Life Cycle Assessment Guide for Alternative Protein Manufacturers

Best practices for alternative protein companies interested in conducting LCAs

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Executive Summary

Global demand for meat is set to almost double by 2050[1]—and our current system of meat production is already driving 20% of global greenhouse gas emissions.[2] It will be impossible to meet the Paris Agreement without a reduction in conventional animal agriculture.[3] Alternative proteins offer a crucial solution to decarbonize our protein production system, while meeting the global demand for protein.

Evidence of the environmental benefits of alternative proteins, compared to conventional animal-based proteins, stems from a few studies primarily conducted at the industry level.

Such studies demonstrate that plant-based meat can be produced with up to 98% fewer emissions,[4] 93% less land, and 99% less water than conventional meat[5] and that cultivated meat can be produced with up to 92% fewer emissions, 95% less land, and 78% less water than conventional meat.[6] However, most alternative protein companies that want to make company- and product-specific environmental claims lack robust, standardized, and representative supporting data, which has resulted in select companies facing criticisms of greenwashing that damage both individual companies and the industry.

Life cycle assessments (LCAs) are the most widely used tool for quantifying and evaluating the environmental impact of producing goods and services.

Conducted accurately, LCAs provide valuable data to inform environmental, financial, and operational decisions. As with any measurement tool, LCAs benefit from being conducted using a high-quality, consistent methodology to enable accurate assessments and cross-company and -product comparability. However, given the wide variety of LCA methodologies—each of which has a slightly different focus—there is currently a lack of consistency in how LCAs are applied and no customized guidance for how to conduct LCAs of alternative proteins.

This best practice guide provides a standardized approach to undertaking LCAs for alternative protein manufacturers. It is not intended to enable alternative protein manufacturers to undertake LCAs themselves—a highly complex process requiring deep expertise and a high degree of instruction beyond a guide—but rather to enable them to commission an expert LCA provider to design and conduct an effective LCA that helps them reach their objectives, while also meeting international standards and LCA industry best practices.

Key LCA pathways

There are three broad pathways for conducting a food LCA:

1. Commissioning an LCA (full scope)

The gold standard, for which this paper provides guidance, is commissioning a bespoke and comprehensive LCA that measures as much of the product's production process as possible, including how it impacts the environment. While this pathway requires significant expertise and time, which tends to correlate to higher costs, it also produces the most reliable results. Such results can be used to identify environmental burden hotspots, process- or material-based production inefficiencies, and support Environmental Product Declarations (EPDs), among other use cases. A bespoke and comprehensive LCA can cost between USD $50K and $100K, or more, as of 2023.

2. Commissioning an LCA (limited scope)

A second pathway, which reduces the overall cost, follows a similar process as above, but with a more limited scope. This can be achieved by either focusing on a specific part of the production process or reducing the number of environmental issues being assessed. This pathway still provides a level of tailoring to specific manufacturing processes, but it is not comprehensive and may not be appropriate for external reporting. A limited-scope LCA will cost less, potentially as low as USD $20K.

3. Using modeling software

A third pathway uses either expert-assisted LCA modeling software or do-it-yourself (DIY) LCA software. Expert-assisted LCA modeling software is an LCA undertaken through an automated model with a prescribed set of methodological assumptions, options, and impact categories. DIY LCA software is becoming increasingly accurate and offers a quick and easy solution to generating initial impact estimates. Some software is accurate enough to provide certification for impacts such as greenhouse gas (GHG) emissions as long as the specific ingredients and processes are included in the software's underlying dataset. However, manufacturers should be cautious regarding how they use the data generated by such modeling software and be cognizant of the limitations of generic data modeling.

The four phases of an LCA

An LCA has four phases: the goal and scope definition, the inventory phase, the impact assessment phase, and the interpretation phase. The process is iterative and it is common to revisit each phase as the assessment progresses, facilitating deeper scrutiny and clarification of the chosen methodology, study decisions, and results.

1. Goal and scope definition

This first phase is arguably the most critical in an LCA. The study's goal should be described clearly and unambiguously in terms of the intended application, the questions being examined, and the study's target audience. The scope of the study describes the geographic, temporal, and technological coverage of the study in relation to the goal. As part of the scope, the manager of the study at the alternative protein manufacturer (“study manager” or “manager”) will need to outline the functional unit, system boundary, and impact categories:

The **functional unit (FU)** is an easily comparable point of reference to evaluate a product’s inputs (e.g., raw materials, energy) and outputs (e.g., the product being produced, the emissions from the process). The FU must be comparable both within the product life cycle and across similar product life cycles. The FU should be selected with care as the choice may significantly influence results. While there are many different options available, and one can use multiple FUs to compare different elements of a product, alternative protein manufacturers should ensure that at a minimum their LCAs use a mass-based FU such as a 250g uncooked burger patty. This will maximize comparability with other food LCAs.

The **system boundary** refers to the processes and materials that will be included in the study. A typical product life cycle covers five stages: resources/raw materials, processing, transportation and distribution, retail/consumer use, and waste. Ideally, all environmental inputs and outputs that are impacted by a product system should be included in the study. However, this can lead to the study of large and difficult to measure systems. Setting a system boundary forces decisions on what portions of the product’s life cycle to include and what to exclude (e.g., whether to include the manufacturing of a tractor in the production of soybeans). The chosen boundary should reflect what the company is trying to measure and achieve. For instance, if conducting a comparative LCA, the system boundaries must be the same as for the comparison products. This guide recommends that the standard system boundary used for alternative proteins is a cradle-to-factory-gate boundary. In other words, all processes—from raw material production, transportation to the processing facility, and the processing of raw materials into a final product—should be included. Given that the post-factory stages such as distribution to retail locations, retailer and consumer use, and waste will be similar for conventional animal proteins, they will not have a large influence on the results and do not need to be included.

An **impact category** groups different types of environmental impacts, such as carbon dioxide emissions, into environmental categories according to the impact they cause. This categorization simplifies how impacts are represented and makes them more easily understandable. For instance, a product's Global Warming Potential (GWP) indicator includes a range of GHGs, such as methane, nitrous oxide, and carbon dioxide. In addition to grouping the impacts, impact categorization also provides a method to calculate impact in one common unit, referred to as the characterization factor (e.g., GWP is measured in carbon dioxide equivalents or CO_2e).

A critical challenge for LCAs is their comparability to one another, which is made more difficult by the range of impact categories and different methods for characterizing their impact.

As a result, numerous LCA methods have been designed to standardize the process. These methods are designed to guide users on which impact categories to include and their respective characterization factors. Common models include ReCiPe 2016, Impact 2002+, CML 2001, and the European Commission's Product Environmental Footprint (PEF). These methodologies include up to 16 impact categories, not all of which are relevant for alternative proteins.

We recommend that, at a minimum, alternative protein manufacturers include GWP, water use, land use, eutrophication, and acidification in their LCAs. Full definitions and methodological recommendations are provided in this guide.

2. Life cycle inventory analysis (LCI)

The second phase of an LCA includes collecting data on all resources required to create a product and the emissions produced from the process. A critical goal during the LCI phase is retrieving accurate and consistent data. Primary data should be used wherever possible. However, a complete assessment will also necessarily rely on secondary data. Most LCA studies will use one or more secondary data sources to ensure a complete dataset. There are several established and recognized LCA food databases, listed in this guide, that can be used to supplement primary data collection. Two of the leading databases are Ecoinvent and the World Food Life Cycle Assessment Database (WFLDB).

3. Life cycle impact assessment (LCIA)

This next phase focuses on the evaluation of the environmental performance of the system that has been analyzed. Guided by the goal and scope, the LCIA draws together the data from the LCI into the selected impact categories.

4. Interpretation

This final phase of an LCA has two main functions. First, the LCA should be iterative, as highlighted above. Through this iterative approach, the interpretation phase aims to steer the study toward improving the methodology to meet the study's goal. Second, the interpretation aims to provide robust conclusions and recommendations. The interpretation phase achieves these functions through three steps. First, identifying any significant issues with assumptions made throughout the study or with the system boundary. Second, evaluating these issues in terms of their sensitivity or influence on the overall results, including evaluating the completeness and consistency with which the significant issues have been managed. Finally, developing conclusions and recommendations.

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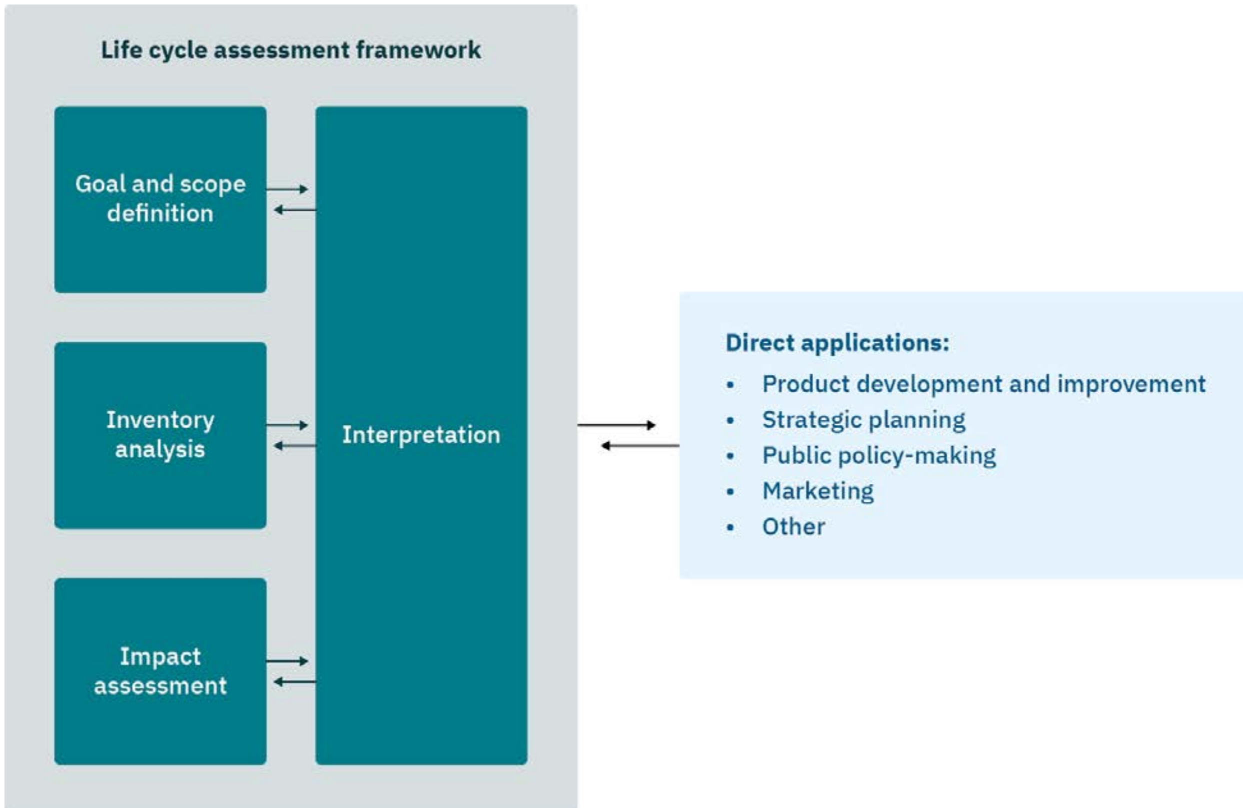
Introduction

In the 1970s, a global shift began that has led to the widespread acknowledgment of the importance of environmental protection and the desire to better measure how the production of goods and services affects the environment. Measurement methodologies have evolved over time, leading to the development and adoption of life cycle assessments (LCAs) as the most widely used tool for quantifying and evaluating the environmental impact of producing goods and services. Conducted accurately, LCAs provide valuable information to inform environmental, financial, and operational decisions. The information provided by an LCA is a critical first step toward improving a company's environmental footprint. The information can also be used to demonstrate the potential for a company's products, such as alternative proteins, to mitigate the contributions of the conventional production system to the climate crisis and to counter greenwashing claims.

What is a life cycle assessment?

The production of any product follows a pathway through space and time, referred to as a life cycle. The production of food starts with agricultural production, upstream transportation, processing, and manufacturing and flows through to downstream transportation, consumption, and disposal. At each stage of this life cycle, resources such as land, water, and energy are used (inputs) to create products and waste (outputs). Some of these outputs are intended and desirable, such as the food itself, while others are not, such as greenhouse gas (GHG) emissions. All these inputs and outputs affect the planet, economies, societies, and individuals.

Life cycle assessments are an internationally recognized method for quantifying and assessing the impact of inputs and outputs related to a product or service. The International Standards Organization (ISO)—a nongovernmental organization of standards bodies from more than 160 countries that develops and promotes international standards for a broad range of areas such as scientific testing, societal issues, and technology—has developed a family of norms for environmental management, including for conducting LCAs. According to these norms, all LCAs follow four key phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.



Adapted from ISO14040:2006

Figure 1: Stages of an LCA (ISO 14040:2006)

Why and when should companies conduct LCAs?

LCAs provide robust quantitative data useful for various decision-making processes, reporting needs, and business goals. Table 1 summarizes how an LCA can assist with these and provides insights into when a company should consider undertaking an LCA.

Table 1: Why and when companies should conduct an LCA

Regulatory compliance	○ Confirm whether a product and/or process meets regulatory or legal requirements. ○ Estimate the impacts of complying with expected or announced new regulations.
Risk management	○ Highlight data and monitoring gaps. ○ Identify environmentally harmful or potentially illegal practices. ○ Determine “hotspot” areas of significant impact.
Innovation and optimization	○ Create baselines and compare with industry benchmarks to identify inefficiencies. ○ Model the product life cycle and test different scenarios to identify optimal production systems. ○ Assist in product and process redesign.
Supplier management	○ Identify supplier bottlenecks and areas of high impact to develop targeted solutions. ○ Assess and discuss supply chain decisions and evaluate different sourcing options. ○ Set and evaluate targets.
Marketing and communication	○ Make Environmental Product Declarations (EPDs), ecolabels, and environmental claims. ○ Improve brand credibility related to making sustainability claims due to an LCA’s impartiality and objectivity.
Business performance	○ Decrease cost by analyzing areas of inefficiency and the impact of changing material and commodity sources. ○ Unify company targets and assist in strategy, planning, and prioritization.

Guide objectives and content

This paper is designed as a guide for alternative protein manufacturers to design, manage, and interpret LCAs for their products. The guide will enable companies to oversee the implementation of an LCA and ensure that it meets their minimum requirements and, where applicable, international best practices and standards. There are several broad pathways for conducting an alternative protein LCA. Each pathway will suit companies at different stages and respond to different needs.

Pathway 1: commissioning an LCA (full scope)

The most accurate and reliable LCA pathway is to commission a bespoke and comprehensive LCA (see Commissioning an LCA). This pathway, while considered the gold standard, will require significantly more expertise and time to complete and is therefore the most expensive option. Part of the cost, as well as the benefit, stems from being able to tailor the study to the manufacturer's specific needs, including adapting or combining different methodologies for calculating impacts. For instance, a manufacturer could use an LCA to identify the most optimal distribution hub locations to reduce environmental impact alongside cost considerations. Alternatively, a different methodological focus could identify the impact of soil quality issues related to the cultivation of ingredients. The range of methodological options, and the skills required to adequately complete the study, means that an LCA following this pathway will need to be conducted by a third party.

