Land-Based Solutions for Plastics in the Sea

D5.6 LCA Methodology to compare plastics

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3	Bundesanstalt fuer Gewaesserkunde	BfG	GERMANY	RTO
4	LABORATORIO IBERICO INTERNACIONAL DE NANOTECNOLOGIA	INL	PORTUGAL	RTO
5	KATHOLIEKE UNIVERSITEIT LEUVEN	KUL	BELGIUM	HES
6	HELMHOLTZ ZENTRUM FUR OZEANFORSCHUNG KIEL	GEOMAR	GERMANY	RTO
7	NATIONAL OCEANOGRAPHY CENTRE	NOC	UNITED KINGDOM	RTO
8	SORBONNE UNIVERSITE	SU	FRANCE	HES
9	OPEN UNIVERSITEIT NEDERLAND	OUNL	NETHERLANDS	HES
10	LEIBNIZ INSTITUTE FOR BALTIC SEA RESEARCH	IOW	GERMANY	RTO
11	ASSOCIACAO PARA O DESENVOLVIMENTO DO ATLANTIC INTERNATIONAL RESEARCH CENTRE	AC	PORTUGAL	RTO
12	BASF SE	BASF	GERMANY	LE
13	TG ENVIRONMENTAL RESEARCH	ER	UNITED KINGDOM	SME
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Executive summary:	This document corresponds to Deliverable 5.6. *LCA Methodology resulting from subtask 5.5.1* of the LABPLAS Project. This document aims to define a methodology to perform a comparative Life Cycle Assessment (LCA) between conventional fossil-based vs bio-based plastics (both non-degradable and degradable) based on the Plastics LCA methodology developed by the Joint Research Centre (JRC) but making adaptations to take into consideration the concerns raised by the European Bioeconomy Alliance (EUBA) and the European Bioplastics Association (EUBP) regarding the previously mentioned methodology. Also, the methodology is defined to allow the inclusion of the LABPLAS Project results in the development of the LCA, overcoming current methodological and data gaps. All the differences and adaptations made from the JRC Plastics LCA method are described in this deliverable.

Version	Date	Comments
1.0	19-Aug-22	First version
2.0	30-Aug-22	Revised and corrected final version

Disclaimer

The views and opinions expressed in this document reflect only the authors' views, and not necessarily those of the European Commission.

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Abbreviation / Acronym	Description
BoM	Bill of Materials
CFC	Chlorofluorocarbon
CFF	Circular Footprint Formula
CFs	Characterization Factors
CTU	Comparative Toxic Unit
CTUe	Comparative Toxic Unit for Ecosystem Toxicity Impacts
CTUh	Comparative Toxic Unit for Human Toxicity Impacts
EC_{50}	Median Effective Concentration
EF	Environmental Footprint
EfF	Effect Factor
EoL	End-of-Life
eq	Equivalent
EUBA	European Bioeconomy Alliance
EUBP	European Bioplastics
Ff	Fate factor
FU	Functional Unit
GHG	Greenhouse Gases
$HC50_{EC50}$	Hazardous concentration at which 50% of the species are exposed to a concentration above their EC_{50}
iLUC	Indirect Land Use Change
JRC	Joint Research Centre
kBq	Kilobecquerel
LABPLAS	Land Based solution for PLAstics in the Sea
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LUC	Land Use Change
MJ	Mega Joules

n.a.	Not applicable
NF	Normalization Factor
NMVOC	Non-Methane Volatile Organic Compounds
PA	Nylon Polyamide
PAF	Potentially affected fraction of species
PBAT	Polybutylene Adipate Terephthalate
PE	Polyethylene
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rule
PET	Polyethylethene Terephtalate
PHA	Polyhydroxyalkanoates
PLA	Polylactic Acid
pt	Points
TBD	To Be Determined
TRL	Technology Readiness Level
XF	Exposure Factor
WF	Weighing Factor

1 INTRODUCTION

Plastic is pouring from land into our oceans at a rate of nearly 10 million tonnes a year. Once in the sea, plastics fragment into particles moving with the currents and ocean gyres before washing up on the coastline. The smaller the size the higher the risk posed by these particles to organisms and human health. Because small, micro- and nano- plastics (SMNP) cannot be removed from oceans, proactive action regarding research on plastic alternatives and strategies to prevent plastic from entering the environment should be taken promptly. The LABPLAS Project is a 48-month project whose vision is to develop new techniques and models for the detection and quantification of SMNPs Specifically, the LABPLAS Project will determine reliable identification methods for a more accurate assessment of the abundance, distribution, and toxicity determination of SMNPs and associated chemicals in the environment. It will also develop practical computational tools that should facilitate the mapping of plastic-impacted hotspots and promote scientifically sound plastic governance.

This document corresponds to Deliverable 5.6. *LCA Methodology resulting from subtask 5.5.1* of the LABPLAS Project. This document aims to define a methodology to perform a comparative Life Cycle Assessment (LCA) between conventional fossil-based vs bio-based plastics (both non-degradable and degradable) based on the Plastics LCA methodology developed by the Joint Research Centre (JRC) but making adaptations to take into consideration the concerns raised by the European Bioeconomy Alliance (EUBA) and the European Bioplastics Association (EUBP) regarding the previously mentioned methodology.

2 INTRODUCTION TO LIFE CYCLE ASSESSMENT (LCA)

Life Cycle Assessment (LCA) is a scientific approach which supports environmental policies and decisions in business in the context of sustainable development. It allows the evaluation of the potential environmental impacts of the whole life cycle of products, processes, or activities in different impact categories, including climate change, ozone depletion, use of resources, use of water, etc. The LCA is usually carried out following four distinguished steps according to ISO 14040:2006 (see Figure 1).
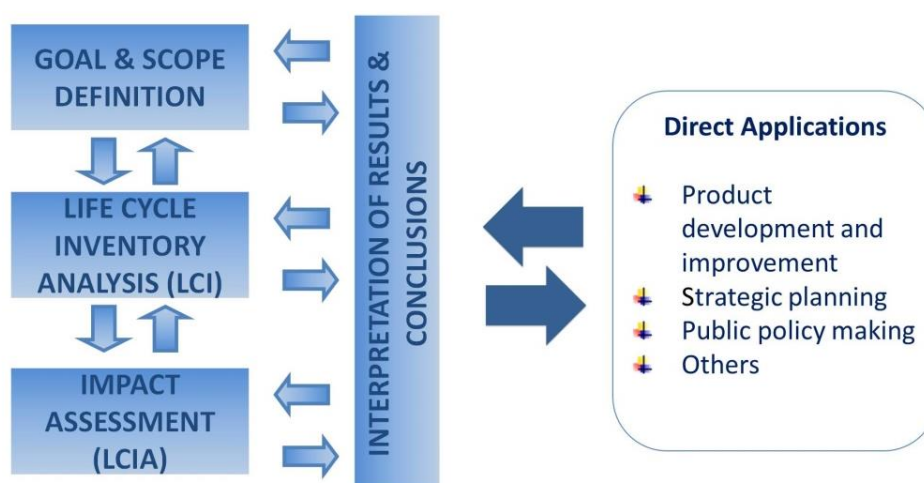

Figure 1. Steps to perform an LCA adapted from ISO 14040:2006.

