scoping review of cultivated meat techno-economic analyses to inform future research directions for scaled-up manufacturing. Nat Food 5(11):901–910. https://doi.org/10.1038/s43016-024-01061-3

Harsini F, Swartz E (2024) Trends in cultivated meat scale-up and bioprocessing. The Good Food Institute. https://gfi.org/wpcontent/uploads/2024/05/Trends-in-cultivated-meat-scale-up-and-bioprocessing.pdf

Heijungs R (2020) On the number of Monte Carlo runs in comparative probabilistic LCA. Int J Life Cycle Assess 25(2):394–402. https://doi.org/10.1007/s11367-019-01698-4

Hischier R, Hellweg S, Capello C, Primas A (2005) Establishing life cycle inventories of chemicals based on differing data availability (9 pp). Int J Life Cycle Assess 10(1):59–67. https://doi.org/10.1065/lca2004.10.181.7

Humbird D (2021) Scale-up economics for cultured meat. Biotechnol and Bioeng 118(8):3239–3250. https://doi.org/10.1002/bit.27848

ISO 14026 (2017). https://www.iso.org/standard/67401.html

ISO/TS 14076:2025(en). (2025) https://www.iso.org/obp/ui#iso:std:iso:ts:14076:ed-1:v1:en

ISO14040:2006 Environmental management—Life cycle assessment—Principles and framework (2006) https://www.iso.org/standard/37456.html

ISO14044; Environmental management—Life Cycle Assessment—Requirements and Guidelines. (2006) https://www.iso.org/standard/38498.html

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

Kim S, Beier A, Schreyer HB, Bakshi BR (2022) Environmental life cycle assessment of a novel cultivated meat burger patty in the united States. Sustainability 14(23):16133. https://doi.org/10.3390/su142316133

Kimmel W (2020) Technology readiness assessment guide: best practices guide. In national aeronautics and space administration. https://ntrs.nasa.gov/api/citations/20205003605/downloads/%20SP-20205003605%20TRA%20BP%20Guide%20FINAL.pdf

Köhler A, Hellweg S, Recan E, Hungerbühler K (2007) Input-dependent life-cycle inventory model of industrial wastewater-treatment processes in the chemical sector. Environ Sci Technol 41(15):5515–5522. https://doi.org/10.1021/es0617284

Kyttä V, Roitto M, Astaptsev A, Saarinen M, Tuomisto HL (2022) Review and expert survey of allocation methods used in life cycle assessment of milk and beef. Int J Life Cycle Assess 27:191–204

Langkau S, Steubing B, Mutel C, Ajie MP, Erdmann L, Voglhuber-Slavinsky A, Janssen M (2023) A stepwise approach for scenario-based inventory modelling for prospective LCA (SIMPL). Int J Life Cycle Assess 28(9):1169–1193. https://doi.org/10.1007/s11367-023-02175-9

Mackenzie SG, Leinonen I, Kyriazakis I (2017) The need for co-product allocation in the life cycle assessment of agricultural systems—is biophysical allocation progress? Int J Life Cycle Assess 22(2):128–137. https://doi.org/10.1007/s11367-016-1161-2

Manufacturing Readiness Level (MRL) Deskbook. (2020)

Marinussen M, Kool A (2010) Environmental impacts of synthetic amino acid production. https://website-production-s3bucket-1nevfd7531z8u.s3.eu-west-1.amazonaws.com/public/website/download/f0e6feeb-d39c-45d2-af25-f94d1de9e074/amino-acids.pdf

Mattick CS, Landis AE, Allenby BR, Genovese NJ (2015) Anticipatory life cycle analysis of in vitro biomass cultivation for cultured meat production in the United States. Environ Sci Technol 49(19):11941–11949. https://doi.org/10.1021/acs.est.5b01614

Mendoza Beltran A, Prado V, Font Vivanco D, Henriksson PJG, Guinée JB, Heijungs R (2018) Quantified uncertainties in comparative life cycle assessment: what can be concluded? Environ Sci Technol 52(4):2152–2161. https://doi.org/10.1021/acs.est.7b06365

