FRAUNHOFER CLUSTER OF EXCELLENCE CIRCULAR PLASTICS ECONOMY CCPE

CHALLENGES AND REQUIREMENTS IN COMPARATIVE LIFE CYCLE ASSESSMENT OF PLASTICS RECYCLING

Position paper

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Position paper

In position papers, the Fraunhofer Cluster of Excellence Circular Plastics Economy (CCPE) addresses issues that are currently of concern to society, science and business. As CCPE researchers, we want to take a stand and contribute our opinion to current debates. At the same time, we want to show whether and how we can contribute to solving these challenges with science-based data and facts. Our position papers are developed jointly by the employees of the Fraunhofer Cluster of Excellence Circular Plastics Economy CCPE – each position paper is the result of an opinion-forming process involving several institutes.

Fraunhofer CCPE combines the competences of six institutes of the Fraunhofer Gesellschaft and cooperates closely with further Fraunhofer Institutes and industry partners. Together, we work on systemic, technical, and social innovations, focusing on the entire life cycle of plastic products. Under the leadership of the Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT, the following research institutes have joined forces: the Fraunhofer Institute for Applied Polymer Research IAP, the Fraunhofer Institute for Chemical Technology ICT, the Fraunhofer Institute for Material Flow and Logistics IML, the Fraunhofer Institute for Process Engineering and Packaging IVV and the Fraunhofer Institute for Structural Durability and System Reliability LBF. The position paper **“Challenges and requirements in comparative life cycle assessment of plastics recycling”** was prepared by the Fraunhofer Institutes UMSICHT, IML and ICT.

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1 Introduction

The plastics value chain needs to become circular and sustainable. The concepts of the circular economy and sustainable development both aim to reduce the extraction of primary resources and to mitigate environmental harms throughout the value chain. One strategy to attain these goals is improved plastics recycling. Life cycle assessment (LCA) based on ISO 14040 and ISO 14044 is the most debated and applied methodology for evaluating the environmental impacts of (end) products or services by considering their entire life cycle. LCA is commonly used in decision-making regarding the selection of a specific material or technology that causes the lowest environmental impact at a given time.

Recently, the LCA methodology has been criticized by the public and the scientific community for lacking consistent and harmonized rules in environmental impact assessments, thus influencing interpretation and, consequently, decision-making. In this context, "*greenwashing", "misleading communication*", *"claiming negative greenhouse gas emissions"* or *"short gains over systemic change"* are a few of the reproaches with regard to comparative LCAs [Ellen MacArthur Foundation – 2022; Tabrizi – 2020]. According to ISO 14040, the intended application and audience need to be defined. Consequently, each LCA study examines what the authors consider to be in scope and is based on data collection and interpretation. To ensure comparability, consistency is one of the main requirements, which is defined as freedom from logical contradictions, i.e. *"that such different procedures are all chosen by consistent application of the same general selection criteria"* [Weidema–2019]. LCA studies should generally exhibit internal consistency; however, achieving consistency when comparing different LCAs is not always feasible due to their case-specific applications intended. Systematic reviews show that the reconstruction and harmonization of LCA studies is difficult due to deficient transparency in data collection descriptions [Roßmann–2020; Saavedra-Rubio–2022]. Interpreting the findings of inconsistent LCA studies can be susceptible to misinterpretation which makes it even more difficult for companies and decision-makers.

LCA studies that focus on plastics recycling have attracted particular attention regarding the comparability of LCA results. Recycling both treats waste and provides new resources. Therefore, it creates a multi-functionality problem in LCA, and the approach used to model recycling has a significant impact on the outcome [Ekvall – 2020]. Current practice is inconsistent in terms of the use of cut-off classifications, allocations, system expansion, and/or substitution approaches to consider the avoided burdens within the scope. Published LCAs outline fundamental incompatibilities and concerns, as highlighted, e.g., by Tabrizi [– 2020]. Another problem is the absence of primary data or suitable default data for LCA studies of plastics in cases where the data could not be provided by those responsible for recycling processes.

The aim of this paper is to encourage companies and LCA practitioners to collaborate and increase transparency and reliability when modelling and reporting the environmental impact assessments of plastics recycling. We want to show whether and how we can contribute to solving existing challenges. Section 2 outlines three main perspectives when modelling plastics recycling. Our opinion concerning the main challenges for comparative LCA of plastics recycling is presented in section 3. Section 4 emphasizes the requirements for carrying out comparisons of LCA studies that center on plastics recycling. Finally, we conclude with suggestions for future work in section 5.

2 Plastics recycling perspectives

The LCA methodology primarily intends to assess environmental impacts of (end) products or services over their entire life cycle from cradle-to-grave. Several approaches and standards provide guidance for the harmonized modelling for a plastic (end) product from cradle-to-grave, such as the "*Plastics LCA method*" of the Joint Research Center (JRC) recommended by the European Commission [Nessi–2021]. The method builds upon and conforms to the Product Environmental Footprint (PEF) method, while complementing and further specifying methodological rules for plastics. However, the LCA methodology is also used to assess a specific life cycle stage, e.g., the end-of-life (EoL) stage or the raw material acquisition and pre-processing stage.

Partial assessments of the recycling of plastics – not covering an entire life cycle – can focus on a single process, a process chain, a technology, or the provision of recycled intermediate products[1]. In such cases, plastics recycling can be evaluated either from a waste treatment perspective or from a material provision perspective. Both individual perspectives are part of an (end) product LCA and integrated in the life cycle stages of a product (see Fig. 01).

