Upstream

FOR WASTE-FREE EUROPEAN RIVERS

Circular and Bio-Based Solutions for the Ultimate Prevention of Plastics in Rivers Integrated with Elimination and Monitoring Technologies

# Deliverable D4.3
# Preliminary LCA/s-LCA Assessment

## Deliverable information

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# Executive Summary

UPSTREAM project aims to improve the cleanliness and water quality of the rivers by deploying and demonstrating in 5 demo sites a suite of 15 advanced solutions to deal with pollution in terms of litter, plastic and microplastic in European rivers. This challenge is afforded by a consortium (22 partners from 11 countries), from top European Research and Technology Organisations (RTOs), specialized Small and Medium-sized Enterprises (SME) technology providers, a large company and completed by promoting a strong engagement of citizens and stakeholders.

The objective of D4.3 Preliminary LCA and S-LCA assessment is to provide an overview of the existing methodologies and potential software tools for life cycle analysis and social life cycle analysis at the demo sites. This community through software-based simulations can increase the utilization of the filtered microplastics and recycle it into the Technosphere material flow system in economically, socially and environmentally responsible ways. This way we can efficiently prevent any further petroleum-based plastics pollution in water streams and thus reduce persistent plastic pollution. Specifically, concepts and software characteristics, main applications, and challenges to be overcome have been collected throughout this document.

This document aims to serve as a preliminary overlook of the currents concepts, frameworks and software tools and available methodologies and data which can be utilized to achieve the goals of cleaning persistent Litter (L), Plastic (P) and Microplastic (MP) materials in the demo sites and their life cycle impact with LCA and S-LCA analysis.

**Deliverable keywords:** *life cycle analysis, social life cycle analysis, software tools, material flows, life cycle inventory*

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# Table of Abbreviations

| Abbreviation | Definition |
|---|---|
| **BOD** | Biochemical Oxygen Demand |
| **CF** | Characterization factors |
| **COD** | Chemical Oxygen Demand |
| **FF** | Fate Factors |
| **ISO** | International Standards Organization |
| **L** | Litter |
| **LCA** | Life Cycle Assessment |
| **LCI** | Life Cycle Inventory |
| **MNP** | Micro Nano Plastic |
| **MMP** | Marine Microplastic Potential |
| **MP** | Microplastic |
| **P** | Plastic |
| **PEF** | Product Environmental Footprint |
| **SLCA** | Social Life Cycle Assessment |
| **WP** | Work Package |
| **WPL** | Work Package Leader |
| **WWTP** | Waste Water Treatment Plant |

# 1. Introduction

## 1.1. Life cycle analysis for microplastic evaluation

Life Cycle Analysis (LCA), also known as Life Cycle Assessment, is a systematic method used to evaluate the environmental impacts associated with all stages of a product's life, from raw material extraction through production, use, and disposal. The goal of LCA is to identify opportunities to improve the environmental performance of products at various points in their life cycle. These days, LCA has been standardized in International Standards Organization (ISO) standards ISO 14040 and ISO 14044. The LCA consists of 4 distinct phases, which can be seen below in Figure 1, and finds its applications in a variety of settings (e.g., new product development or policy).

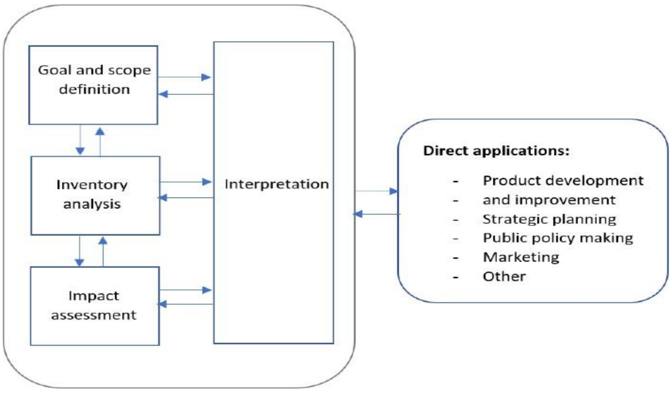


*Figure 1: 4 phases of LCA study*

The LCA study on microplastics, just like any other LCA study will be conducted through the 4 distinct phases:

**Goal and Scope Definition**

The objective is to clearly define the purpose of the LCA, the intended application, and the audience. This step also involves setting the boundaries of the study and determining the functional unit, which is a measure of the function of the studied system. As we shall see, there is not yet a standard functional unit for the evaluation of microplastics. The overall scope is to establish the depth and breadth of the study, including the system boundaries (e.g., cradle-to-grave, cradle-to-gate) and the assumptions and limitations. This is important as some of the demo-sites are part of a wastewater treatment plant (WWTP), some operate on open rivers and some deal with biodegradable plastics. So, it is not so easy to define common goals for all demo sites due to the diversity of the microplastic cleaning solutions.