The objectives of the LCA and main methodological decisions are defined in the Goal and Scope section, where the product system and the system boundaries are also described. Also, the quality requirements of data, hypothesis made, and limitations found are defined. The Functional Unit (FU), the so-called unit of analysis in the Product Environmental Footprint (PEF) Guide, and the reference flows are also determined at this stage and they represent the function, quantity, quality and lifetime of the product or activity under study. The adequate selection of the FU and reference flows are key aspects in defining, comparing, and communicating the environmental profiles of products. Subsequently, specific quantified data describing the product system under study concerning material, energy inputs, emissions, products and co-products are collected in the Life Cycle Inventory (LCI). The Life Cycle Impact Assessment (LCIA) is the following stage where the LCI data are transformed into potential environmental impacts by using an LCIA method. Classification and characterization of emissions are two mandatory steps in which the impact category on which each emission affects is determined and quantified using characterization factors (CFs). On the other hand, normalization and weighting are optional and can be done by applying normalization and weighting factors. These optional steps facilitate communication of results while incorporating subjectivity and decreasing the scientific robustness of the results. Finally, the results are interpreted, and conclusions are extracted to develop and improve products and activities, plan strategies, public policy making or other applications. All the steps are redefined in a continuous process during the development of the LCA, after finding limitations and identifying solutions to tackle them.

3   LCA METHODOLOGIES THAT COMPARE BIO-BASED PLASTICS VS FOSSIL-BASED ALTERNATIVES

Given the increasing interest in the use of bio-based products and plastics to tackle environmental issues, such as climate change, loss of biodiversity, or fossil resource depletion (European Commission, 2018b), bioeconomy-related activities are being supported by European policies. In the Bioeconomy strategy recommendation (European Commission, 2018a) and the European Strategy for Plastics, biodegradability is highlighted as one of the main properties that plastics should present to decrease environmental impacts linked to littering. However, efforts must be made to not present biodegradability as the ultimate solution to the issue of mismanaged plastic waste.

The life cycle environmental consequences of switching from a fossil-based to a bioeconomy must be addressed before changing the landscape of the market with innovative technologies and products. In consequence, to evaluate two differently sourced products a comparative assessment must be performed using an LCA methodology that allows a scientific and holistic comparison of life cycle environmental impacts. The application of different LCA methodologies could lead to different results, depending on the assumptions, limitations, system boundaries, type of data, or cut-offs made. In consequence, the first step before performing any calculation must be the selection of the methodology or the methodology definition. However, current LCA methodologies show significant methodological gaps when the objective is to compare bio-based plastics with their fossil-based counterparts. The most relevant ones were highlighted in the Plastics LCA method developed by the Joint Research Centre (JRC) (Pant et al., 2018):

- ➲ **Inclusion of indirect effects**, **such as Indirect Land Use Change (iLUC)**: increasing the production of bio-based plastics may produce indirect effects in the market and production systems that are currently difficult to assess and there is no commonly used methodology to quantify the impacts yet. In addition, available methodologies are mostly focused on the indirect impacts of Greenhouse Gases (GHG) emissions and soil quality after changing the use of land. All the impacts in other impact categories should be also considered when changing the land use and are not currently accounted for.

- **Scarcity of data on type and amount of additives used**: due to confidentiality issues, precise data on additives used in plastics are not usually available in secondary datasets or LCA literature. They could play a role in the life cycle environmental impacts given some of them are classified as hazardous substances (Wiesinger et al., 2021), especially if the littering rates of the product are significant.
- **Recycling incompatibilities**: plastic mix recycling performance is not well addressed. In the bio-based plastics case, the economic and technical feasibility of recycling these materials should be first validated as well as the conditions to quantify the environmental burdens of such processes.
- **Asymmetries in data availability and quality**: as the European Bioeconomy Alliance (EUBA) also points out (see later section 3.2) the quality and availability of data for bio and fossil-based plastics differ significantly. They also state that the data quality requirements to perform LCAs are lower for fossil-based materials in the Plastics LCA method.
- **Quantities of leaked plastics and share of leaked products**: the lack of statistics on product littering is an issue that prevents the accurate quantification and comparison of environmental impacts between different types of products.
- **Toxicity characterization factors for macro and micro plastics including additives**: impacts of leaked plastics could be estimated within the current toxicity impact categories if characterization factors (CFs) were available, which is not yet the case. For this reason, among the LABPLAS Project objectives is to understand the fate and distribution of macro, micro and nano-plastics.
- **Inclusion of a littering impact category or deal with it using current toxicity impact categories**: both approaches can be tested, including the littering category as additional information using previous methodologies which require a low amount of data to perform an environmental impact assessment of littering or including impacts in mid-point impact categories (such as climate change, human and ecotoxicity) or end-point categories (biodiversity loss and damage to human health).

LCA of plastics should evolve trying to fill these gaps while maintaining a coherent methodology to allow harmonization. In consequence, the JRC Plastics LCA method will be used as starting point to develop the LABPLAS Project methodology (LABPLAS Project LCA methodology from now on), whilst at the same time taking into consideration the EUBA and EUBP concerns and potentially fulfilling current methodological gaps. In the next sections, a brief description of the two main documents used as references to define the LABPLAS Project LCA methodology is presented. Due to its connection with the LABPLAS Project, a brief introduction to the practice of dealing with toxicity characterization factors (CFs) of littered plastics in LCA is also included.

3.1 The JRC Plastics LCA method

The European Commission recently published the Recommendation on the use of the Product Environmental Footprint (PEF) Method[1] to evaluate the life cycle environmental performance of products, although bio-based product systems need further specifications. In consequence, the JRC developed the Plastics LCA methodology and a comparative attributional LCA was performed highlighting the potential environmental impacts and hotspots of bio-based and bio-degradable plastics in comparison to current alternatives. The JRC prepared a technical report (Nessi et al., 2021) with three objectives: i) comparing both product systems, (ii) testing and supporting the development of the Plastics LCA methodology and iii) highlighting challenges and gaps. An LCA of alternative feedstocks, including seven bio-based plastic products (beverage bottles, horticultural clips, single-use cups, single-use cutleries, agricultural mulch films, food packaging films and single-use carrier bags) were compared to their fossil-based counterparts. In this study, the bio-based products were modelled using mostly primary data while fossil-based products were assessed using the Eco-profiles provided by Plastics

Europe. The results showed better environmental performance of bio-based products in climate change and fossil resource depletion while they presented higher impacts in the particulate matter impact category. Inconclusive results were obtained in the comparison of photochemical ozone formation and terrestrial eutrophication results. However, these results were calculated using European average End of Life (EoL) mix of technologies without any further regionalization. Besides, littering was not modelled and the full chemical composition of biodegradable plastics was unknown, while the fossil-based counterparts were modelled using the chemical composition of the product at the EoL stage, which includes inks and labels. In the end, the JRC highlighted that significant knowledge and data gaps in the LCA of plastics must be filled regarding the impacts of indirect land use change (iLUC), the non-GHG-related impacts related to land use change, scarcity of data on type and amount of additives used in plastic production and potential recycling on incompatibilities between bio-based/biodegradable and fossil-based plastics mechanical recycling.

Littered or mismanaged plastics waste impacts

The JRC Plastics LCA report, especially in Annex I, describes how the impacts of mismanaged waste or littered products are not commonly accounted for in LCAs of plastic products. Therefore, the methodology suggests including information about the potential littered quantity of a product as additional information as littering may lead to the release of additives, micro and nano-plastics as well as other organic compounds after degradation processes. In addition, it can cause direct effects on biodiversity via ingestion, entanglement or suffocation; or indirectly by transporting non-indigenous species. Plastics littered in the ocean also present risks to human health, given that toxic substances may end in the human food chain. The report also highlights the need to increase the knowledge on the degradation and biodegradation processes of plastics. Furthermore, the lack of reliable littering rates is also seen as a relevant issue, but recent developments like the Plastic Leak Project (Quantis, 2020) provide some product-based metrics that can be used. Another alternative is the approach based on probabilities of products to participate in a littering event using literature and Ecoinvent data as developed by Ciroth & Kouame, 2019.

Thus, the JRC Plastics LCA method conclusions question whether the inclusion of an independent littering impact category is needed.