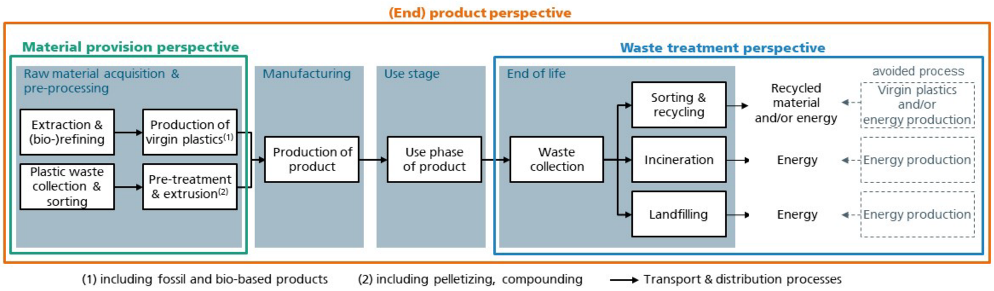

Fig. 01: Simplified and exemplary system boundaries of (end) product, waste treatment and material provision perspectives (adapted from Nessi [2021]).

To clearly differentiate the focus in modelling plastics recycling in LCA, we subdivide the field into the three perspectives highlighted in Fig. 01. The three perspectives overlap in processes and system boundaries but look at recycling from different perspectives, thus answering different research questions. To provide a recycled plastic, a recycling activity and a waste material for treatment would generally be required. The recycled material would not exist without a previous waste stream to be recycled. Here, the subdivision distinguishes between: the waste treatment perspective focusing on recycling as an EoL activity, and the material provision perspective which centers recycling as a stage for acquiring raw materials. Both is needed when modelling the (end) product perspective including possibly a product made from recycled plastics and/or whose plastics may be recycled at the EoL. Tab. 01 summarizes the perspectives and associated research questions.

[1] Often referred to as cradle-to-gate studies or sometimes waste-to-gate studies.

Tab. 01: Main perspectives of modelling plastics recycling in LCA

Perspective	Research question
Waste treatment perspective: EoL activities of a waste stream from collection to the final treatment, often including avoided processes of the recycled materials and recovered energy.	What are the environmental impacts of waste treatment activities (of a certain waste stream)?
Material provision perspective: Focus is on the raw material acquisition and preprocessing phase from collection to provided (re-)granulate[1].	What are the environmental impacts of recycled plastics in raw material acquisition (compared to primary plastics)[2]?
(End) product perspective: All life cycle stages from cradle-to-grave including recycling from waste treatment and material provision perspective.	What are the environmental impacts of a certain plastic product along its whole life cycle (possibly made from recycled plastics and whose plastics may be recycled at the EoL)?

Results of LCA studies are commonly used to support decision-making, which, in some cases, must deal with different perspectives. However, in business practice and society, the importance of dealing with the different perspectives on (plastic) recycling in LCA and the associated challenges and influence on the result are barely recognized. This paper focuses on challenges and requirements of comparative LCA of plastics recycling activities only, and thus on the distinction between the waste treatment and the material provision perspective.

3 Challenges of comparative LCA of plastics recycling

After introducing the different perspectives on recycling, this section highlights challenges in modelling plastics recycling that hinder the comparability and, therefore, the usability of LCA results for decision-making. Any study performed according to the ISO LCA standards should maintain consistency throughout. A particular problem arises when comparing different studies that were carried out independently of each other, e.g., by different institutions or based on different databases or impact assessment methods. To increase the comparability of LCA results of different studies of plastics recycling, the following challenges need to be addressed.

Challenge 1: The diversity of plastics recycling technologies

At present, the predominant technology used in plastics recycling is mechanical recycling. However, several emerging technologies are expected to become available in the future with a high technology readiness level (TRL). These technologies have the potential to complement or rival existing technologies by recycling waste streams that are presently not or poorly recycled due to high costs and/or environmental impacts. The harmonization of different technological scales in one particular challenge.

[1] from a *cradle-to-gate* perspective neglecting the use and EoL stage

[2] This question can also be applied to include the comparison of bio-based plastics, but this is out of the scope of this paper.

Moreover, different collection systems, sorting processes, pretreatment steps, and even recycling processes themselves, challenge the comparison of plastics recycling technologies. Even within one technology route and TRL, processes can vary at company, plant and technology level. For instance, different mechanical recycling machinery, such as single-screw or twin-screw extruders, vary in their output and yield of quality grades. These differences can influence the system boundaries, functional unit, as well as input and output flows of an LCA study. Fig. 02 illustrates that not all recycling technologies are focused on plastic-to-plastics recycling, which involves converting plastic waste back into polymers. Instead, some technologies primarily aim at achieving recycling through monomers, naphtha, synthesis gas or even CO_2, to replace virgin resources in chemical production. Consequently, setting comparable system boundaries is a core challenge regarding the diversity of plastics recycling technologies.

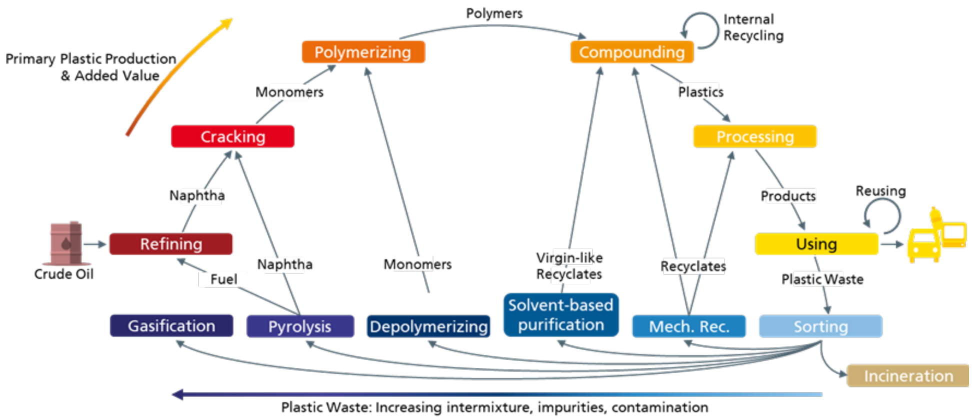

Fig. 02: Recycling cascade of various plastics recycling technologies entering the value chain at different processing steps [Fraunhofer UMSICHT–2023]

