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Life Cycle Assessment in a Nutshell—Best Practices and Status Quo for the Plastic Sector

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Life cycle assessment (LCA) is an internationally standardized methodology to evaluate the potential environmental impacts of products and technologies and assists in lowering their negative environmental consequences. So far, extensive knowledge of LCA—their application and interpretation—is restricted to experts. However, the importance of LCA is increasing due to its application in business, environmental, and policy decision-making processes. Therefore, general knowledge of LCA is critically important. The current work provides an introduction to LCA for non-experts discussing important steps and aspects and therefore can be used as a starting point for LCA. In addition, a comprehensive checklist for non-experts with important content and formal aspects of LCA is provided. Specific aspects of LCA for the plastics sector along the value chain are also discussed, including their limitations.

1. Introduction

Sustainability and in particular environmental impacts of products and technologies have been the focus of academia, industry, and policymakers in recent decades. Due to the global challenges of climate change, resource depletion, and biodiversity loss, it is imminent to quantify environmental impacts of products and technologies.[1,2] However, to enable a holistic sustainability assessment, all three pillars of sustainability have to be addressed, that is, environmental, social, and economic aspects. An established method to quantify environmental impacts of products and technologies is life cycle assessment (LCA) based on ISO 14040 and 14044.[3,4] While LCA focuses on the environmental dimension, the combination with social life cycle assessment (S-LCA) for the social dimension as well as life cycle costing (LCC) for the economic dimension enables a full life cycle sustainability assessment (LCSA),[5] see also **Figure 1**.

LCSA should be performed to enable a holistic view on sustainability and quantification for products and technologies. However, currently, the LCA standards for social sustainability (S-LCA) are still in development.[6] Therefore, the focus of the current work is on the environmental dimension of sustainability. LCA has been developed during the last decades to become the state-of-the-art methodology to quantify environmental impacts of products and technologies highlighting the importance for researchers and other stakeholders to gain a basic understanding of LCA. Equally important is an understanding of the implications for their area of expertise and research, for example, plastics, to enable an ongoing optimization of their products and technologies and therefore reduction of environmental impacts. As shown by Zheng and Suh[7] in 2015 the conventional plastic sector contributed to around 1.7 Gt CO_2-eq. to greenhouse gases (GHG) globally (this equals 3.5% of the total global GHG). It is estimated that the contribution could increase based on the growing demand for plastics to 6.5 Gt CO_2-eq. in 2050 if plastic-specific emissions stay as today and do not decrease. A study conducted by Cabernard et al.[8] estimates the GHG emissions to be 16% higher than the results provided by Zheng and Suh.[7] This highlights the importance of assessing the impacts of the plastics sector and utilizing the results to further reduce the impact. While the focus has been on GHG emissions in recent years, the impact of plastics must be analyzed for all environmental impacts (including land use, water use, resource use, etc.) to enable a holistic optimization of impacts and reduce burden shifting (reduction of impacts in one category and increase of impacts in another). The current work is intended to further increase the knowledge of LCA among researchers and other stakeholders in the plastic sector and therefore contribute to improve the quality and quantity of LCA information.

The goal of this perspective is to introduce LCA with a focus on the plastics sector and discuss guidelines for best LCA practices. The work is divided into 5 sections. 1) Introduction, 2) LCA in a nutshell, 3) Hot to spot a good LCA?, 4) Status quo of LCA for

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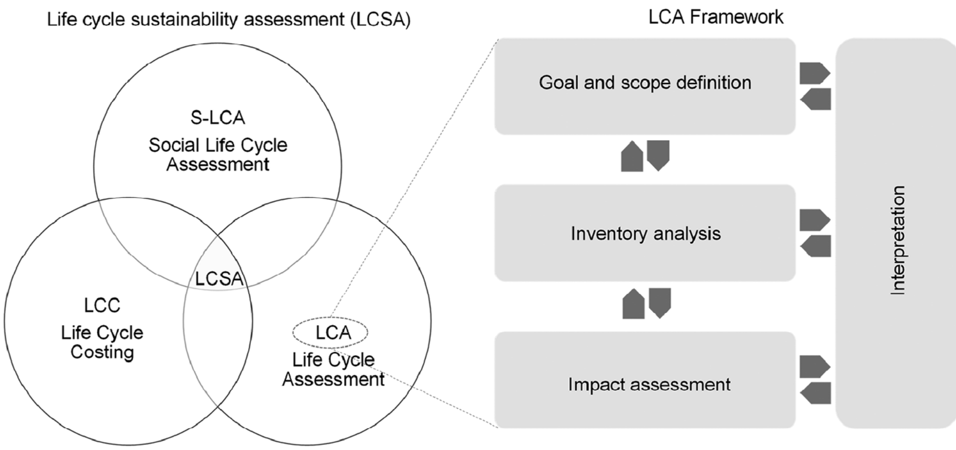

Figure 1. Life cycle sustainability assessment and life cycle assessment framework (adapted from ISO 14040/44).

Plastics, and 5) Summary and conclusion (**Table 1**). Section 2 provides an overview of LCA, its motivation and goals, the methodological aspects of LCA and the structure of an LCA. Section 3 highlights important aspects which have to be considered when preparing or analyzing an LCA and shall help in particular non-LCA experts to better understand and assess LCAs. Section 4 focuses on the development of plastic-related LCAs, special aspects to be considered for LCAs of plastics, and current limitations of LCA methodology with regard to an application in the plastic sector.

2. LCA in a Nutshell

2.1. Motivations and Goals for LCA

LCA is a modeling tool that can be used for a wide variety of purposes, for example, legislative, corporate, and scientific.

2.1.1. Legislative Purpose

LCA is a valuable instrument in supporting policy development, implementation, and regulation, and can also be utilized for evaluation of policies. Due to the need to shift toward more sustainable societies, LCA has gained increased recognition at high government levels, with some countries or regions formalizing its role in policy development. Additionally, political authorities can support industry by promoting the methodological progress regarding LCA. For example, communicating the environmental performance of products is a significant challenge when utilizing LCA. To overcome this issue, the European Commission has developed LCA-based methods to provide reliable and reproducible information on the environmental footprints of products and organizations. Consequently, LCA can serve legislative stakeholders as a tool for science-evident decision-making.[9]

Table 1. Structure of the current perspective article.

Nr.	Sections	Key aspects
1	Introduction	• Introduction to sustainability assessment and LCA • Importance of LCA and purpose of this work
2	LCA in a nutshell	• Motivations and goals for LCA • Methodological aspects of LCA • Structure of an LCA
3	How to spot a good LCA?	• Aspects of implementation • Aspects of reporting
4	Status quo of LCA for plastics	• Plastic LCA over the years • Special aspects for plastic LCAs • Limitations of LCA for plastics
5	Summary and conclusion	• Summary of the work • Outlook for plastics

2.1.2. Corporate Purpose

Owsianiak et al. have identified five primary applications of LCA in enterprises. These include providing decision support in product and process development, using LCA for marketing purposes such as eco-labelling, selecting indicators to monitor environmental performance, choosing suppliers or subcontractors, and strategic planning. In product development, LCA is commonly used to detect environmental hotspots and improve products or processes. Furthermore, LCA is utilized for marketing as companies attempt to address public concerns about the environmental impact of their products while consumer awareness of environmental issues grows. Businesses can use LCA to quantify their environmental performance and communicate it to consumers, with eco-labels and environmental product declarations serving as useful tools in highlighting the environmental benefits of a product. LCA can also be employed to monitor environmental performance at the corporate level, though its application is presently restricted to selected impact categories such as carbon or water footprints. Additionally, companies can use LCA to establish internal strategic objectives, for example implementing an environmental management system.[9]

2.1.3. Scientific Purpose

The primary aims of scientific work in the area of LCA are the improvement of LCA methodology and the promotion of its application. The ongoing improvement of LCA methodology is crucial for supporting decision-making in companies and its contribution to international policy-making and scientific consensus building. Scientific journals like "The International Journal of Life Cycle Assessment" are an essential medium for publishing LCA studies for research and decision-making purposes. Over the years, there has been a substantial increase in the number of published papers related to LCA. The development of the LCA methodology is ongoing, with increasing attention given to international scientific consensus building on central aspects of the methodology and the standardization of LCA and related approaches.[10] At the same time, characterization models are further improved. These models describe how emissions or resource extractions contribute to environmental impacts. They are still being adjusted and updated based on new scientific findings.[11]

2.2. Methodological Aspects of LCA

LCA methodological aspects can strongly impact the approach and results of the impact analysis. Understanding these methodological considerations is crucial to fully comprehend the complexities of LCA and how it can be applied in practice.

There are two primary modeling frameworks used in LCA: attributional and consequential modeling. Attributional LCA examines a product system in isolation from the rest of the economy and attempts to attribute any environmental impacts to the product system. However, this approach has some shortcomings in relation to real world problems because product systems interact with other external systems through multifunctional processes that cannot be fully described in isolation. Consequential LCA on the other hand examines the consequences to the economy that emerge from the introduction of the studied system. This approach requires a good comprehension of the dynamics of the economic system. Therefore, the attributional modeling framework is still the most commonly used one and will be the focus of the current work.[9]

An LCA can be performed on a product or an organizational level. Both approaches follow the same methodology outlined in the ISO standard 14040/44, but they differ in their scope and objectives.[3,4] Product LCA is used to evaluate the environmental impact of individual products or services, while organizational LCA assesses the impact of an entire organization. The goal of organizational LCA is to identify environmental hotspots throughout the entire value chain of the organization. In contrast, product LCA provides insights into the environmental impact of specific products and activities. Product LCA aims to achieve comparability between products providing the same service. In contrast, organizational LCA is not intended for comparisons between different organizations, but is primarily for performance tracking via regular assessment of an organization's environmental performance over time to measure continuous improvement.[12]

LCA studies describe complex product systems that often include numerous processes and different locations. Designing models for these systems involves incorporating data from various sources, such as measurements and unit process databases. Assumptions can play a significant role while designing these models. Critically, the results of LCA studies can be used by decision-makers who lack understanding over the study's quality. Due to the subjective nature of LCA and its complexity, there is room for possible errors and manipulation, which has been a challenge encountered by the LCA community over the years. Consequently, the necessity for an independent critical review of LCA studies emerged early. In this context, two main types of review processes are relevant: scientific peer-review and critical review as per ISO 14040/44. These two review types differ in terms of duration, depth, cost, and confidentiality with the critical review being in general the more detailed and therefore more complex to implement. Both evaluations are independent and should be considered based on the intended utilization of the LCA study.[13]