This paper is designed to facilitate a manufacturer to design and manage an LCA conducted by an expert LCA provider to the gold standard and is not designed to facilitate manufacturers to undertake this type of LCA themselves.

Pathway 2: commissioning an LCA (limited scope)

A second pathway is to conduct a more focused LCA with a limited scope. A limited-scope LCA uses more standardized methodologies and measures a reduced number of environmental burdens or parts of the product's production system. This reduces both the time and scope of expertise needed to complete the study and therefore lowers the overall costs. Focused LCAs are useful because they provide accurate results against predefined areas of study. However, how the results are used is restricted due to the limited assessment of specific manufacturing processes or environmental impacts.

The recommendations in this guide should still be considered when designing a focused LCA, particularly when determining which production processes and environmental impacts are included. If conducting a focused LCA, manufacturers should give special attention to ensure the scope of the study is sufficient to meet their objectives. For example, an LCA with the objective of identifying the water footprint of a product must include all processes and ingredients that use a significant amount of water across the entire production process, including ingredient or raw material production, otherwise, the study risks misrepresenting the product's true impact.

Pathway 3: using modeling software

Finally, the most cost-effective pathway is to use expert-assisted LCA modeling software or do-it-yourself (DIY) LCA software. Expert-assisted LCA modeling software is an LCA undertaken through an automated model with a prescribed set of methodological assumptions, options, and impact categories. An LCA expert operates the model and inputs the data, guiding the manufacturer on what data are required for a realistic assessment. DIY LCA software is becoming increasingly accurate and offers a quick and easy solution to generating initial impact estimates. In particular, they are useful for companies with budget constraints who are interested in understanding their product's environmental impacts and rapidly assessing how different ingredients or processes can affect those impacts. However, manufacturers should be cautious regarding how they use the data generated by such modeling software and be cognizant of the limitations of generic data modeling.

In line with the requirements for pathways 1 and 2, the structure of this guide mirrors the four distinct phases of an LCA, as outlined by ISO 14040:2006.

Throughout the guide, recommendations are provided for alternative protein manufacturers with the objectives to:

- Identify and share LCA best practices for the alternative protein industry.
- Align the alternative protein industry to maximize comparability of product LCA results, both within the alternative protein industry and across the broader food sector (including the conventional protein industry).
- Improve the capacity of alternative protein manufacturers to design and commission LCAs that subsequently build robust evidence of the environmental impacts of alternative protein products.
- Increase alternative protein manufacturers' knowledge of a tool that can aid their environmental, financial, and operational business decisions.

Recommendations are provided for each step of an LCA. While there are many reasons why an LCA would and should be undertaken, this guide aligns recommendations to three likely scenarios for why an alternative protein manufacturer would undertake an LCA.

Scenario A: value chain hotspot analysis. This type of analysis enables a company to determine the relative environmental impact of each component of a product's life cycle and to use such data to improve product or process impacts where possible.

Scenario B: comparative assertion. Companies can use the results of an LCA to compare their product's environmental impact with that of a conventional animal product or another similar existing product.

Scenario C: environmental claim. Companies can use an LCA to understand and make environmental claims for a product, including via an Environmental Product Declaration (EPD).

Recommendations are listed throughout the guide using the letter code A, B, and C to represent these scenarios. In regard to scenario C, this guide will not provide full details for undertaking an EPD, but aims to ensure that an LCA undertaken to support an EPD conforms to the minimum requirements.

Note that the mention of specific companies, certifications, or methodologies throughout this paper does not necessarily constitute an endorsement by GFI. All recommendations should be assessed against the particular situation relevant to the company, individual, or investor, as appropriate.

Application and relevance of ISO standards

The ISO standard for LCAs, ISO 14040, defines an LCA as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle."[7] An LCA achieves this by systematically analyzing the environmental impacts of all processes and materials used to create and, depending on the scope, distribute and dispose of a product.

This guide focuses on applying the ISO standards and therefore the manager of the study at the alternative protein manufacturer (“study manager” or “manager”) who is implementing an LCA in line with this guide should also be ISO compliant; however, each company should review the ISO standards and any applicable regional or local standards before designing an LCA to ensure that they are compliant. PRé Sustainability has prepared a helpful summary of relevant standards.[8]

Currently, there are two leading international standards applicable to LCAs.

1. ISO 14040:2006 Environmental Management – Life cycle assessment – Principles and framework.[9]
2. ISO 14044:2006 Environmental Management – Life cycle assessment – Requirements and guidelines.[10]

ISO 14040:2006 and 14044:2006 focus on the process of performing an LCA and provide the requirements and guidelines for defining the goal and scope of an LCA, as well as conducting the life cycle inventory analysis phase, the life cycle impact assessment phase, and the interpretation phase, which includes how to report and undertake a critical review. It is important to note that these standards do not provide guidance on LCA methodologies and leave this to the implementor's discretion as long as the method follows the principles outlined in the two ISO standards. As a result, these standards lack specific guidance on how to conduct an LCA. In addition, the ISO standards are not designed as certifications. Therefore, LCAs should simply state within the study whether or not they follow the ISO principles and requirements in line with the two standards highlighted above.

In addition to the standards covering LCAs, there are three ISO standards that cover different types of environmental labels. Companies looking to make an environmental claim for their product should carefully review the appropriate standard:

Type I Eco-label (ISO 14024):	This is for eco-labeling schemes where there are defined criteria for products. It is the most common environmental label attached to consumer-facing goods. The label is designed to be consumer-friendly and informative, is based on meeting set criteria, is awarded by a certified third-party program, and is sometimes supported by other institutions and governments. Examples of such labels include “Fair Trade,” “Forest Stewardship Council,” and “certified organic farming.” There are a limited number of eco-labels based on LCA data for food products.[11] If a company wants to certify for a type I eco-label, it should follow the specific criteria for that label.
Type II Eco-label (ISO 14021):	This is for a self-declared environmental claim. Products and services where there are neither criteria nor labeling schemes (e.g., “Dolphin safe” or “percentage of recyclable material”). This eco-label is self-declared and not independently verified. It should be verifiable, but is not always and, as such, can raise questions about the validity of the certification.

Type III Environmental Product Declarations (EPDs) (ISO 14025): This is for voluntary declarations of the sustainability of a product or service. EPDs are third-party certified documents describing a product's potential environmental impacts. Therefore, LCAs are often used as the basis to calculate the impacts that will be included in EPDs. EPDs are supported by robust quantitative data and are typically used by companies that have a business-to-business (B2B) product or business model. To promote consistent assessments, the ISO 14025:2006 standard states that program operators[1] should provide general guidance on how to assess the environmental impact of a product. However, these general program instructions often fail to specify how to assess products. This has led to several organizations developing product category rules (PCRs) (see more below). PCRs provide category-specific guidance for estimating and reporting product life cycle environmental impacts. PCRs are particularly important when making EPDs as they provide greater consistency and comparability of assessments, improved guidance for users undertaking assessments within product sectors, and transparency of the requirements.[12]

If a company plans to make an EPD for their product, they should check to see if an applicable PCR is available.

A note on PCRs

Several institutions are producing PCRs. The International EPD System, the largest, has a PCR library that users can search for product-specific PCRs.[13] The International EPD System is creating a PCR for Food and Beverages that will be released in mid-2023. For European products, the European Commission's Product Environmental Footprint (PEF), a multi-criteria assessment for measuring and communicating the environmental performance of products, includes category rules for 11 foods, with more planned.[14]

[1] A company or a group of companies, industrial sector or trade association, public authorities or agencies, or an independent scientific body or other organization designated to oversee the EPD criteria for a product or group of products (ISO 14025:2006).

Recommendations for alternative protein manufacturers

For **scenarios A, B, and C** (see here), care should be taken to ensure that the LCA is designed according to the principles outlined in ISO 14040:2006 and that each of the four phases is completed.

For **scenario B**, supporting a comparative assertion that is to be publicly disclosed, a critical review must be conducted. A critical review is a process to verify whether an LCA meets the requirements set out in ISO 14040:2006. Further detailed guidance is provided in ISO 14040:2006. The critical review must be undertaken by a panel of at least three interested and appropriately qualified members, one of whom must be a certified LCA expert. The goal of a critical review is to ensure that:

- LCA methods are consistent with ISO 14044:2006 Standards, and that they are scientifically and technically valid.
- Data used are reasonable and appropriate in relation to the study.
- Interpretations and assumptions accurately reflect the identified limitations and goal of the study.
- The report is communicated consistently, clearly, and transparently.

For **scenario C**, making an environmental claim, the LCA needs to be independently verified and administered by a program operator. A program operator can be a company or a group of companies, an industrial sector or trade association, a public authority, or an independent scientific body. The LCA should ideally follow a PCR agreed upon by the program operator. While some PCRs for food products are available, the current and established LCA methods do not capture the full environmental impact of agricultural production.[15] In addition, a PCR for alternative proteins does not currently exist. In the interim, companies looking to make an EPD should work with a program operator to identify a PCR that could apply to their product.

Commissioning an LCA

As previously mentioned, there are three broad pathways to conducting an LCA. The gold standard, full-scope LCA, which provides the most robust and accurate information, requires an experienced and qualified third party to deliver a comprehensive and tailor-made assessment. A full-scope LCA is also the most effective at combating criticisms of greenwashing. This section provides brief recommendations on the external and internal resource considerations when commissioning a bespoke and comprehensive LCA.

External resource considerations

There are two main factors to consider when evaluating and hiring an expert LCA provider. The first is to ensure they have the necessary expertise, either in-house or available through their networks, to adequately complete the study. Each environmental burden being measured may require specific technical expertise. As such, it's critical that a third-party's experience (related to the processes and product types being assessed) and access to expertise are carefully reviewed.[2]

Second, is the overall cost of an LCA. The cost will largely depend on the LCA's scope and the availability and nature of data that need to be collected. Typically, the most time-consuming process is the life cycle inventory (LCI) phase in which data are collected for all inputs and outputs included in the study's scope. Key influences on the overall cost of an LCA include:

- The system boundary (i.e., which parts of the product's life cycle will be included in the study). The more processes included, the greater the cost.
- The number and selection of impact indicators included (i.e., the number of environmental burdens that will be measured). Typically, the more indicators selected, the greater the cost will be, as each indicator requires additional data and potentially different subject matter expertise to measure accurately. In addition, some indicators (e.g., marine eutrophication) may be more difficult to measure (e.g., requiring greater data collection, site visits, and the collection of samples for lab analysis).
- The number of products being analyzed. The cost will be affected if the products have significantly different inputs and manufacturing processes, which require separate modeling and data collection.
- The complexity of the study design related to elements such as the number of functional units (i.e., the comparable unit expressing a product's impact), the allocation method (i.e., how environmental burdens are assigned to different products produced through the same process, such as beef vs. leather), and the level to which the data are evaluated for quality, consistency, and accuracy.
- The complexity of the product's supply chain. Long supply chains where primary data need to be collected from multiple sites can increase the time and resources needed for the LCI phase, which drives up costs.

[2] The American Center for Life Cycle Assessment provides useful information on LCA certification specific to the US. See more information https://aclca.org/. For other regions, certification can be obtained from relevant university programs.

Depending on the factors above, an LCA can cost anywhere between $20K to $100K USD or more. A study conducted at the lower end of this range would be considered a limited scope LCA where a relatively simple product supply chain is modeled and a reduced number of standardized environmental burdens, with similar manufacturing processes and ingredient inputs, are assessed. If the LCA is conducted through DIY software or expert-assisted LCA software, there would typically be a subscription fee as opposed to a one-off fee common for third-party LCAs.

Internal resource considerations

The majority of an LCA study's design, data collection, and analysis will be undertaken by a third-party expert LCA provider. However, it is still important to consider the necessary internal resources required to maximize the study's success. Alternative protein manufacturers should consider the following:

- Typically, the most time-consuming element of an LCA is the data collection. Study managers should ensure they budget enough time for both the third-party expert LCA provider and their internal staff who will be responsible for providing access and gathering the data.
- The study manager and any other participating employees should devote adequate time and care to identifying the goals and scope of the LCA as it affects all other elements of the study. It can be difficult to amend the goal and scope once the study is underway.
- Outlining and conducting a thorough tendering/request for proposal (RFP) process will be critical to obtaining the right skills at the right price. Study managers should aim to pre-identify relevant organizations or individuals that can undertake the study and share their RFP in a targeted manner. Managers should aim to ensure that the organization they ultimately select has, or has access to, all necessary specialist skill sets. A list of LCA consultancies is provided in Annex 1. Please note that this is not an exhaustive list and that the firms identified do not constitute an endorsement by GFI.

Conducting an LCA

ISO 14040:2006 provides a framework for undertaking an LCA and breaks this down into four distinct steps: defining the goal and scope, undertaking an LCI followed by an LCIA, and interpreting the results of the goal and scope definition, the inventory phase, the impact assessment phase, and the interpretation phase.

Although they are conducted sequentially, these steps must go through continuous iteration to ensure results respond to the study's goal, represent the system being assessed, and include the most robust and recent data.[16] An iterative LCA approach is particularly relevant because the alternative protein sector is still nascent. Companies are frequently developing new manufacturing techniques, and food sector data are improving in availability and accuracy. This means new information will likely become available during the implementation of an LCA. By using an iterative approach companies can integrate new data during the study. LCAs should include at least three stages of iteration: when conducting the LCI, when conducting the LCIA, and when interpreting the results. Each stage of iteration will facilitate deeper scrutiny of the chosen methodology, study decisions, and results.

There are three overarching principles to guide each iteration:

1. **Scope definition:** Is the scope still accurately defined to ensure the study's goal is being adequately addressed?

2. **Accurate and up-to-date data sources:** Have all relevant data sources been included? Have the initial data changed or been replaced/improved by newer data sets?

3. **Representative process models:** Have the foreground processes (the processes directly related to the manufacturing of a product) been accurately modeled? Have the background processes (processes associated with third-party manufacturing of an input or intermediate product) been accurately modeled? Are related data sources up to date?

Figure 2 provides a detailed visual of the required steps to undertake an LCA using an iterative approach. This figure aligns with ISO 14040:2006.