Challenge 2: Intrinsic multi-functionality of recycling

The distinction between the waste treatment perspective and the material provision perspective is not trivial. Recycling (as well as energy recovery) are intrinsically multi-functional, since they fulfill two functions simultaneously:

1. the proper treatment of waste for the product system producing the waste, and
2. the production of secondary resources as input for the same or a new product system, i.e., the provision of recycled material and/or recovered energy.

Thus, recycling is a multi-functional activity that is shared between two product systems [van der Harst–2016]. The waste treatment perspective centers on the first function, while the material provision perspective focuses on the second function. For multi-functional activities, it is not obvious to which product system the environmental impacts should be attributed [Finnveden–2014]. A plastics recycling chain is defined as a row of activities from the point of collection (PoC)[1] to the point of substitution (PoS)[2]. Each recycling chain fulfills both functions and does not have an equivalent functionality to, e.g., mono-functional virgin granulate production. Consequently, comparisons between recycling activities, waste treatment processes and virgin material provision are challenging due to the distinct functionalities of the systems being compared. LCA practitioners strive to solve this issue in extensive debates, e.g., in Frischknecht [2000], Guinée [2004], or Pelletier [2015]. Isolating one the two functions of recycling can only be conducted artificially [Heijungs–2007]. "*There is no 'correct' way of solving the multi-functionality problem, even not in theory*" [Guinée–2004].

[1] Defined here as the beginning of the waste property, i.e., disposal of waste at its EoL.

[2] Defined here as the point in the recycling chain that produces a recycled granulate that can substitute virgin plastic granulate in a certain proportion.

Several modelling operators for handling multi-functionality are practiced including subdivision, partitioning (allocation), cut-off classifications, and system extension with or without substitution. The use of modelling operators can exacerbate the complexity of the interpretation of the results, hinder generalizability, and limit their relevance to decision-making, especially when comparing results that are based on different modelling operators. The literature provides extensive overviews on existing approaches for modelling recycling in LCA [Ekvall–2020]. Official guidance documents for the application of LCAs on (end) products often recommend combinations of allocation procedures, e.g., combining partitioning with substitution methods [Schrijvers–2016].

The PEF initiative still aims to develop a harmonized European-wide methodology for the calculation of the environmental footprint of products, including recycling through the so-called "*Circular Footprint Formular*" (CFF), which recognizes material and energy credits at the EoL [European Commission–2021]. The modelling of the waste treatment perspective, focusing on the first function, is usually conducted through system extension including substitutions for all produced secondary resources that can be used as inputs in other production activities. The environmental impacts of the avoided production activities are credited to the system under consideration. In principle, the waste treatment function can be isolated by substituting all secondary products (recycled materials and recovered energy). In contrast, the main function of the material provision perspective should not be isolated by claiming negative impacts for avoiding a certain treatment activity. The treatment of waste is an input function for a recycling process, whose by-products (recycled materials and recovered energy) can be substituted as inputs in another production activity, but not the waste treatment function itself. The substitution of avoided waste treatment activities can be misleading [Tabrizi–2020] and is not in line with the PEF method.

Results of the material provision perspective are typically presented for two commonly used modelling approaches referred to as "*recycled-content approach*[1]" or "*open-loop approach*[2]" with or without the inclusion of substitutions and/or quality ratios to account for down-cycling effects [van der Harst–2016]. We argue that the recycled-content approach disregards the multi-functionality of recycling by attributing all impacts to the recycled material (without substitution). This includes activities for the management of misdirected waste, which are actually pertaining to the waste treatment function. If the recycling chain has less environmental impacts than the virgin material provision, the use of the recycled materials is incentivized. Recycled plastics, which are obtained from waste that is particularly difficult to recycle, can cause a higher environmental impact than the corresponding virgin material. However, treatment options other than recycling of such waste might also cause high or even higher impacts. In such cases, neglecting the waste treatment function in recycling when applying the cut-off approach can lead to a misinterpretation in the assessment of the material provision perspective. The high impacts are mainly caused by the waste treatment, which must be treated anyway, but is fully attributed to the recycled material. The use of recycled plastics from waste streams that are difficult to recycle is a particular issue and should be incentivized as well.

Applying the open-loop approach to the material provision perspective, a recycled plastic typically carries a share of the impacts from the virgin plastic provision and a share of the impacts from the recycling process. According to the PEF method, a 50/50 allocation is recommended as default allocation ratio for recycled plastics [European Commission–2022]. Regardless of whether a 50/50 or other material-specific allocation factor is applied, the resulting environmental impacts of recycled plastics cannot be compared to virgin plastics if the latter are referring to 100 % of the impacts of virgin production.

[1] Sometimes referred to as "cut-off approach".

[2] The CFF is a specific formula for applying the open-loop approach but can be arranged to reflect the recycled-content approach as well. The application of the CFF for the material provision perspective referring to cradle-to-gate studies on plastic recycling can be found in section in Nessi [2021, p 91f].