LCA studies can involve comparisons of systems, such as multiple products serving the same purpose. The ISO 14040/44 standard introduces specific requirements for defining the scope of comparative studies, ensuring the feasibility of system comparisons.[3] These requirements include methodological factors like system boundaries, data quality, allocation procedures, and impact assessment. Any divergences between systems in these parameters must be identified and reported. When a comparative study aims to determine the environmental benefits of a product over alternatives and proclaims these conclusions to the public, the ISO standard labels it as a "comparative assertion intended for public disclosure." For such cases, a critical review is mandatory to assess the aspects mentioned above. These measurements aim to prevent the misuse of LCA for market competition.[3]

2.3. Structure of an LCA

The methodological framework for conducting an LCA contains four phases according to the ISO standard 14040/44.[3] The four phases are:

1) Goal and scope definition
2) Inventory analysis
3) Impact assessment
4) Interpretation

The methodology is refined through an iterative process, and its results are assessed and improved at each phase.[14]

2.3.1. Goal and Scope Definition

The initial stage of an LCA involves defining the goal of the study, which shapes the entire LCA process. The purpose of the study is defined and explained, influencing subsequent decisions that need to align with the established goal. An example of a goal could be the identification of hotspots across a plastic product value chain or to decide on a more environmentally friendly plastic type for a product. However, the goal definition can also be influenced by subsequent steps, for example, if unexpected data limitations arise during the inventory analysis, leading to a revision of the initial goal. The ISO standard outlines aspects that should be covered by the goal definition, such as the intended applications of the findings, limitations due to methodological

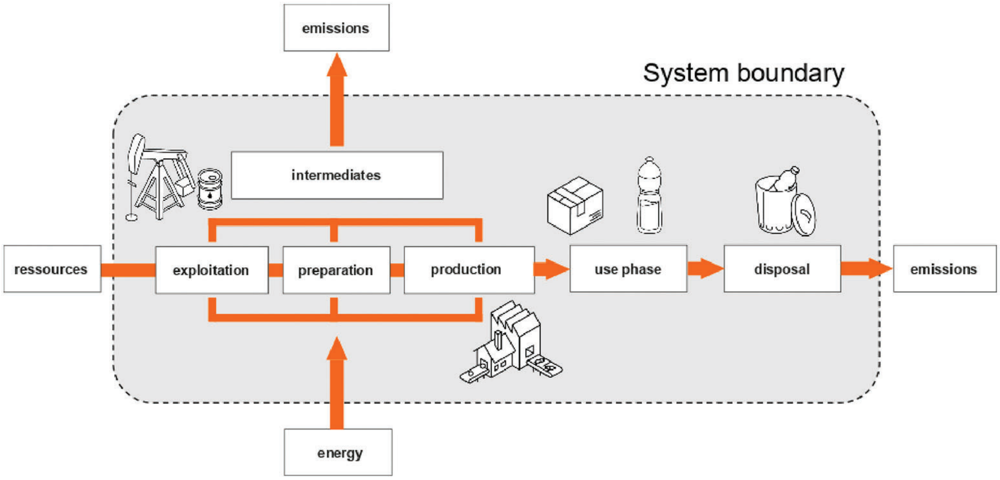

Figure 2. Exemplary system boundary and process sections over the life cycle phases of a product system.

choices, or target audience. Subsequently, the definition of scope establishes the parameters for assessing product systems and outlines the approach for conducting the assessment.[15] Along with the goal definition, the scope definition acts as a guide for the following phases of the LCA. One of the primary objectives of the scope definition is to ensure consistency in methods, assumptions, and data, while also enhancing the reproducibility of the study.[16] The central aspects of the scope definition will be briefly explained in the following sections.

System Boundaries: System boundaries serve as the limits that distinguish the product system under study from the surrounding economy and the environment. The selection of system boundaries significantly influences the outcomes of an LCA since it determines the specific unit processes from which potential environmental impacts are calculated. When defining the scope, it is helpful to illustrate the system boundaries in a diagram that outlines which parts of the product system are included and excluded (see **Figure 2**). The diagram typically focuses on life cycle stages such as manufacturing, transportation, use, and disposal. Additionally, "completeness requirements" are established to determine which processes should be included within these boundaries to achieve a product system model that aligns with the study's objectives.[16]

Functional Unit: The functional unit (FU) enables a meaningful comparison of different (product) systems that provide a specific function. It covers the qualitative and quantitative aspects of the function by addressing questions such as "what?," "how much?," "for how long/how many times?," "where?," and "how well?." The FU should always represent a function rather than a physical value like 1 kg, 1 L, or 1 MJ. Accurate definition of the FU is critical as it significantly influences the approach, results, and interpretation of an LCA, especially in comparative studies.[16] An example for an FU could be to compare the environmental performance of a glass bottle or milk container to a PET bottle: "transport of one liter of liquid in a sealed environment which ensures freedom from contamination for at least 2 years." In some cases, a system does not have a clear definable function due to the diverse or indefinite potential applications. This applies for example to material production, as well as multi-use machines. In such cases, a declared unit, usually a physical quantity is employed to accurately identify and quantify the reference flow of the system. This allows for proper data selection and use in other systems, replacing the need for a general functional unit.[17]

Data Representativeness: The target of an LCA model is to accurately represent the real-world conditions of a product or organization system. This involves using unit processes that are representative of the actual processes used in the analyzed system. Primary data collected first-hand by the LCA practitioner, alongside secondary data acquired from databases or literature, is used to create the foreground and background systems of the model. It is important to ensure the representativeness of the chosen or constructed unit processes compared to the actual processes they represent. The representativeness of data can be described in three dimensions: geographical, time-related, and technological. The scope definition phase is used as guidance for following inventory analysis by defining requirements for data representativeness based on the study's goals. Considering data representativeness and completeness is crucial, not only during the inventory analysis but also later during the result interpretation to evaluate how well the product system model aligns with reality.[16]

2.3.2. Life Cycle Inventory

During the life cycle inventory (LCI) phase of an LCA, data collection and modeling of flows within the product system take place, aligned with the goal and scope definition. The LCI results in a quantification of elementary flows crossing the system boundary, serving as the input information for the following life cycle impact assessment (LCIA). These flows cover inputs (e.g., material, water, energy) and outputs (e.g., emissions, waste). Usually, the LCI is the phase that requires the most amount of time and effort during an LCA. While high-quality data collection for all processes is often impractical, a structured approach is needed to identify the most impactful process units. Multiple iterations between LCI and LCIA are often required to meet study goals, with each iteration highlighting the most important inventory data for the LCA result.[18] Obtaining primary data, that is, collecting specific data from production sites for processes, is not always possible. The availability and acquisition of primary data can also largely depend on the involvement of the product manufacturer in the LCA process. As a result, a comprehensive LCI typically includes a combination of primary data, generic data, and estimations for when specific data is not accessible. It is crucial to document the origin and quality of the data as transparency is a fundamental requirement according to ISO 14040/44.[19] Data sources can be ranked according to their reliability and therefore in order of preference. The most preferable data source after those that involve primary data is to rely on LCI databases or literature sources that offer process-specific information. This data is often based on the best available technology standards or country averages, providing a generalized representation of the processes. Alternatively, generic LCI databases or literature sources can be utilized. These sources cover a mix of technologies in a particular country or region, giving a broader overview but lacking specific details. The least preferred source of LCI data are assumptions based on expert judgment or input from LCA practitioners as they involve subjective assessments, may introduce biases and uncertainties into the LCI data, and should therefore always be the last choice.[18]

Multifunctional processes provide more than one function, for example, by delivering multiple outputs or services. Secondary functions, which are not relevant to product users, are associated with these processes and connected to other systems outside of the defined system boundaries. Analyzing multifunctional processes poses a challenge in LCA, which focuses on individual product systems and primary functions. The ISO 14040/44 standard offers three solutions to address multifunctionality in LCA.[3] The first and most preferable solution is to increase modeling resolution by dividing multifunctional processes and separating the production of the primary product from the co-products. However, this approach is not always feasible, as some processes cannot be separated. The second solution is system expansion. Here, the secondary function of the process is accounted for by subtracting the environmental impacts of the most likely alternative method for providing that function from the multifunctional process. The third solution is allocation, where inputs and outputs of the multifunctional process are divided among the different products or functions based on causal physical relationships or representative parameters, for example, their mass. If no common physical relationship exists, economic allocation can be used based on market values. Economic value allocation is widely used in practice, despite being the least preferable solution according to ISO 14040/44. However, other solutions for handling multifunctional processes are often impractical due to the nature of the process or insufficient information.[16]

After the specified unit processes and multifunctionality rules are defined, the unit processes must be connected to create an accurate representation of the system being evaluated. This task can be achieved by utilizing commercial and open-source software programs. These solutions offer input interfaces and connections to accessible commercial and open-source databases. Nevertheless, it is important to note that LCA software alone cannot ensure a reliable integration of the processes within the system. LCA practitioners must accurately comprehend the logic of the system to achieve a reliable base for the following impact assessment calculation.[19]

2.3.3. Life Cycle Impact Assessment

The life cycle inventory is followed by the life cycle impact assessment (LCIA) phase. While the LCIA is typically automated by the LCA software, understanding its underlying principles and indicators is important for informed decision-making and result interpretation. In principle, the LCIA evaluates the environmental impacts of the elementary flows of the product system, transforming the gathered inventory data into potential consequences for the environment. However, it is important to note that LCIA results are not exact predictions of real-world effects or risks. Instead, they offer scores representing potential impacts. These scores are expressed in midpoint or endpoint impact categories. While midpoint impact categories address one specific environmental issue like climate change, eutrophication of freshwater, or human toxicity, endpoint categories represent an area of protection such as natural resources or human health. **Figure 3** shows the principle of going from emissions via midpoint categories to endpoint categories. The selection of impact categories is typically decided during the scope definition phase to guide the collection of inventory data. Predefined sets categories called LCIA methods (e.g., ReCiPe, CML, TRACI) combine category indicators and characterization models and are available via LCA software.[11]

In general, the transformation of emission and resource use information into environmental impact category results can be expressed in the steps of classification and characterization. During classification, the elementary flows of the LCI are assigned to the relevant impact categories they contribute to. This process can be challenging as some substances have multiple impacts either simultaneously or sequentially. Simultaneous impacts occur when a substance has multiple effects at the same time, like SO_2 affecting both acidification and human toxicity. Sequential impacts happen when a substance's initial effect leads to another consequence, such as SO_2 causing acidification, which can mobilize toxic heavy metals in soil. LCA software automates this step using pre-programmed classification tables, eliminating the need for manual effort by LCA practitioners. Following the classification is characterization, where elementary flows within a specific impact category are multiplied with their corresponding characterization factor. The characterization factor represents the environmental contribution of each quantity of an elementary flow to a specific impact category. For example, methane in the Global Warming Potential impact category has a characterization factor of 28 since its impact per mass is 28 times higher as the one from the reference unit CO_2. The characterization factor is determined using scientifically valid and quantitative models that simulate arising environmental effects. After the application of the characterization factors, the resulting values are summed up over all relevant interventions, such as emissions or resource extractions, resulting in an impact score for the environmental impact category with one representative unit like kg CO_2-Equivalents in the Global Warming Potential impact category.[11] These impact results can be presented in tables or graphs. However, there is no mandatory standard on how these impact results should be presented.