Moerman F, Rizoulières P, Majoor FA (2014) 10—Cleaning in place (CIP) in food processing. In: Lelieveld HLM, Holah JT, Napper D (eds) Hygiene in food processing, second edition. Woodhead Publishing, pp 305–383. https://doi.org/10.1533/9780857098634.3.305

Nikkhah A, Trinidad K, Kaplan DL, Blackstone NT (2024) Life cycle assessment of Beefy-9 and Beefy-R serum-free culture media for cell-cultivated beef production. Sustain Prod Consum 50:168–176. https://doi.org/10.1016/j.spc.2024.07.023

Ott D, Goyal S, Reuss R, Gutzeit HO, Liebscher J, Dautz J, Degieter M, de Steur H, Zannini E (2023) LCA as decision support tool in the food and feed sector: evidence from R&D case studies. Environ Syst Decis 43(1):129–141. https://doi.org/10.1007/s10669-022-09874-y

Parvatker AG, Eckelman MJ (2019) Comparative evaluation of chemical life cycle inventory generation methods and implications for life cycle assessment results. ACS Sustain Chem Eng 7(1):350–367. https://doi.org/10.1021/acssuschemeng.8b03656

Pelletier N, Ardente F, Brandão M, De Camillis C, Pennington D (2015) Rationales for and limitations of preferred solutions for multifunctionality problems in LCA: is increased consistency possible? Int J Life Cycle Assess 20:74–86

Piccinno F, Hischier R, Seeger S, Som C (2016) From laboratory to industrial scale: a scale-up framework for chemical processes in life cycle assessment studies. J Clean Prod 135:1085–1097. https://doi.org/10.1016/j.jclepro.2016.06.164

Poore J, Nemecek T (2018) Reducing food's environmental impacts through producers and consumers. Science 360(6392):987–992. https://doi.org/10.1126/science.aaq0216

Product environmental footprint category rules guidance version 6.3—May 2018. (2018). https://eplca.jrc.ec.europa.eu/permalink/PEFCR_guidance_v6.3-2.pdf#page=144.31

Provost-Savard A, Majeau-Bettez G (2024) Substitution modeling can coherently be used in attributional life cycle assessments. J Ind Ecol 28(3):410–425. https://doi.org/10.1111/jiec.13480

Purnawan I, Angputra D, Debora SC, Karamah EF, Febriasari A, Kartohardjono S (2021) Polyvinylidene fluoride membrane with a Polyvinylpyrrolidone additive for Tofu industrial wastewater treatment in combination with the Coagulation–Flocculation process. Membranes 11(12):948. https://doi.org/10.3390/membranes11120948

Risner D, Negulescu P, Kim Y, Nguyen C, Siegel JB, Spang ES (2025) Environmental impacts of cultured meat: a cradle-to-gate life cycle assessment. ACS Food Sci Technol 5(1):61–74. https://doi.org/10.1021/acsfoodscitech.4c00281

Rodríguez Escobar MI, Cadena E, Nhu TT, Cooreman-Algoed M, De Smet S, Dewulf J (2021) Analysis of the cultured meat production system in function of its environmental footprint: current status, gaps and recommendations. Foods 10(12):2941. https://doi.org/10.3390/foods10122941

Sabarudin T, Kartohardjono S (2020) The combination of coagulation-flocculation and membrane processes to minimize pollution of Tofu wastewater. Evergreen 7(1):56–60. https://doi.org/10.5109/2740942

Sacchi R, Terlouw T, Siala K, Dirnaichner A, Bauer C, Cox B, Mutel C, Daioglou V, Luderer G (2022) Prospective environmental impact asement (*premise*): a streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. Renew Sustain Energy Rev 160:112311. https://doi.org/10.1016/j.rser.2022.112311

Scharf A, Breitmayer E, Carus M (2020) Review and gap-analysis of LCA-studies of cultured meat

Sinke P, Swartz E, Sanctorum H, van der Giesen C, Odegard I (2023) Ex-ante life cycle assessment of commercial-scale cultivated meat production in 2030. Int J Life Cycle Assess 28(3):234–254. https://doi.org/10.1007/s11367-022-02128-8