Assuming two life cycles of a material and a 50/50 allocation, a virgin plastic would also have to carry 50 % from its virgin production and 50 % from recycling to avoid double counting. As a result, both would have the same impact. However, the literature compares virgin plastic, which has 100 % of its impact from its virgin production, with recycled plastic, which has 50 % from virgin production and 50 % from recycling, such as Franklin Associates [–2018]. Consequently, if the virgin plastic provision causes higher impacts that the recycling process, results of the open-loop approach cause higher impacts compared to the recycled-content approach, which even disregards the multi-functionality of recycling. In summary, different approaches are applied to different multifunctionality problems, which hinders comparability. The intrinsic multi-functionality issue of recycling is not fully solved, especially if comparing virgin and recycled plastics.

Challenge 3: Complexity of joint plastics recycling

The majority of plastic waste generated in Europe is collected, sorted and recycled via joint treatment activities [Plastics Europe–2023]. In addition to multi-functionality at system level (see challenge 2), post-consumer recycling chains often treat a multitude of different wastes as well as provide a range of recycled materials and recovered energies from mixed waste collection at the same time and in (economic) relation to each other. Consequently, the multi-functionality issue is even more exacerbated the more complex the joint recycling system is and the more co-activities are fulfilling numerous functions of treating waste and providing resources as shown in Fig. 03.

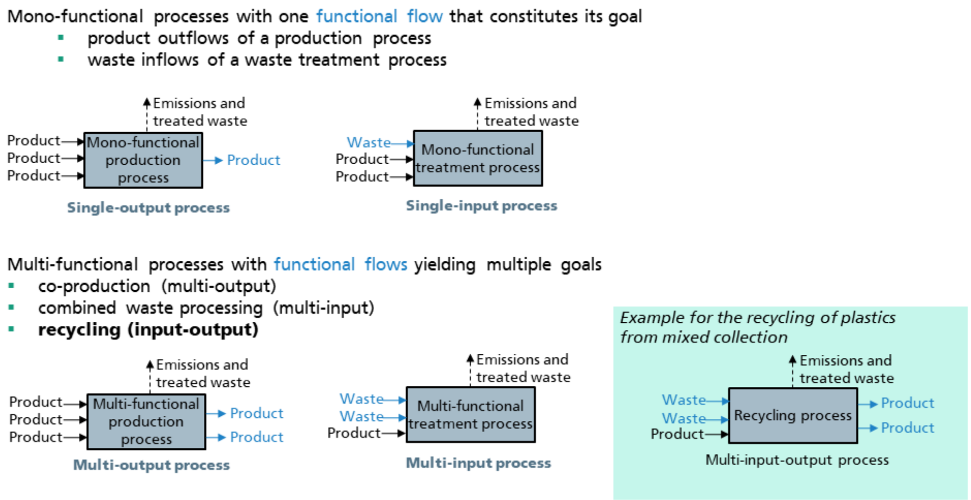

Fig. 03: Definitions and typologies of mono- and multi-functional processes (adapted from [Life Cycle Initiavtive–2013])

Appendix A contains a draft process diagram developed by the authors to illustrate the complexity of possible recycling activities and the multitude of recycled materials and process steps in the recycling of lightweight packaging from household waste. What complicates the holistic modelling of extensive recycling chains is that the entire process from PoC to PoS is rarely in the hands of one company alone. Such joint plastics recycling chains include multiple stakeholders, such as waste collectors, sorters, recyclers as well as other downstream treatment actors. However, multi-stakeholder LCA studies covering the complete (plastics) recycling chains are currently rare.

Challenge 4: Different waste origins

The origin of recycled plastics can be distinguished between post-industrial recycled (PIR) and post-consumer recycled (PCR) material. PIR materials (also referred to as pre-consumer material) originate from industrial production processes. According to DIN EN ISO 14021, post-industrial waste is diverted from the waste stream during a manufacturing process, with the exclusion of the reutilization of materials such as rework, regrind or scrap generated in a process and capable of being reclaimed within the same process that generated it. Virgin production should be optimized to minimize post-industrial waste. Hence, the quantity of available PIR input depends on the efficiency of the production and the quantity of virgin material processed. Post-consumer waste, on the other hand, is recycled after products have been used. The waste for PCR plastics is obtained at the EoL of the products. PCR plastics can be recycled and reused in new products several times.

By its nature and given definition, environmental impacts of PIR plastics will be lower in most cases compared to PCR plastics. To reduce the environmental impact at (end) product level in perspective 3, companies would have to use PIR material. So far, LCA modelling approaches do not have enough incentives for companies to use plastics from PCR. The LCA methodology has not yet been sufficiently explored with respect to the complexity of multiple PCR loops, thus lacking a decision basis to support the use of PCR plastics.

Challenge 5: Misdirected and non-recyclable or partly recyclable waste

Waste from mixed (post-consumer) collection contains a high proportion of impurities and pollutants that must be separated prior to recycling. This is due to incorrect disposal of non-recyclable waste (referred to as misdirected waste) and waste that can only be recycled partially or not at all within a certain waste stream. Misdirected waste is primarily generated by consumers when disposing of non-recyclable products in a waste stream that is intended for recycling and, thus, contaminated. In addition, the lack of separate containers or incorrect separation of recyclable materials by the consumer can harm recyclability. Moreover, upstream plastics manufacturers should only place recyclable plastics on the market or at least contribute to the treatment of non-recyclable or partially recyclable products. Currently, a significant share of waste collected as recyclable household and commercial waste is separated as residues and sent to incineration [Conversio–2022].

Fig. 04 demonstrates the diversity of products collected in household waste including misdirected and non-recyclable or partially recyclable waste. Following commonly proposed modelling approaches, such as recycled-content approach or open-loop method, the environmental burdens from removing and treating such residues are shifted to the recycling chain.