ISO 14040/44 introduces three optional steps for the LCIA phase: normalization, grouping and weighting.[3] Normalization calculates the relative magnitude of environmental impact

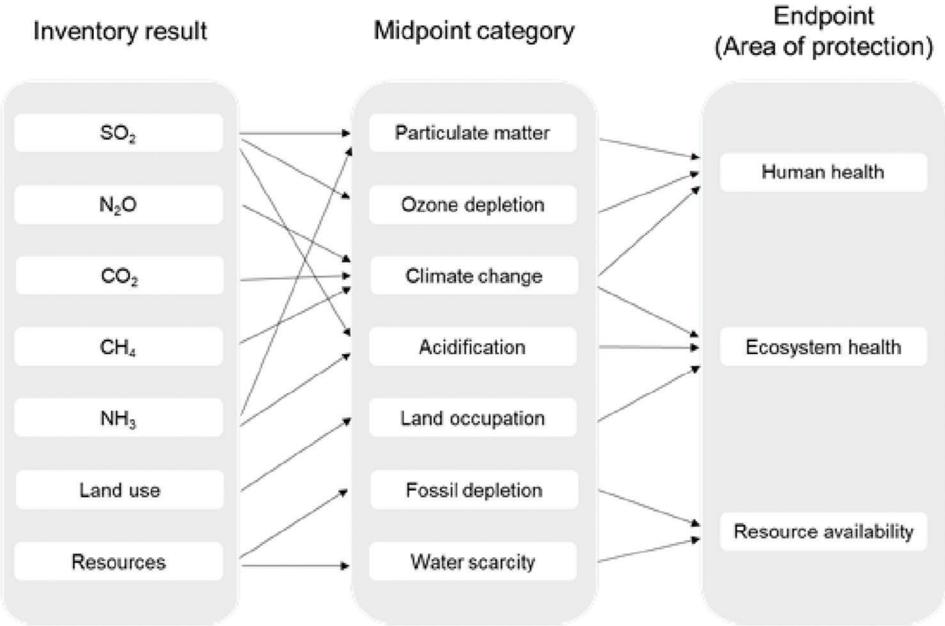

Figure 3. Principle of assigning emissions to midpoint and endpoint categories (based on ref. [11]).

category results compared to a reference. It helps to understand each indicator's scale by dividing characterization results with regional, national, or international reference values (e.g., EU, North America, or OECD). Grouping involves categorizing impact categories without value choices based on the goal and scope definition. Unlike grouping, weighting allows numerical factors based on value choices, converting and potentially aggregating indicator results. However, the scientific justification for this approach is lacking, as value-based decisions determine the weighting factors and which impact categories are considered. Therefore, weighting is prohibited in comparative LCAs intended for public access.[19]

2.3.4. Interpretation

The interpretation phase in an LCA involves analyzing and evaluating the results of the previous phases combined with the uncertainties and assumptions documented throughout the study. The objective is to draw conclusions and recommendations that align with the study's goal and scope definition. The interpretation phase aims to present the LCA findings in a clear manner, allowing users to assess their reliability and identify potential weaknesses based on identified study limitations. Integral components of the interpretation phase, such as completeness, sensitivity, and consistency checks, are iteratively used throughout the LCA process. Completeness checks assess the sufficiency and adequacy of data for significant processes and impacts. If any missing or incomplete information is identified, further investigation or revisiting of the inventory and impact assessment phases may be required. Sensitivity analysis is used to identify key processes and elementary flows that have the most substantial contributions to overall impacts within the product system. Consistency checks examine the alignment between assumptions, methods, and data used in the study with the established goals and scope. All these checks combined ensure that data quality, representation, and uncertainty align appropriately.[20]

3. How to Spot a Good LCA?

LCAs are increasingly being accepted as a standardized instrument for quantifying multiple environmental impacts along the whole life cycle, since unsubstantiated sustainability claims and advertising regarding the environmental benefits are misleading and a form of greenwashing. Therefore, LCAs can be a good instrument for assessing potential environmental impacts and presenting them in a largely reliable and transparent way. However, there is also a risk of greenwashing within LCA itself, especially as there is significant freedom of choice due to the basic structure of the standard containing general specifications applicable to any product system(s).[3,4] Therefore, during an LCA, several decisions have to be made by the practitioner that could influence the outcomes of a study in an advantageous way and potentially harm the reception of the LCA.

As the LCA methodology is becoming more important in the regulatory context for the establishment of green markets, for example, in the form of product category rules and product environmental footprint category rules or greenhouse gas calculations, a process was initiated to further define the many LCA decision moments within the ISO framework in order to reduce the degrees of freedom for the sake of comparability and reproducibility of the results. More and more companies and stakeholders are realizing the importance of LCA and therefore the question arises as to whether a non-expert can recognize and evaluate whether an LCA is good or not. As described in the previous section, an LCA according to ISO 14040/44 is based on a defined structure. However, this structure is only a basic framework and needs to be adapted to the product and systems under investigation.

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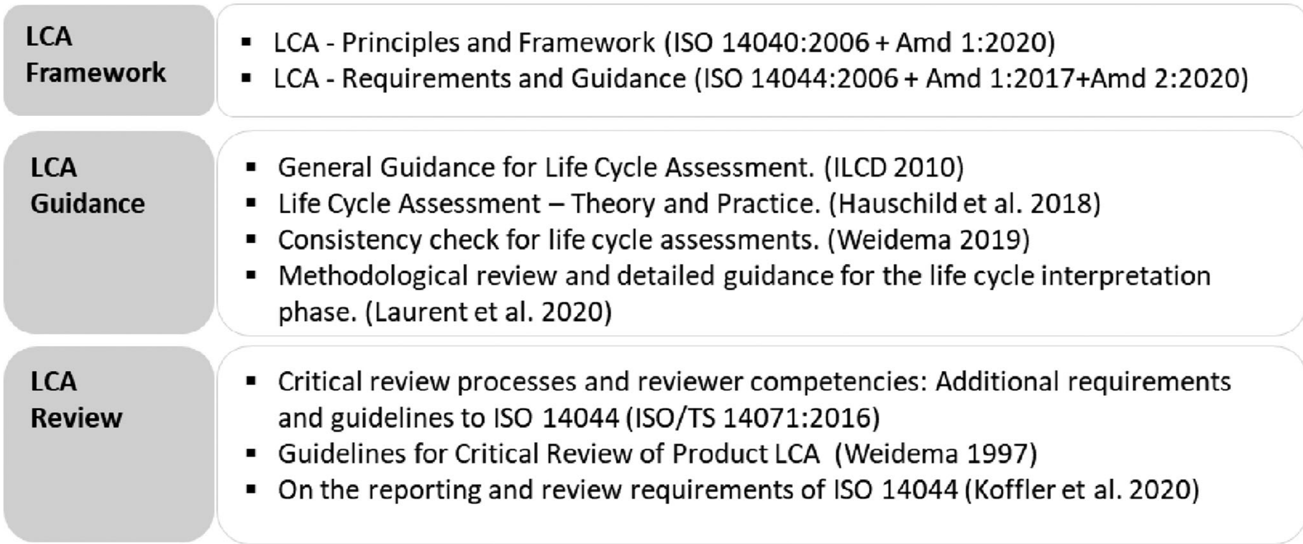

Figure 4. Overview of LCA literature.[1,3,4,17,21–25]

As Bo Weidema, a well-known expert in the field of LCA, wrote back in 1997: "Many of the judgements a practitioner will have to make in the course of a life cycle assessment cannot be said to be true or false, but only more or less justifiable. Therefore, the ultimate quality judgement can only be subjective – although based on professional experience."[21]

Therefore, "good" in the LCA context is rather to be approached as "justifiable" or "appropriate." In order to assess the appropriateness of LCAs, it is necessary to have general knowledge of the form and methodology of LCAs, but also of the topic-specific aspects of modeling. In the following, several aspects of the evaluation of an LCA are described. However, we would like to emphasize that this overview discusses aspects deemed relevant by the authors and has no claim to full completeness. A more in-depth assessment is usually based on sufficient experience and practical knowledge depending on the specific study to be assessed.

Our discussion is based on the documents presented in **Figure 4** as well as the practical experience of the authors. ISO 14040 and 14044 are referred to as the basic methodological framework of LCA. Guidance documents specifying further aspects or the whole LCA procedure are the ILCD Handbook, the "LCA-Theory and Practice" book, and the publications from Bo Weidema and Laurent et al.[1,17,22,23] Since the evaluation of whether an LCA has been carried out appropriately is intended to be ensured by the instrument of the "critical review," guidelines and manuals regarding the review process have been taken into consideration, such as the technical Review Standard ISO/TS 14071 and the specifications by Bo Weidema and Koffler et al.[21,24,25]

There are two levels on which an LCA can be evaluated by an external reader. The first is how the LCA itself has been implemented, referring to the definition of phases and the study preparation process of LCA. Aspects regarding the implementation are presented in Section 3.1. The second is the reporting document of the LCA in which the analyzed system, organization, or research question is described and the implementation of the methodological procedure as well as the results and their interpretation are documented and referenced. Aspects regarding the report are presented in Section 3.2.