Smanski MJ, Aristidou A, Carruth R, Erickson J, Gordon M, Kedia SB, Lee KH, Prather D, Schiel JE, Schultheisz H, Treynor TP, Evans SL, Friedman DC, Tomczak M (2022) Bioindustrial manufacturing readiness levels (BioMRLs) as a shared framework for measuring and communicating the maturity of bioproduct manufacturing processes. J Ind Microbiol Biotechnol 49(5):kuac022. https://doi.org/10.1093/jimb/kuac022

Smetana S, Mathys A, Knoch A, Heinz V (2015) Meat alternatives: life cycle assessment of most known meat substitutes. Int J Life Cycle Assess 20(9):1254–1267. https://doi.org/10.1007/s11367-015-0931-6

Soleimani T, Ferber DL, Junqua G, Ferber ML (2025) An approach for modular environmental life cycle assessment of effluent treatment: configuration of effluent treatment modules based on decision tree tailored to best available techniques. Environ Impact Assess Rev 112:107782. https://doi.org/10.1016/j.eiar.2024.107782

Sotos ME (2015) GHG protocol scope 2 guidance. World Resources Institute, 8. https://www.wri.org/research/ghg-protocolscope-2-guidance

Steubing B, De Koning D, Haas A, Mutel CL (2020) The activity browser—an open source LCA software building on top of the Brightway framework. Softw Impact 3:100012. https://doi.org/10.1016/j.simpa.2019.100012

Trinidad KR, Ashizawa R, Nikkhah A, Semper C, Casolaro C, Kaplan DL, Savchenko A, Blackstone NT (2023) Environmental life cycle assessment of recombinant growth factor production for cultivated meat applications. J Clean Prod 419:138153. https://doi.org/10.1016/j.jclepro.2023.138153

Tsoy N, Steubing B, van der Giesen C, Guinee J (2020) Upscaling methods used in ex ante life cycle assessment of emerging technologies: A review \textbar the international journal of life cycle assessment. Int J Life Cycle Assess 25:1680–1692. https://doi.org/10.1007/s11367-020-01796-8

Tuomisto HL, de Mattos MJT (2011) Environmental impacts of cultured meat production. Environ Sci Technol 45(14):6117–6123. https://doi.org/10.1021/es200130u

Tuomisto HL, Allan SJ, Ellis MJ (2022) Prospective life cycle assessment of a bioprocess design for cultured meat production in Hollow fiber bioreactors. Sci Total Environ 851(Pt 1):158051. https://doi.org/10.1016/j.scitotenv.2022.158051

van der Giesen C, Cucurachi S, Guinée J, Kramer GJ, Tukker A (2020) A critical view on the current application of LCA for new technologies and recommendations for improved practice. J Clean Prod 259:120904. https://doi.org/10.1016/j.jclepro.2020.120904

van der Hulst MK, Huijbregts MAJ, van Loon N, Theelen M, Kootstra L, Bergesen JD, Hauck M (2020) A systematic approach to assess the environmental impact of emerging technologies: a case study for the GHG footprint of CIGS solar photovoltaic laminate. J Ind Ecol 24(6):1234–1249. https://doi.org/10.1111/jiec.13027

Watson E (2024) Cultivated meat in the spotlight at Tufts cellular ag innovation day. https://agfundernews.com/cultivated-meat-in-the-spotlight-at-tufts-cellular-ag-day-focusing-on-science-experiments-that-cannot-scale-is-misleading-people

Weidema BP, Ekvall T, Pesonen HL, et al (2004) Scenarios in life-cycle assessment. Society of Environmental Toxicology and Chemistry (SETAC), Pensacola FL, USA

Weidema BP, Bauer C, Hischier R, Mutel C, Nemecek T, Reinhard J, Vadenbo CO, Wernet G (2013) Overview and methodology. Data quality guideline for the ecoinvent database version 3. St Gallen: Ecoinvent Centre(Ecoinvent Rep 1(v3).), 83–85. https://lca-net.com/files/Overview_and_methodology.pdf

Wernet G, Hellweg S, Fischer U, Papadokonstantakis S, Hungerbühler K (2008) Molecular-structure-based models of chemical inventories using neural networks. Environ Sci Technol 42(17):6717–6722. https://doi.org/10.1021/es7022362