Fig. 04: CCPE researcher analyzing misdirected and non-recyclable or partially recyclable waste from household collection (Copyright: CSCP[1] – photograph: Ramon Külpmann).

[1] Collaborating Centre on Sustainable Consumption and Production in Wuppertal (Germany)

Challenge 6: Quality losses of recycled plastics

Plastics recycling can suffer from downcycling effects, which may influence the functional properties, such as the melt flow index (MFI), the tensile strength and the modulus [Golkaram–2022]. Regarding the MFI, for instance, film and bottle grades require a lower MFI than injection molded products, such as caps and closures [Demets–2021]. A deterioration in functional properties can affect the processability, but also the usability of a recycled plastics from a marketing or safety point of view. The diversity of commercially available grades for each type of polymer is extensive due to (i) the continual advancements in technology and reaction systems, (ii) variations in reaction conditions such as temperature, pressure and time, (iii) the employment of various catalyst types and (iv) the introduction of new monomers and polymers (also with a view to recyclability) [Lu–2018; Spalding–2016]. Beside the mentioned properties, consumer requirements regarding aesthetic properties, such as the absence of pinholes and odors, are quality criteria from a subjective perspective [Schulte–2023]. Fig. 05 shows two recycled samples blown into films from post-industrial and post-consumer waste.

Fig. 05: Recycled granulate from different waste films and produced dog bone samples [Fraunhofer ICT–2023].

Several studies have found that the selection of quality factors in LCA affects the environmental impact results of recycling [Schwarz–2021; van der Harst–2016]. The literature recommends utilizing quality factors that are reliant on economic ratios [Nessi–2021]. However, it is pertinent to consider whether economic factors indicate downcycling effects or merely mirror prevailing market demand, which may not necessarily be identical. Functional requirements could better reflect the substitutability of recycled plastics with virgin plastics. Nevertheless, existing standards, such as the Plastics LCA method, fail to introduce an approach for selecting pertinent functional requirements.

Challenge 7: Non-disclosure of data and reporting of assumptions

Different stakeholders are involved in the collection, sorting and recycling of plastic waste, particularly in post-consumer recycling chains, as stated previously. Rarely does one company have all the data to map out an entire post-consumer recycling chain. Data on subcontracted activities are often not readily obtainable to the company conducting or commissioning the LCA. There is currently a lack of holistic, transparent, and verified data across companies and sectors that can be used as default data in case primary data are missing. Consequently, allocation or cut-off classification are often applied for intermediate flows before the PoS is accomplished to cope with the lack of data, which should be avoided to prevent inconsistencies. A review of stepwise guidelines for data collection for life cycle inventories shows that only 40% of the reviewed case studies provide a complete description of their data collection process and a transparent account of their life cycle inventories to allow full reproducibility [Saavedra-Rubio–2022].

Challenge 8: Inadequate data sources, monitoring and acquisition schemes

Various institutions provide guidance on how to conduct LCAs on recycling, but they do not use the same data monitoring and acquisition schemes. Data sources for modelling the foreground systems are primary company data, scientific articles, patents, expert interviews, unpublished experimental data and process modelling [Thonemann–2020]. Furthermore, existing databases for modelling the background system may use different data sources and calculation rules so that inconsistencies may arise. There is even a database provider who offers different system models including methodological rules to attribute impacts between products and along aggregated processes in the database [Ecoinvent–2020]. In relation to a specific research question and intended application, the availability of different system models is an advantage, but harmonization is required for comparative assessments of studies.

Challenge 9: Outdated or unavailable location-based data

Inconsistencies can arise due to the use of outdated LCA datasets, or in cases where representative data regarding the geographical or technological correlation are even unavailable. It is obvious that the impacts of a recycled plastic material based on process data collected many years ago and/or for a specific location or technological route, cannot be compared to the impacts of a similar material based on current primary data and/or a different location or technology. Often, there are only generic datasets available that are then used to model alternatives with varying temporal, geographical or technological differences.

Moreover, when conducting interstudy comparisons of two different recycling technologies at two sites, the input and output parameters are usually not consistent. If, for instance, the composition of the waste to be recycled differs at two recycling sites, the environmental impacts are affected, as larger or smaller amounts of contaminants must be sorted out prior to recycling (see also challenge 5). To decide, however, which recycling technology shows environmental advantages for one or more of the perspectives on recycling, the same recycled material, with identical quality and properties, shall be considered. So far, location-based differences, such as the composition of the waste input, can hardly be investigated due to missing location-based datasets and information.

Challenge 10: Significant changes in background conditions over time

In addition to the mentioned technological and material innovations from emerging recycling technologies in the foreground system (see challenge 1), technologies in the background system, consumer behavior and trends as well as political decisions can influence a plastics LCA background system and the scenario analysis. Examples are the trend to prefer paper-based packaging materials, the plastic ban in China and the effect of the single-use plastics directive and increasing recycling rates on waste collection and composition. Future scenarios of our prospective plastic consumption, use and treatment are widely missing.

4 Requirements for comparative LCA of plastics recycling

For improving the comparability between LCA studies of plastics recycling, further research and guidance are needed to address the mentioned challenges with a view to the different perspectives. Whereas standards provide guidance on the harmonized modelling regarding the plastic (end) product perspective, requirements for comparative LCAs focusing exclusively on recycling, either on the waste treatment perspective or on the material provision perspective, are less specified and are therefore discussed below.