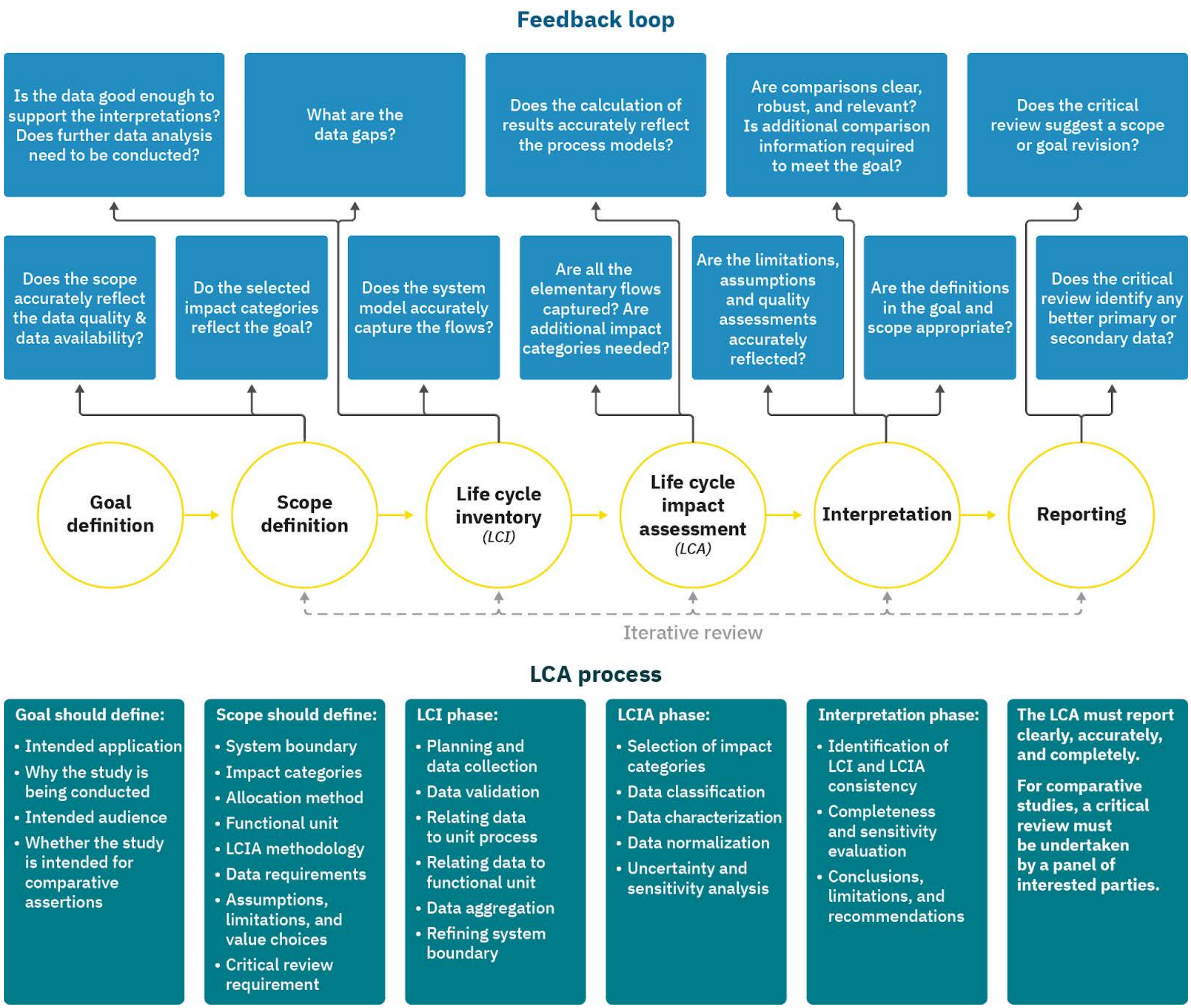


Figure 2: Detailed LCA development process

Goal and scope

Defining the goal and scope is the first phase of the LCA, and is arguably the most important. The study's goal should be described clearly and unambiguously in terms of the intended application, the questions being examined, and the study's target audience. The scope of the study describes the geographic, temporal, and technological coverage of the study in relation to the goal. The scope also defines which products will be analyzed in terms of their function and, consequently, their functional unit and reference flows.

The goal is the LCA's vision, while the scope is the LCA's strategy.

Defining the goal

Aligned with ISO 14044:2006 section 4.2.2

There are six components to developing a clear and unambiguous LCA goal.

1. The intention of the study.
2. The reason why the study is being undertaken.
3. The study's methodology and data choice limitations.
4. The study's target audience.
5. Whether the study will publicly disclose a comparison with another product.
6. Who is undertaking, commissioning, and financing the study and thus has an influence on the results.

These six components are outlined in more detail in Table 3.

Table 3: Steps to defining the goal of an LCA study

Steps	Considerations	Examples
Intention What is the intended application of the study?	○ Why is the study being undertaken? ○ How are the results going to be applied?	○ The study will compare product A with product B. ○ The study will benchmark product A against the product group's average. ○ The study will identify manufacturing environmental hotspots for product A.
Why Why are you carrying out the study?	○ What is the motivation for conducting the study? ○ What is the decision-context within which the study is being undertaken?	○ To support decisions on commodity sourcing. ○ To provide robust evidence of the environmental impact of product A.
Limitation What are the impact coverage limitations?	○ What will not be included? ○ Does the selected methodology reduce the ability to compare with other industries?	○ Carbon footprints effectively demonstrate a product's GHG impact, but do not allow assessments on, for example, their water use. ○ Selecting the ReCiPe LCA methodology produces a single composite score, but this makes it difficult to compare impacts with other studies not using the same methodology.
Target audience Who are the intended recipients of the study's results?	○ Who is the primary target audience? ○ Who is the secondary target audience? ○ How will this impact the technical level of reporting?	○ The target audience is governmental decision makers. ○ The target audience is the general public.
Public disclosure Will the study make a comparative assertion and disclose this publicly?	○ Publicly disclosed comparative assertions are subject to additional mandatory requirements under ISO14040 and 14044:2006. ○ The scope of the system must be defined in such a way that a representative comparison can be undertaken.	○ The study compares the cradle-to-gate life cycle of product A and product B. ○ The study includes an external critical review conducted by interested parties to validate the comparative assertions presented.

	○ Who can be selected as part of the critical review that meets ISO14044 criteria as being ‘interested parties’?	
Influential actors Who commissioned the study?	○ Are there any co-financiers or other influential actors involved? ○ Who is undertaking the study and what is the role of their organization?	○ The study has been commissioned by the Environmental Protection Agency and co-financed by the Food and Agricultural Organization. ○ The study is undertaken by LCA expert ‘XXX’, Senior LCA expert at ‘XXX’.

Defining a clear goal helps identify the parameters of the study's scope and the methodologies and standards that will apply.[17]

A note for study managers

To conduct a high-quality LCA, study managers should consider the following:

- **Consistency:** ensure that methods and data are consistent throughout the study (i.e., the same characterization factors for impact categories are used throughout).
- **Reproducibility:** all results should be reproducible by a third party.
- **Assumptions:** all assumptions should be clearly articulated and presented for each phase.
- **Data quality:** accurate data about cultivation and product transformation should be sourced and, where possible, should be primary data. This is arguably the most important issue for food LCAs.

Defining the scope

Aligned with ISO 14044:2006 section 4.2.3.1

The scope defines what is and is not included in the LCA study. More specifically, it draws the parameters of the temporal, geographic, and technological coverage, as well as the mode of analysis and level of detail. At its most expansive, an LCA's scope could cover a product's life cycle from cradle (raw material extraction or agricultural production) to grave (end-of-life product disposal). This can result in the need to assess huge numbers of environmental impacts.

The scope should include the following:

- **Product's function and functional unit:** defines the product's function or functions and the unit of that function/s.
- **System boundaries:** define what the product system is and what is included within the boundaries of the study.
- **Allocation methodology:** describes how the impact of processes and sub-products are assigned to calculate the total impact (e.g., how one disaggregates the environmental impact of wheat for food, bioethanol, and/or animal feed, which are all produced from the same wheat cultivation process).
- **Data quality requirements and sources:** describe what data are needed, how they will be collected, and what data quality measures will be taken.
- **Impact categories:** outline the types of environmental burdens (impact categories) being measured and how they will be measured (characterization factors). For example, Global Warming Potential is an impact category that includes many measurements of GHGs via a characterization factor that expresses the impact of all GHGs via one comparable unit (i.e., CO_2-equivalent).
- **Additional requirements:** any additional, applicable special requirements needed to maximize the study's utility.

The next section provides guidance for each item described above.

Functional unit (FU)

Aligned with ISO 14044:2006 section 4.2.3.2

What is a functional unit?

Life cycle assessments rely on an easily comparable point of reference to evaluate the various inputs and outputs that flow through a system.[18, 19] This reference point must be comparable both within the product life cycle and across similar product life cycles. The standard method is to identify the product's function and the unit in which that function can be measured. This is termed the functional unit (FU). The FU should be selected with care as the choice may significantly influence the results. There are multiple ways to select the FU. ISO 14044:2006 states the FU should be:

- An accurate reflection of the study's goal and scope. This should also reflect whether the study is directly comparing two products, in which case the FU should accurately reflect both products.
- Representative of the product's function to the consumer.
- Clearly defined and measurable.

A typical approach for food products is to use a mass-based FU (e.g., 1 kg of fresh product), or the stated weight in which the final product is sold to the consumer (e.g., a single 250 g uncooked burger patty).[20]

Mass-based FUs are suitable when comparing products with a similar function; for example, a 250 g plant-based beef burger may be compared to a 250 g animal-based beef burger.[21] However, in many cases, only using a mass-based FU is inadequate as it may not reflect the reason the product is consumed. In some cases, a multi-issue FU is used to assess a product. For example, a plant-based burger’s multi-issue FU could be a 250 g uncooked burger patty and 20 g of protein. This multi-issue FU provides insights on the total impact by weight as well as protein content, enabling a closer comparison with, for instance, a beef burger of the same product weight. One of the primary drivers of meat consumption is to reach a desired level of protein consumption. As a result, some alternative proteins are designed to replicate animal product protein levels. Including a multi-issue FU covering both protein content and weight may lead to a clearer value chain environmental hotspot analysis and can assist with the identification of alternative, lower-impact ingredients to meet protein content goals. As such, while multi-issue FUs are more complex to design and measure, they can provide a significantly more effective unit of comparison.

Recommendations for alternative protein manufacturers

In **Scenario A**, a multi-issue FU can provide greater insights into environmental burdens, value chain hotspots, and product input comparisons than a single-issue FU. However, for **Scenario B**, when making a comparative assertion, a single mass-based FU is appropriate if the product functions are similar.

A study by Teixeira et al. (2013) compared nine different production systems' carbon footprints using mass-based (100 g of product), calorie-based (kcal), and nutrition-based (protein) FUs.[22] The study found that the carbon footprint was different depending on what FU was used. The study looked at pigmeat pâté produced in France, categorized via farming practice—either conventional, organic, Label Rouge (a French governmental certification based on organoleptic properties determined by sensory panels), or Bleu-Blanc-Coeur (an initiative which promotes omega-3 fatty acid content through feeding regimes).

The study found that when using a mass-based FU, organic pâtés had the highest carbon footprints, while when using a protein-based FU, organic systems performed marginally better than conventional systems due to the higher protein content from the cuts of organic meat used in the pâtés. Meanwhile, when using an energy-based FU, the organic system again was worst, while the performance of conventional and Bleu-Blanc-Coeur systems varied depending on the calorific content of individual pâtés.

This study shows that the choice of FUs is an important consideration and that, when possible to implement, a multi-issue FU will provide a more accurate and holistic assessment of a product.

Note to study managers:

A company should assess each FU for relevance against their study's goal and scope. The common FUs used in food LCAs are outlined in the table below. In each method, a mass-based FU is used in combination with an additional one or more FUs. The table below also provides recommendations for companies based on the Scenario they are pursuing.

Common functional units and recommendations

Functional unit	**Mass**

Including a mass-based FU is standard practice for food product LCAs. Typically represented as 1 kg of the final packaged product (not including the weight of the packaging), though the unit of weight can be set based on the needs of the study and the assessed product(s).

Recommendations for alternative protein manufacturers

Applicable to all Scenarios

For comparability, all alternative protein LCAs should include a mass-based FU. Mass-based FUs are standard across food products and can provide a reliable comparison. However, they will be open to criticism as they may not accurately reflect the product's function or cover the impact of including some ingredients over others. For example, a mass-based FU would not appropriately capture how ingredients for nutrient enrichment can improve product parity with animal products.

Functional unit	**Nutritional density unit (NDU)**

Food LCAs are increasingly adopting various methodologies to include nutritional profiles.[23] There are various approaches to including nutrition as an FU. In 2021, the Food and Agriculture Organization (FAO) released a paper looking at the integration of environment and nutrition in LCA food items. The FAO paper recommends a nutritional LCA (nLCA) methodology, which it notes should report the quantities of as many essential nutrients as possible and aim to provide information on the nutritional quality and health impacts of a food product in addition to nutrient quantities. However, the paper also found that a considerable amount of work still needs to be done to create a standardized approach.[24]

One leading approach is the nutrient density unit (NDU).[25] The NDU aims to select several standardized nutritional properties that are weighted and combined to provide a single unit representing a product's nutritional value. The NDU includes total protein, essential fatty acids, and dietary fiber, among others. The advantage of this methodology is that it has a relatively simple application compared to other nutrient profiling methods, such as comprehensive trophic indexes. [26]

Recommendations for alternative protein manufacturers

While nutritional FUs can be valuable, the methodology for nLCAs is nascent and unable to account holistically for the nutrition of a product in all regions and scenarios, or according to cultural or individual preferences. Therefore, LCA studies should use nutritional FUs cautiously.

Applicable to Scenario B and C companies

Scenario B: An NDU is particularly effective for alternative proteins looking to draw comparisons with analogous meat products, where the company wants to compare both environmental impact and nutritional content. While the NDU can be effective in drawing comparisons because it is a composite indicator, it measures a limited number of nutritional properties instead of more comprehensive nutrient profiling methods, which may significantly affect the results.

Scenario C: The NDU could be a valuable component for product promotion to B2B customers. However, specific PCRs should be followed for EPDs. Similarly, eco-labels will likely require companies to meet specific nutrient profiling criteria.

Functional unit	Calories

A defined amount of calories, usually expressed as kilocalories (Kcals), for individual products.

Recommendations for alternative protein manufacturers

Calories could be a valuable measure for comparison across products. Methodologies for calculating calories are also better established. Thus, it would be a more accessible measure to implement than an NDU (see Nutritional FUs above).

Applicable to Scenario B and C companies

Scenario B: Defining the FU in calories can be a useful contribution to understanding the nutrient profile of a product and how it compares to similar products.

Scenario C: Users should refer to specific PCRs if/when available. Eco-labels would likely require companies to meet specific criteria that may or may not include calories. Companies should review whether this is an appropriate FU or not for their purposes.

Functional unit	Energy

A defined amount of energy, usually expressed in megajoules (MJ), to create a particular product(s).

Recommendations for alternative protein manufacturers

Applicable to Scenario A and B companies

Scenario A: Energy as an FU is useful in identifying high energy consumption hotspots (areas of high usage) along the value chain for remedial action.[27] This makes its application particularly relevant for companies focused on Scenario A. Specifically companies producing cultivated meat or precision fermentation products will find this FU useful as energy consumption can be particularly high for these technologies.

Scenario B: Novel manufacturing techniques used by alternative proteins can have a high energy use. The inclusion of energy as an FU assists in benchmarking products, thus enabling comparison and driving competition around improvements.

Note for Scenario C: Energy as an FU is less relevant for EPDs and eco-labels unless this is a specific requirement for a particular label or customer.

Functional unit	Protein

Typically expressed as 100 g of protein per mass-based FU.