**Inventory Analysis (LCI)**

For gathering the Life Cycle Inventory (LCi) is the data collection stage where we gather data on all inputs and outputs of the product system. This includes raw materials, energy consumption, emissions, and waste. After gathering the data, we proceed with modelling where we create a model of the product system that quantifies the inputs and outputs for each process within the system boundaries. Here we shall see due to the unavailability of exact data some challenges arise as this inventory data have a profound effect on the results in the LCA.



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**Impact Assessment (LCIA)**

In the impact assessment we start with classification where we assign the inventory data to specific environmental impact categories, such as global warming potential, ozone depletion, acidification, and eutrophication. In this step we need to do also the characterization and normalization and weighting. In the characterization step we quantify the potential impacts by converting inventory data into common units for each impact category using characterization factors. In the normalization and weighting steps which are optional steps we can compare the impacts to a reference value and assign weights to different impact categories based on their relative importance. Here also due to the diversity of the demo sites setup and an overall lack of standardized impacts connected directly with microplastics we have explored the availability of impact categories which relate to toxicity elements of other plastic litter or microplastic contamination.

**Interpretation**

After comparison and impact assessment of the calculated data we evaluate the results from the inventory analysis and impact assessments to identify significant issues and opportunities for improvement. Based on the analysis we can finally draw conclusions and recommendations for reducing environmental impacts. This step also involves assessing the robustness and reliability of the results through sensitivity and uncertainty analysis.

## 1.2. Applications and limitations of LCA and S-LCA methodology and tools

At the beginning of this document, we want to stress the importance of conducting LCA and S-LCA studies as a support tool for decision-making processes, including:

- Product Development and Improvement: Identifying opportunities to reduce environmental impacts during the design and development of new products. Here we refer to the decision on the new polymer's blends, the use of biodegradable or compostable plastic solutions and the wastewater treatment technologies regarding their overall environmental impact. While their cleaning operations can be efficient in filtering out unwanted microplastic particles, their energy consumption can cause additional unwanted environmental impacts.
- Policy Making: Informing regulations and policies aimed at reducing environmental impacts. This overview will try to help policymaking to focus more on investments in the development of tools and methodologies to clearly define the scopes and environmental impacts for both LCA and S-LCA studies.
- Marketing and Communication: Providing transparent and credible information about the environmental performance of products to consumers and stakeholders. Here the local communities with the water treatment plants can be clearly informed how efficient the potential microplastic cleaning site from water streams is, and which social impacts can be expected from stakeholders and communities near such sites, or by using bio-based and biodegradable solutions.

These applications face several challenges and limitations which mainly derive from three main sources:

- Data Quality: The accuracy of LCA results depends on the quality and availability of data.
- Complexity: LCA can be complex and time-consuming, requiring expertise in various disciplines.
- Subjectivity: Some steps, such as setting system boundaries and weighting impact categories, involve subjective decisions.

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## 1.3 Limitations and data quality for LCA and S-LCA analysis for microplastics

A recent paper published by the European Union's Directorate-General for Environment (16th of January 2025) in their publication [1] declare the study that the management of microplastics is complex and this complexity requires an integrated approach that combines interdisciplinary techniques and involves multiple groups, or 'helixes', in society. They propose the use of the quintuple helix framework to manage this complexity. By expanding the stakeholders and the overall impacts, this approach is very welcomed but further adds complexity in the overall underdeveloped field of LCA studies which focus on microplastics. Also, some recently published meta-analysis put this perspective into numbers, as the study by [2] where a detailed analysis of 187 studies revealed that microplastics are rarely quantified, or even qualitatively discussed, in most LCAs. Thus, the true impacts of plastic products may be underrepresented and underestimated, leading to biased decision-making.

Based on their study they believe that this status quo is attributable to four fundamental issues:

(i) lack of microplastic leakage data.
(ii) lack of quantitative cause-effect relationships between microplastic concentration and their impacts.
(iii) exclusion of the "use" phase from the scope of analysis; and
(iv) exclusion of long-term effects from landfilled plastic waste.

There are some developments which propose a more unified approach in implementing the risk assessment for both microplastics and nano plastics in the LCA studies. LCA inherently relies on data from other scientific fields either directly or indirectly where the most important ones are:

- Toxicology
- Ecotoxicology
- Materials Science
- Marine Pollution (environmental sampling/monitoring)
- Other fields like hydrology, sedimentology and oceanography….

In the work by [3] the authors stress out that the current situation, where much MNP (micro nano plastic) data gathered from a recipient perspective is discarded by LCA analysts and LCIA method developers, is very inefficient. The argue that the LCA of Monitoring micro- and nano plastic pollution is usually from a receptor perspective and that 3 levels of the reporting requirements are proposed for receptor-oriented studies. They also recommend very detailed guidance for scientists gathering data in the field or lab. Their three levels are presented in Table 1.