In Parker & Edwards, 2012, the authors used two simplistic methods to account for the impacts of plastic littering in terrestrial environments in an independent impact category. The first one was based on the adaptation of sanitary landfill LCI datasets of plastic bags to littering in terrestrial environments. In their second approach, they used an indicator calculated by multiplying the area of the littered product times the time spent in the environment (which depends on the biodegradation rate). A similar indicator was used by the developers of the named "litter – marine biodiversity" approach (ExcelPlas Australia) which is based on the potential for ingestion or entanglement of marine fauna during the time the littered product is in the ocean, influenced by its floating properties. However, the impacts of microplastics are not accounted for and toxicity effects are completely neglected using these approaches.

The MariLCA project (Boulay et al., 2021) is currently developing an LCIA method to quantify the impacts of littered plastics in the ocean, depending on the physical and chemical properties of the materials (this framework is not yet available). The proposed framework links inventory data of plastic leaked into a specific environmental compartment to six Areas of Protection (AoP): ecosystem quality, human health, socio-economic assets, ecosystem services, natural heritage and cultural heritage, by including existing (e.g., human and ecotoxicity) and new impact categories (e.g., physical effect on biota) in the LCA. The method is built to consider the material released, the location, the quantity, the environmental compartment, and the size of the material

Internal

(macro, micro or nano). However, it will only consider the effects of littered plastics (macro, micro and nano plastics) in the ocean, but not the effects in previous environmental compartments such as air, soil, or freshwater.

Another option to account for the impacts of littered products in LCAs is to include the effects of littering in the midpoint impact categories like climate change (after GHG are released after degradation) or eco and human toxicity, including additives that will eventually have an end-point effect on biodiversity loss. However, better knowledge of fate, exposure and effects of plastics released into the environment is needed to use this approach. Until that knowledge is gained, the toxicological impacts of littering may be included in a separate impact category.

3.2 Position of the European Bioeconomy Alliance and European Bioplastics regarding the JRC Plastics LCA method

In regards to the Plastics LCA method published by the JRC, the European Bioeconomy Alliance (EUBA) and European Bioplastics (EUBP) (EUBA & EUBP, 2021) claim that the JRC Plastics LCA methodology is very relevant for the European industry "but it is not suitable for making well-balanced and complete LCA comparisons" as "it structurally tends to favour fossil-based plastics" and they "urge the JRC to stop wider dissemination of this methodology and start a new review". They also provide conclusions from a study made by Jungbluth[2], where it is stated that unintentional methane emissions are not well monitored and therefore not accounted for in life cycle inventories, which leads to an underestimation of environmental impacts of fossil-based products, especially towards climate change. To emphasize the benefits of bio-based products compared to current fossil-based plastics EUBA and EUBP consider that the JRC methodology needs improvements in the following areas:

- ⮑ Carbon sequestration
- ⮑ Comparison of mature and immature production systems
- ⮑ Data reporting requirements
- ⮑ Incorporation of land use change
- ⮑ Incorporation of indirect effects
- ⮑ Requirements for providing proof
- ⮑ Biodiversity impacts
- ⮑ Reflecting end-of-life realities
- ⮑ Normalisation and weighing
- ⮑ Feedstock supply data requirements

3.3 Toxicity characterization factors (CFs) of littered plastics for LCAs

One of the main challenges regarding the LCA of plastics is the lack of CFs to estimate the toxicity impacts of littered plastics in different environmental compartments. It is possible to develop new CFs if the necessary data are available. Research has been conducted on interim and simplified CFs for microplastics from a polyester-based t-shirt and microplastics from a shower gel in freshwater (Salieri et al., 2021). According to the authors, the influence of microplastics in those cases is marginal due to the small mass of substances reaching the environment. Other products with higher littering mass rates could present a higher influence in

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[2] https://www.linkedin.com/pulse/update-life-cycle-inventory-data-crude-oil-natural-gas-jungbluth/?trackingId=TWvvxXqcQteCoqirrQ423g%3D%3D

LCAs considering the toxicity impacts of microplastics. If the data available from the LABPLAS Project allows for the calculation of CFs, the same procedure used in the Environmental Footprint (EF) method (used in the JRC Plastics LCA) should be used to be consequent with the Product Environmental Footprint (PEF). The EF method toxicity CFs were calculated according to USEtox®. However, no CFs regarding micro- or nanoplastics were included. The methodology can be consulted in their paper published in 2022 (Sala et al., 2022).

The impact category from the EF method representing the ecotoxicity is called "Ecotoxicity, freshwater", measured in Comparative Toxic Units for Ecosystem Toxicity Impacts (CTUe). It considers the emissions produced to water, soil and air. The CFs are calculated as represented in equation 1:

$$CF\ (CTUe) = FF \times XF \times EfF \qquad [1]$$

- FF: Fate Factor (days) represents the distribution of the substance in the environment. It depends on the environmental compartment where this substance is found (air, soil, and water) at a steady state.
- XF: the Exposure Factor (%) represents the bioavailable fraction of the substance that may affect the organisms in the biosphere.
- EfF: the Effect Factor (PAF m^3 kg^{-1}) represents the intrinsic toxicity potential

To calculate FFs and XFs by using the USEtox® model (Fantke et al., n.d.), it is necessary to know at least nine physical-chemical properties:

- Molecular weight
- Acid dissociation
- Octanol-water partition coefficient
- Water solubility
- Vapor pressure
- Degradation in water
- Degradation in sediment
- Degradation in soil
- Degradation in air

In Salieri et al., 2021, the FFs (120-143 days) were calculated considering only the degradation in freshwater (values for water degradation rate of 1.6E-8 and 5.8E-8 s^{-1}) and degradation rates of plastics (not microplastics) from different products (bags, food containers, plastic bottles, etc.) from literature. The other physical-chemical properties were set according to the assumption of modelling a worst-case scenario and not from empirical evidence. For the molecular weight, a high value was chosen to confer impact resistance. A low partitioning coefficient between octanol and water was used to represent the non-solubility of plastics. Furthermore, a low Henry law coefficient was used, given microplastics have no potential of partitioning between air and water, and an extremely low vapor pressure and no solubility were assumed.

The EfF was calculated using the USEtox® model using equation 2:

$$EfF = 0.5/HC50_{EC50} \qquad [2]$$

The $HC50_{EC50}$ value was calculated as the mean EC_{50} value at the species level by Saling et al., 2020, which is aligned with the USEtox® requirements. 26 ecotoxicity impacts for algae, crustaceans and fish were used. In addition, they set the XF as 1, again, intending to represent the worst-case scenario.

The resulting CFs were in the range of 2712 to 3231 CTUe, but given the great number of assumptions used, those factors are too uncertain and inconclusive to be used in attributional and comparative LCAs. Product or

material-specific data, as well as reliable data to evaluate the fate, exposure and effects of littered plastics, would be required to perform comparative assertions.

4   LABPLAS PROJECT'S POTENTIAL CONTRIBUTION TO THE LCA METHODOLOGY

The LABPLAS Project methodology will be defined with the intention to reduce some of the current gaps and make use of the LABPLAS Project data. as listed in **Error! Reference source not found.**.

Current gaps in the JRC Plastics LCA method	Possibility of contribution from the LABPLAS Project	Type of contribution	Source of contribution from LABPLAS
Inclusion of indirect effects, such as Indirect Land Use Change (iLUC):	No	n.a.	n.a.
Scarcity of data on type and amount of additives used	Yes	Characterization and quantification of additives found in products	WP4
Recycling incompatibilities	No	n.a.	n.a.
Asymmetries in data availability and quality	No	n.a.	n.a.
Quantities of leaked plastics	No	n.a.	n.a.
Share of leaked products	Yes	Field samples analysis in different regions and environmental compartments	WP2 and WP3
Toxicity characterization factors for macro- and microplastics including additives	Yes	Development of effect (EfF) and fate factors (FF) for macro-, micro- and nanoplastics from LABPLAS ecotoxicity and degradation results (WP5 and WP6) and fate and transport models (WP7)	FF: WP5 and WP7 EfF: WP5, WP6 and WP7
Inclusion of a littering impact category or deal with it using current toxicity impact categories	Yes		

Table 1. Potential contribution of the LABPLAS Project to overcome LCAs current methodological gaps.