3.1. Aspects of Implementation

Some methodological aspects and the handling of modeling decisions in the preparation of the study seem primarily relevant for the assessment of the quality. The implementation depends on the question investigated. It is hardly possible to give general guidelines on appropriateness here, as it depends largely on the goal formulated, so the focus here is to show how these aspects can be presented as completely as possible and to what aspects the reader can pay attention to. The basic principles should always be recognizable, that is, transparency in implementation, comprehensibility through justification and explanation, and consistency in implementation (Section 3.1.2)

3.1.1. Goal

The goal is the basis for the implementation of the following phases as well as for methodological decisions and sets the framework for the scope of the study, the corresponding life cycle inventory, and the interpretation of the impact assessment results.[17] The goal can be described using the content items described in **Table 2**.

Quality control and evaluation of the appropriateness of a study are primarily done in relation to the goal definition. Therefore, a study should state as clearly as possible what the goal is. Applying the items of goal definition can ensure "that the deliverables of the LCI/LCA study cannot unintentionally and erroneously be used or interpreted beyond the initial goal and scope for which it was carried out."[17]

Limitations of an LCA study are particularly important and should be explicitly stated. For example, if only one impact category is covered in the results, no overall environmental benefit

Table 2. Items of goal definition according to Hauschild.[15] Items exceeding requirements of ISO 14040/14044 are marked with +. Item requested in scope by ISO 14040/44 is marked with *.

Item	ISO	Description
1) Intended applications of the results		Describes the intended deliverables of the study, for example, comparison of product systems, hot spot identification, documenting the environmental performance, etc.
2) Limitations* due to methodological choices		The initially set limitations stemming from the choices made in the goal and scope phase of the study. For example, a limited impact coverage (if only climate change or water footprint is assessed), methodological limitations (cradle-to-gate analysis), or limitations due to uncommon or specific assumptions. Assumptions and limitations arising during inventory and impact assessment phase are documented at a later point in the report.
3) Decision context and reasons for carrying out the study	+	Explanation why the study is performed. Based on the intended applications (1) and the reasons of the study, the decision context to identify the applying situation can be used to determine the methodological implications to be applied. For example, regarding the handling of multifunctional processes or the use of specific data types.
4) Target audience		Describes to whom the results are intended to be communicated. The choice of the targeted audience influences the technical level and type of the LCA report.
5) Comparative studies to be disclosed to the public		An explicit statement whether the study is comparative and disclosure to the public is required. If so, the requirements made by ISO 14040/44 for comparative studies regarding reporting, documentation, critical review process, and documentation are to be applied.
6) Commissioner of the study and other influential actors	+	Commissioners, financiers, practitioners of the study, and other organizations involved in the preparation of the study are documented in the report. The aim is to declare conflict of interests.

can be claimed. Importantly, if a (plastic) product is assessed only on a cradle-to-gate basis, it cannot claim environmental superiority for the use phase based on the results.[15] It should also be explicitly stated whether a comparative LCA has been performed, as this will result in further requirements for implementation.

ILCD and Hauschild describe use cases ("Situations") based on the goal definition, from which the corresponding approach and other methodological implications are derived. The differentiation of these situations is not part of ISO and therefore not mandatory for an LCA according to ISO. However, the differentiation of these use cases has proven itself in practice, so that the new studies should at least address whether an attributional or consequential LCA approach is pursued as it affects the choice of data and the range of application for the results. For the choice of approach, both ILCD and Hauschild present a decision context that can be used to define the appropriate situation based on the intended application and reasons for the study. The respective situations are provided with the corresponding methodological implications for the conduct of the study.[15,17]

3.1.2. Scope

The scope describes what is to be analyzed and how this will be performed. It specifies the goal in more detail and describes under which conditions and assumptions the results are valid (**Table 3**). Scope definition items are based on ISO but are further differentiated and substantiated by the works of ILCD and Hauschild. Each item should be addressed and described in a study. Some of the items (1, 7, 8, 9) relate more to reporting and communication of the study while others relate more to implementational aspects of the study (2, 3, 4, 5, 6, 7).[16,17]

Deliverables: In general, an LCA study includes the two deliverables, LCI and LCIA results. A study can aim to just present a Life Cycle Inventory (LCI-study) if this matches the goal of the study to prepare an inventory. According to ISO, it is required that each LCA providing an impact assessment as deliverable should also include the corresponding LCI to ensure reproducibility.[4]

Object of Assessment: A comparison of different product systems is only meaningful if the systems provide approximately the same function to the user. Therefore, a functional unit is defined to describe what function is assessed (see section "Functional Unit").

When a declared unit is based on mass—as it might be in the case for chemicals or polymer granulates—it is important to be aware that a comparison on mass basis cannot answer the question of whether a material has a better environmental performance in certain product application. For example, in the case of polymer granulates different physical properties may lead to different amounts per polymer type needed for the special product or to an extended lifetime expectancy due to better mechanical properties.

Impact Coverage: As type and scope of the impact assessment are determined in advance, impact categories should not be selected or restricted according to the results. If only a single environmental impact is to be analyzed, the study should be named for what it is: for example, a carbon footprint or a water footprint.

Data Quality Requirements: Data is the substantial cornerstone of an LCA and its outcome. Therefore, data goals are set for the analyzed system in the form of representativeness requirements. During the preparation of an LCA study, after the data has been collected, matching of the collected data to the goals set should be performed. Therefore, a study should describe the requirements for the choice of data in the scope as well as the final data used in the life cycle inventory (LCI). The representativeness goals should be clearly stated in any study since they are relevant for the validity of the results. An example of data representativeness requirements is shown in **Table 4**. According to this definition, the data are selected and included in the life cycle inventory. If this definition cannot be adhered to in some places,

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Table 3. Scope definition items according to Hauschild.[16] Items exceeding requirements of ISO 14040/14044 are marked with +.

Item	ISO	Description
1) Deliverables	+	A full LCA study usually includes the two deliverables: life cycle inventory (LCI) and life cycle impact assessment (LCIA) results. The type of deliverable (e.g., LCI or LCA/LCIA study) is derived from the goal. A study can aim to just present a life cycle inventory (LCI-study) if this matches the goal of the study to prepare an Inventory.
2) Object of assessment: • Function(s) • Functional unit • Reference flow(s)		The functions of the studied product system(s) are described. The functional unit covers qualitative and quantitative aspects of the function(s) provided by the analyzed (product) system(s). The reference flow quantifies the amount of product system(s) needed to fulfill the function. All process flows of the LCI are quantified based on the reference flow. When a functional unit cannot be defined because the product system provides no or multiple functions, the reference flow serves as "declared unit" for which the results are presented. The reference flow should then be quantitatively and qualitatively specified, for example, 1 kg pf polylactic acid granulate, fermentation route from sugar beet, 98.2 wt%, Germany.
3) LCI modeling framework and handling of multifunctional processes • Secondary functions and multifunctional processes • Modeling framework: attributional/consequential LCA	+	It should be described where in the system multifunctional processes exist and what procedure has been applied to solve multifunctionality (via subdivision, system expansion, mass-based allocation, economical allocation, etc.). Different modeling approaches have emerged in practice but are not addressed in ISO (attributional, consequential). A systematic modeling framework as methodological decision hierarchy for the application of the approaches depending on the chosen goal is presented in ILCD and Hauschild. It should be stated what type of modeling is applied in the study: attributional or consequential and what methodological choices and applicability of the results this implies.
4) System boundaries and completeness requirements		The analyzed product system(s) and the associated unit processes are described and ideally also represented graphically (see Figure 2). System illustrates what life cycle phases are assessed, which processes are considered or cut off, and where the system boundaries are. It is also shown which unit processes are part of the foreground and background processes of the system.
5) Representativeness of LCI data • Technological • Geographical • Time-related		The requirements for data selection are defined via the technological, geographical, and time-related representativeness that is applied to the system. The data for the life cycle inventory should then correspond to the criteria defined here and deviations should be presented in the context of the life cycle inventory.
6) Selection of impact coverage and LCIA Methods		For the impact assessment the impact categories to be analyzed and the applied life cycle impact assessment method(s) (LCIA) should be defined in the scope. The application of normalization and weighting methods to be used should also be specified here in order not to favor a selection based on favorable results.[17] It should be described what LCIA method is chosen and why. Internationally accepted and scientifically sound methods should be chosen (e.g., CML, ReCiPe, EF, etc.). A comprehensive set of relevant impact categories should be chosen to make sure that all relevant environmental issues related to the (product) system(s) are covered. If only one category is to be analyzed (carbon footprint, water footprint), this has to be addressed as limitation in the goal (2).
7) Special requirements for system comparisons		ISO 14044 states that "Systems must be compared using the same functional units and equivalent methodological specifications, such as performance, system boundary, data quality, allocation procedures, criteria for assessing inputs and outputs, and impact estimation. Any differences between systems regarding these parameters shall be identified and reported" and also that "the comparability of the systems must be assessed before the results are evaluated."[4] If a study making comparative assertions is intended for public, a critical review has to be done.
8) Needs for critical review		The need for a critical review is to be stated, if the study making comparative assertions is intended for the public. If for the study a critical review is prescribed according to ISO requirements, it should be described what type of critical review has been done.
9) Planning reporting of results		Relates to the items "1) Intended application of results" and "4) Target audience" in goal definition.What type of report is planned (see Section 3.2.1) • Report for internal use • Third party report • Report on comparative study to be disclosed to the public

Table 4. Examples for data quality requirements.