Recommendations for alternative protein manufacturers

Applicable to Scenario B and C companies

This FU is useful for sub-products, companies providing B2B products, or companies producing products via fractionation and precision fermentation techniques. For example, comparing 100 g protein is helpful for products such as soy protein isolate or pea protein isolate, whose function is to replace the protein content in analogous animal products.[28]

Given that the function of alternative proteins is to provide protein that is comparable to animal proteins, it should be noted that a protein measure alone can insufficiently represent the bioavailability of amino acids. A more comprehensive protein assessment can be conducted using the Digestible Indispensable Amino Acid Score (DIAAS).[29] This methodology directly compares the protein quality, and if combined with a mass-based FU, it would provide a quantity and quality comparison.

Functional unit	**Economic value**

The FU is based on the economic value of the food product. Using an economic-value-based FU emphasizes, and improves the ability to compare systems producing superior quality products[30]—as price typically correlates with product quality.[31] This methodology reflects consumers having a specific budget, thus, if results are published, the economic-value-based FU can guide consumers toward reducing their impacts per dollar spent.

Recommendations for alternative protein manufacturers

While economic-value-based FUs can provide interesting insights, they should not be used in isolation, but rather in combination with the FUs mentioned in this section to create a holistic picture of a product's environmental burden. In addition, the economic value may not be an accurate measure for pre-commercialized companies, especially in a nascent industry and thus supply chain, that have not reached price optimization as many manufacturers will necessarily have high product costs at an early stage.

System boundaries

Aligned with ISO 14044:2006 section 4.2.3.3

What is a system boundary?

A typical product life cycle covers five stages: resources/raw materials, processing, transportation and distribution, retail/consumer use, and waste (see Figure 3). An LCA initially maps the whole system needed to develop a product; this is termed the product system. Once the product system has been identified, the LCA study will define which parts of the system are included or excluded. This process creates a system boundary.

A system is defined by the European Commission's International Reference Life Cycle Data (ILCD, 2010) handbook as:

"Any good, service, event, basket-of-products, average consumption of a citizen, or similar object that is analyzed in the context of the LCA study."

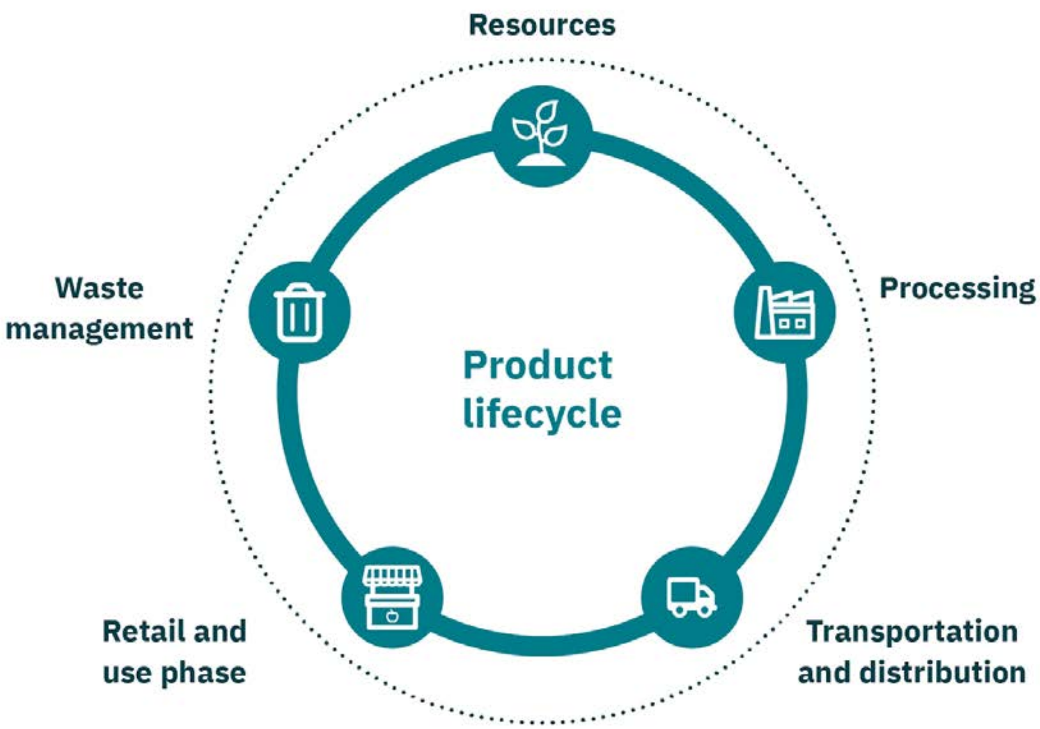


Figure 3: A product life cycle. Adapted from Ecochain 2022 (https://ecochain.com/knowledge/life-cycle-assessment-lca-guide/)

Ideally, all environmental inputs and outputs that are affected by a product system should be included in the study. However, given the interconnected nature of our global production and consumption system, mapping every process and company linked to a product system could ripple and eventually include the whole economy.[32] System boundaries force decisions on what is and is not included; for instance, whether to include the manufacturing of a tractor in the production of soybeans. Some studies purposely limit the system boundary to focus on the impacts created by a particular production stage.[33] For example, an assessment may cover production techniques for a crop rather than post-production impacts. In either case, the important aspect is that the chosen boundary should reflect what the company is trying to measure and achieve. For instance, if conducting a comparative LCA, the system boundaries must be the same for the products that are being compared.

A system boundary is further divided into foreground and background processes. Foreground processes are directly related to the manufacturing of a product, while background processes are associated with third-party manufacturing of an input or intermediate product. Ideally, primary data should be collected for all foreground processes. For food product LCAs, estimates and existing secondary data are often used to model background processes, such as electricity or gas generation that powers the manufacturing process.

At a more granular level, a product system is further divided into unit processes, the individual steps required throughout the product life cycle to produce one or more products. As shown in Figure 4, each unit process is linked by a flow of materials, energy, or sub-products. The system boundary draws a distinct cut-off point for what should be included in the study by reviewing each input, output, intermediate flow, and product flow and deciding whether their inclusion will have a significant contribution to the results.

Note to study managers:

Managers should be closely involved in defining what should and should not be included in the study based on their company's goals and available resources. Managers should factor in both the time and expertise required from their team. It is good practice to include all elementary flows into the system boundary. An elementary flow is any material or energy entering the system that has been extracted from the environment without human transformation, or material or energy leaving the system that is released into the environment without subsequent human modification. In addition, when considering input flows, it's important to include all material and other inputs used to produce the product for the full scope of the study. See Figure 5 for an illustrative example of a simplified product system for a plant-based milk from cradle-to-factory-gate.

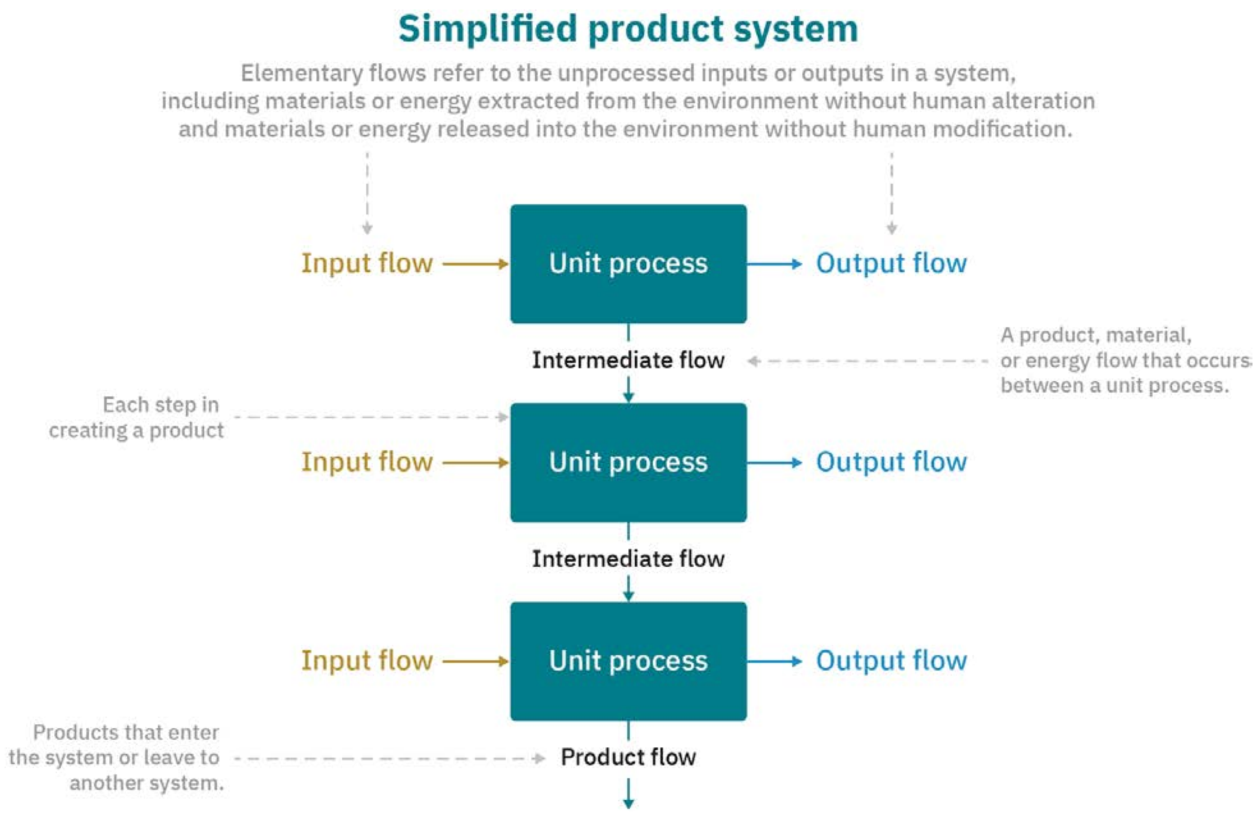


Figure 4: Simplified product system, modified from ISO14040:2006E

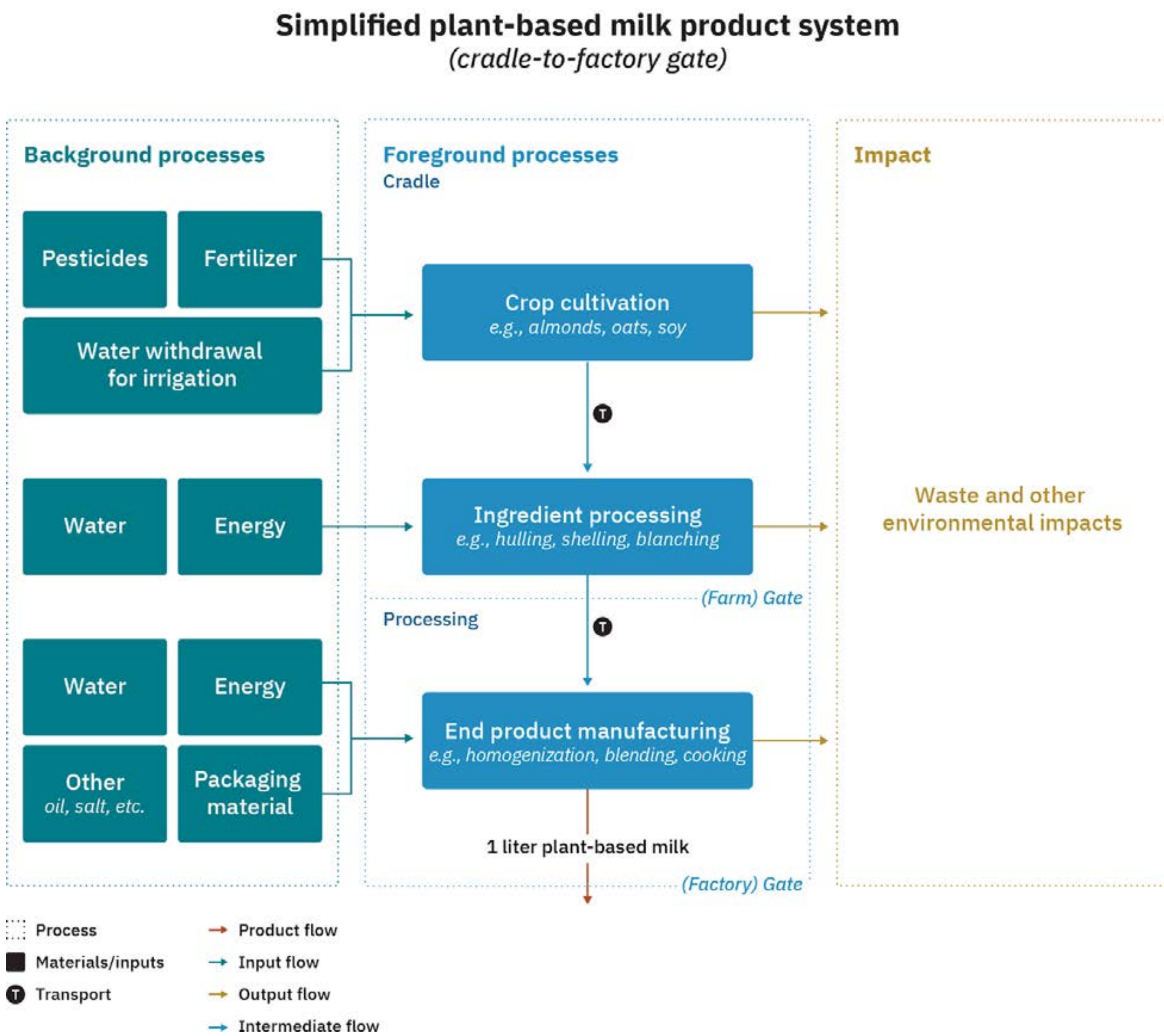


Figure 5: simplified plant-based milk production system from cradle-to-factory gate

Annex 3 provides a list of the common alternative protein manufacturing processes with links to existing scientific LCAs that provide a detailed description of the process.

Common system boundaries and recommendations

There are several common industry-standard system boundaries. The choice of which boundary to apply relates to the needs of a study's goal and scope. Figure 6 highlights the common boundaries used in LCA studies. The subsequent section defines these boundaries, and provides recommendations for alternative protein manufacturers.