Requirement 1: Ensure comparable technological scales of plastics recycling

If emerging and mature technologies are compared, the emerging technology should be modelled prospectively, i.e., the technology is modelled at a future, more-developed phase [Arvidsson–2018]. Particular attention must be given to any comparisons among products, processes or technologies at different TRLs, as they might be assessed and used only within R&D activities until the technology matures. Nonetheless, prospective, and comparative assessments can provide early insights using future scenarios which might lead to environmental investments or changes in environmental regulations.

Requirement 2: Pay attention to the choice of system boundaries

Especially in the case of different recycling technologies and routes that provide resources for reuse at diverse stages of the value chain, system boundaries are to be defined with caution. To improve comparability with other LCA studies, we recommend a comparison of a plastic-to-plastics recycling from the PoC to the PoS, i.e., starting from the plastic waste collection to the point in the supply chain where recycled granulate can substitute fossil plastics. If system boundaries differ between studies, no comparisons can be made, neither about the environmental advantages of managing a certain waste stream nor about the provision of the resources obtained.

Requirement 3: Maintain the recycling chain as a coherent row of activities

We recommend avoiding cut-off classifications or allocations of impacts within the recycling chain from the PoC to the PoS. Consequently, all flows need to be modelled until they have been fully treated as waste or transformed into marketable products (recycled materials or energy), including those that leave the system boundary of a company (e.g., to be treated by subcontractors). This can be particularly challenging for complex recycling systems that treat various waste materials and are managed by multiple stakeholders. The availability of reliable and transparent default data is necessary to tackle this challenge (see also requirement 8).

Requirement 4: Handle multi-functionality using substitution of secondary products when modelling recycling as EoL option

To isolate the main function of the waste treatment perspective, we acknowledge the use of system expansion through substitution as a valid method. Thus, credits should be given for all secondary products (recycled materials and recovered energy) to assess the waste treatment perspective of recycling. The choice of substituted processes and possibly corresponding substitution ratios must be transparently reported and disclosed separately from the environmental burdens directly associated with the recycling chain. Results should be communicated with and without credits to understand both the burdens only as well as burdens in relation to the benefits of the recycling process as EoL option. For comparable studies, we recommend refraining from claiming negative environmental impacts from other treatment activities, such as incineration of the plastic waste, that are to be replaced by the new recycling activities. The substitution of avoided waste treatment activities hinders comparability with other studies and is not compatible with the PEF method.

Requirement 5: Find a consensus regarding the issue of multi-functionality in the modelling of recycled plastics

Regarding the material provision perspective, we suggest that substitution is not the right modelling approach. The waste treatment function usually cannot be substituted by an (economic) activity because waste producers often pay for its treatment. Claiming negative impacts in the assessment of recycling due to avoided treatment processes has been criticized by several studies, such as Tabrizi [2020]. We encourage LCA practitioners to refrain from substitutions in the material provision perspective, even for other co-products, such as recovered energy. If recycling is modelled as a material provision stage, credits lead to misinterpretations and should only be considered at the EoL to avoid double counting. Referring to challenge 2 (intrinsic multi-functionality of recycling), there is currently no consensus regarding the modelling of recycling as a material provision stage. The two frequently mentioned modelling approaches, the recycled-content and the open-loop approach, do not solve the challenge of the intrinsic multi-functionality looking at recycling from a material provision perspective.

The main objective in the choice of narrowing the multi-functionality issue in recycling from the perspective of material provision is to provide information that allows a better understanding of environmental impacts with efforts to meet the needs of our economic production activities through recycling. The creation of economic value is the driver of economic processes looking at recycling from a material provision perspective with its main function to provide marketable products. An economic allocation at the PoS might be currently the best option to reflect the economic purpose of recycling from a material provision perspective. The products of multi-functional and economically optimized joint recycling systems are interdependent and must be evaluated holistically together. Substituting, omitting, or cutting off an intermediate flow within the recycling chain that needs further treatment before becoming an economic product[1] will always create inter-consistency, especially between LCA studies. We demand for standardized rules for comparative modelling of recycling as a material provision stage in LCA. This should map and allow the comparison between recycled and virgin material, taking into account the multi-functionality of recycling.

Requirement 6: Depict the input waste quality at the PoC

The documented input waste quality should include the waste origin, the collection scheme, its composition and level of impurities. This requirement is mandatory to check inter-consistencies of studies dealing with varying waste input qualities. It is evident that recycling from a mixed-collected and contaminated waste stream causes higher environmental impacts compared to a mono-collected waste stream. The use of recycled plastics from mixed-collected and contaminated waste streams is challenging and should not be penalized by the high environmental impact that these resources currently have. This requirement is in alignment with requirement 5, i.e., there is currently no standardized method for isolating the material provision function in the corresponding perspective. However, when comparing diverse recycling technologies, it is essential to document the quality of the input waste and, if feasible, to harmonize the quality of the input waste stream for comparative assessments.

Requirement 7: Indicate the quality based on the functional properties at the PoS

The subsequent application of a recycled plastic depends on the output quality. The quality can be indicated by the change in functional properties of recycled material compared to the virgin material (e.g., mechanical performance) and/or economic substitutability (e.g., current market prices). If functional properties are documented, comparisons can be made between different output qualities of recycled and virgin plastics. This requirement is of relevance for both perspectives 1 and 2, either when

[1] Recycled material or recovered energy that can be used in another production activity.

defining substitution ratios to avoid virgin production processes or when assessing the usability of recycled plastics in conjunction with a specific product application.