Representativeness	Requirement
Technological coverage	The data should represent the industrial production technology for the production route(s) via fermentation.
Geographical coverage	The data should be representative for the production in Europe.
Temporal coverage	The data should represent the situation in the specific year (e.g., 2023) and cover a whole calendar year.

for example, due to data gaps, deviations should be transparently explained in a comprehensible manner or shown as a limitation. A formal procedure for data quality management is presented by Weidema & Wesnaes.[26] The outcomes of such a data quality analysis performed by the practitioner during the preparation of a study, should be included in the final report, at least by highlighting the limitations arising from poor data match. Depending on the system and data point, a deviation may have major implications or little impact, so that it can be a major limitation or an acceptable deviation. For example, a transport dataset that is not representative for a country or is outdated may have a major impact in a transport-intensive system, but only minor relevance in a system with few or short transports.

3.1.3. Inventory

The life cycle inventory contains the final compiled data that quantifies the investigated (product) system(s). This deliverable should be part of every LCA and should be presented in a clear and comprehensible way for transparency and reproducibility. Ideally, the data should be presented as inputs and outputs of each process unit, but often it is summarized for the entire (product) system, which may make further use or remodeling more difficult. The data should be presented in SI-units and refer to the reference flow or functional unit (**Tables 5** and **6**).

Different types and sources of data can be used. The selection criterion is the goal of the study and the representativeness requirements (geographical, technical, time-related) set in the scope. If, for example, the objective is to analyze the production process of a specific company in the year 2022, primary data of the company itself representing the year 2022 should be used for the foreground processes (e.g., energy inputs, operating materials inputs, waste outputs, etc.). Furthermore, it is important to specify what the data includes and how it was collected (e.g., for an injection molding process of a product, the energy consumption is measured directly during production. The measured data does not include the heating phase of the machine; the heating phase is recorded separately and divided up mathematically on a pro rata basis over the total number of units produced).

Table 5. LCI data presentation example.

Flow	Amount	Unit	Source
Inputs			
Electricity	1.45E-02	MJ	Based on literature data
Water	5	kg	Measured, primary data (producer)
Virgin material	4.65E-03	kg	Primary data (producer)
Additive	9.15E-05	kg	Estimated data (producer)
…			
Outputs			
Manufactured product	4.03E-03	kg	Measured, primary data (producer)
Waste for recycling	7.11E-04	kg	Primary data, company
…			

Any deviations from the data quality requirements set in the scope need to be described. If for example the geographical scope for producing a product is set to Europe, as all materials in the process are sourced from varying suppliers in Europe, but no dataset for the production of a minor component in Europe is available, a dataset from the US is applied. This needs to be highlighted, as the production processes and especially the energy supply can differ greatly, so that a higher impact can arise from production in a different geographical scope.

Missing data should be estimated and highlighted with a best approximation rather than omitted. The assumptions on which the approximation is based should be described and justified. Overall, all assumptions made should always be justified so that the choice is understandable for the reader. If data is taken from secondary resources, such as literature, databases, or other, the reference should be unambiguously, for example, using the Globally Unique Identifier (GUID) or Universally Unique identifier (UUID) numbers and specific version numbers of the databases for the reference of datasets. In particular, energy data should be accurately described, as these can usually account for a significant proportion of environmental impacts (e.g., electricity generating mix, assumptions on fuel sources, choice on transportation and vehicle type).

3.1.4. Impact Assessment

The impact assessment is usually automated with the help of modeling software that allows the application of various impact assessment methodologies. This links the inventoried flows of the processes with emissions into the ecosphere and assigns them to environmental impact categories based on the models and characterization factors stored. Therefore, both the software and the impact assessment method must be clearly stated, including the version numbers.

The LCIA results can be calculated at midpoint or endpoint level (see Figure 3). The results should always be stated with the reference unit to which they refer, which is usually the quantified reference flow or the functional unit itself. Hauschild states, that the "LCIA results must be documented by the numerical values of the characterised results for each impact category covered."[16] When an endpoint-related evaluation is made, the data for midpoint results should be included.[4,17] Optional procedures such as normalization and weighting must be clearly explained in terms of applied factors and methods. The numerical data of the unweighted results should be presented.[1,4] Studies with comparative statements intended for third parties must make comparisons only based on midpoint level impact categories, not based on endpoint level categories or based on

Table 6. LCI dataset documentation example.

Flow	Geography	Year	Dataset	Provider/source	Identifier/UUID
Electricity	EU	2022	Electricity grid mix 1–60 kV	Sphera, Professional Database (version 2023.1)	{A1388758-0402-40C4-976B-6A805C8E46E0}
Virgin material	DE	2022	Polyethylene low density granulate (LDPE/PE-LD)	Sphera	{6DE31FE6-71E3-41F9-A166-4AFC89961653}
Carbon black	DE	2022	Carbon black (furnace black; deep black pigment)	Sphera	{7B23381E-133A-48D8-A4AD-8DAEF2723B32}
Water	EU	2021	Market for tap water	Ecoinvent (version 3.8)	{e06972ed-9b3c-46ac-80bf-b5a99dfeb29c}

weighted/normalized results. Furthermore, a sufficiently comprehensive set of impact indicators must be used for comparisons. The comparison must be conducted impact indicator by impact indicator.[4]

3.1.5. Interpretation of Results

In the interpretation phase, the impact results are analyzed and interpreted in relation to the goal of the study considering the restrictions set in the goal and emerged during preparation. Interpretation comprises three elements:

Identification of Significant Issues: First, the most environmentally important issues are determined by identifying issues that have a significant impact on the results. These significant issues could be single contributors from LCI or methodological choices made by the practitioner. Depending on the type of issue, a different assessment approach can be applied as shown in **Table 7**.

Evaluation: The evaluation comprises completeness, sensitivity, and consistency checks. In general, consistency and completeness checks are iterative and may lead to revisions during the preparation of the study. The reader of a study should merely be aware that these steps are part of the evaluation phase. Sensitivity analysis is used to analyze the effect of single parameter variation uncertainties and uncertainty range on the overall results and is mandatory for studies that contain comparative statements intended for publication. It can especially be applied to data uncertainties for the identified significant issues, as their influence on impact results can be meaningful. During the completeness check, it is the responsibility of the LCA expert to analyze the data quality of the inventory data used for the product system. This is done to ensure transparency in the comparability, origin (measured, calculated, estimated, or assumed), and the representativeness (temporal, spatial, and technological) of the collected data. This step helps in analyzing not only the data quality of the product system under study but also helps in conducting comparative LCA of the analyzed product with other product systems.

Conclusions, Limitations, and Recommendations: Final conclusions, as well as recommendations, should be based on the findings as well as identified limitations and relate to the objective and scope of the study. A comprehensible guidance framework on how to perform the interpretation phase in LCA is presented by Laurent et al., also referring to the guidance document on how to perform a consistency check for an LCA by Weidema.[22,23] These documents are primarily intended for practitioners or reviewers who are preparing or reviewing LCA studies. Nevertheless, they can be a good basis for interested readers to get an overview of the procedure. Specific aspects regarding the methodological implementation, especially in the plastics sector, are presented in Section 4.2.

3.2. Aspects of Reporting

An LCA report includes a comprehensive description about the conducted study and its components. A good report contains all relevant information in sufficient depth to be comprehensible and reproducible for the reader. Although there is no official uniform template for a report, there are various general and specific requirements for report content and form in the ISO 14040/44, which are elaborated in more detail by ILCD and structured as requirements at three reporting levels. Also, some general reporting principles can be identified and are shown below.

3.2.1. Reporting Levels

The following three factors which are defined in the goal and scope phase determine what level of requirements for the reporting should be applied.

- The type of deliverable(s) of the study
- The purpose and intended applications of the study and report

Table 7. Identification of significant issues. Own compilation based on Hauschild.[20]

Issue type	Example of significant issue	Assessment approach
Main contributors	Life cycle stage, process, elementary flow, impact category	Quantifying what contributor contributes how much to the total result (Contribution analysis, e.g., hotspot analysis, gravity analysis, charts, etc.)
Significant choices	Assumption, system boundary, handling of multifunctional processes, EoL-modeling	Applying different methodological choices as scenarios and comparing results (scenario analysis)

- The intended target audience (especially technical or non-technical and internal or third-party/public)

The three levels of requirements for the reporting are presented according to ILCD and go beyond ISO:

- Level 1: report for internal use
- Level 2: third party report
- Level 3: report on comparative studies to be disclosed to the public

No formal guidelines are provided for internal level reports (level 1). However, ILCD lists several requirements for third-party reports (level 2) and reports on comparative studies (level 3) that are discussed in the following section. On a voluntary basis, level 2 requirements are recommended as well for level 1 reports.[17]

A third-party report is required whenever results are intended to be communicated to a third party ("i.e. an interested party other than the commissioner or the LCA practitioner performing the study").[17] The report should be made available to all for whom the communication is intended.[4] In principle, every LCA report that is not only for the internal use of the commissioning company or institution should meet the requirements mentioned for this purpose. It is therefore likely that an LCA presented to a reader for evaluation will fall into either the level 2 or level 3 category.

The third level of report for comparative studies has the highest requirements. It refers to studies that compare product systems and are intended for publication. These studies and reports should be reviewed prior to publication with the review documented as part of the report. Koffler et al. clarify the misunderstanding that a comparative LCA only applies in the case of comparisons of products from competitor's products to the fact that this is also the case for different products from one and the same company. According to the ISO formulation the author concludes, that "any two products that compete for market share would fall under this language, even if they were made by the same company or two companies owned by the same corporation."[25]

Bjørn et al. provide a well-structured report template that includes the requirements for third party (level 2) and comparative study (level 3) reports based on provisions of ISO and ILCD.[27] This template could be used as a good reference for comparing the content and structure of a study to be evaluated.

3.2.2. Basic Reporting Principles

The type and structure of the report intended for the study are to be specified in the phase of the scope definition and should include the different phases of the LCA framework. Based on the formulated targets, a reporting level can be selected. In addition, a few general principles applying to LCA reports can be identified and are listed below.

Target Group-Oriented Communication: The target audience is defined in the goal phase. Types of audiences can be for example: internal, (defined) external, public, and technical or non-technical audiences. The formulation and presentation of the report should consider the target group and be comprehensible to them. The information must be communicated in an appropriate form while being correct, complete, and unbiased.