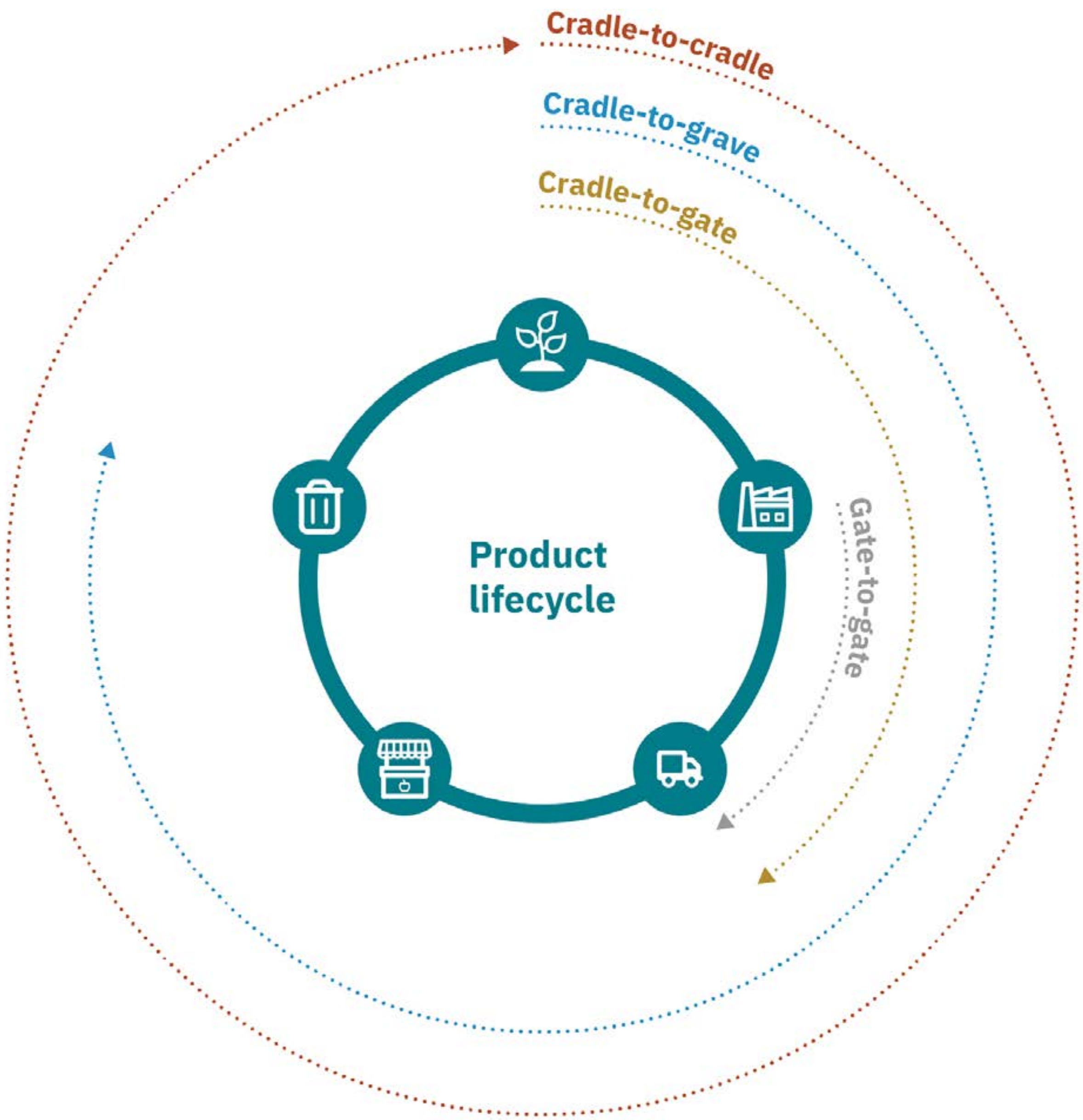


Figure 6: Common system boundaries. Adapted from: Ecochain 2022 (https://ecochain.com/knowledge/life-cycle-assessment-lca-guide/)

Raw material | Processing | Transportation | Retail use phase | Waste | Recycling & reuse

System boundary:
Cradle-to-cradle

Product life cycle stages included:

All stages, including recycling or repurposing processes, that are needed to convert waste into raw material that feeds back into the manufacturing or product processing stage. Note that for food products, this system boundary also includes product use (i.e., cooking and consumption by consumers).

The processes for an assessment of a manufactured product typically include:

- Agricultural processes relating to soil preparation and plant cultivation, including emissions of gasses, use of chemical agri-inputs, land, water, and initial packaging of commodities.
- External transport to and from the core processes.
- Maintenance and operation (e.g., of machines, vehicles, and offices).
- Preparation of the final product.
- Waste and waste treatment generated during manufacturing.
- Transport to the average consumer, either to retail or direct to the customer.
- Consumer use of the product (e.g., cooking, disposal).
- End-of-life processes, both packaging and waste products.
- Processes and resources required to recycle and reuse a product.

Processes typically not included:

- Manufacturing of production equipment, buildings, or other capital goods.
- Business travel of key personnel, including commuting of staff.

Alternative protein recommendations

Typically not applicable

A cradle-to-cradle LCA is the most comprehensive level of assessment. It requires a complete assessment of all stages of the product life cycle and largely eliminates problem shifting[3] as all stages are included. However, collecting data on consumption practices and accurately tracking the disposal and repurposing of large quantities of products can be difficult and may reduce the accuracy of assessments.

Many alternative proteins are designed to replicate existing products' functions in the market. Typically, alternative protein LCAs do not include a cradle-to-cradle system boundary as the distribution, retail, consumption practices, and waste disposal are equivalent to the existing comparison products (conventional animal-based proteins). The significant differences in environmental impact between alternative proteins and animal proteins are derived from the raw material/farm commodity production and processing stages.

[3] Problem shifting occurs when a problem from one stage of the life cycle (that is measured) is shifted to another (that is not measured). For example, substituting a hazardous material for a less hazardous one, but when the latter requires more intensive waste processing, which is not measured. This has the potential to skew results as the more intensive waste processing happens further downstream in the product life cycle and therefore may not be included within the system boundary, while the LCA assessment benefits from including a less hazardous material at the processing stage, which is included.

System boundary:
Cradle-to-grave

Product life cycle stages included:

This includes all stages from raw material production, processing, distribution, retail, and waste disposal. This also includes product use (i.e., cooking and consumption by consumers).

The processes for an assessment of a manufactured product are the same as a cradle-to-cradle assessment but exclude:

- Processes and resources required to recycle and reuse a product.

Alternative protein recommendations

Applicable to limited forms of Scenario A

Given the similar functions of alternative proteins to existing food products, the analysis of retail processes, consumption practices, and waste disposal may not provide statistically significant and valuable data.

This approach may be useful if the study's goal is to analyze value chain hotspots in downstream processes (e.g., to understand the impact of new packaging material on a product's retail shelf life).

System boundary:
Cradle-to-gate

Product life cycle stages included:

This includes raw material production and product processing stages. Typically, this boundary also includes distribution up until a product reaches a retailer, but does not include any retail or downstream processes. Care should be taken to define “gate,” including whether this includes the distribution to the retailer and what (if any) retailer processes are included.

The processes for an assessment of a manufactured product are the same as a cradle-to-cradle assessment but exclude:

- Transport to the average consumer, either to retail or direct to the customer.
- Consumer use of the product (e.g., cooking, disposal).
- End-of-life processes, both packaging and waste product.
- Processes and resources required to recycle and reuse a product.

Alternative protein recommendations

Applicable to all Scenarios

Cradle-to-gate is the most common system boundary applied to food product LCAs and alternative protein LCAs. This scope is recommended as the standard approach for alternative protein manufacturers across scenarios. Cradle-to-gate is the standard because it maximizes comparability across products within the industry and the broader food sector. However, as in all cases, the system boundary should be assessed against the study's goal to ensure it is fit for purpose.[4]

Scenario A: Typically, the highest environmental burdens for food products occur during the earlier stages of a product's life cycle that fall within a cradle-to-gate system boundary. Thus, when identifying hotspots, the focus should be on these early stages. In addition, a manufacturer has more direct control and influence on the upstream and processing stages of the product life cycle and therefore, identified hotspots can be more easily addressed.

Scenario B: As this is the most common system boundary applied to food products, this scope likely provides the best opportunity for comparison to conventional proteins. However, this should be assessed case-by-case to ensure direct comparability to the identified products.

Scenario C: The cradle-to-gate approach is standard practice, though specific PCRs will outline what is required for an EPD or other eco-labels. Even in the case of different guidance in a specific PCR, certain stages may still be excluded if they are not significantly relevant to the overall impact as long as the reason for exclusion is clearly justified.

[4] Typically, anything that is expected to contribute less than 1% of the environmental impact, or it makes up less than 1% of the total mass, is reasonably expected to be excluded. That is, unless there is reason to expect that the environmental impact will be greater than 1% regardless of the mass being under 1%, such as with hazardous substances. Typical elements excluded include ancillary services not directly linked to the product production system such as legal, accounting services, and executive travel.

System boundary:

Gate-to-gate

Product life cycle stages included:

This includes processes starting after raw material production (the farm gate), until the completion of the product processing phase (the factory gate).

The processes for an assessment of a manufactured product typically include but are not limited to:

- Maintenance and operation (e.g., of machines, vehicles, and offices).
- Preparation of the final product.
- Waste and waste treatment generated during the manufacturing.

Processes typically not included:

- Manufacturing of production equipment, buildings, or other capital goods.
- Business travel of key personnel, including commuting of staff.

Alternative protein recommendations

Applicable to Scenarios A and B

Gate-to-gate is typically used when there are many value-added processes after producing a raw material until the final product. This level of analysis can be useful for manufacturers in scenarios A or B if there has been a significant system change at the processing stage, but other upstream and downstream stages are similar to conditions from a previous LCA.

Allocation methodology

Aligned with ISO 14044 section 4.3.4.2

Many product systems result in multiple useful products. For example, wheat can be used as food, feed, or to produce bioethanol. The process of allocation determines how to account for the impact of a single product when multiple products are produced via the same process. In line with ISO 14044:2006, there are three mechanisms to address system allocation.

Allocation by system expansion: This process avoids allocation altogether by expanding the system boundary to include all products produced by a system (e.g., including all wheat produced regardless of its use as food, feed, or an ingredient in bioethanol). Allocation by expansion effectively provides a single impact for all products produced by that system, which can be misleading. For instance, when comparing wheat used as food with another food crop, including the emissions from all wheat products misrepresents the proportion of impact from wheat that is only used as food. While in most cases it is more accurate to split the impact between the different products, ISO 14044:2006 indicates that allocation by system expansion should be the primary allocation method where possible. It should be noted, however, that system expansion necessarily increases the size of the system being studied, which can significantly escalate the complexity and thus the cost of conducting an LCA.

Allocation by substitution: This process identifies alternatives to the co-product on the global market. The principle is that the production of this co-product removes the need for the same product's production elsewhere. For example, producing wheat for feed and food removes the need to produce other similar feed. In this method, if calculating the impact of wheat produced for food, the total impact is calculated minus the wheat's feed impact. However, this approach is subject to methodological uncertainties when calculating system impacts because it is difficult to prove reliably that substitution will occur from the production. This uncertainty reduces the viability and comparability of results.[34] While ISO 14044:2006 sanctions the use of allocation by substitution, it is recommended that this method be avoided for alternative protein LCAs due to the methodological uncertainties.

Allocation by physical relationships: This process can take several forms: either economic, by the value the co-products have in the market, or physical, such as mass-based allocation. Economic allocation is relatively simple and widely used for multi-output agricultural systems. It is also sensible, as revenue through consumer demand is a primary driver of production systems.[35] The use of economic allocation in situations in which system expansion is not feasible is recommended for alternative protein manufacturers. A caveat when using economic allocation is that many alternative protein companies' product(s) may not yet have an economic price structure or their economic value will fluctuate greatly over time. In these cases, allocation by mass can be used. In mass-based allocation the impacts are allocated proportionally according to the mass of each co-product.

Additional system boundary considerations

In addition to setting process boundaries, the system boundary should also define the temporal and geographic boundaries of the study.

Geographic boundary: Many manufacturers operate across various geographies to produce a product, and this is especially the case for food producers. Where a commodity is grown can significantly impact its environmental impact. For example, soy sourced from Brazil has high linkages with deforestation that may influence the overall results of the LCA, whereas soy grown in Canada does not. In addition, electricity production, waste management, and transport systems will differ by location, which will significantly impact the final analysis (e.g., energy from a predominantly coal-powered energy grid will have higher GHG emissions than renewable-energy-powered grids). Geographic boundaries ensure that data collection and analysis are consistent with the product's actual impact.

Temporal boundary: LCAs are concerned primarily with the current impact of a product and thus should be focused on the present. However, several temporal aspects should be considered. First, it is important to consider prior pollution levels to ensure that the impact of the product is measured accurately (e.g., measuring acidification or eutrophication is more accurate if existing levels of chemicals in the soil and waterways are known). Second, when the study's scope includes end-of-life, disposal, or recycling stages, such as a cradle-to-cradle scope, it is important to understand a product's lifespan (and that of its packaging) to assess the overall impact accurately (e.g., understanding the decomposition time of different packaging materials will affect the overall impact of different products).

Impact categories

What are impact categories?

A product system has a range of impacts depending on the inputs used (e.g., water, energy, land, raw materials) as well as outputs created (e.g., emissions, waste, products). An LCA measures these impacts and groups them into environmental categories according to the impact they cause. Given the range of different impacts, this categorization simplifies how they are represented and makes them more easily understandable. For instance, a product's Global Warming Potential (GWP) is an indicator that includes a range of GHGs, such as methane, nitrous oxide, and carbon dioxide. In addition to grouping the impacts, impact categorization also provides a method to calculate impact in one common unit, referred to as the characterization factor (e.g., GWP is measured in carbon dioxide equivalents or CO_2e).

The impact of a product can be grouped into mid-point indicators (direct impacts, such as GWP) and end-point indicators (the effect these impacts have on humans and ecosystems). While end-point indicators assist in communicating a product's overall impact, the modeling of end-point indicators is associated with significantly higher uncertainties that reduce the robustness of results. This guide focuses on mid-point indicators only. Some LCA methods, such as ReCiPe 2016, provide detailed guidance on end-point indicators. [36]

Since a critical issue for LCAs is their comparability, numerous LCA methods have been designed to standardize the LCA process, including to guide users on which impact categories to include and how to derive their respective characterization factors. Common models include ReCiPe 2016, Impact 2002+,[37] CML 2001,[38] and the European Commission's Product Environmental Footprint (PEF).[39] The choice of methodology will be influenced by both the goal and scope of the study as well as where the study is being conducted and for which audience. The European Commission's PEF is a standard methodology for LCAs conducted in Europe; however, the methodology requires specific product category rules (PCRs) to be developed to ensure alignment for products in each category. As discussed earlier in this guide, there is a very limited number of PCRs for food and beverage products which reduces the level of specific guidance available for those conducting alternative protein LCAs following the PEF. Companies should aim to follow the PEF if creating an EPD to be published in Europe if an appropriate PCR exists, but this will not always be possible. Many LCAs combine methodologies to achieve their goal. For instance, in their paper *Multi-criteria evaluation of plant-based foods – use of environmental footprint and LCA data for consumer guidance*, Potter and Roos identify and provide data for impact categories considered relevant for the food sector.[40] They select these indicators based on the Planetary Boundary framework and use ReCiPe midpoint indicators.[41]

Mixing and matching of methodologies within an LCA is common practice when evaluating a large number of impact categories. This is because some methodologies are regarded as better at evaluating specific impact categories than others. The impact category descriptions below include recommendations on which methodologies should be considered. However, it should be noted that these LCA methods are not designed specifically for food products, and while food PCRs are being developed, it may be some time until they are released due to the variety of food and agricultural products.

Each of the methods noted above requires measuring an extensive number of impact categories. The more impact categories measured, the more complex and resource-intensive the study. In many cases, a shorter list of mid-point indicators, following one methodology, helps focus the study on specific issues and respond more concretely to the study's goal and scope.