Since plastic field samples from different regions (under different anthropogenic pressure) and environmental compartments will be collected and analyzed, the LABPLAS Project intends to improve the knowledge about the presence of leaked plastics, such as micro- and nanoparticles. Additives deriving from the field samples will also be analyzed using different spectroscopy techniques and the NORMAN database[3]. Considering that the Methodological adjustments will be made to minimize the impacts of the gaps linked to recycling incompatibilities or asymmetries in data availability and quality in the comparative LCA. During the LABPLAS Project, the ecotoxicity and biodegradability of different plastics will be assessed and models will be created to predict the fate and transport of plastics from the land through different environmental compartments to the ocean. The results obtained from the LABPLAS Project will be used to increase the knowledge about fate, transport, degradation processes and impacts on ecosystems of littered plastics, which is needed to improve currently used LCA methodologies. Thus, the aim is to develop FF, Xf, and EfF factors, or calculate them following the EF methodology applied to calculate other toxicity CFs. The data needed for the development of toxicity characterization factors are described in section 5. These developments would contribute to determining whether an independent category to consider littering impacts is needed.

5 THE LABPLAS PROJECT LCA METHODOLOGY

The LABPLAS Project LCA methodology will be defined based on the JRC Plastics LCA methodology due to its alignment with PEF, but making adaptations to take into consideration the concerns raised by the European Bioeconomy Alliance (EUBA) and the European Bioplastics Association (EUBP) as described in **Error! Reference source not found.**2.

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[3] https://www.norman-network.com/nds/susdat/

Issue	JRC Plastics LCA	EUBA and EUBP position	LABPLAS Project LCA methodology proposal
Carbon sequestration	All emissions and removals of the product over the lifetime and first 100 years should be considered, but biogenic carbon emissions will only be accounted for at the inventory level, given that the characterization factor of biogenic CO_2 from/to air will be 0. The lack of commonly accepted methodologies to handle this issue in the scientific community is acknowledged.	The JRC Plastics LCA undermines carbon sequestration into products. Setting the characterization factor of biogenic carbon to 0 seems a good approach for biofuels but not for products that can be recycled, composted or landfilled or stored in products for 50 years.	The JRC Plastics LCA approach will be followed given the lack of commonly accepted dynamic LCA approaches to consider the time dimension to account for carbon uptakes and emissions. In addition, products to be assessed in the LABPLAS Project are not expected to store biogenic carbon for relevant time periods (i.e., 50 years as suggested by the EUBA) and, the carbon dioxide stock in soil or biomass is considered in the crop production and the Environmental Footprint (EF) impact assessment method. However, when the carbon emission and uptake are relevant, they will be included in the life cycle inventory to support further studies and the interpretation of results.
Comparing mature and immature production systems	Particular care shall be taken when comparing products from different maturity levels of production technology. No optimised data from the theoretical process shall be used and if so, can be communicated only internally. Comparisons under PEF studies must be done with a minimum Technology Readiness Level (TRL) of 5 and in compliance with a Product Environmental Footprint Category Rule (PEFCR).	The JRC Plastics LCA does not allow the communication of environmental impacts of technologies with TRL below 5, which prevents the development of such technologies. The JRC Plastics LCA does not provide a real answer to compare mature and immature production systems.	The goal of the LCA in the LABPLAS Project is to compare both types of products, bio-based vs fossil-based. This comparison will take place even if there is no available PEFCR for the specific products assessed in the LABPLAS Project. The LCA will be performed with available secondary data given that there is no primary data available for the production stage. In consequence, the results will be obtained from the data available from secondary databases or literature at the current maturity of production, which will be communicated in the inventory step and will be remarked on again during the interpretation of the results.

Issue	JRC Plastics LCA	EUBA and EUBP position	LABPLAS Project LCA methodology proposal
Data reporting requirements	Fossil-based polymers data should reflect the average supply mix to refineries in the specific location of the production system to be assessed. All upstream stages (exploration, drilling, extraction, distribution, refining and transport) should be considered. It is cited how current LCAs normally exclude burdens from accidents, disasters or conflicts associated with fossil-based product systems. Regarding bio-based polymers, the activity data of the bill of materials (BoM) and process data shall be specific to the product in scope modelled with company-specific data. In addition, biogenic carbon removals and emissions shall be modelled separately, cultivation data shall be collected over a sufficient period of time to develop an average inventory, the fertiliser and manure emissions shall be differentiated per type and pesticide emissions shall be modelled as specific active ingredients.	Data quality requirements are higher for bio-based than for fossil-based systems given that the use of Plastics Europe eco-profiles (aggregated datasets) is acceptable while much more detail is requested for the inventory of bio-based products.	Given that no LCIA method includes the impact of disasters linked to production systems, these impacts of fossil-based systems should be based on statistics and included as additional information. The LABPLAS Project LCA will be performed with secondary data from the same geographical location, with the same scope, and updated within the last 3 years. No data quality assessment will be performed in this study. The use of disaggregated datasets will be prioritized because they enable higher transparency. In case no transparent datasets are available, data from Eco-profiles will be used instead.

Issue	JRC Plastics LCA	EUBA and EUBP position	LABPLAS Project LCA methodology proposal
Incorporation of Land-Use Change (LUC)	For bio-based plastic products, land clearing and related land transformation (land use change) burdens shall be included under the "Raw Material Acquisition and Pre-processing" stage. For fossil-based products, land transformation and occupation burdens shall be accounted for land-based oil sources (e.g., oil sands). While land-based sources also normally generate impacts on the landscape (e.g., visual/aesthetic impacts from mining), these are typically not captured in the LCA (nor in the default impact categories considered in this method), and no specific flows are generally inventoried in this respect.	According to the JRC Plastics LCA, LUC must be included for bio-based plastics while fossil-based systems requirements are less strict. Furthermore, soil carbon uptake needs to be considered in calculations and not just added as additional information.	The JRC Plastics LCA guidelines will be followed. LUC will be considered in the selected datasets, highlighting potential identified gaps from both systems. On the other hand, the JRC Plastics LCA method, which uses the EF 3.0 impact assessment method, accounts for the carbon dioxide uptake from soil or biomass with a characterization factor of -1 using the elementary flow "Carbon dioxide, to soil or biomass stock".
Inconsistent inclusion of indirect effects	iLUC is only considered as additional information. Some indirect effects of fossil-based systems such as agricultural land expansion, military operations associated with fossil-based product systems and changes in petroleum usage and price are cited.	Negative indirect effects of bio-based plastics, such as iLUC, are considered relevant and recommended to be included, while the inclusion of negative indirect effects of fossil-based plastics is explicitly ruled out. i.e., process inequality - process favours fossil-based products. A clear biased approach. To get to a level playing field these different approaches are obstacles that need to be removed.	Given the lack of robust data and methods to account for indirect effects, the LABPLAS Project LCA will be performed with an attributional approach without considering indirect effects (or consequential approach), although this decision will be highlighted in the interpretation of results as a need for future studies. However, as Schrijvers et al., 2021 state, the Circular Footprint Formula (CFF) used in the JRC Plastics LCA method has a consequential character by including the benefits of recycling by avoiding the production of virgin materials. Nevertheless, it is not a full consequential approach because it does not include all indirect effects. Any relevant and proven indirect effect will be communicated as additional information.