Wernet G, Papadokonstantakis S, Hellweg S, Hungerbühler K (2009) Bridging data gaps in environmental assessments: modeling impacts of fine and basic chemical production. Green Chem 11(11):1826–1831. https://doi.org/10.1039/B905558D

Wernet G, Conradt S, Isenring HP, Jiménez-González C, Hungerbühler K (2010) Life cycle assessment of fine chemical production: a case study of pharmaceutical synthesis. Int J Life Cycle Assess 15(3):294–303. https://doi.org/10.1007/s11367-010-0151-z

Wernet G, Hellweg S, Hungerbühler K (2012) A tiered approach to estimate inventory data and impacts of chemical products and mixtures. Int J Life Cycle Assess 17(6):720–728. https://doi.org/10.1007/s11367-012-0404-0

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Nicole Tichenor Blackstone[1,2] · Anisiya Pavlova[3,4] · Kirsten R. Trinidad[2] · Amin Nikkhah[1] · Pelle Sinke[5] · Martin Heller[6] · Joe Duncan-Duggal[7] · Brad Ridoutt[8,9] · Sergiy Smetana[10,11] · Tamar Makov[12] · Shira Shabtai[12] · Ashley Green[13] · Will Barnes[14] · Ira Bhattarai[15] · Shashank Goyal[16] · Nicole Imholz[5] · Tamar Meshulam[12] · Cresha Gracy Nadar[17] · Gregory A. Norris[18] · Julian Quandt[19,20] · Natalie Ronco[21] · Hanna L. Tuomisto[3,4,15]

✉ Nicole Tichenor Blackstone
Nicole.blackstone@tufts.edu

1 Friedman School of Nutrition Science and Policy, Tufts University, 150 Harrison Ave, Boston, MA 02111, USA

2 Department of Biomedical Engineering, Tufts University, 4 Colby St Medford, Medford, MA 02155, USA

3 Future Sustainable Food Systems – Research Group, Department of Agricultural Sciences, Faculty of Agriculture and Forestry, University of Helsinki, P.O. Box 27, Helsinki 00014, Finland

4 Helsinki Institute of Sustainability Science (HELSUS), University of Helsinki, P.O. Box 4, Helsinki 00014, Finland

5 LCA Department – Food Chains Team, CE Delft, Oude Delft 180, Delft 2611, HH, the Netherlands

6 Merieux NutriSciences | Blonk, 250 24th St. NW, Suite 8107, Washington DC 20037, USA

7 Foodsteps, Number 22 Mount Ephraim, Tunbridge Wells TN4 8AS, England

8 Agriculture and Food, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Clayton South, Melbourne, VIC 3169, Australia

9 Department of Agricultural Economics, University of the Free State, Bloemfontein 9300, South Africa

10 German Institute of Food Technologies (DIL e.V.), Prof.-von-Klitzing-Str. 7, 49610 Quakenbrück, Germany

11 Institute of Food Quality and Food Safety, University of Veterinary Medicine Hannover, Foundation, Bischofsholer Damm 15, 30173 Hannover, Germany

12 Management Department, Ben-Gurion University of the Negev, P.O.B. 653, Beer-Sheva 8410501, Israel

13 Sustainable Food Processing Laboratory, ETH Zurich, Schmelzbergstrasse 9, Zürich 8092, Switzerland

14 Department of Life Sciences/Institute of Biological, Rural and Environmental Sciences (IBERS), Aberystwyth University, Ceredigion, UK

15 Natural Resources Institute Finland (Luke), Latokartanonkaari 9, Helsinki 00790, Finland

16 Sustainability Department, EurA AG, Krämpferstraße 2, 99084 Erfurt, Germany

17 Queensland Alliance for Agriculture and Food Innovation, The University of Queensland, St. Lucia, QLD 4072, Australia

18 Sustainability and Health Initiative for NetPositive Enterprise (SHINE), Massachusetts Institute of Technology, Cambridge, MA 02139, USA

19 Corsus-corporate sustainability GmbH, Großneumarkt 50, 20459 Hamburg, Germany

20 Augsburg University, Universitätsstraße 2, 86159 Augsburg, Germany

21 Pembroke College, University of Cambridge, Trumpington St, Cambridge CB2 1RF, UK