Requirement 8: Use and disclose a uniform process scheme for data collection and reporting

For robust and reliable evaluation of recycled plastics, collect primary data based on a given point in time whenever possible. The alignment of LCA data collection and existing monitoring activities of recycling activities could serve as a first starting point to improve data quality and availability. To guarantee reproducibility, aggregated disclosure of the life cycle inventory, i.e., inputs and outputs, allows the generation of generic default data and fills existing data gaps. Data disclosure and availability are needed to remove logical contradictions and conduct a consistent comparison. As a result, transparent data transfer across company borders must take place. Certifications exist to improve the traceability of plastic materials in the supply chain throughout the recycling process, such as EuCertPlast[1]. Currently, they are used to quantify the recycled content of an (end) product or allow the recyclers to fulfill REACH[2] requirements and food contact compliance but might also be used in the context of LCA in the future.

Requirement 9: Be careful with claiming recycled content when using PIR plastics

Both PIR and PCR plastics can replace virgin plastics, in specific cases, and reduce primary resource extraction. Generally, PIR materials tend to be cleaner and more consistent in quality because they have not undergone the wear and tear associated with consumer use. Therefore, the extent to which PIR and PCR materials close the loop differs. Strictly speaking, PIR does not really close the loop, it is more related to production efficiency of the upstream material processed. Comparative assessments of PIR and PCR are challenging due to (again) different system boundaries, relevant input parameters and qualities. Any post-industrial material that is reused within a process chain or pool of process chains should not be claimed recycled material within a product, especially if it has a positive economic value [Nessi – 2020].

Requirement 10: Use prospective background data for future scenarios

To model future scenarios and cope with different TRLs comparing emerging and mature recycling technologies, reliable prospective data and assumptions are needed for a future plastics recycling industry. This should include not only technological changes but also market trends, consumer behavior and possible political decisions.

[1] European Certification of Plastics Recyclers. Online available: www.eucertplast.eu (last access: 22.11.2023)

[2] REACH: Registration, Evaluation, Authorisation and Restriction of Chemicals (https://environment.ec.europa.eu/topics/chemicals/reach-regulation_en. Last access: 12.01.2024)

5 Conclusions and future work

This position paper examines the challenges and requirements in comparing the perspectives of modelling plastics recycling in LCA as either a material provision or an EoL stage. In such comparative assessments, consistency is a mandatory requirement to avoid inappropriate conclusions and/or ensure the comparability of LCA results, specifically during meta-studies[1]. Due to the comparative nature of LCAs and the associated consequences for environmental decision-making, the consistency and transparency of different LCA studies must be increased – especially when conducted independently. This applies not only to LCA studies of plastics recycling but also to recycling in general.

At the methodological level, it is important to sharpen modelling approaches in terms of multi-functionality and system boundaries. Comparing different recycling options at an EoL stage is challenging, because mechanical and chemical recycling technologies provide resources for reuse at different stages of the value chain. The comparison of virgin plastics and recycled plastics (from a multi-functional recycling chain that potentially recycles mixed collected waste) is flawed in terms of the functionality. Consensus is missing to create robust and reliable LCA results currently exists in the material provision perspective. First and foremost, we therefore call for clarification of the modelling of recycling as a material provision stage in relation to the issue of multi-functionality issue when comparing recycled and virgin plastics.

At the data and technology level, a comparison of different plastics recycling technologies requires a harmonized waste input quality and should consider the substitutability of recycled plastics compared to virgin plastics. Comparisons of different LCA studies are particularly challenging for plastics due to varying input and output parameters as well as different process schemes. The fact that the recycling chain is rarely entirely in the hands of one single company challenges the generation of reliable data and LCA results because current studies are based on a lot of assumptions, such as the disregard or rough estimation of flows that are treated and recycled elsewhere.

Our requirements aim to support further standardization and harmonization of LCA for plastics recycling, as intended by the European Commission and its Product Environmental Footprint Initiative. We recommend harmonizing existing monitoring and auditing schemes of recycling activities for certification purposes to align and integrate requirements from different attempts of standardizing into LCA practice. Furthermore, we encourage companies and LCA practitioners to work together to solve mentioned challenges. The provision of proxy and default data to model complex recycling chains from mixed collection is essential to fill existing data and modelling gaps.

[1] In a meta-study, existing studies are harmonized to compare the results with each other and make generic interpretations of a research topic based on multiple studies.

References

Arvidsson, R.; Tillman, A.; Sandén, B. A. et al. (2018): Environmental Assessment of Emerging Technologies: Recommendations for Prospective LCA. In: Journal of Industrial Ecology, 22(6), pp. 1286–1294.

Conversio (2022): Stoffstrombild Kunststoffe in Deutschland 2021:. Zahlen und Fakten zum Lebensweg von Kunststoffen. Langversion.

Demets, R.; van Kets, K.; Huysveld, S. et al. (2021): Addressing the complex challenge of understanding and quantifying substitutability for recycled plastics. In: Resources, Conservation and Recycling, 174, p. 105826.

Ecoinvent (2020): System Models - ecoinvent. Last time checked: 2023, November 28. https://ecoinvent.org/the-ecoinvent-database/system-models/.

Ekvall, T.; Björklund, A.; Sandin, G. (2020): Modeling recycling in life cycle assessment.

European Commission (2021): Environmental Footprint methods. Last time checked: 2023, January 10. https://green-business.ec.europa.eu/environmental-footprint-methods_en.

European Commission (2022): European Platform on LCA | EPLCA. EF reference package 3.1 - Annex C transition phase. Last time checked: 2024, January 9. https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml.

Finnveden, G.; Potting, J. (2014): Life Cycle Assessment. In: : Encyclopedia of Toxicology: Elsevier, pp. 74–77.

Franklin Associates (2018): LIFE CYCLE IMPACTS FOR POSTCONSUMER RECYCLED RESINS: PET, HDPE, AND PP.