Issue	JRC Plastics LCA	EUBA and EUBP position	LABPLAS Project LCA methodology proposal
Requirements for providing proof	For bio-based products, soil carbon uptake must be included only if scientific proof is provided.	No proof is required for negative indirect effects of bio-based products while proof is required for positive effects. Proof of negative indirect effects should be provided as well.	Positive and negative impacts will only be accounted for in LABPLAS if they are supported by scientific studies (e.g., soil carbon storage) or if they are already accounted for in reviewed datasets.
Biodiversity impacts	Biodiversity impacts are only provided as additional information due to a lack of accepted methodology. Sustainable management certifications can be used to justify the protection of biodiversity.	Impacts on biodiversity are much more associated with bio-based systems while fossil-based systems' biodiversity impacts have less attention and are not properly considered.	Biodiversity impact assessment methods are not currently addressed by the EF method 3.0. Additional information may be supplied by the LABPLAS Project if relevant. The LABPLAS Project LCA will use primary experimental data from plastic biodegradation experiments. Since higher degradability of plastic potentially leads to lower impacts in biodiversity caused by physical effects, but the potential release of additives could have harmful effects, the results of degradation tests will be incorporated as additional information to discuss potential impacts on ecosystems in different impact categories. An additional "litter effects" impact category accounting for the area and the time of the product littered may be used to represent the effects of biodegradability using ExcelPas methodology (Parker & Edwards, 2012). In this case, a landfill dataset from Ecoinvent will be used as a proxy to account for the impacts of littering, adjusting the carbon emissions and additive emissions (if available from the LABPLAS Project tests).

Issue	JRC Plastics LCA	EUBA and EUBP position	LABPLAS Project LCA methodology proposal
Reflecting end-of-life realities	End-of-life (EoL) realities are described using the CFF parameters listed in the annex of the guide, but own data or more updated data from official data sources can be used.	LCA should be performed at the waste stream level rather than on the product level to evaluate the potential benefits of recycling, including organic recycling.	Realistic scenarios will be modelled using the CFF formula and their recommended R1, R2 and R3 factors for European countries and EoL scenarios. Notably, they may be modified if updated data or littering data for the products assessed are openly available in the literature. Given that mature recycling systems and value chains are not well developed for bio-based plastics, a sensitivity analysis may be performed to evaluate the potential impacts of bio-based plastics in the recycling process. The goal is to assess a scenario where bio-based plastics reach the same maturity and efficiency as fossil-based polymers in terms of recycling systems. Another sensitivity analysis can be performed for uncertain parameters reflecting the EoL stage (littering rate, recycling, landfilling or incineration rate, etc.)
Normalization and weighing	Normalization factors are based on global average person impacts and weighing factors are calculated using a panel-based approach. Normalization and weighing are mandatory steps for conducting PEF studies.	It is unclear whether the proposed weighing factors are representing reality given that they should also be applied to non-EU production systems.	Normalization and weighing will be implemented using the factors included in the EF method to identify hotspots, but the comparisons among fossil-based and bio-plastics will be performed at the characterization level. They will be applied to non-EU production systems as well given the normalization factors are calculated using the global average impacts per person, and not European average impacts per person as was recommended in previous versions of the EF method.
Feedstock supply data requirements	Additional information can be included to show good practices regarding feedstock production, such as sustainable forest management or chain of custody certificates.	Sustainable feedstock sourcing must be included or attached to the LCA at least for those systems where the feedstock origin plays a major role in the environmental performance.	Certified sustainable feedstock production will only be communicated as additional information unless secondary datasets representing feedstock production from sustainably managed production systems are available for the feedstocks needed.

Table 2. LABPLAS Project LCA Methodology definition based on the JRC Plastics LCA and EUBA and EUBP concerns.

5.1   GOAL AND SCOPE

The LABPLAS Project LCA to be developed will be an attributional LCA where no indirect impacts will be accounted for, except the potential benefits obtained by recycling included in the Circular Footprint Formula (CFF). The description and the justification of the use of the CFF are provided in section 5.2.5.1.

5.1.1   Goal definition

The main goals of the LCA performed during the LABPLAS Project are:

- Compare the life cycle impacts of bio-based and fossil-based bio-degradable and non-biodegradable plastics using the cradle-to-gate approach aligned to the PEF method.
- Use results from the LABPLAS Project to overcome current LCA methodological gaps and test their validity.
- Highlight new data and methodological gaps in the current LCAs of plastics.
- Perform a sensitivity analysis on key and uncertain parameters to find breakeven points where two different types of products meet. Subsequently, change trends to show higher or lower impacts of the respective product type.
- Guidance on deciding between fossil-based and bio-based, degradable and non-degradable plastics.
- Perform a hotspot analysis: identify the most relevant impact categories, life cycle stages, processes and elementary flows.
- Evaluate the data availability for plastics to perform cradle-to-gate LCAs.

5.1.2   Target audience

Different conclusions will be made for different stakeholders. LCA practitioners will be addressed with conclusions regarding the methodology applied, whereas industry, policy-makers, and the general public will be addressed in the conclusions regarding the result of the comparison of two product systems.

5.1.3   Geographic context

The geographic situation of the production, use and disposal of plastic products is critical in the LCA as the energy production impacts vary significantly from one country to another. In addition to the different sources of energy used in the average mix of the country, the EoL and technologies mixes are different from one country to another and even inside different regions of the same country. Consequently, the potential impacts of intended EoL scenarios for plastic products will vary from one location to another given that products may be processed differently depending on the place where it is disposed of.

The LCA will be performed on the products used and managed in Europe by using European electricity and EoL mixes. The sensitivity analysis may be performed by varying the electricity mixes and the share of different EoL scenarios based on country-specific data to understand the contribution of the geographical location of the production, use and disposal of plastic products in the life cycle environmental impacts.

5.1.4   Reference documents and literature

The LABPLAS Project LCA methodology is defined to allow comparability of results and ensure that a scientific approach is followed to provide a transparent report developed to fulfil the objectives of the LCA. Thus, the methodological choices are based on previous documents, guidelines, standards, and studies covering the LCAs of bio-based and fossil-based plastics (both degradable and non-degradable):

- ISO 14040 (ISO, 2006)
- Commission Recommendation on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations (Commission, 2021) and Annex I (Commission, 2021).
- Plastics LCA method: Life Cycle Assessment (LCA) of alternative feedstock for plastic production (Nessi et al., 2021).
- Environmental impact assessment of innovative bio-based products (COWI A/S & Utrecht University, 2019).
- MarILCA project (Boulay et al., 2021)
- Plastic Leak Project (Quantis, 2020)
- EUBA position on the JRC LCA Methodology, November 2021
- EN 16760 Bio-based products - Life Cycle Assessment (BSI Group & MI/2 Bio-based Products, 2015)

As previously commented, the JRC Plastics LCA method will be the core of the LABPLAS Project LCA methodology, given that it was defined after the development and testing of previous methodologies. The response from EUBA and the potential contribution from the LABPLAS Project results to overcome current LCA methodological gaps have also been taken into account when defining the methodology and should be considered while conducting the LCA.

5.1.5 Scope

The scope of the LCA to be developed in the LABPLAS Project is divided into the following sections:

5.1.5.1 Product system

The product systems are selected to fulfil the objectives of the study (see section 5.1.1) according to data availability, product relevance and products that will be assessed in the LABPLAS Project toxicity tests. Single-use products banned in recent European regulations should be avoided unless the LCA has a particular scientific interest. A draft selection of products, potentially studied in the LABPLAS Project, is displayed in **Error! Reference source not found.**.

Product	Material	Source (bio/fossil)	Biodegradability	Function/Quality	Performance indicators	Reference flow - mass - (g)
Garbage bag	PBAT and PHA	Hybrid	Biodegradable	Garbage bag	Volume: 50L	30,596
	PE	Fossil	Non-biodegradable	Garbage bag	Volume: 50L	27,200
	Mater-bi (PET and polyester)	Hybrid	Biodegradable	Garbage bag	Volume: 10L	11,218
	PE	Fossil	Non-biodegradable	Garbage bag	Volume: 10L	8,540
Packaging net	PLA	Bio-based	Degradable	Clams and other food products packaging	0.003 g/cm^2	To be determined (TBD)
	Nylon Polyamide (PA)	Fossil	Non-biodegradable	Clams and other food products packaging	0.003 g/cm^2	(TBD)

Table 3. Potential products to be assessed in the LABPLAS Project LCA. The term 'hybrid' refers to a blend of materials made from bio-based and fossil-based components.