Depending on the target group, different demands for the presentation and supplementary explanations exist. External groups might need further explanations that internals will not need. For the public group, the complexity and the limitation of the results must be especially emphasized as LCA-derived information is more likely to be taken out of context. The principal report can be the basis on which summary reports for target audiences are prepared. Those summary reports need to be labelled as summaries and include reference to primary report. A third-party primary report should be available.[17]

Transparency: Since LCAs are inherently complex, it is essential that they are presented in a transparent and comprehensible manner. This means that all data used, methods and methodological choices applied, assumptions made, and limitations to the results have to be presented in sufficient detail. Assumptions made by the practitioner should be emphasized and justified based on comprehensible information or source. The basic presentation of the results should also be unbiased, which means that especially for the interpretation phase, possibly applied value attitudes, rationale, and expert judgments should be presented transparently. Regarding the deliverables of a study, the results from the impact assessment should always be reported together with the used LCI data. LCIA results on endpoint level should always be supplemented by midpoint results and the corresponding LCI data as well.[17]

Consistency: Consistency mainly concerns implementational aspects. The basic framework of LCA is the ISO 14040/44 standard, but there are now numerous methodologies that build on the ISO framework and have extended methodological requirements. Therefore, to understand the framework of the study, it is important that a study specifies which explicit methodology it is adhering to. If ISO compliance is claimed, the provisions should be followed, and deviations should be explicitly addressed and justified. In addition, the derived results and the interpretation of the results should be consistent with the stated goal and scope of the study. Aspects regarding the consistency in reporting are for example the consistent use of terms and definitions throughout the study and especially for comparisons that the compared systems are presented and implemented with the same pattern regarding included life cycle stages and data quality.[17]

A guideline on how to perform a consistency check for LCAs is presented by Bo Weidema addressing comprehensively relevant aspects. However, this checklist is aimed at LCA practitioners performing a consistency check in the interpretation phase of an LCA-study.[23]

Reproducibility: The reproducibility of results has to be ensured by providing enough information regarding all data used, methods and methodological choices applied, and assumptions made. This implies, for example, that impact assessment results are presented together with LCI data, that numerical values are presented for impact assessment results, and applied weighting and normalization factors. In particular Software and Data and LCIA methods used, should be clearly specified via version numbers or identifier codes.

Confidentiality: LCAs may contain sensitive data that is declared confidential. However, if the objective of such a study is also aimed at a third-party audience, a report based on the study can be prepared in which the confidential data is not presented. ISO14044 states that "the third-party report can be based on study documentation that contains confidential information that may not be included in the third-party report."[25] Koffler emphasizes that this would not imply that the LCA-report as a whole can be classified as confidential while making no third-party report available at all when communicating the results to a third party and proposes three ways of dealing with confidential data:

- Share the third-party report under NDA
- Black out or aggregate sensitive information in the report
- Create a confidential annex, which can be easily removed prior to sharing[25]

3.2.3. Quality Reviews

(Published) LCAs can basically be subject to two types of quality assuring reviews: scientific peer-review for LCAs in manuscripts for publication and the so-called "critical review" as an LCA-internal instrument that is defined in ISO 14040/44 and specified in ISO TS 14071.

Peer-Review: Scientifically published papers will undergo the scientific peer review process prior to publication, in which anonymous reviewers from the same research field review the manuscript and supporting information. This can be seen as a quality indicator for published LCAs, although the review focuses primarily on the scientific publication quality. The reviewers have no insight into other material than the one to be published. Since the review is done by specialists in the same field, a peer-reviewed scientific LCA may be considered as a quality indicator compared to an LCA without any review.

Critical Review: As mentioned in Section 2, a "critical review" as quality assuring instrument within the ISO framework, is only required for LCAs with comparative assertions that are intended for publication. The critical review shall ensure the consistency with the ISO standards and the quality of the study regarding methods, assumptions, data as well as the interpretation in view of the intended goal and the transparency and consistency of the report. A critical review also helps to check the assumptions made, identify potential mistakes, and improve the overall quality of a study, since external experts can give valuable feedback on the implementation regarding the initial scope. A critical review is, therefore, a quality indicator for an LCA, provided that the review is appropriately documented.

Two types of review procedures can be applied as a critical review of an LCA study. It can either be performed by a single internal or external expert or as a stakeholder review panel with at least three members. The performance of a critical review must be documented in the LCA report itself with the following elements:

- Name and affiliation of reviewer(s)
- Critical review report
- Recommendations from the reviewer(s)
- Comments on recommendations

3.2.4. Requirements Overview

- A detailed overview of all ISO provisions can be found in ILCD—Chapter 10 in ref. [17].
- To enhance uniformity in LCA reporting, a template covering all provisions made by ISO and ILCD is presented in the chapter "Report Template" by Bjørn et al.[27]

A summarized LCA study checklist for non-experts is presented in **Figure 5**.

4. Status Quo of LCA for Plastics–Qualitative Aspects

4.1. Plastic LCA over the Years

To understand and assess the environmental impacts of polymers and plastic products, both industry and academia have contributed significantly to the development of LCA over the recent decades. In 1969, the Coca-Cola Company performed an environmental assessment to evaluate packaging alternatives paving the way for other industries such as the oil sector.[28] Subsequently, organizations like the Environmental Protection Agency (EPA) in USA as well as other environmental organizations in Europe developed their own environmental studies for a range of materials.[29]

In the early 1990s, several efforts to standardize LCA emerged which resulted in the development of ISO Standards for conducting LCA. In the plastics sector, industrial associations like Plastics Europe—in order to make inventory data for the polymers from the upstream processes accessible–started publishing Eco-profile reports for different polymers, which are used by industries and other stakeholder when conducting assessments like LCA, EPD, and carbon footprinting for their plastic products.[30] Consulting companies like Franklin Associates have also published reports for Life Cycle Inventory and Impact Assessment of polymer resins, keeping the USA as a geographical location over the last two decades.[31]

In 2002, the Society for Environmental Toxicology and Chemistry and the United Nations Environmental Programme launched the Life Cycle Initiative to enable the global use of credible life cycle knowledge to achieve a more sustainable society.[32] To harmonize the environmental assessment of different polymer feedstocks, the European Commission along with the Joint Research Commission has published methodological framework and modeling rules to conduct LCA for different plastics products within the framework of "The European Strategy for Plastics in a Circular Economy."[33] They have also published a guidance document on the assessment of environmental impacts of different EoL options of plastics.[34]

Despite all these developments in the LCA of plastics, there still exist challenges and limitations when performing LCA of plastic products which will be discussed in Section 4.3.

4.2. Special Aspects for Plastic LCAs

When performing an LCA for products made of plastics, it is always important to evaluate the value chain of the plastics as

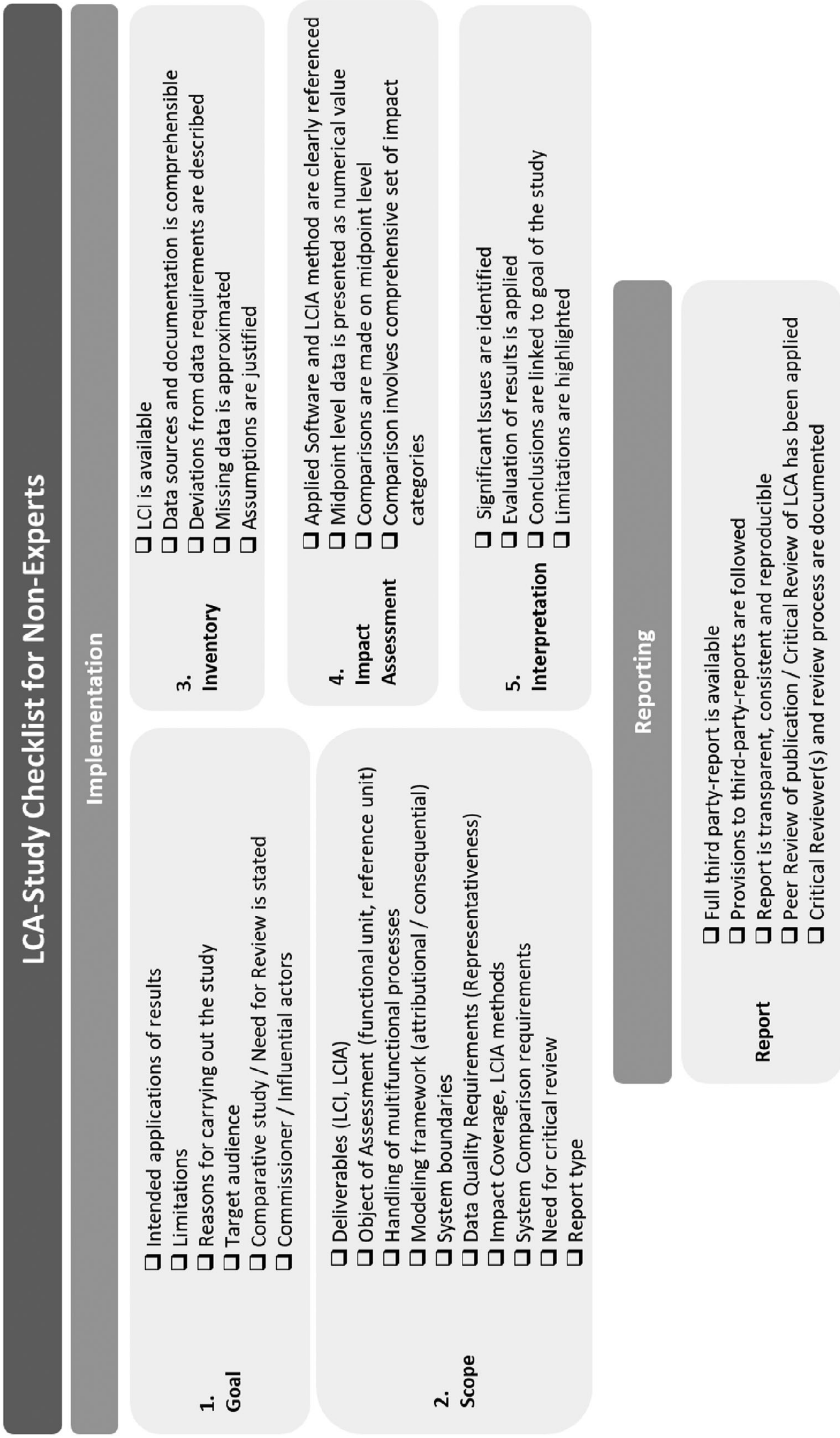

Figure 5. LCA study checklist for non-experts.