Fraunhofer ICT (2023): Picture of recycled granulates and produced dog bones from waste films.

Fraunhofer UMSICHT (2023): Recycling cascade. Editor: Martin Nieberl. Sulzbach-Rosenberg.

Frischknecht, R. (2000): Allocation in Life Cycle Inventory Analysis for Joint Production. In: The International Journal of Life Cycle Assessment, 5(2).

Golkaram, M.; Mehta, R.; Taveau, M. et al. (2022): Quality model for recycled plastics (QMRP): An indicator for holistic and consistent quality assessment of recycled plastics using product functionality and material properties. In: Journal of Cleaner Production, 362, p. 132311.

Guinée, J. B.; Heijungs, R. Huppes, G. (2004): Economic allocation: Examples and derived decision tree. In: The International Journal of Life Cycle Assessment, 9(1).

Heijungs, R.; Guinée, J. B. (2007): Allocation and 'what-if' scenarios in life cycle assessment of waste management systems. In: Waste management (New York, N.Y.), 27(8), pp. 997–1005.

ISO 14021 (2016): Environmental labels and declarations - Self-declared environmental claims (Type II environmental labelling). Last time checked: 2023, December 5. https://www.iso.org/standard/66652.html.

ISO 14040 (2006): Environmental management. Life cycle assessment. Principles and framework. Geneva: International Organization for Standardization. Last time checked: 2023, December 5. https://www.iso.org/standard/37456.html.

ISO 14044 (2006): Environmental management. Life cycle assessment. Requirements and guidelines. First edition. Geneva: International Organization for Standardization. Last time checked: 2023, December 5. https://www.iso.org/standard/38498.html.

Life Cycle Initiavtive (2013): Life Cycle Assessment. A product-oriented method for sustainability analysis. UNEP LCA Training Kit: Module g – Multifunctionality, allocation

& system boundaries. Last time checked: 2023, November 20. https://www.lifecycleinitiative.org/wp-content/uploads/2013/06/Module-g-Multifunctionality-allocation-system-boundaries.pdf.

Lu, X.; Liu, Y.; Zhou, H. (2018): Learning Nature: Recyclable Monomers and Polymers. In: Chem. Eur.J., (24), pp. 11255–11266.

Nessi, S.; Sinkko, T.; Bulgheroni, C.; Garcia-Gutierrez, P.; Giuntoli, J.; Konti, A.; Sanye Mengual, E.; Tonini, D.; Pant, R.; Marelli, L. and Ardente, F. (2021): Comparative Life Cycle Assessment (LCA) of Alternative Feedstock for Plastics Production. Final report for stakeholder consultation - Part 1 - the Plastics LCA method. Luxembourg (EUR 30725 EN). Last time checked: 2023, December 5. https://publications.jrc.ec.europa.eu/repository/handle/JRC125046.

Pelletier, N.; Ardente, F.; Brandão, M. et al. (2015): Rationales for and limitations of preferred solutions for multi-functionality problems in LCA: is increased consistency possible? In: The International Journal of Life Cycle Assessment, 20(1), pp. 74–86.

Plastics Europe (2023): Plastics – the fast Facts 2023. Last time checked: 2023, December 5. https://plasticseurope.org/wp-content/uploads/2023/10/Plasticsthefastfacts2023-1.pdf.

Roßmann, M.; Stratmann, M.; Rötzer, N.; Schäfer. P.; Schmidt, M. (2020): Comparability of LCAs — Review and Discussion of the Application Purpose: Springer.

Saavedra-Rubio, K.; Thonemann, N.; Crenna, E. et al. (2022): Stepwise guidance for data collection in the life cycle inventory (LCI) phase: Building technology-related LCI blocks. In: Journal of Cleaner Production, 366, p. 132903.

Schrijvers, Dieuwertje L.; Loubet, Philippe; Sonnemann, Guido (2016): Critical review of guidelines against a systematic framework with regard to consistency on allocation procedures for recycling in LCA. In: The International Journal of Life Cycle Assessment, 21(7), pp. 994–1008.

Schulte, A.; Velarde, P. Á. S.; Marbach, L. et al. (2023): Measuring the circularity potential of recycled LDPE based on quantity and quality conservation - a functional requirement matrix approach. In: Resources, Conservation & Recycling Advances, 17, p. 200127.

Schwarz, A. E.; Ligthart, T. N.; Godoi Bizarro, D. et al. (2021): Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach. In: Waste management (New York, N.Y.), 121, pp. 331–342.

Spalding, M. A.; Chatterjee, A. M. (2016): Handbook of industrial polyethylene and technology : definitive guide to manufacturing, properties, processing, applications and markets: John Wiley & Sons.

Tabrizi, S.; Rollinson, A. N.; Hoffman, M.; Favoino, E. (2020): Understanding the Environmental Impacts of Chemical Recycling. Ten concerns with existing life cycle assessments.

Thonemann, N.; Schulte, A.; Maga, D. (2020): How to Conduct Prospective Life Cycle Assessment for Emerging Technologies? A Systematic Review and Methodological Guidance. In: Sustainability, 12(3), p. 1192.

van der Harst, E.; Potting, J.; Kroeze, C. (2016): Comparison of different methods to include recycling in LCAs of aluminium cans and disposable polystyrene cups. In: Waste management (New York, N.Y.), 48, pp. 565–583.

Weidema, Bo P. (2019): Consistency check for life cycle assessments. In: The International Journal of Life Cycle Assessment, 24(5), pp. 926–934.

Weidema, B. P. (2019). Consistency check for life cycle assessments. International Journal of Life Cycle Assessment, 24, 926-934. https://doi.org/10.1007/s11367-018-1542-9