The products to be compared must have the same function but different origins (fossil or bio) and/or different biodegradability properties (biodegradable or non-biodegradable according to ISO 14855, ISO 15985, ISO 17556 or other standards used in the LABPLAS Project to define biodegradability properties). Two product systems to be compared might be one product made from fossil-based plastics showing biodegradability properties in soil and compostability against a bio-sourced plastic showing similar degradation and compostability properties. Another example could be a fossil-based and non-biodegradable plastic vs a bio-based and bio-degradable.

5.1.5.2 Functional Unit (FU)

The FU must be defined according to the JRC Plastics LCA method and must include the function, the extent of the function of service, the expected level of quality, the duration of the function or service, and the location where the product is used and the beneficiary or user of the product. Once the FU is defined, the reference flow representing that FU should also be defined in physical units (kg, L, etc.), as shown in **Error! Reference source not found.**4.

Aspect	Example
"What" (function(s) or service(s) provided)	Carrying shopping from supermarket to home
"How much" (extent of the function or service provided)	An average volume of 22 litres and an average weight of 12 kg of purchased goods
"How well" (expected level of quality of the function or service)	Without tearing, puncturing, and excessively deforming during the shopping trips
"How long" (duration of the function or service/product lifetime)	A minimum of ten times/trips
"Where" (location/geography of the function or service)	In the entire EU-28 market
"For whom" (beneficiary of the function or service)	By the entirety of consumers

Table 4.. Example of functional unit (FU) for shopping bags from the JRC Plastics LCA method report (Nessi et al., 2021).

5.1.5.3   System boundaries

The LABPLAS Project LCA will be performed considering all life cycle stages with a cradle-to-grave approach, given that one of the objectives is evaluating the performance of different alternatives in intended/unintended EoL scenarios, the feedstock or raw materials used, biodegradation properties, etc. For all the products assessed, the life cycle stages included will be described. Littering is intended to be included as a life cycle stage of these products, although no impact assessment method can be used to assess it. Results on littering environmental impacts of the products assessed will be included as additional information. The life cycle of plastics differs in the first stage of the obtention of raw materials depending on if the product is bio-based or fossil-based. In Figure 2, a conventional plastic product life cycle is represented. In red colour, the flows between the technosphere and nature are presented, which can be either inputs (natural resources) or outputs (waste to incineration or landfill or littered plastics). Blue arrows represent flows within the technosphere among different life cycle stages and green arrows represent circular economy related flows after the end-of-life stage, where the product can be reused or recycled and reincorporated into the economic cycle. The possibility to recover the energy during the incineration, and reintroducing the energy into the loop is not represented.
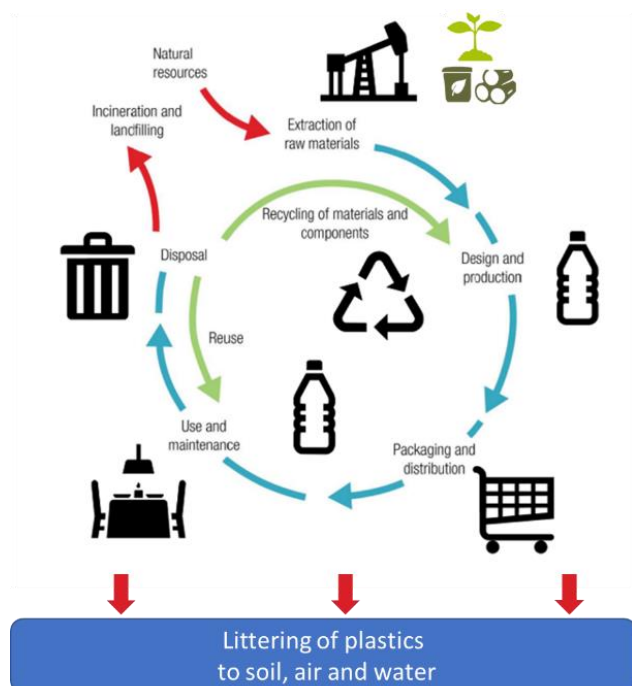

Figure 2. Life cycle of plastics. Original image Source: Life Cycle Initiative (https://www.lifecycleinitiative.org/life-cycle-approach-to-plastic-pollution/). Edited to include bio-based materials raw material obtention and littering life cycle stages

Fossil-based plastics are produced using co-products from the petroleum industry as **raw material** whereas bio-based plastics use plant-based resources or biowaste as raw material. Some products use a hybrid formulation, composed of a mixture of bio-based and fossil-based materials. The **design and production** phase is the stage that provides the function and quality to the product and where the specifications of the raw materials and polymers are defined. The **design and production phase** for bio-based and fossil-based plastics is different in terms of raw materials used and unit processes. However, the downstream steps are similar: i) monomers production and ii) polymer production, including polymerization, blending and addition of additives. Considering the specifications of the designers, the final polymers are selected and used for the synthesis of the final product. Products with the same application follow similar downstream life cycle stages: **distribution, use and maintenance**, **reuse,** and **disposal (**EoL); the

latter **include incineration, landfilling, and recycling**. The **disposal** or EoL stage considers the intended EoL scenarios, where the product is managed by an approved waste manager according to a validated waste management scheme. Normally, due to the physical-chemical properties of plastic products, their low production costs, low market prices, as well as short lifespan; a fraction of the plastic is littered in the environment. Littering mainly happens after the use phase, but the production stage is also a relevant source of littered plastics (Quantis, 2020). **Littering** leads to emissions of plastics in the form of macro, micro and nano plastics into the soil, air and/or water. Emitted particles, including additives, are distributed among environmental compartments, and some of them may eventually reach the ocean. When products are littered, degradability properties play a very relevant role in minimising impacts caused by physical effects on

biodiversity (i.e. ingestion, entanglement). However, the toxicity effects of biodegradable plastics are not well understood and there is a lack of reliable, complete, and product-specific data (Zimmermann et al., 2020) regarding additives and toxicity effects.

According to the objectives of the LCA, all the life cycle stages and the different possibilities for a product should be reflected in the LABPLAS Project LCA to provide a holistic view of whether bio-based plastics show better environmental performance than fossil-based conventional plastics and to understand into what extent the LABPLAS Project can contribute to filling current methodological gaps in Plastics LCAs.

5.1.5.4   Impact assessment method and selected impact categories

The impact assessment method will be the toolbox recommended by the PEF method EF method 3.0. In the case of using SimaPro, the EF method 3.0 adapted to the software shall be used. In July 2022, an updated package (version 3.1) was released and should be used instead of version 3.0 if the method is available for the software to be used (SimaPro or Brightway2).

This method considers only mid-point impact categories (see **Error! Reference source not found.**) although end-point impact categories could be interesting for several applications (communication, policy development, etc.). However, end-point impact categories (such as human health, resource availability or biodiversity loss) require the application of more uncertain factors than mid-point impact categories. Consequently, scientific robustness gets lost during the calculation. In the LABPLAS Project LCA, ecosystem health or biodiversity loss are very relevant. It should be considered that at least eight categories contribute to the loss of biodiversity: climate change, eutrophication (freshwater, marine and terrestrial), acidification, water use, land use and ecotoxicity (freshwater). Additionally, ozone depletion or stratospheric photochemical ozone formation may affect significantly animal and plants life. However, end-point effects should only be included as additional information.