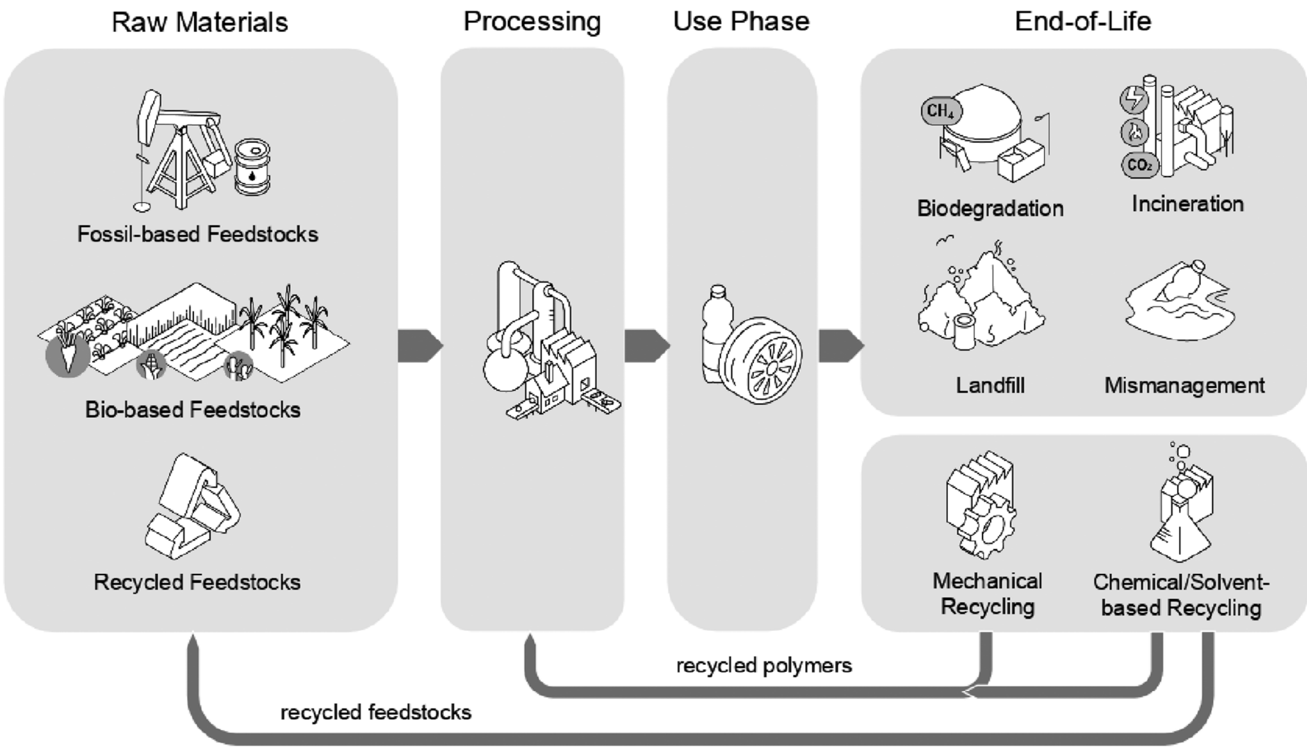

Figure 6. Overview of life cycle stages of plastic products mentioned in the following sections.

a whole, that is, from the raw material extraction, for example, cracking of crude oil, to polymer production until the EoL phase, where the plastic products after use are either recovered or disposed to the environment. The complete value chain of a plastic product is shown in **Figure 6**.

Certain life cycle aspects like the infrastructure required for the processing and distribution of the polymers/product across the value chain and the amount of labor required to fulfill the functional unit of LCA depending on the goal and scope of the study might be neglected. However, the life cycle phases that are excluded from the system boundaries must be documented in the LCA report.

4.2.1. Raw Materials

The raw material phase or the raw material extraction phase is a life cycle phase in which feedstocks are sourced for polymer production. Feedstocks could be either conventional crude oil or gas, or renewable biomass which are then processed to produce monomers. The monomers then undergo polymerization under specific conditions. The resulting polymers are subsequently used for plastic products. It is important to collect inventory data of the input materials along with the auxiliary materials and their associated environmental impacts. Transportation of these materials to the plant and their impacts are also included in the background system. The processes to produce monomers (e.g., cracking in the case of conventional fossil-based plastics and conversion of biomass into monomers in the case of bio-based plastics) along with the resources required and the emission/wastes generated in these processes are taken into account for conducting the LCA of a particular plastic product.

If an organization has insufficient inventory and environmental data of these processes, then commercial LCI datasets can be used. Also, Eco-profiles published by Plastic Europe can be used at times for LCA of plastic products that use conventional fossil-based polymers.[30] The uncertainty of this inventory data can be addressed with the help of sensitivity analysis. Also important is the consideration of biogenic carbon (which is the carbon stored inside the biomass during photosynthesis) when conducting LCA of bio-based plastics on a cradle-to-gate basis. However, in the case of the cradle-to-grave approach, the stored carbon gets released into the atmosphere when the products are either incinerated or landfilled at the EoL phase.[35]

4.2.2. Processing

In the processing phase, polymers are further processed to different plastic products depending on the choice of manufacturing processes and the corresponding applications. Some of the widely used processing techniques of polymers include extrusion, injection molding, and blow-molding. In this phase, both virgin polymers and recycled polymers, that are recovered after use, are utilized for processing. Along with these polymers, additives such as color pigments, fillers, nucleating agent, and softeners are mixed together to improve the properties of the manufactured plastic products. Therefore, to include the processing phase of plastics, it is essential to include the inventory data and the corresponding environmental impacts of manufacturing these additives along with their transportation to the plant. The auxiliary resources like electricity, steam, compressed air, and other chemicals like lubricants and cooling agents are also included within the system boundaries, and their corresponding inventory data are used for LCA. Also depending on the system boundaries of the product system, an organization can also conduct a gate-to-gate LCA approach, wherein the environmental impacts of a particular process (in this case a manufacturing process for a plastic product) can be assessed for a corresponding functional unit. The processing scale of plastic products is also a critical factor when comparing the environmental impacts of two different plastic products (pilot scale production vs industrial scale production). In this case, the comparability of the environmental impacts is a challenge. If the inventory data of certain additives are not available, then either substitute/proxy inventory datasets are used for modeling in LCA. However, all these data gaps are then studied in detail in the form of data quality matrix and the uncertainties are addressed in the form of scenario or sensitivity analysis.

4.2.3. Use Phase

After processing the polymers into specific plastic products, these products are then distributed to the consumers where they are put into use. In the use phase, the design of the plastic product is a critical factor that influences the longevity of keeping the product in the system and is not disposed. Also, the products produced from plastics can have two different kinds of use phases: 1) active phase, where the usage of these products requires a constant input of auxiliary resources like electricity, fuel, or energy and 2) passive phase, where the plastic products do not need any auxiliary resources for their usage. Based on the type of applications, factors like lightweight, timeless design, ergonomics, availability of spare parts, and repairability are considered during the processing phase, which is then reflected in the usability of these products. Plastic products with a passive use phase have less to no significance to the total environmental impacts of plastics across the value chain. Whereas in the case of active phase, inventory data required to fulfill the function of the product during the use phase have to be collected and used in the modeling (for example, plastic component in a car, whose weight might influence the fuel consumption of the car over the course of its use phase). It is also important to track and document how the plastic products after the use phase are collected. The inventory data required for the transportation of these products to either the recyclers or landfill facility need to be collected for LCA modeling.

4.2.4. End-of-Life

Many treatment processes exist for end-of-life (EoL) plastic waste, depending on different parameters like the type of plastic, the type of product, and technical possibilities at the location of disposal. These treatment processes include recycling processes (e. g. mechanical recycling, chemical recycling, or solvent-based recycling), energy recovery through incineration, biodegradation, and landfill. Mismanagement of plastic waste cannot be completely avoided and will therefore also be addressed.

Mechanical Recycling: For mechanical recycling, the plastic waste is collected and sorted first before entering the recycling facilities. The collection, sorting, and recycling efficiencies vary greatly depending on the type of plastic, treatment options, and geographical locations. For some plastics, separate collection systems with or without deposits are available.[36] Recycled plastic material can replace virgin material to produce new plastic products. However, due to contamination with other materials or inferior technical properties of the recycled plastics, either regarding the intended application or processing technique, a 1:1- substitution is rare.[37] Examples for substitution potentials based on technical functionalities are 0.75:1 for HDPE, 0.85:1 for PLA, and 0.94:1 for PP.[38] A study by Faraca et al.[39] assessed sorting efficiencies and technical yields alongside market substitution factors for mechanical recycling scenarios and plastic types (**Table 8**).

Table 8. Sorting efficiencies, technical yields, and market substitution factors of different plastic types. Values taken from Faraca et al.[39]

Plastic type	Sorting efficiency [%]	Technical yield [%]	Market substitution factor [-]
Simple mechanical recycling			
PP	55	69	0.48
PE	62	76	0.66
Advanced mechanical recycling			
PP	81	86	0.83
PE	84	91	0.91
PET	65	88	0.95
PS	65	77	0.66

As the mechanical recycling process not only treats plastic waste, but also produces recycled materials, it is considered a multifunctional process. Standard approaches in LCA for multifunctional processes include cut-off and allocation. General information on these approaches is included in Section 2. It is challenging, however, to distribute environmental impacts (burdens) from recycling and credits or avoided burdens for potentially replacing virgin material in a way that reflects the product's impact but also encourages the supply and use of secondary materials.[40] Many guidelines propose approaches to model recycling processes like mechanical recycling (**Table 9**). Regardless of the choice of approach, an additional credit can be applied to account for the substitution of virgin plastics and therefore the avoided environmental burdens associated with the virgin plastic production. However, many other approaches to model recycling processes in LCA are available in scientific literature and no consensus has been reached yet.[41]

Chemical and Solvent-Based Recycling: Chemical recycling, sometimes also referred to as feedstock recycling, presents an alternative to assist mechanical recycling, producing high quality feedstocks to be used again in polymer production. The polymers are depolymerized under controlled conditions.[43] This approach is increasingly highlighted as an addition to an improved plastic waste management. In general, chemical recycling processes perform worse than mechanical recycling from an environmental perspective but can serve as a good alternative for waste streams that cannot be treated by mechanical recycling (e.g., plastic films), outperforming incineration and landfill. Chemical recycling includes many different processes. Pyrolysis is currently by far the most researched method, next is depolymerization, followed

Table 9. Selection of approaches to model multifunctional recycling processes in LCA.