Note to study managers:

This guide outlines a short list of impact categories and their respective characterization factors to drive standardization across alternative protein LCAs. This list should be evaluated against each specific study's goal and scope. Moreover, study managers may rely on LCA practitioners to select the most suitable impact categories and which methodology to follow. It should also be noted that characterization factors change over time as more effective ways of measuring impacts are developed. Those implementing an LCA should review the latest and most accurate characterization factors before implementing a study. The international EPD system has an extensive resource hub that provides information on impact indicators and their characterization factors.[42] It is regularly updated to reflect the latest trends and most accurate ways to measure environmental impacts.

This guide's list is divided into two sections. First are the impact categories that should be included as standard. Second are the impact categories that should be considered for specific scenarios. If a specific LCA method needs to be applied, that method supersedes the recommendations provided here.

Things to consider when selecting your impact categories, depending on your study goal and scope, include:

- Which categories best reflect the goal and scope of the study?
- Does the selection of categories enable problem shifting, when a problem from one stage of the life cycle (that is measured) is shifted to another (that is not measured)?
- What categories facilitate product comparisons?
- What categories enable the best identification of value chain environmental burden hotspots?

Priority impact categories for alternative protein manufacturers

Summary of impact categories

Table 4 lists the high and lower priority impact categories to be considered when designing an LCA. The sections that follow describe these impact categories, provide a justification for their inclusion, and discuss how to measure them.

High priority Impact Categories	Lower priority Impact Categories
Global Warming Potential (GWP)	Ecotoxicity and human toxicity
Water use	Ozone depletion
Land use	Resource use
Eutrophication	Biodiversity
Acidification	

Table 4: Summary of impact categories for alternative protein LCAs

Global warming

Why it is important

Global warming, a process of heat-trapping GHGs and increasing the average global temperatures, is already having a devastating and widespread effect on our environment, society, and economy. Some of the resulting impacts, such as droughts, wildfires, and extreme rainfall, are happening faster than scientists previously expected.[43] According to the Intergovernmental Panel on Climate Change (IPCC)—the United Nations body established to assess the science related to climate change—modern humans have never before seen this level of observed changes in our global climate.[44] To keep global temperatures within safe limits, industries rapidly need to improve their carbon measurement, reporting, and management.

Description, characterization, and key methodologies

There are many GHGs; however, the primary gasses measured include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

The IPCC developed the Global Warming Potential (GWP) metric as an integrated measure that represents the change in global warming from anthropogenic (originating in human activity) GHGs released into the atmosphere. The GWP provides the characterization factors for each GHG measured against the impact of CO_2 to create a single unit.

GWP can be divided into three types: fossil, biogenic, and land use and land-use change. GWP-fossil refers to emissions related to the burning of fossil fuels. GWP-biogenic refers to emissions related to the burning of biomass or emissions released from GHGs stored in biomass. GWP-land use and land-use change includes emissions as a result of changes to stores of carbon in soils and native vegetation due to the use of land for purposes such as agriculture. These are combined into a GWP total. Although the IPCC's sixth assessment report (AR6) provides the latest GWP characterization factors, most food LCAs utilize the IPCC 2013 (AR5) characterization factors.[45] A summary of the changes in GWPs across IPCC reports is provided in Annex 2.

Measurement unit: GWP is measured in weight of carbon dioxide equivalents (Kg CO_2e)

Methodological resources to consider:

- Baseline model of 100-year GWP of the IPCC (based on IPCC 2013).[46]
- ISO 14067:2018 Greenhouse gasses – Carbon footprint of products – Requirements and guidelines for quantification.[47]
- European Commission's Product Environmental Footprint (PEF).[48]

Recommendations for alternative protein manufacturers

It is recommended that GWP is included as standard in all alternative protein LCAs and that the study follows an established methodology (see methodological resources to consider above). Resources such as the GHG protocol can be helpful, but methods such as the PEF provide more rigorous guidance for LCAs. In the case of PEF, there are also strict requirements on the types of data that can be used. The LCA method chosen should be determined by the goal and scope of the study. For instance, if the goal is to publish and comply with European legislation on carbon footprinting, then the PEF is most likely to be the best methodology.

For **scenario B**, using the IPCC AR5 100-year GWP for this characterization factor is reasonable to maximize comparability with existing product LCAs. However, it should be noted that the 100-year GWP significantly underestimates the impact of methane given that non-fossil-based methane is 80.8 times more powerful than CO_2 over a 20-year period (compared to 27.2x stronger over a 100-year period, as outlined in IPCC AR6). Alternative protein manufacturers should consider using both IPCC AR5

100-year GWP and AR6 20-year GWP values when conducting LCAs. While the AR6 20-year GWP measurement will have a limited effect on the results of alternative protein LCAs (with the possible exception of rice-based products) as the majority of alternative protein products do not use resources that emit high levels of methane, there will be a significant impact on the results of a comparative assessment, especially when comparing with large ruminant animal products, such as beef. Implementation of both measures can allow alternative protein manufacturers to highlight the significant impact of large ruminant proteins in comparison to alternative proteins. It will also contribute to market recognition of the differences in how methane is measured and thus may lead to wider adoption of the 20-year measurement method.

If the desired outcome of the LCA is a product's carbon footprint, this can be achieved by undertaking a single-issue methodology that focuses solely on GHG emissions and the impact on climate change. However, it is recommended that studies include multiple impact categories to provide a more holistic view of a product's impact.

Water use

Why it is important

Water scarcity is rapidly becoming one of the most globally critical stresses on the environment and humans. Water scarcity increases disease and malnutrition in communities and reduces biodiversity. Overusing or polluting water can also cause significant risks to business operations and food security. The FAO estimates that two-thirds of the world's population could be living in water-stressed countries by 2025 if current consumption trends continue. [49]

Description, characterization, and key methodologies

Water footprints are theoretically similar to carbon footprints. However, given that water is a resource–rather than an emission like carbon dioxide–it requires a different approach that considers supply and regionality. The total water used to produce the product within the system boundary is calculated during the inventory stage. At the impact assessment stage, a mid-point characterization factor is applied to understand the impact of this water use.

As water is unequally distributed, using more water in a region with low water stress may have a lower impact than using less water in a region with high water stress. While there are several methodologies to calculate the effect of water use, the most recent widely used method is AWARE (Available WAter REmaining). AWARE is useful because it provides a simple, single indicator to represent the impact of water use and water scarcity in a given region or country.

Measurement unit: Water use is measured in cubic meters (m^3).

Methodological resources to consider: Available WAter REmaining (AWARE).[50]

Recommendations for alternative protein manufacturers

It is recommended that water use is included as standard in all alternative protein LCAs.

Some useful water use terms:

- **Water withdrawal:** anthropogenic removal of water from any water body, either permanent or temporary.[51]
- **Consumed water:** water withdrawal where there is no release back to the source (e.g., due to evaporation[5], evapotranspiration, product integration, or discharge into a different drainage basin).[52]
- **Green water:** precipitation on land that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation, eventually evaporating or transpiring through plants.[53] It corresponds to the volume of rainwater consumed during the production process.
- **Blue water:** fresh surface and groundwater used for irrigation or production.
- **Gray water:** wastewater generated in households or office buildings from streams without fecal contamination (i.e., all streams except for the wastewater from toilets).

[5] The process by which water is transferred from land to the atmosphere by evaporation from soil and other surfaces and by transpiration from plants.

Land use/Land occupation

Why it is important

Agricultural land use is the leading driver of biodiversity loss, deforestation, and soil degradation as up to 50% of habitable land is used for agriculture.[54] Forests are primarily cleared to make space for cattle grazing and to grow feed for animals. In addition, despite the fact that 77% of agricultural land is used for livestock, this only provides a minority of the global human calorie supply (18%) and protein supply (37%).[55]

When land is changed (e.g., forests are cut down to make space for animal grazing), the functionality of that land also changes. This can result in the loss of ecological systems such as rainfall and water regulation, which endangers biodiversity, and local, regional, and, in some cases, global human populations.

From a global warming perspective, land use changes are critical. Native vegetation and soils store significant quantities of carbon. These are often released due to agricultural expansion and, together with emissions from agricultural production (plant and animal), contribute between 20 and 25% of greenhouse gas emissions[6]. [56,57,58]

Description, characterization, and key methodologies

In LCAs, land use is commonly assessed across two dimensions. First, the amount of land used to produce a predefined quantity of food, measured in terms of area and time (e.g., m^2 per year). For instance, to produce 1000 kg of flour might require 1 hectare of agricultural land for a full year. This is referred to as land occupation.

The second dimension looks at the amount of land that needs to be transformed (land transformation). This is broken down into direct land use change (dLUC) and indirect land use change (iLUC). dLUC arises when the input chosen directly causes the change to happen, while iLUC occurs further up the supply chain. For instance, dLUC could be caused by a company needing additional soy protein isolate and contracting a farmer to produce additional soybeans, and then the farmer converting wild grassland to cultivate additional soybeans to meet the demand. However, if the use of soy protein isolate by the same company was hugely successful and led to an increase in global demand for soybeans, which resulted in the conversion of land used for wheat cultivation into soybean cultivation, this could cause land use change at another time to meet global demand for wheat, and would be an indirect land use change.

[6] The Food and Agricultural Organization (FAO) calculates the global contribution of GHG emissions from agriculture, including land use change to be 17%. https://www.fao.org/3/cb3808en/cb3808en.pdf

Changing land use has myriad impacts on soil properties (e.g., carbon content or compaction), nutrient leaching, N_2O emissions, biodiversity, and biotic production.[59] It also impacts other environmental aspects such as landscape albedo[7], and evapotranspiration.[60]

While some LCAs take a relatively simple approach and measure dLUC through the area by time (e.g., m^2 per year), others encompass more complex elements. For instance, the PEF uses a relatively new method that creates a dimensionless aggregated indicator, the Soil Quality Index.[61] Moreover, new characterization factors are increasingly being designed to include elements of biodiversity or to examine the carbon opportunity cost of land use change, which is based on the assumption that land occupied for crops and livestock rearing could alternatively be used to grow grasses or forests to sequester carbon.[62]

Measurement unit: m^2 per year or dimensionless (e.g., through Soil Quality Index).

Methodological resources to consider:

- Soil Quality Index: LANd use indicator value CAlculation (LANCA) model.[63]
- For a more straightforward method that looks at agricultural land occupation, see ReCiPe2016 midpoint indicators.[64] Land occupation is simpler as it calculates the direct amount of land used to produce a product in m^2 and thus is fairly easy to calculate.
- For emissions factors when calculating the carbon opportunity cost of land, see Searchinger et al., Assessing the efficiency of changes in land use for mitigating climate change.[65]

Recommendations for alternative protein manufacturers

At a minimum, alternative protein LCAs should look to understand the dLUC defined by area and time. However, the expert LCA provider can offer more detailed guidance on additional specific methodologies.

For comparative studies, including metrics on the opportunity cost of land can add further evidence to the benefits of alternative proteins over large ruminant animals.

[7] An expression of the ability of surfaces to reflect sunlight (heat from the sun).

Eutrophication

Why it is important

Eutrophication is the process in which ecosystems, typically water systems (either freshwater or marine), receive excess amounts of nutrients, primarily nitrogen and phosphorus.[66] In water systems, the excessive nutrients cause rapid growth of phytoplankton that blocks sunlight to water and causes a reduction in dissolved oxygen concentrations in the water, subsequently damaging livable conditions for other species except for phytoplankton and creating "dead zones."[67]

The largest dead zone in the United States—about 6,500 square miles—is in the Gulf of Mexico and occurs every summer due to nutrient pollution from the Mississippi River Basin. Elevated nutrient levels resulting in algal blooms can also cause drinking water problems in communities near and downstream from dead zones as algal blooms release toxins that contaminate drinking water, causing illnesses for animals and humans.[68]

Meanwhile, terrestrial eutrophication includes only airborne nitrogen oxides and ammonia emissions. These airborne emissions are sometimes regionalized per country, as some biomes are more sensitive to eutrophication than others.

Description, characterization, and key methodologies

LCAs work to connect anthropogenic emissions such as synthetic fertilizers, manure, sewage, treated and untreated wastewater, and related sludge to eutrophication impacts.

It should be noted that different LCA methodologies treat eutrophication differently regarding which chemicals are included in which measurement. This can result in significantly different results depending on the methodology chosen.[69]

There are three types of eutrophication: freshwater, marine, and terrestrial. Freshwater and marine eutrophication are widely covered in LCA literature. Terrestrial eutrophication is not typically included in food LCA studies as it is less relevant for food production.

Measurement unit:

- Freshwater eutrophication is measured in weight of phosphate equivalents (g PO4eq).
- Marine eutrophication is measured in weight of nitrogen equivalents (g Neq).
- Terrestrial eutrophication is measured in Moles per nitrogen equivalents (Mol Neq).

Methodological resources to consider:

- For freshwater and marine eutrophication, see the EUTREND model.[70]
- For terrestrial eutrophication, see Accumulated Exceedance.[71]

Recommendations for alternative protein manufacturers

It is recommended that freshwater eutrophication is included across all alternative protein LCAs, as eutrophication is increasingly a significant ecological issue and alternative proteins have the potential to measure favorably compared to conventional proteins . Freshwater eutrophication can more easily be linked to specific locations (e.g., farms). This makes its measurement more manageable. Marine eutrophication can be more difficult to link directly to sources given that it is affected directly by coastal practices as well as upstream sources.

In **scenario B**, specifically for seafood-focused alternative protein manufacturers, marine eutrophication should be included, as this is more directly comparable with the impacts of aquaculture.

Depending on the PCR, all three types, freshwater, marine, and terrestrial eutrophication, may be included for **scenario C**.

Acidification

Why it is important

Acidification is the increase in acid content in terrestrial or aquatic ecosystems. While acidification occurs naturally, anthropogenic activities are the most significant global contributors.[72] In relation to alternative proteins, acidification is caused by the overuse of fertilizers and by transportation-related emissions.

The increase in acidification of both the land and oceans severely impacts humans, plants, and animals. Acidic water (acid rain) reduces plant growth and metabolism. In addition to harming the natural landscape and ecology, this reduces agricultural productivity which will have a significant effect on food security and the economy.

Description, characterization, and key methodologies

Most LCA methods, such as ReCiPe 2016, include an impact category for terrestrial acidification. These methods focus on calculating the emissions from sulfur dioxide (SO_2), nitrogen oxides (NOx), and ammonia (NH_3). The PEF method measures the impact of terrestrial acidification in terms of accumulated exceedance. This method identifies the change in the critical load[8] of sensitive areas in terrestrial and freshwater ecosystems. It is considered a critical load exceedance when acidic substance deposits are greater than the critical load of that environment.

[8] A critical load is a threshold for the loading rate of an air pollutant, such as sulfur or nitrogen, above which a specific deleterious effect may occur.

Measurement Unit: Accumulated exceedance or kg equivalent SO_2 (SO_2eq).

Methodological resources to consider:

- Accumulated Exceedance.[73]
- European Commission's Product Environmental Footprint.[74]
- CML 2001.[75]

Recommendations for alternative protein manufacturers

It is recommended that acidification is included across all alternative protein LCA scopes. While the characterization factor SO_2eq is still widely used, there is an increasing shift toward the PEF's accumulated exceedance method. An expert LCA provider can provide guidance on which methodology is most appropriate, based on the LCA's goal and scope and available data.