The progress of the MarILCA will be closely monitored to see if the impact assessment method under development is released and suitable to be applied in the LABPLAS Project LCA to evaluate the impacts on the marine environment of plastics littered. Also, the potential contribution of LABPLAS to the completeness of the LCIA method will be studied.

The impact categories in the EF 3.0 method are presented in

Impact category	Indicator	Unit	Method and description
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO2 eq	Baseline model of 100 years of the IPCC 2013
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC11 eq	Steady-state ODPs (WMO 2014)
Ionising radiation, human health	Human exposure efficiency relative to U235	kBq U-235 eq	Human health effect model based on Dreicer et al. 1995 (Frischknecht et al, 2000)
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS-EUROS model (Van Zelm et al, 2008) - ReCiPe 2008
Particulate matter	Impact on human health	disease inc.	PM method recommended by UNEP (UNEP 2016)
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	CTUh	USEtox® model 2.1 (Fankte et al, 2017)
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh)	CTUh	USEtox® model 2.1 (Fankte et al, 2017)
Acidification	Accumulated Exceedance (AE)	mol H+ eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model (Struijs et al, 2009) - ReCiPe
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model (Struijs et al, 2009) - ReCiPe
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	USEtox® model 2.1 (Fankte et al, 2017)

Table 5. EF 3.0 method impact categories and impact assessment methods. Individual references can be found in the EF 3.0 package.

The result of these impact categories should be included in the LIFE CYCLE IMPACT ASSESSMENT (LCIA) section. However, end-point or littering impacts should be added as additional information.

5.1.5.5   Treatment of multi-functionality

The PEF Guide establishes the following priorities to deal with multi-functionality:

1. System expansion or sub-division: wherever possible, this option should be used to avoid allocation. Subdivision refers to identifying the impacts associated with each final outcome of a multifunctional process. Where a subdivision is possible, inventory data should be collected independently for each outcome. System expansion refers to including all the impacts associated with a multifunctional process including additional functions.
2. Physical allocation (including direct substitution): refers to fractioning the impacts per a quantifiable and relevant physical relationship (e.g., mass, density, volume). Direct substitution implies the use of a relevant proxy where a direct and empirically demonstrable substitution effect and the substitute product inventory can be subtracted in a representative manner.
3. Allocation based on some other relationships (including indirect substitution): for example, economic allocation or market price refers to partitioning the inputs and outputs according to the economic value of the products and co-products.

The allocation of impacts at the end of life will be performed using the CFF and additional factors to consider the littering rate of products.

5.1.5.6   Additional information

Additional information not covered by the EF 3.0 impact assessment method may be included as additional information, such as end-point impact categories like biodiversity loss or damage to human health. Also, littering environmental impacts or results of modelling of fate and transport of plastics, toxicity, degradation or characterization experiments performed by the LABPLAS Project or indirect effects could be included as additional information.

In addition, information about the products under assessment, such as sustainable management certifications, could be communicated as additional information.

5.1.5.7   Assumptions and limitations

All the assumptions and limitations found during the development of the LCA must be described in detail in this section of the LCA report, including data gaps and proxies used. All must be justified and aligned with the objectives of the study.

The circularity and criticality of materials will not be assessed in this LCA, even though they could be key parameters in the life cycle environmental performance of these kinds of products. Any information regarding the circularity or criticality performance of the different product systems should be added as additional information.

If toxicity impacts of littered plastics were calculated with high uncertainty using a worst-case scenario approach as in Salieri et al., 2021, the results should be communicated as additional information.

5.2 LIFE CYCLE INVENTORY (LCI)

In the LCI section, all inputs and outputs of the product systems must be presented and described. The calculations to obtain some of the data and the data sources should be detailed, as well as allocation procedures. All the specifications from the Plastics LCA method should be met when possible, considering also the methodological differences presented in **Error! Reference source not found.**. In the following sections, the LABPLAS Project LCA methodological specifications are described.

5.2.1 Data quality requirements

No specific data quality requirements methods will be used to calculate the data quality ratings. Primary data will be used, when possible, from the results of experiments of the LABPLAS Project, especially regarding the EoL stage if product toxicity and degradation data are available and applicable. Also, characterization results should be used to consider the impacts of raw materials extraction and specific emissions not accounted for in secondary datasets, like additives for example. According to the JRC Plastics LCA method, the amount of additives in bio-based materials can range from 10 to 30% of the total mass of the final plastic product.

5.2.2 Sources of data

The main sources of data for the LABPLAS Project LCA will be:

- Primary data from the LABPLAS Project results
- LCA databases: Ecoinvent (Wernet et al., 2016), Industry Data (including Plastics Europe Eco-profiles).
- Plastics LCA method default scenarios, including CFF parameters from EF method package (most updated version).
- Plastic Leak Project data (Quantis, 2020)
- Updated scientific literature

Primary data will be used only from the toxicity, degradation and characterization tests of products performed in the LABPLAS Project. All the other data will be sourced from secondary databases such as Ecoinvent. Given that the aim is not to conduct a PEF compliant LCA, the EF compliant datasets from the European Commission node will not be used.

Updated data to define some parameters such as EoL ratios or parameters describing the performance at the use stage will be obtained from official sources, reports or literature. If no available data, default scenarios and CFF parameters from the EF package will be used.

Rates of transport and distribution of littered plastics, including microplastics, can be obtained from the Plastic Leak Project when suitable for the products assessed and available. However, different approaches will be followed for intended and non-intended EoL scenarios.

5.2.2.1 Intended EoL scenarios

There are available datasets for different fossil-based plastics and EoL scenarios (incineration, recycling and landfilling). Some datasets can be used for bio-based plastics, especially to model the incineration and landfilling, whereas there is a lack of data to evaluate the impacts on the recycling of bio-based plastics. The modelling of the EoL scenarios should be described in detail, including the source of data, the modifications made to existing datasets and the science-based justification for those changes.

5.2.2.2 Littering

Data needed to evaluate the impacts of littering are related to i) share of product mass littered, ii) life cycle stage where the littering is produced, iii) the initial environmental compartment where it is produced and iv) emissions produced during littering. The share of product mass littered should be estimated using updated official reports or literature on product littering rates or the Plastic Leak Project. The littering rates for certain products will also be calculated based on the LABPLAS Project field sampling and modelling efforts. The life cycle stage and environmental compartment where the initial emissions are produced, even for macro, micro or nano plastics, can be obtained from field samples and modelling results from LABPLAS as well as from the Plastic Leak Project if applicable. Finally, the emissions produced, such as climate change related emissions or toxicity emissions, should be inventoried from degradation and ecotoxicity tests performed in the LABPLAS Project or literature if data needed to assess the product system under assessment is not available.

5.2.3 Biogenic carbon accounting

EUBA highlighted (see section 3.2) that the time of carbon emission and uptake is relevant to the environmental performance of products. However, as PEF or Plastic LCA do not consider any method to include the time dimension of carbon emissions, it will not be included in the LABPLAS Project LCA either but it will be included in the inventory phase.

5.2.4 Exclusions

In the LABPLAS Project LCA, some exclusions can be performed if the excluded aspect of the LCA is common for both product systems to be compared and if it is not a critical aspect of the LCA according to the objectives of the study, i.e., the distribution life cycle stage. Similar distribution stages could be assumed for both product systems if no data are available. Therefore, the distribution could be excluded from the assessment. If the product systems to be assessed present different storage requirements and there are data available, they must be included in the assessment.

5.2.5 Default scenarios

When no data are available for a specific life cycle stage, but it is needed to model that stage due to its high relevance or to the availability of relevant and differentiating data, default scenarios found in the JRC Plastics LCA could be used for the product use phase, distribution and EoL stages. For the EoL, the CFF and the default parameters could be used if no more specific data are available.