*Table 1: Data needs from laboratory and field studies for microplastics LCA evaluation*

| *Data needs - field studies* | | |
|---|---|---|
| *Aim of empirical data study* | *Metadataa* | *Data type(s)/units* |

| | | |
|---|---|---|
| *MNP occurrence and distribution, MNP lifetime (e.g. persistence or degradation rate), and MNP impacts at the ecosystem scale.* | *Level 1<br>1) location in latitude and longitude<br>2) date and time of sampling<br>3) depth of sampling<br>4) sampling device used<br>a) Description<br>b) size<br>c) mesh size (if relevant)<br>5) conditions of the sampling environment:<br>a) wind speed (knots)<br>b) wind direction (degrees)<br>c) sea state (Douglas scale (0–9) or Beaufort scale (0–12))<br>d) temperature (°C)<br>e) pH<br>f) oxygen<br>g) salinity<br>h) habitat<br>6) In the case of effluent sampling (LCI):<br>a) production rate of products from factory or wastewater treatment plant at time of sampling.<br>b) total volume of effluent water being discharged at time of sampling.* | *Level 1<br>1) Qualitative:<br>a) polymeric composition: e.g. PET, HDPE, LDPE, PVC, PP, PS, PBS, PBAT<br>b) evidence of fragmentation: yes/no<br>c) morphology: categorised as fragment, pellet, fiber, film, or foam<br>d) colour of particles<br>2) Quantitative:<br>a) total mass of particles<br>b) dimensions: nano (≤1 µm), small micro (>1 µm ≤ 1 mm), large micro (>1 mm ≤ 5 mm)<br>3) Units:<br>a) SEAWATER/FRESHWATER<br>i) # of MNP/volume water<br>ii) mass MNP/volume water<br>b) SEDIMENT/SOIL<br>i) # of MNP/sediment or soil weight (dry, or wet, if wet weight provide moisture content)<br>ii) mass of MNP/sediment or soil weight (dry, or wet, if wet weight provide moisture content)<br>c) BIOTA<br>i) # of MNP/unit (specify if unit is body mass, biomass or individual – if individual also provide mass of individual; dry, or wet, if wet weight provide moisture content)<br>ii) mass MNP/unit (specify if unit is body mass, biomass or individual – if individual also provide mass of individual; dry, or wet, if wet weight provide moisture content).* |
| | *Level 2<br>As for Level 1* | *Level 2<br>As for Level 1, plus:<br>1) Qualitative:<br>e) biofouling: yes/no<br>f) additives in particles<br>2) Quantitative:<br>b) dimensions:<br>ii) small micro: >1 µm ≤ 100 µm, >100 µm ≤ 250 µm, >250 µm ≤ 500 µm, >500 µm ≤ 1000 µm<br>c) mass of particles per size range<br>d) aspect ratio<br>3) Units:<br>a) SEAWATER/FRESHWATER<br>iii) size distribution (%)<br>b) SEDIMENT/SOIL:<br>iii) size distribution (%)* |



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| | | |
|---|---|---|
| | | *c) BIOTA:*<br>*iii) size distribution (%)* |
| | *Level 3*<br>*As for Level 2, plus:*<br>*7) other chemicals or additives found in samples* | *Level 3*<br>*As for Level 2, plus:*<br>*2) Quantitative:*<br>*b) dimensions: all raw sizes listed along with a size distribution*<br>*e) mass of individual particles*<br>*f) % monomers within polymers observed*<br>*3) Units:*<br>*a) SEAWATER/FRESHWATER:*<br>*iv) MNP surface area (m2/g)*<br>*b) SEDIMENT/SOIL:*<br>*iv) MNP surface area (m2/g)*<br>*c) BIOTA:*<br>*iv) MNP surface area (m2/g)* |
| *Data needs - laboratory analysis* | | |
| *Aim of empirical data study* | *Metadata*[b] | *Data type(s)/units* |
| *MNP lifetime (e.g. persistence or degradation rate) or MNP effects (e.g. to determine endpoints associated with toxicity)* | *Level 1*<br>*1) state of plastic particles (e.g. virgin, fragmented, and/or biofouled)*<br>*2) polymer type(s): e.g. PET, HDPE, LDPE, PVC, PP, PS, PBS, PBAT*<br>*3) additives in polymers*<br>*4) ecotoxicological information: effect concentration (ECx) - species, exposure duration and which effect endpoint (mortality, growth, reproduction, development), effect level and units.*<br>*5) MNP lifetime information:*<br>*a) Test level (lab, tank)*<br>*i) test material, replicates, test duration, sampling points*<br>*ii) measured parameters (e.g. $CO_2$, $CH_4$, $O_2$, disintegration, weight loss) and units.*<br>*b) Test conditions*<br>*i) matrices used, i.e. soil, freshwater, marine*<br>*ii) grain size distribution (soil/sediment)*<br>*iii) Nutrient concentration*<br>*iv) temperature (°C)*<br>*v) conductivity*<br>*vi) pH* | *Level 1*<br>*1) Qualitative:*<br>*a) mass-based dose metric*<br>*b) polymeric composition: e.g. PET, HDPE, LDPE, PVC, PP, PS, PBS, PBAT*<br>*c) fragmentation: yes/no*<br>*d) morphology: categorised as fragment, pellet, fiber, film, or foam*<br>*e) colour of particles*<br>*f) BIOTA: presence or absence of significant effects (yes or no)*<br>*g) BIOTA: direction of effect (up = induction, down = inhibition)*<br>*2) Quantitative:*<br>*a) total mass of particles*<br>*b) dimensions: nano (≤1 μm), small micro (>1 μm ≤ 1 mm), large micro (>1 mm ≤ 5 mm)*<br>*3) Units:*<br>*a) SEAWATER/FRESHWATER*<br>*i) # of MNP/volume water*<br>*ii) mass MNP/volume water*<br>*b) SEDIMENT/SOIL*<br>*i) # of MNP/sediment weight (dry, or wet, if wet weight provide moisture content)*<br>*ii) mass of MNP/sediment weight (dry, or wet, if wet weight provide moisture* |