Note that oceanic acidification is not usually covered in LCAs. Alternative protein manufacturers looking to compare seafood products with alternatives may require further exploration with an LCA provider on the available options.

Additional impact categories to consider (lower priority)

The following impact categories can provide a broader perspective on the impacts of food products. This is not an exhaustive list of additional impact categories, but rather specific categories related to the impact of food products. All companies considering an LCA should consult an expert LCA provider to ensure that the impact categories chosen fit the goal and scope of the study and that there is reasonable quality data to support the analysis.

Impact category: **Ecotoxicity and human toxicity**	*Unit:* CTUe and CTUh	*Methodological resources:* USEtox model[77]

The PEF methodology includes three impact categories that address toxicity-related impacts: freshwater ecotoxicity, human toxicity cancer, and human toxicity non-cancer. Examples of toxicity issues relevant to alternative proteins include particulate air pollution (from crop residue burning) and ingested chemicals from pesticide and fertilizer use on crops.

For freshwater ecotoxicity, a comparative toxic unit for ecosystems (CTUe) is expressed as an estimate of the potentially affected fraction of species, integrated over time and volume, per unit mass of a chemical emitted (PAF m^3year/kg).

Similarly, for cancer and non-cancer human toxicity, a comparative toxic unit for humans (CTUh) is expressed as an estimated increase in morbidity in the total human population, per unit mass of a chemical emitted.[76]

Each type of toxicity records a specific set of chemicals.

Impact category: **Ozone depletion**	*Unit:* Kg CFC-11 eq	*Methodological resources:* Steady-state ODPs 1999 as in WMO assessment[78]

Ozone depletion potential (ODP) calculates the destructive effects on the stratospheric ozone layer over a time horizon of 100 years.

Impact category: **Resource use**	*Unit:* Megajoules (MJ) and/or Kg Sb eq	*Methodological resources:* CML 2002 (van Oers, L., et al, 2002)[79]

Resource use, or resource depletion, is measured through the depletion of abiotic and biotic resources. Abiotic resources refer to inorganic or non-living materials at the moment of extraction (e.g., water, metals, fossil fuels). Biotic resources refer to living–at least at the moment of extraction–natural resources (e.g., wood, fish). Biotic resources do not include resources reproduced by an industrial process (e.g., livestock, agricultural crops, wood from a plantation).

The characterization factor for abiotic resources is MJ, while for biotic resources, it's Kg antimony equivalents (Kg Sb eq).

Impact category: **Biodiversity**	*Unit:* Biodiversity/ ecosystem services	*Methodological resources:* ReCiPe 2016[82]

Currently, there are limited approaches to including biodiversity within LCAs. Some quantification methods include the proportion of species lost due to an activity, the number of hectares of habitat affected, and the amount of sustainably sourced raw materials used.[80] These methods result in significantly different results, and few investigate the indirect impacts of company activities.

Regardless of the specific method to quantify the individual impacts, biodiversity (given that it is a multifaceted set of interrelated systems) is not possible to accurately measure by a single indicator. As a result, biodiversity should be measured as an end-point indicator where several mid-point indicators are combined to understand the overall impact.[81]

A useful methodology for a biodiversity end-point indicator is ReCiPe 2016.

Life Cycle Inventory Analysis

Aligned with ISO14044:2006 section 4.3

What is an inventory analysis?

The life cycle inventory analysis (LCI) phase includes collecting data on all resources required to create a product and the emissions produced from the process. The data collected should include:

- The quantity of all resources, such as all raw materials, energy, and water used.
- The upstream and downstream (depending on the system boundary) transportation, including both the distances traveled and the transportation methods used.
- The quantities of the various products produced by a system.
- Waste from production processes.

The collected data are categorized into three types of process flows: elementary, product, and waste flows.

Elementary flows include all raw materials and waste emissions, product flows include all products produced by a system, and waste flows include all wastewater and solid/liquid waste.

Emissions are then estimated for each of these flows, such as CO_2 emissions for the energy used to produce the chosen functional unit. The data are often a combination of primary and secondary data, depending on the system boundary. Ideally, data for all foreground processes should be primary data; for background processes, secondary data from existing databases are suitable.

A key part of the inventory phase is deciding how to address multifunctional product systems (i.e., when more than one product is produced from the same system). Different approaches to allocating impacts to products are explored in more detail in the Allocation methodology section.

Note to study managers:

Study managers should be cognizant that the LCI can be a labor-intensive phase. Collecting data for a comprehensive LCA will require primary data for all resources and emissions in the foreground system, and secondary data for all resources and emissions in the background system. Managers should budget adequate internal resources to facilitate data collection.

Data collection and modeling

A critical issue for an LCA during the LCI phase is retrieving accurate and consistent data. Primary data should be used wherever possible. However, a complete assessment will use some secondary data. At a minimum, secondary data quality should be assessed against the following criteria: [83]

- **Data sources:** the data sources are reliable and scientifically accepted.
- **Data accuracy:** the data have been collected according to data collection methodologies and have not been adjusted or tampered with, and no parts of the data were omitted.
- **Data age:** the data are up-to-date and reflect the current system.
- **Technology coverage:** the data reflect the technological processes within the system being assessed.
- **Time-related or temporal coverage:** the time period of the data provides enough statistical evidence to make a robust assessment.
- **Geographical coverage:** the data reflect the specific geographies in the system.

Additional points to consider:

- **Completeness:** the data cover the identified study scope and system boundaries.
- **Consistency:** the data and sources are consistent with each other, and efforts have been made to ensure alignment between comparative datasets.
- **Reproducibility:** the data could be reproduced by an independent practitioner. [9] [84]

[9] For additional resources on data quality assessment see the pedigree matrix for data quality, in Weidema, Bo Pedersen, and Marianne Suhr Wesnæs. "Data Quality Management for Life Cycle Inventories—an Example of Using Data Quality Indicators." *Journal of Cleaner Production* 4, no. 3–4 (January 1996): 167–74. https://doi.org/10.1016/S0959-6526(96)00043-1.

For secondary data, several well-established LCA food databases can be used to supplement primary data. LCA studies may use one or more databases to ensure a complete dataset. The next section summarizes the main LCA food databases and provides recommendations for alternative protein manufacturers. However, given the novel processes and supply chains utilized in manufacturing alternative proteins, many environmental datasets for specific inputs will not be readily available. For instance, there is little data on the impact of scaled amino acid production or recombinant protein production for cultivated meat. LCAs focusing on these areas will be needed to build a foundation of data that will then benefit future alternative protein LCAs.

In the interim, there are two approaches to obtaining the required data. The first approach is working with mature companies in the sector that have already commissioned LCAs or already have sufficient information on their processes to calculate the environmental impact. The second approach is using proxy data from existing studies. This may require assessing and fact-checking specific data points against a number of sources (see the case study in Box 1). When using existing study data as a proxy, it's important to deeply understand the elements being assessed. For instance, are the molecular structure and chemical function of cultivated meat similar to the element in the existing dataset, and do they have similar environmental efficiencies?

GFI commissioned an LCA of cultivated meat. This study was an anticipatory LCA because it was based on projections of cultivated meat produced at commercial scale. This required the use of proxy data to estimate the impact.

One aim of this study was to understand the impact of food-grade production of glutamine, which is anticipated to be used heavily in cultivated meat. To explore this, the study first reviewed the single existing LCA that examined feed-grade production of three different amino acids (lysine, methionine, and threonine). Subsequently, the study evaluated the impact difference between food and feed-grade production by consulting with amino acid producers. Finally, the study averaged the production volumes of lysine, methionine, and threonine to estimate the impact for glutamine. Thus, effectively using proxy data to estimate the impact.

Box 1: Case study on LCA of cultivated meat

LCA food databases and recommendations

The following table provides a summary of the main LCA databases that contain significant quantities of data on food.

Database	Description
Agribalyse[89]	AGRIBALYSE is a French LCI database for the agriculture and food sector. Provided by The French Agency for Ecological Transition (ADEME), the database includes LCIs for 2,500+ agricultural and food products produced and/or consumed in France. It combines a production-based and a consumption-based approach. AGRIBALYSE 3.1 is built on previous versions with contributions from a network of partners including INRAE, the agriculture and agro-food French technical institutes (ACTA-ACTIA), and the consultancies Gingko 21, Sayari, Blonk, Koch Consulting, and EVEA. For imported products, Agribalyse 3.1 relies on Ecoinvent and WFLDB data. Agribalyse is freely available to use.
Agri-footprint[87]	The Agri-footprint database, created by Blonk Consultants, is a comprehensive database specializing in agricultural LCAs. It enables users to access a wide range of agriculture-specific impact categories such as water and land use, land use change, fertilizers, and soil carbon content. It complies with the ISO standards and the PEF initiative of the European Commission. In addition, users can also choose among three predefined allocation options: mass, energy, and economic. The database is completely focused on agricultural and farming products and contains approximately 5,000 products and processes. Agri-footprint is available via subscription.

Ecoinvent[86]	Ecoinvent is a not-for-profit association. The Ecoinvent database provides well-documented process data for thousands of products that can be used in a broad range of environmental studies, including LCAs, EPDs, and carbon footprinting. The database includes 3,300 unique products and services across energy supply, agriculture, transport, biofuels and biomaterials, bulk and specialty chemicals, construction materials, wood, and waste treatment. Ecoinvent is currently the gold-standard resource for LCA data. Most LCA providers will have access to the Ecoinvent database and will use this in cases where there are no primary data. However, the Ecoinvent database is not food-product specific; therefore, the other databases listed can be used to supplement the data as necessary, as long as the characterization factors used are consistent Ecoinvent is available via subscription.
Exiobase[88]	Exiobase is one of the most extensive sources of international supply-chain impacts. Funded by the European research framework and created by a consortium of research institutes, Exiobase was developed by harmonizing and detailing supply-use tables, otherwise known as input-output tables (IOTs), for a large number of countries, estimating emissions and resource extractions by industry.[10] It is available through OpenLCA (an LCA modeling software) for free. However, because Exiobase uses IOTs as the basis for its LCIA data it is not compatible with other databases using a different modeling technique. [90] Exiobase is available under a creative commons license and therefore freely available to use.

[10] Input-output tables (IOTs) describe the sale and purchase relationships between producers and consumers within an economy. They can either show flows of final and intermediate goods and services defined according to industry outputs (industry × industry tables), or according to product outputs (product × product tables). https://www.oecd.org/sti/ind/input-outputtables.htm

Hestia[84]	Hestia was launched in 2021 in partnership with the University of Oxford and WWF. The Hestia platform allows users to upload and download sustainability and productivity data on farming, food processing, and other processes in the agri-food system for various geographic-specific food products and production practices. These data are continually being updated. The platform provides data across many mid-point and end-point impact indicators, but the range of data available for each food product and geography is varied. The Hestia platform is open-source and freely available. Therefore, it is an excellent resource for gaining an initial understanding of the sustainability of specific agricultural foods and can be used to supplement primary data. However, care should be taken that the data being supplemented are consistent with the scope of the study.
World Food LCA database[85]	The World Food Life Cycle Assessment Database (WFLDB) is a global initiative launched in 2012 and led by Quantis. WFLDB aims to create a database representing primary agricultural and processed food products. The database covers a range of agricultural products, including inputs such as fertilizers and pesticides. WFLDB contains 2,300+ datasets for 120 products in 56 countries. The database applies two different system boundaries depending on the product. A cradle-to-gate approach is used for crop and animal production, while a gate-to-gate method is used for food transformation. This creates a modular system whereby products can be summed to understand the full impact. WFLDB is available via subscription.

Table 5: LCA food databases

Life Cycle Impact Assessment

Aligned with ISO 14044:2006 sections 4.4.2 and 4.4.3

The life cycle impact assessment (LCIA) phase focuses on the evaluation of the environmental performance of the system that has been analyzed. Guided by the goal and scope, the LCIA draws together the data from the LCI into the selected impact categories (explored in detail in the Impact categories section).

The impact assessment at midpoint level[11] is performed by first assigning the elementary flows to the relevant impact category, otherwise known as classification. Subsequently, the inventory results for the individual elementary flows are usually linearly multiplied by the relevant impact characterization factors. The resulting characterized indicator results are then totaled within each impact category to produce the total impact for that category.

Note to study managers

The following should be considered when selecting, applying, and calculating impact categories:

- Impact categories should be selected during the goal- and scope-setting phase. This is to ensure that impact categories are not selected based on an interest-driven view after seeing initial results.
- The impact categories, category indicators, and characterization factors should be internationally accepted, and care should be taken to ensure that the models reflect relevant regional regulations.
- The characterization model for each category indicator shall be scientifically and technically valid and based upon a distinct, identifiable environmental mechanism or reproducible empirical observation.
- Double counting should be avoided as much as possible across included characterization factors.
- Value choices and assumptions made during the selection of impact categories and LCIA methods should be minimized and clearly documented.
- A common error is having incomplete LCIA characterization factors assigned to elementary flows. In other words, incorrectly identifying how to calculate the impact of different elementary flows. Ensuring you have a clear understanding of which elementary flows you are calculating and that you are using the latest characterization factor methodologies can address this issue.

[11] Impact assessment would also include end-point indicators if the scope included end-point indicators. This guide does not focus on end-point indicators as they require a further level of assumptions and modeling and are thus subject to significantly higher uncertainties that reduce the robustness of results.

Interpretation

Aligned with ISO14044:2006 section 4.5

The interpretation phase of an LCA has two main functions. First, as the LCA should be iterative (as described at the beginning of this paper), the interpretation phase aims to steer the study toward improving the methodology to meet the study's goal. Second, the interpretation aims to provide robust conclusions and recommendations.

The interpretation phase has three steps:

1. **Identification of significant issues:** Within the key processes, parameters, assumptions, and elementary flows. For **scenario B**, where comparative assertions are made the interpretation phase should include a critical review conducted by a panel that includes LCA specialists. More detail is provided below under the "sensitivity check" section.

2. **Evaluation:** These issues are then evaluated in terms of their sensitivities and their influence on the overall results of the LCA. This includes evaluating the completeness and consistency with which the significant issues have been managed.

3. **Conclusions:** Development of conclusions and recommendations.

Identification of significant issues

Identification of significant issues can be divided into two searches. First, what are the main contributors to the LCIA result (i.e., the most relevant life cycle stages, processes and elementary flows, and the impact categories)? Second, what are the main choices that can influence the precision of final results (i.e., methodological choices, assumptions, and data sources)?

The identification of significant issues should be assessed through a weak-point analysis. Initially, a weak-point analysis will require quantifying the completeness of the inventory data, identifying any gaps, and determining which aspects significantly contribute to the overall results. For companies in **scenario A** that are undertaking a hotspot analysis of their product system, the weak-point analysis can be instrumental in identifying contributing processes and individual elementary flows that significantly impact the overall system. In practice, the weak-point analysis is supported by professional LCA tools.

Evaluation

The evaluation aims to strengthen and support the LCA results by undertaking several quality assessments such as completeness, sensitivity, uncertainty, and consistency checks. These processes are designed to improve the accuracy and quality of the study's results and enable the results to be used as background data in subsequent studies.

The following quality assessments should be undertaken.