Approach	Alternative names	Basic principle
0:100[41,42]	Recyclability substitution approach, EoL recycling approach, allocation to material losses	Burdens from recycling are fully allocated to the product producing a recycled material, with no environmental burdens allocated to downstream products using input recycled materials
100:0[41,42]	Recycled content approach, cut-off approach, allocation to virgin material use	Recycling impact is fully allocated to the product using a recycled material, with no burdens from recycling operations allocated to the upstream product
100:100[41]	–	Recycling impact is fully allocated to both the product producing a recycled material and to the product using a recycled material (recycling burdens are accounted for twice in the overall context)
50:50[41]	–	Variation of the 100:100 approach, allocating 50% of the recycling burdens to the product producing a recycled material and 50% to the product using the recycled material
Circular footprint formula (CFF)[42]	PEF approach	Recycling burdens are split between supply and demand of recycled materials using the CFF to reflect market realities and material quality (developed by the European Commission)

by gasification and hydrocracking. While they can contribute to closed material cycles by producing high quality recycled feedstock to produce new plastic material, some of these do not necessarily produce alternatives to fossil feedstocks, but rather fuel alternatives. In that case, the plastic material is lost from the value chain.[44] When applying credits for substitution of virgin plastic feedstock or fossil fuels, the individual products of the chemical recycling process need to be considered.

In solvent-based recycling, solvents are used to separate a specific plastic type from other plastic types, additives, and fillers. Solvent-based recycling is sometimes also referred to as physical recycling. Case studies of successful separation of plastics like PS, PC, PE, PP, PET, ABS, and PVC have been reported.[45] The efficiency of the process depends on both the solubility of the plastic waste in a certain solvent and the interaction between solvent and plastic. Physical recycling processes require complex technical equipment.[43,46] The polymeric material can be recovered and directly used in plastic processing applications.

Incineration: An alternative treatment option for plastic waste is incineration. Ideally, the incineration facility includes energy recovery. This treatment option makes use of the high heating value of plastics. During incineration with energy recovery, heat and steam are produced, therefore this treatment can replace other energy sources. However, the plastic material cannot be recovered for further use and is lost from the value chain, resulting in this end-of-life option not being considered a circular technology.[44,46] Also, any biogenic CO_2 that was initially captured by biomass feedstock used to produce bio-based plastics is now released back into the atmosphere.

Analogously to recycling credits, often a credit is applied for incineration processes to address the substitution of other energy sources. These credits depend on the energy source that is being replaced. Higher credits can be applied if fossil fuels are replaced, lower credits are applied for renewable sources.[44] However, the overall development of more environmentally friendly energy production technologies results in lower environmental impacts for the energy supply in LCA modeling. This means that the credits for energy recovery during incineration are expected to decrease in the future when they no longer replace fossil-fueled energy sources but renewable ones. Therefore, this end-of-life option will become less attractive regarding potential environmental impacts.

The worst-case incineration scenario is uncontrolled, open burning that does not involve any kind of energy recovery or emission capture.

(Bio-)Degradation, (Industrial) Composting/Digestion: Biodegradable plastic waste can additionally be treated using (bio-)degradation and composting, sometimes also called digestion. Biodegradation processes can be aerobic or anaerobic treatments that use microorganisms like bacteria or fungi to produce CO_2 or methane and H_2O from plastic waste. These treatment processes are sometimes also called biological or organic recycling. However, they do not produce plastic material that can directly be reprocessed.[43]

During aerobic digestion, additional humus is produced and sometimes highlighted as added value. However, plastics only degrade to CO_2 and H_2O and the humus is not a benefit contributed to by biodegradable plastics but rather by other input streams. Therefore, no credit can be applied for the humus yield. Anaerobic digestion on the other hand can take place in biogas plants and produce methane (CH_4) along with the other by-products. This methane can be used for further incineration and energy recovery. It can also function as a feedstock for bio-based plastic production, for example to produce polyhydroxyalkanoates (PHA).[46]

Landfill: If the plastic waste cannot be treated by one of the above-mentioned recycling processes or cannot be incinerated for energy recovery, it will be sent into landfill. The environmental impacts of landfilling vary greatly between different landfill technologies and geographical locations. Some landfills provide a controlled environment where gases or leakages are captured, while others do not implement special measures to reduce environmental impacts. While the immediate environmental impacts of landfilling may be very small, they occur for a long period of time, ranging from ten to thousands of years. For modeling these so called "delayed emissions" in LCA, approaches exist for different time horizons and impacts. For global warming potentials, explicit time horizons are modeled (e.g., 20 and 100 years). While for other impact categories, these timespans are implicit.[11] When assessing bio-based plastics, these delayed

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emissions and different modeling approaches are also important for biogenic carbon accounting depending on the chosen modeling approach.[47] Another important issue is the formation of methane during the anaerobic digestion of biodegradable plastics that can also occur in landfill. While the methane is used for energy recovery in biogas plants, it results in considerable climate change impacts if not captured in these landfills.[48]

Mismanagement (Littering, Leakage, Degradation): Although the correct disposal and recycling of plastic waste is strongly promoted, not only politically, it is inevitable that incorrect waste disposal cannot be completely eliminated. Mismanagement can happen in the form of littering, leakage, and degradation in an uncontrolled environment. Littering is not only an aesthetic disturbance of the landscape but can also lead to leaching of chemicals and additives or killing of animals by ingesting plastic products.[47]

4.3. Limitations of LCA for Plastics

As described in the sections above, LCA is an important tool for modeling the environmental impacts of products and services including in the plastic sector. However, it needs to be stressed that LCA has limits regarding the aspects of environmental impacts that are covered, that is, not all factors that can influence the environment in a positive or negative way are included. Currently, there is a wide range of plastics' impacts on the environment that are not included in LCA.

4.3.1. Littering and Pollution

If plastics are not properly managed at end-of-life, or during use and production (e.g., plastic pellets), they can be littered into the environment (land as well as marine) and contribute to environmental pollution. Jambeck and co-workers described the effects of plastic pollution on marine life, ranging from ingestion and entanglement of macroplastics, the effects of toxic plastic additives and micro- and nanoplastics on marine life, to entering the food web. None of these impacts are currently modeled in LCA.[49] Some approaches have been proposed, for example determining the percentage of a product being disposed of improperly and evaluation of this percentage using existing or new impact categories. Relevant environmental impacts could be covered by ecotoxicity or human toxicity impact categories.[47] Additionally, a new category called "direct non-intended killing of animals" could be proposed. However, these proposals have not been established in current LCA practice.

4.3.2. Plastics Ingestion

Recently published research by Lavers and co-workers investigated the impact of plastics ingestion on flesh-footed Shearwaters fledglings on Lord Howe Island, Australia. They found that plastic ingestion was linked to directly induced severe, organ-wide scar tissue formation and coined the term "plasticosis." Critically, the impact of plastic ingestion on organisms is not yet well-understood and further research is urgently needed. So far, impacts on plastic ingestion on organisms are not implemented in LCA.[50]

4.3.3. Micro- and Macroplastics

On land, plastics are widely used in agriculture—for example as mulch films or pipes—and can therefore lead to the contamination of agriculture soils with macro- and microplastics with harmful side effects. Agricultural soils can also be contaminated with microplastics via the application of sewage sludge from wastewater treatment plants used as fertilizers or compost. Sa'adu and Farsang recently reviewed the available scientific research into plastic contamination in agriculture and found that microplastics can lead to environmentally negative impacts on the soil, surface, as well as water resources. Currently, these detrimental impacts are not considered in LCA.[51]

4.3.4. Additives

Additives are important ingredients for plastics equipping them with important properties. However, implementing additives into LCA is challenging due to limited available data of the wide range of additives. In addition, the end-of-life fate of the plastic product influences the impact of the additives. LCA practitioners in the plastic sectors should develop methods including additives.

4.3.5. Impact on Biodiversity

Another important environmental aspect that is not yet adequately addressed is biodiversity and an overall method still needs to be developed. Biodiversity can be reduced for example by growing plants to produce plant-based polymers. Indirect land use change (iLUC) can also play a role in bio-based polymer production, that is, when agricultural land is used that was formerly farmed for food crops. Regarding plants for bio-based polymer production, the use of genetically modified organisms, for example, genetically modified corn, is not considered in LCA practice.

5. Summary and Conclusion

It is imminently important for a sustainable future to understand and quantify the environmental impacts of products and technologies and to support the reduction of GHG emissions, careful use of water and land, improvement of biodiversity, and other important environmental factors.

Early on, researchers and product owners have to understand the impact of their products and technologies, that is, during the design and development state, to enable ongoing improvement with regard to environmental impacts. LCA has been established as a method to quantify the impact of the environmental dimension of sustainability. In the future, if LCA is combined with S-LCA and LCC, a holistic LCSA of products and technologies will be possible and improve overall sustainability. To improve the application of LCA in the plastic sector and beyond, it is important that non-LCA experts have a basic understanding of the methodology and its application. The improvement of environmental impacts of plastics and the plastic sector in general over the whole life cycle from cradle-to-grave is a significant challenge, which can only be achieved if stakeholders along the whole value chain work together.

Therefore, we urge that life cycle thinking and methodologies like LCA be adopted by all stakeholders in the plastics sector. In addition, the general knowledge of life cycle thinking would reduce the risk of greenwashing. We would like to ask you—the reader of the current work—to actively increase your knowledge of LCA and LCSA and involve life cycle thinking in your daily professional work to reduce the impact of products and technologies. We all must work together on this important challenge in order to achieve life on a sustainable planet.

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Conflict of Interest

The authors declare no conflict of interest.

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