| Data needs - laboratory analysis | | |
|---|---|---|
| *Aim of empirical data study* | *Metadata[b]* | *Data type(s)/units* |
| | | *content)*<br>*c) BIOTA*<br>*i) # of MNP/individual (also provide mass of individual; dry, or wet, if wet weight provide moisture content)*<br>*ii) mass MNP/individual (also provide mass of individual; dry, or wet, if wet weight provide moisture content)* |
| | *Level 2*<br>*As for Level 1, plus:*<br>*6) Additional Information:*<br>*a) NOEC*<br>*b) LOEC*<br>*5) MNP lifetime information:*<br>*a) Test level*<br>*ii) $CO_2$, $CH_4$, $O_2$ emissions*<br>*iii) disintegration and weight loss* | *Level 2*<br>*As for Level 1, plus:*<br>*1) Qualitative:*<br>*h) biofouling: yes/no*<br>*i) additives in particles*<br>*2) Quantitative:*<br>*b) dimensions:*<br>*ii) small micro: >1 µm ≤ 100 µm, >100 µm ≤ 250 µm, >250 µm ≤ 500 µm, >500 µm ≤ 1000 µm*<br>*c) mass of particles per size range*<br>*d) aspect ratio*<br>*e) mass of $CO_2$, $CH_4$ and $O_2$ emissions/mass of plastic tested (degradation studies).*<br>*f) mass loss/mass of plastic tested (degradation studies).*<br>*3) Units:*<br>*a) SEAWATER*<br>*iii) size distribution (%)*<br>*b) SEDIMENT:*<br>*iii) size distribution (%)*<br>*c) BIOTA:*<br>*iii) size distribution (%)* |
| | *Level 3* | *Level 3*<br>*As for Level 2, plus:*<br>*2) Quantitative:*<br>*b) dimensions: all raw sizes listed along with a size distribution*<br>*g) mass of individual particles*<br>*h) % monomers within polymers*<br>*i) degradation rate*<br>*3) Units:*<br>*a) SEAWATER/FRESHWATER:*<br>*iv) MNP surface area ($m^2/g$)*<br>*b) SEDIMENT/SOIL:*<br>*iv) MNP surface area ($m^2/g$)* |

| Data needs - laboratory analysis | | |
|---|---|---|
| Aim of empirical data study | Metadata[b] | Data type(s)/units |
| | | c) BIOTA:<br>iv) MNP surface area ($m^2/g$) |

Due to this complexity of acquiring all this data with different tools and methodologies and having reliable data for future buildup of LCIAs we conclude with the scopes and limitations of most LCA studies in Table 2.