5.2.5.1 Circular Footprint Formula (CFF)

The CFF is applied to allocate the EoL impacts to the producer and manager of waste. It considers the recycled content in the product assessed (R1), the recycled proportion of the material (R2) and the proportion of material that goes to energy recovery via incineration (R3). The allocation factor between supplier and user of recycled material is A, which is recommended to be set as 0.2, 0.5 or 0.8. The B factor allocates the burdens and credits of energy recovery processes to the material assessed.

The equation is divided into three parts: the material equation, energy recovery and disposal. In the material equation, the impacts of the production of virgin material (E_v), recycled material ($E_{recycled}$) and recycling process ($E_{recyclingEoL}$) are considered, as well as the impacts avoided by recycling (E_{v*}), which correspond to the impacts of the production of the material that the recycled material assessed substitutes. It also considers a quality loss ratio during the recycling processes (Q_{sin}/Q_p and Q_{sout}/Q_p). On the other hand, the energy recovery equation is

Internal

used to calculate the emissions and benefits provided by producing energy from incineration with the energy recovery process. Finally, the disposal part of the CFF considers the impacts of landfilling (E_D) (see Figure 3).

Material recovery:

$$(1 - R_1)E_V + R_1 \times \left(AE_{recycled} + (1 - A)E_V \times \frac{Q_{Sin}}{Q_p} \right) + (1 - A)R_2 \times \left(E_{recyclingEoL} - E_V^* \times \frac{Q_{Sout}}{Q_P} \right)$$

Energy recovery:

$$(1 - B)R_3 \times (E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec})$$

Disposal:

$$(1 - R_2 - R_3) \times E_D \qquad\qquad\qquad \text{[Equation 2]}$$

Figure 3. Circular Footprint Formula. Figure extracted from Plastics LCA.

This formula and the default parameters for products provided by the EF method should be used and selected according to the guidelines described in the JRC Plastics LCA method. R_1, R_2 and R_3 should be updated if higher quality data are available. In addition, all those parameters should be multiplied by a new fraction that represents the share of material non-littered, which should be obtained from literature or official data sources on waste management.

5.3 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

In this section, characterization results should be provided in tables and figures together with some information to interpret the displayed results for the selected impact categories (**Error! Reference source not found.**). Then, EF normalization and weighting factors can be applied for hotspot analysis in the interpretation phase.

Regarding the impacts of littered plastics, mid-point indicators would be prioritized over end-point indicators. However, end-point effects such as impacts on biodiversity loss or human health can be communicated as additional information if complete models were available.

If all data required to develop CFs are available, they can be developed and integrated into the ecotoxicity impact categories. The required data to include CFs in ecotoxicity impact categories is described below.

Characterization of littered plastic emissions

CFs for the impact on the marine environment of littered plastics (macro, micro and nano scale) could be obtained from MarILCA, if available, although they may provide impacts on new impact categories not included in the EF method like, e.g., physical effects on biota or human toxicity. In the LABPLAS Project LCA, only ecotoxicity will be assessed due to the developments that the project will do in this aspect.

To evaluate the ecotoxicity impacts of littered plastics in the LCA there is a need for specific CFs.

The USEtox® model, together with the LABPLAS Project results from the toxicity assessment, degradation and modelling related activities can be used to develop CFs similarly to what was used for the elaboration of toxicity CFs for the EF method (Sala et al., 2022). The LABPLAS Project results from samples analysis, biodegradation and toxicity tests, as well as modelling and literature data will mainly contribute to calculating FF and EfF in different environmental compartments, while Xf could be obtained from other scientific sources. All the potential contribution from the LABPLAS Project is described in **Error! Reference source not found.**. If the lack of physical-chemical parameters (see section 3.3) was still an issue, the worst-case scenario assumptions applied

in Salieri et al., 2021 could be used. In that case, results should be communicated separately as additional information. In any case, the approach applied should be transparently described in the report with all the calculations, assumptions, data, and data sources used.

5.4 INTERPRETATION

In the Interpretation stage of the LCA report, the results of the study and their alignment with the goal and scope, life cycle inventory and impact assessment stages should be discussed. Also, the discussion must incorporate any conclusions extracted from the additional information provided. In addition, a hotspot analysis to identify the most relevant sources of impacts and a final discussion on the conclusions and recommendations should be provided and included in this section.

5.4.1 Hotspot analysis

The hotspot analysis must be performed following the guidelines from the JRC Plastics LCA method to identify the most relevant impact categories, life cycle stages, processes and elementary flows. This process requires the application of normalization and weighing factors to the characterization results. EF 3.0 method includes normalization and weighing factors for all the impact categories. However, more updated normalization and weighing factors were published in July 2022, which should be applied. The current normalization and weighing factors are presented in **Error! Reference source not found.**.6.

Impact categories	Normalization factor (NF)	Unit NF	Weighing factor (WF) [%]
Acidification	5,56E+01	mol H+ eq./person	6,20%
Climate change	7,55E+03	kg CO_2 eq./person	21,06%
Ecotoxicity, freshwater	5,67E+04	CTUe/person	1,92%
EF-particulate matter	5,95E-04	disease incidences/person	8,96%
Eutrophication, freshwater	1,61E+00	kg P eq./person	2,80%
Eutrophication, marine	1,95E+01	kg N eq./person	2,96%
Eutrophication, terrestrial	1,77E+02	mol N eq./person	3,71%
Human toxicity, cancer	1,73E-05	CTUh/person	2,13%
Human toxicity, non-cancer	1,29E-04	CTUh/person	1,84%
Ionising radiation	4,22E+03	kBq U-235 eq./person	5,01%
Land use	8,19E+05	pt/person	7,94%
Ozone depletion	5,23E-02	kg CFC-11 eq./person	6,31%
Photochemical ozone formation	4,09E+01	kg NMVOC eq./person	4,78%
Resource depletion, fossils	6,50E+04	MJ/person	8,32%
Resource depletion, minerals and metals	6,36E-02	kg Sb eq./person	7,55%
Water use	1,15E+04	m^3 water eq of deprived water/person	8,51%

Table 6. Normalization and weighing factors from EF 3.1 package.

More information about the development of normalization and weighing factors can be found on the developer page of the Environmental Footprint method[4].

Once these factors are applied, a threshold of the categories with 80% of the total impact is applied. Those impact categories, life cycle stages, processes, and elementary flows are considered the **"most relevant"**.

The 80% should be applied to the total environmental impact to identify the most relevant impact categories. For those defined as the most relevant, the 80% threshold is applied again to identify the most relevant life cycle stages and the most relevant processes.

If negative numbers are present in the results as a consequence of the benefits obtained by recycling or energy recovery, the procedure explained in the JRC Plastic LCA method on page 154 should be followed.

5.4.2   Sensitivity analysis

To assess how sensitive the resulting impacts to a determined parameter are, a sensitivity analysis can be performed with varying values of certain parameters and a comparison of the result with the baseline scenario.

Usually, these types of analyses are performed on uncertain parameters, which have been set for low-quality data sources or if the factors' uncertainty is very high. Considering current challenges and data gaps (see section 3), parameters that determine the EoL impacts of the product may be targeted for sensitivity analysis if the maturity level of the industrial processes is significantly lower than its counterpart but expected to improve in upcoming years (e.g. littering rate, R_1, R_2 or R_3 from CFF (5.2.5.1), the impacts from the production of virgin material (Ev), or the recycling impacts process of bio-based materials).

5.4.3   Conclusions and recommendations

A final section with all conclusions and recommendations on the comparison of life cycle environmental impacts of these product systems should be incorporated. It should be divided into two paragraphs or sections. The first should be addressed to LCA practitioners and the scientific community working on the environmental impacts of plastics and the second should be addressed to consumers and policymakers.

5.5   Verification and validation of the LCA

Verification and validation will not be mandatory steps to communicate the results of the LCA in the framework of the LABPLAS Project but are advised to be performed in the future. The lack of verification and validation by an external verifier should be highlighted in the interpretation stage.

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[4] https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml

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