Completeness check

Evaluation of the LCI model to ensure that the system boundaries and associated flows have been systematically applied. This would help verify that the final inventory dataset is complete and meets the predefined data quality requirements. The completeness check must ensure that all relevant processes in a system within the defined boundary are included and that data are allocated appropriately.

Sensitivity check

A sensitivity analysis can be conducted to understand the influence of data gaps and assumptions on the uncertainty of results. Sensitivity analysis should be conducted for all production stages where data uncertainties and gaps exist, or where assumptions are used. In most cases, to varying degrees, a sensitivity analysis will be needed for each stage.

For example, an analysis could calculate the impact on the product distribution stage of various distances between the manufacturing facility and retail outlets. While average distances covered are accessible through distribution records, future changes in demand and/or production capacity could lead to changes in distribution distances. Sensitivity analysis is a useful tool to model the influence of potential changes in the data on results, and thus measure the study's accuracy and longevity.

There are three areas where sensitivity analysis must be applied:

1. **Sensitivity of data:** Evaluate the sensitivity of the LCIA results to key flows, process parameters, flow properties, and other data items such as recyclability and product lifespan. This includes understanding the sensitivity of different data sources and how those influence the results. The variability of inventory data can be modeled using LCA software. Software such as SimaPro includes modeling techniques such as a Monte Carlo simulation that can assess the uncertainty and variability of embedded inventory data.[92]

2. **Sensitivity of LCIA characterization factors:** Due to the modeling complexity and lack of in-depth tried and tested methodologies, some impact categories are subject to higher uncertainties. For example, GWP is a methodologically robust and standard impact category, whereas ecotoxicity is highly uncertain. The level of sensitivity analysis will need to reflect the impact categories selected.

3. **Sensitivity of modeling choices and assumptions:** There may be a need to assess the sensitivity of different modeling choices (e.g., how do different functional unit choices or allocation methods impact the results?).

Undertaking a sensitivity check is particularly important for **scenario B** comparative LCAs. As required under ISO 14044:2006, where the evaluation includes interpretative statements, these must be based on detailed sensitivity analyses when an LCA is intended to be used in comparative assertions that will be publicly disclosed.

Consistency check

The consistency check evaluates whether the assumptions, methods, and data have been applied consistently throughout the study. For comparative LCAs, the consistency check applies to the analyzed and compared systems' life cycles. Key issues to focus on include the modeling framework and approaches, i.e., allocation criteria, system boundaries, data sources, and impact categories and characterization factors.

Furthermore, **Scenario B** companies that are making comparative assessments must undergo a critical review in line with ISO 14044. This helps guard against liability when publicly declaring environmental results.

The review must be undertaken by a panel of no less than three reviewers with a relevant technological and scientific understanding of the processes and LCA practices, and at least one member must be a certified LCA expert. An LCA provider will typically have a list of potential peer reviewers. The panel should be selected during the study and typically will require some compensation for their technical review. Results of the critical review are shared directly with the LCA provider and should ideally be included as supplementary material to the final study.[93] Full guidance on critical reviews is available in ISO14040.

Conclusions

The final step is to develop conclusions and recommendations based on the LCA results and tailor these for the intended audience. Conclusions should identify the results while accounting for the completeness, sensitivity, and consistency of these results. For example, the conclusions should highlight where significant differences exist (e.g., when the use of a particular functional unit has had a significant impact on the results). It should also note any limitations of the study (e.g., the limited completeness of data associated with elementary flows). If possible, conclusions should indicate how and to what degree these limitations influence the results.

Finally, it is critical that the conclusions and recommendations represent the results produced and do not:

- Try to over-interpret the results by exaggerating small or insignificant differences.
- Draw general conclusions from specific case studies.
- Put high confidence in observed differences between compared systems based on uncertainty analysis alone that doesn't cover the full uncertainty of the results.

Conclusion

We hope this guide has served as a clear and nuanced description of the different phases of life cycle assessments, the various ways they can be conducted, and critical considerations for alternative protein manufacturers. Alternative protein companies that follow a standardized, rigorous approach to undertaking an LCA will be able to make more effective operations decisions that minimize environmental impact, highlight the environmental benefits of their products, and counter greenwashing claims. The more high-quality alternative protein LCAs are published, the better the available data for subsequent LCAs. This will create a virtuous cycle to help propel the industry forward.

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Annex 1: Additional resources

LCA Consultancies

This paper provides an overview of the best practices for conducting an LCA for alternative protein manufacturers. It is not designed to provide a step-by-step guide to undertaking an LCA. Therefore, it is important that any LCAs following pathway 1 or 2, particularly if the LCAs are intended to be published, are undertaken by a qualified LCA practitioner. The International EPD system includes a comprehensive database of LCA consultants.

Sharing this list does not constitute in an endorsement by GFI of any listed parties. Companies should conduct a thorough procurement process to evaluate the suitability of LCA practitioners to ensure they meet the requirements of their study's goal and scope.

Detailed LCA guidance

For in-depth guides on how to undertake an LCA, see the following publications by the European Commission's Joint Research Centre:

- European Commission. Joint Research Centre. Institute for Environment and Sustainability. (2010). International Reference Life Cycle Data System (ILCD) Handbook general guide for life cycle assessment: detailed guidance.
- European Commission. Joint Research Centre. Institute for Environment and Sustainability. (2010). International Reference Life Cycle Data System (ILCD) handbook. Framework and requirements for life cycle impact assessment models and indicators.

Annex 2: IPCC assessment report global warming potentials comparison table

Greenhouse gas	100-year time period			20-year time period		
	AR4 2007	AR5 2013	AR6 2021	AR4 2007	AR5 2013	AR6 2021
CO_2	1	1	1	1	1	1
CH_4 (fossil origin)	25	28	29.8	72	84	82.5
CH_4 (non-fossil origin)	—	—	27.2	—	—	80.8
N_2O	298	265	273	289	264	273

Annex 3: Common alternative protein manufacturing processes

Manufacturing technique	High-level description	Example LCAs
Plant-based products		
Dry fractionation	A process to concentrate and extract protein content from plant-based ingredients through sieving or sifting, air classification, electrostatic separation, or a combination of these solvent-free techniques.	Vogelsang-O'Dwyer, M., Petersen, I. L., Joehnke, M. S., Sørensen, J. C., Bez, J., Detzel, A., Busch, M., Krueger, M., O'Mahony, J. A., Arendt, E. K., & Zannini, E. (2020). Comparison of Faba bean protein ingredients produced using dry fractionation and isoelectric precipitation: Techno-functional, nutritional and environmental performance. Foods, 9(3). https://doi.org/10.3390/foods9030322
Wet fractionation	A process to isolate and extract protein content from plant-based ingredients using solvents to extract, precipitate, and centrifuge proteins, oils, carbohydrates, and fibers.	Berardy, A., Costello, C., & Seager, T. P. (2015). Life Cycle Assessment of Soy Protein Isolate Sustainable Intelligence View project Anticipatory LCA: Environmental Consequences of New Technologies View project. https://doi.org/10.6084/M9.FIGSHARE.1517821
High moisture extrusion (HME)	Heating plant-based ingredients in a twin-screw extruder that is then cooled, in a precisely thermal-controlled dye leading to the formation of fibers.	Saerens, W., Smetana, S., Van Campenhout, L., Lammers, V., & Heinz, V. (2021). Life cycle assessment of burger patties produced with extruded meat substitutes. Journal of Cleaner Production, 306, 127177. https://doi.org/10.1016/j.jclepro.2021.127177
Low moisture extrusion (LME)	Mixing plant-based ingredients through an opening in a perforated plate or die designed to produce the required shape.	Heller, M. C., & Keoleian, G. A. (2018). Beyond Meat's Beyond Burger Life Cycle Assessment: A detailed comparison between a plant-based and an animal-based protein source.

Manufacturing technique	High-level description	Example LCAs
Mixing and molding	A processing step that mixes plant-based proteins (either outputs from an HME or LME process, or whole-food plant proteins), with fats/oils, hydrocolloids, emulsifying agents, oleogels, thickeners, binders, gelling agents, coloring agents, and flavoring agents, and then molds them into a final product.	Saerens, W., Smetana, S., Van Campenhout, L., Lammers, V., & Heinz, V. (2021). Life cycle assessment of burger patties produced with extruded meat substitutes. Journal of Cleaner Production, 306, 127177. https://doi.org/10.1016/j.jclepro.2021.127177
Hulling/shelling	The separation of nuts or grains from the case or shell to expose the main body of the plant prior to extracting liquid for use in, for instance, plant-based milks or yogurts.	Oatly, & CarbonCloud. (2020). Climate footprint for Enriched ambient oat drink, Sweden. https://www.oatly.com/stuff-we-make/climate-footprint
Homogenization	A homogenizer is a mixer used to create a uniform and even mixture by forcing material through a narrow, confined space. Multiple industries rely on homogenizers to produce stable, uniform, and consistent products.	Winans, K. S., Macadam-Somer, I., Kendall, A., Geyer, R., & Marvinney, E. (2020). Life cycle assessment of California unsweetened almond milk. International Journal of Life Cycle Assessment, 25(3), 577–587. https://doi.org/10.1007/s11367-019-01716-5
Biomass fermentation-derived products		
Solid state	Solid state fermentation (SSF) takes place in a solid matrix (inert support or substrate) in the absence or near absence of free water. The substrate is provided with specific moisture or feedstock to support the growth and metabolic activity of microorganisms.	Brancoli, P.; Gmoser, R.; Taherzadeh, M.J.; Bolton, K. The Use of Life Cycle Assessment in the Support of the Development of Fungal Food Products from Surplus Bread. Fermentation 2021, 7, 173. https://doi.org/10.3390/fermentation7030173

Manufacturing technique	High-level description	Example LCAs
Submerged	Submerged biomass fermentation involves cultivating microorganisms in liquid nutrient media, often in an enclosed vessel or bioreactor. It also includes fermentation using gas feedstocks and hydrogen-fixing microorganisms to generate whole-cell protein.	Souza Filho, P. F., Andersson, D., Ferreira, J. A., & Taherzadeh, M. J. (2019). Mycoprotein: environmental impact and health aspects. World Journal of Microbiology & Biotechnology, 35(10). https://doi.org/10.1007/s11274-019-2723-9 Natasha Järviö, Netta-Leena Maljanen, Yumi Kobayashi, Toni Ryynänen, Hanna L. Tuomisto, An attributional life cycle assessment of microbial protein production: A case study on using hydrogen-oxidizing bacteria, Science of The Total Environment, Volume 776, 2021.https://www.sciencedirect.com/science/article/pii/S0048969721008317 Upcraft et al. 2021. Protein from renewable resources: mycoprotein production from agricultural residues. Green Chemistry 23,5150
Biomass fermentation downstream processing (DSP)	The series of operations required to take the biomass produced through the biomass fermentation process and derive from them a pure and homogeneous protein product. The key steps for biomass fermentation DSP are heat-inactivation and dewatering.	Smetana S, Mathys A, Knoch A, Heinz V (2015) Meat alternatives: life cycle assessment of most known meat substitutes. Int J Life Cycle Assess 20:1254–1267. https://doi.org/10.1007/s11367-015-0931-6

Manufacturing technique	High-level description	Example LCAs
Precision fermentation-derived products		
Submerged	Submerged precision fermentation is a process in which microbial hosts are designed and fed nutrient media to produce specific functional ingredients (e.g., proteins, fats/oils).	WSP. (2021). Iso-conformant report comparative life cycle assessment of perfect day whey protein production to dairy protein perfect day, inc. (caveat: this study will not list all variables due to some trade secrets like DSP yields and production titers. The Ovalbumin LCA listed below might have more information and datasets.) Järviö N, Parviainen T, Maljanen N-L et al (2021) Ovalbumin production using Trichoderma reesei culture and low-carbon energy could mitigate the environmental impacts of chicken-egg-derived ovalbumin. Nature Food 2:1005–1013 Behm et al., 2022. Comparison of carbon footprint and water scarcity footprint of milk protein produced by cellular agriculture and the dairy industry. The International Journal of Life Cycle assessment 27, 1017-1034. Davis, D., Morão, A., Johnson, J. K., & Shen, L. (2021). Life cycle assessment of heterotrophic algae omega-3. Algal Research, 60, 102494. http://dx.doi.org/10.1016/j.algal.2021.102494
Precision fermentation downstream processing (DSP)	The series of operations applied to the functional ingredients produced through the precision fermentation process to derive from them a pure and homogeneous product. The key stems for precision fermentation DSP are dewatering (strained and centrifuged), micro filtration / polishing, diafiltration/concentration and drying (spray drying).	Voutilainen, Eveliina, Ville Pihlajaniemi, and Tuure Parviainen. 2021. “Economic Comparison of Food Protein Production with Single-Cell Organisms from Lignocellulose Side-Streams.” Bioresource Technology Reports 14 (June): 100683.* Behm et al., 2022. Comparison of carbon footprint and water scarcity footprint of milk protein produced by cellular agriculture and the dairy industry. The International Journal of Life Cycle assessment 27, 1017-1034. Feijoo, S., S. González-García, J. M. Lema, and M. T. Moreira. 2017. “Life Cycle Assessment of β-Galactosidase Enzyme Production.” Journal of Cleaner Production 165 (November): 204–12.

Manufacturing technique	High-level description	Example LCAs
Cultivated products**		
Stirred tank bioreactor	Bioreactors provide the housing and control the conditions that enable cells to grow by controlling the temperature, oxygen levels, and delivery of cell culture media. Continuous stirred tank bioreactors permit the growth of cells in suspension via mechanical stirring while maintaining high mass transfer of oxygen.	CE Delft life cycle assessment (LCA) of Cultivated meat (see updated version below – Sinke, 2023) Sinke et al (2023). Ex-ante life cycle assessment of commercial-scale cultivated meat production in 2030. Mattick et al (2015). Anticipatory life cycle analysis of in vitro biomass cultivation for cultured meat production in the United States. Kim, S., Beier, A., Schreyer, H. B., & Bakshi, B. R. (2022). Environmental Life Cycle Assessment of a Novel Cultivated Meat Burger Patty in the United States. Sustainability: Science Practice and Policy, 14(23), 16133. http://dx.doi.org/10.3390/su142316133
Hollow fiber bioreactor	Bioreactors provide the housing and control the conditions that enable cells to grow by controlling the temperature, oxygen levels, and delivery of cell culture media. Hollow fiber bioreactors permit the growth of adherent cells using a smaller overall reactor and media footprint.	Tuomisto et al (2022). Prospective life cycle assessment of a bioprocess design for cultured meat production in hollow fiber bioreactors.

*There was not a specific LCA on this process, however the reference provided is a good overview of the process and TEA for both biomass and precision fermentation on lignocellulosic sugar. However, lignocellulosic sugar assumption may not be a via proxy for wider alternative protein fermentation processes.

**Please note that all the cultivated products example LCAs are ex-ante or forward-looking studies. The process designs are based on assumptions, as are the important metrics related to, for example, yield, with varying degrees of confidence. Much of the data is lab-scale, and others are extrapolated, with studies using scenario analysis to help flesh this out. Specific assumptions (e.g., how much cooling is needed) can have very large downstream effects on environmental indicators. Additionally, many LCA and agricultural databases don't have the needed information for important inputs, especially media ingredients; as a result, proxies have to be created (this is discussed in Sinke 2023).

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