*Table 2. Limitations of using LCA on microplastic studies [4] [5], [6]*

| *What Can Be Done* | *What Cannot Be Done* |
|---|---|
| *Quantify Environmental Impacts: LCA can quantify the environmental impacts of microplastics across their life cycle, including production, use, and disposal.* | *Detailed Health Impact Analysis: LCA is not designed to provide detailed health impact assessments of microplastics on human health.* |
| *Identify Hotspots: LCA can identify stages in the life cycle where microplastics have the most significant environmental impacts.* | *Real-Time Monitoring: LCA cannot provide real-time monitoring of microplastic pollution in the environment.* |
| *Compare Alternatives: LCA can compare the environmental impacts of different materials or products, such as bioplastics versus conventional plastics.* | *Predict Long-Term Effects: LCA cannot predict the long-term environmental effects of microplastics, as it typically focuses on current and short-term impacts.* |
| *Support Policy Making: LCA can provide data to support policy decisions and regulations regarding plastic use and waste management.* | *Address All Environmental Issues: LCA may not address all environmental issues related to microplastics, such as their impact on biodiversity.* |
| *Assess Ecotoxicity: LCA can include ecotoxicity impacts, evaluating how microplastics affect aquatic and terrestrial ecosystems.* | *Comprehensive Time Horizon Analysis: LCA often struggles with incorporating long-term time horizons, especially for persistent pollutants like microplastics.* |

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To make things more distinctive between LCA and S-LCA the S-LCA tools and methodologies will be dealt in separately from the LCA studies in distinctive chapters.

# 2. State of the art research on methodologies and tools for microplastics evaluations through LCA analysis

Based on the setup of the projects and that the demo sites are basically a "pilot plant" setups inside or outside step in wastewater treatment plants on river water streams the methodology analysis will focus more on this type of LCA studies rather than the marine ones. Also, a separate chapter is dedicated to bio-based biodegradable materials and solutions (NVMT).

Incorporating microplastics into LCA is challenging due to the lack of comprehensive data on their release and impact. The basic interaction for building this data into the LCIA is presented in Figure 2.

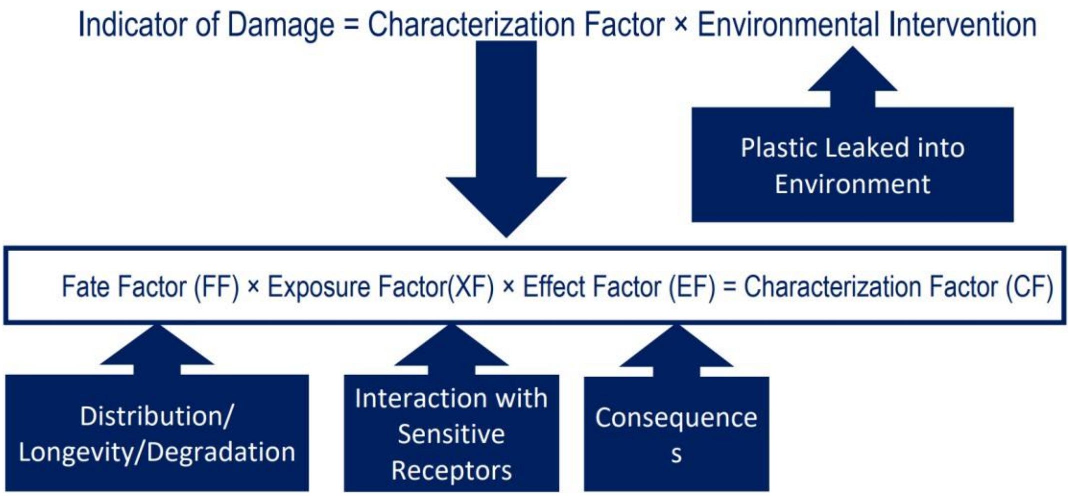


*Figure 2. LCIA Characterization factors and the meta data from other fields.*

The USEtoxTM model [7] is a consensus model of the international LCA community for the assessment of toxicological effects and its use is recommended e.g., by the European Commission's Product Environmental Footprint (PEF) initiative [8].

USEtoxTM allows for the computation of 16 characterization factors for organic and inorganic substances for the impact categories of human toxicity and freshwater ecotoxicity (Figure 3).



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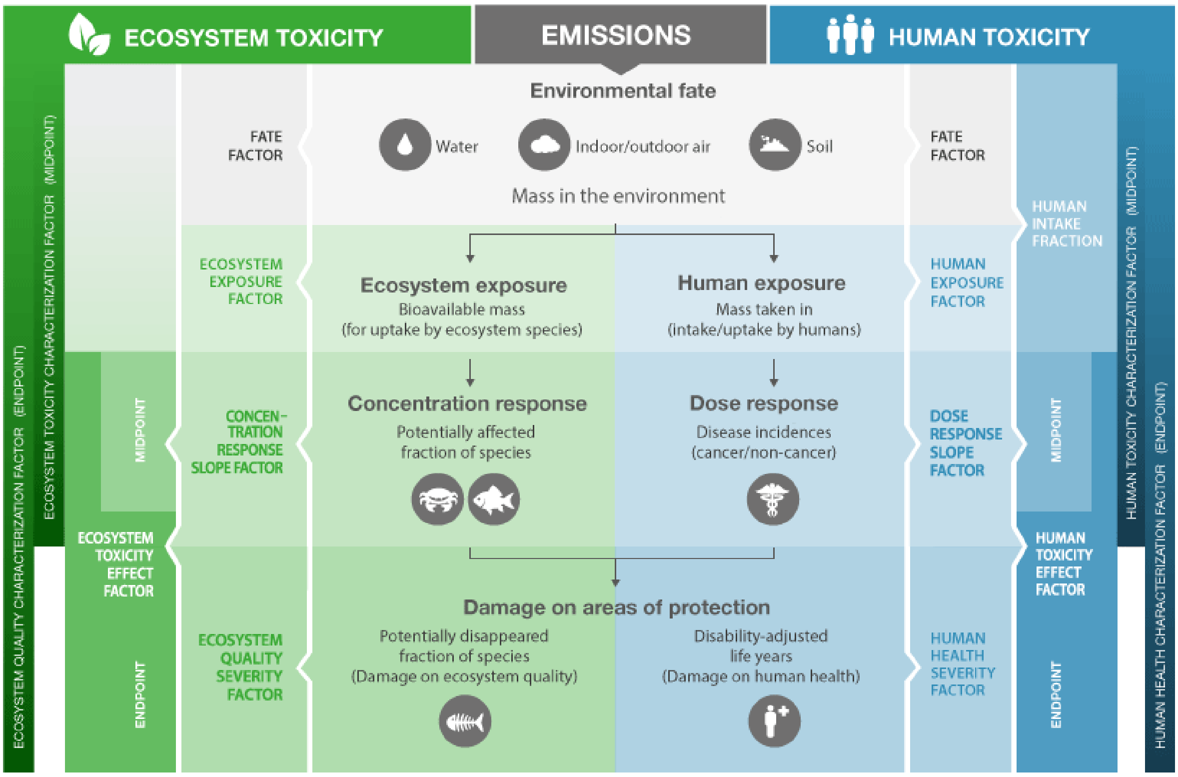


*Figure 3. USEtoxTM framework*

The USEtox model operates on different scales, indoor environment, urban scale, continental scale and global scale. The continental and global scales each consist of five compartments, namely rural air, agricultural soil, natural soil, freshwater, and (coastal) marine water.

The freshwater is built mainly of freshwater ecotoxicity characterization for cationic metals where partitioning adjusted for truly dissolved fraction are made and is based on parameterized freshwater archetypes.

A study about microplastics which partly used the USEtox model started to implement these by developing characterization factors ecotoxicity factors in freshwater environments [9]. Their research identifies several points: while the underlying fate model of USEtoxTM is well established for organic and inorganic compounds, it can a priori not be applied directly to particulate pollutants. The LCA results revealed that microplastic releases to freshwater do not influence the potential impacts on freshwater ecotoxicity to a very high degree, under the conditions of a state-of-the-art wastewater treatment which has been shown to remove microplastics. This result shows that the main ecotoxicological impact of plastic products is caused by other life cycle stages, such as the production and/or manufacturing stages and the other compounds that are released during all life-cycle stages, rather than the microplastic release. However, scenarios with less efficient wastewater treatment yield different results, with microplastic releases increasing the overall freshwater ecotoxicity impacts substantially. The share of wastewater going to wastewater treatment plants is therefore an important geographical factor that needs to be considered when evaluating the effect of microplastic releases.

Salieri and co-workers showed for engineered nanoparticles that a fate model for particles can be developed within the USEtoxTM context [10]. This was achieved by incorporating in the USEtox2.0 modelling framework with SimpleBox4Nano (SB4N), an advanced environmental fate model for nanomaterials, and to demonstrate its application to life cycle assessment (LCA) by the estimation of characterization factor (CF) for nano-TiO2 for the impact category of freshwater ecotoxicity.

Further works of challenges regarding integration of these different approaches were undertaken by [11] really including characterization factors (CFs) for human toxicity and freshwater ecotoxicity accounting for the impacts of engineered nanomaterials (ENMs) beyond their manufacturing stage. The work compiled the USEtox® consensus model (which is not nano specific) and the SimpleBox4Nano model (which accounts for nano specific processes, e.g. aggregation, attachment and dissolution for Fate Factor derivatization) to assess the possibility of integrating the two to derive size-dependent CFs for the varying sizes of ENMs throughout their life cycle. The authors found that the possibility to combine and integrate the two models appeared to be limited since there is no absolute correspondence between the two of them.

One of the most recent studies on the topic by [12] substance characterization factor (CF), addressing both environmental fate ecological effects on species of the substance, were obtained for microplastics (MiP) and macroplastics (MaP) for three polymers (LDPE, PP, PET), aligned with impact categories marine and freshwater ecotoxicity in the LCIA methodology ReCipe2016. The ReCiPe method is a widely used and comprehensive framework for conducting life cycle impact assessment (LCIA). A defining feature of ReCiPe is its ability to incorporate different philosophical and cultural perspectives on environmental damage, acknowledging that there is no single, universally agreed-upon way to value environmental impacts. These perspectives, known as cultural perspectives, are defined by how a society views and manages environmental risks [13]. This makes the method more compatible with social LCA studies:

- **Individualistic Perspective:** This viewpoint is characterized by a short-term, optimistic outlook on technology. It assumes that human innovation and market forces can solve most environmental problems. Therefore, the individualist model assigns lower weighting to long-term or uncertain impacts, and it prioritizes impacts that are well-established and have immediate consequences. It is a pragmatic, "can-do" approach that focuses on efficiency and economic viability.
- **Hierarchical Perspective:** This is a more cautious and structured approach, guided by the principle of **precaution**. It relies on expert consensus and scientific data to set long-term goals and boundaries for environmental protection. The hierarchical model assigns a moderate weighting to both short-term and long-term impacts, based on what is scientifically agreed upon by regulatory bodies and institutions. It reflects a belief in structured management and regulated control to prevent harm.
- **Egalitarian Perspective:** This perspective is defined by an extreme sense of caution and a very long-term view of potential environmental damage. It assumes that all future risks, no matter how remote, should be given serious consideration, and it places a high value on preventing even the slightest potential for environmental harm. The egalitarian model is deeply pessimistic about human technology's ability to solve problems it has created, so it assigns a high weighting to all impacts, especially those with long-term, irreversible consequences. It emphasizes collective responsibility and a more sustainable, less consumptive lifestyle.

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Within the ReCiPe framework, these perspectives are applied to the process of converting **midpoint impacts** to **endpoint impacts**. Midpoint impacts are specific, single-category environmental issues, such as 'climate change' or 'freshwater eutrophication'. Endpoint impacts, on the other hand, are grouped into three broader, more tangible categories of damage: **Human Health, Ecosystems, and Resource Scarcity**. The choice of perspective (Individualistic, Hierarchical, or Egalitarian) determines the weighting factors used to aggregate midpoint impacts into these three endpoint categories. For instance, the egalitarian perspective will give more weight to midpoint impacts that have a far-reaching, long-term effect on ecosystems, while the individualistic perspective will prioritize those with immediate human health or economic consequences [14]; [15]; [13].

To apply and assess the extended LCIA methodology, a comparative LCA is performed for two case studies of multilayer packaging films for consumer products were tested. Environmental fate of plastic pollution was comprehensively assessed using the multimedia fate model Simplebox4plastics, while the effect factor was based on a species sensitivity distributions, based on L(E)C50 toxicity data. The results show low density MiP dominates the midpoint impacts for freshwater and marine ecotoxicity impact factors with contributions between 88 and 100 % for the Individualist and Hierarchist ReCIPe perspective. In the Egalitarian perspective, MiP contribution was minimal for marine ecotoxicity, highlighting the importance of cultural perspective choices for an LCA. Overall impacts on ecosystem quality of the two packaging films were, however, dominated by climate change impacts. One of the important outcomes of this study is the assessment of the Fate Factors (FF) of MiP emissions assessed through Simplebox4plastics, in days which is presented in Table 3. [12]

*Table 3. Fate Factors for freshwaters and marine waters calculated in [12]*

**Table 1**

The Fate Factors (FF) of MiP emissions assessed through Simplebox4plastics, in days.

| | Receiving compartment | Freshwater | | | Marine | | |
|---|---|---|---|---|---|---|---|
| Substance | Emission compartment | Individualist | Hierarchist | Egalitarian | Individualist | Hierarchist | Egalitarian |
| PP | Freshwater lake | 121 | 154 | 154 | 3,300 | 22,205 | 45,431 |
| PP | Freshwater | 159 | 159 | 159 | 4,135 | 25,399 | 47,073 |
| PP | Ocean water | 0 | 0 | 0 | 6,925 | 25,503 | 47,129 |
| PP | Natural/ industrial soil | 158 | 158 | 158 | 6,663 | 25,185 | 46,747 |
| PP | Agricultural soil | 158 | 158 | 158 | 6,578 | 25,134 | 46,735 |
| LDPE | Freshwater lake | 99 | 113 | 113 | 1,174 | 1,551 | 1,551 |
| LDPE | Freshwater | 157 | 157 | 157 | 2,119 | 2,163 | 2,163 |
| LDPE | Ocean water | 0 | 0 | 0 | 2,151 | 2,191 | 2,191 |
| LDPE | Natural/ industrial soil | 146 | 146 | 146 | 1,971 | 2,013 | 2013 |
| LDPE | Agricultural soil | 136 | 136 | 136 | 1,830 | 1,872 | 1,872 |
| PET | Freshwater lake | 9.61E-06 | 1.01E-05 | 1.01E-05 | 2.23E-07 | 3.44E-07 | 3.46E-07 |
| PET | Freshwater | 9.49E-02 | 9.95E-02 | 9.95E-02 | 2.21E-03 | 3.40E-03 | 3.41E-03 |
| PET | Ocean water | 0 | 0 | 0 | 4.24 | 5.44 | 5.46 |
| PET | Natural/ industrial soil | 9.36E-02 | 9.84E-02 | 9.84E-02 | 2.16E-03 | 3.36E-03 | 3.37E-03 |
| PET | Agricultural soil | 9.30E-02 | 9.79E-02 | 9.79E-02 | 2.13E-03 | 3.34E-03 | 3.35E-03 |

Simplebox4plastics is the first multimedia fate model used to quantify MiP fate factors (FF). Multimedia fate models are valuable tools for risk assessment and LCA methodologies but are not without uncertainties, partially due to dependency on input variables. The marine FFs assessed in the current study are observed to be sensitive for aquatic degradation rate.

The SimpleBox4Plastic model has been applied probabilistically using the @Risk Excell plugin (v8, Pallisade), to calculate concentrations in air, natural soil, agricultural soil, industrial soil, river water, river sediment, seawater, and marine sediment [16]. The model is based on the calculation of total particulate Predicted Environmental Concentration of microbeads.

($PEC_{[total\ particulate]}$; e.g. $g/m^3$ or $particles/m^3$). This is the sum of the three particulate species accounted for in SimpleBox4Nano:

$$PEC_{[total\ particulate]} = PEC_{[microbead]} + PEC_{[microbead\text{-}natural\ colloid]} + PEC_{[microbead\text{-}coarse\ particulate]}. \quad (1)$$

The authors nevertheless provide a caveat that it may be important to include studies of other fate processes such as sea spray or beaching of floating microplastics, as well as the effects of particle shape. Also, biota influence fate and transport processes of microplastics, such as degradation, fragmentation or deposition. However, no quantitative relationships are currently available to implement these. Furthermore, the application of size, shape and density distributions (Probability Density Functions) of microplastics that are representative of their application, emission route, or the compartments in which they occur can lead to further improvement of the results.

## 2.1 Fate models for other water systems (oceans)

While the papers presented in previous sections were dealing with freshwater analysis which is analogous to river setup as its main focus of our project several other LCA studies were made and developed mainly for the marine environment. In a paper published by [17] they also developed the Marine Microplastic Potential (MMP), we have defined the two different time horizons of 100 and 500 years in order to be able to map the behavior of different materials. Products with slower fragmentation and faster degradation have lower environmental impacts due to a lower number of microplastics of a defined size in each time frame. This can be considered in the model as well as different toxic effects of different types of materials. Larger particles or particulates with different shapes than perfect spheres which fragment slower can cause different effects to marine life than particulates with other shapes. Their work derives a new factor for impact assessment can be defined as the following characterization model for microplastics in the marine environment:

$$MMPt = Nt \times E \quad (1)$$

MMP = Marine Microplastic Potential

Nt – Number of particles each year based on the fragmentation and

degradation rate E – Effect factor

t – Time relation

The study applied the new approach to an example of different materials for bottles. They compared PE and PET plastics for the functional unit of the transport of 1 L of fluid goods, and their results showed difference in number of particles and their toxicity potential (Table 4.).



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*Table 4. Marine Microplastic Potential calculated for (LDPE film and PP fabric)*

| LDPE film | PP fabric |
|---|---|
| $MMP_{100} = N_{100} \times E$ | $MMP_{100} = N_{100} \times E$ |
| $MMP_{100} = 4.3 \times 10^6 \times 3.3$ | $MMP_{100} = 2.1 \times 10^6 \times 9.1$ |
| $MMP_{100} = 1.42 \times 10^7$ pellet equivalent points | $MMP_{100} = 1.91 \times 10^7$ pellet equivalent points |
| $MMP_{500} = N_{500} \times E$ | $MMP_{500} = N_{500} \times E$ |
| $MMP_{500} = 7.9 \times 10^6 \times 3.3$ | $MMP_{500} = 1.1 \times 10^7 \times 9.1$ |
| $MMP_{500} = 2.61 \times 10^7$ pellet equivalent points | $MMP_{500} = 1.00 \times 10^8$ pellet equivalent points |
| Total $MMP_{agg} = 4.03 \times 10^7$ pellet equivalent points | Total $MMP_{agg} = 1.19 \times 10^8$ pellet equivalent points |

The paper does not present a full LCA study but implies the use of this MMPt as a step toward a full scale LCA study (Figure 4.).

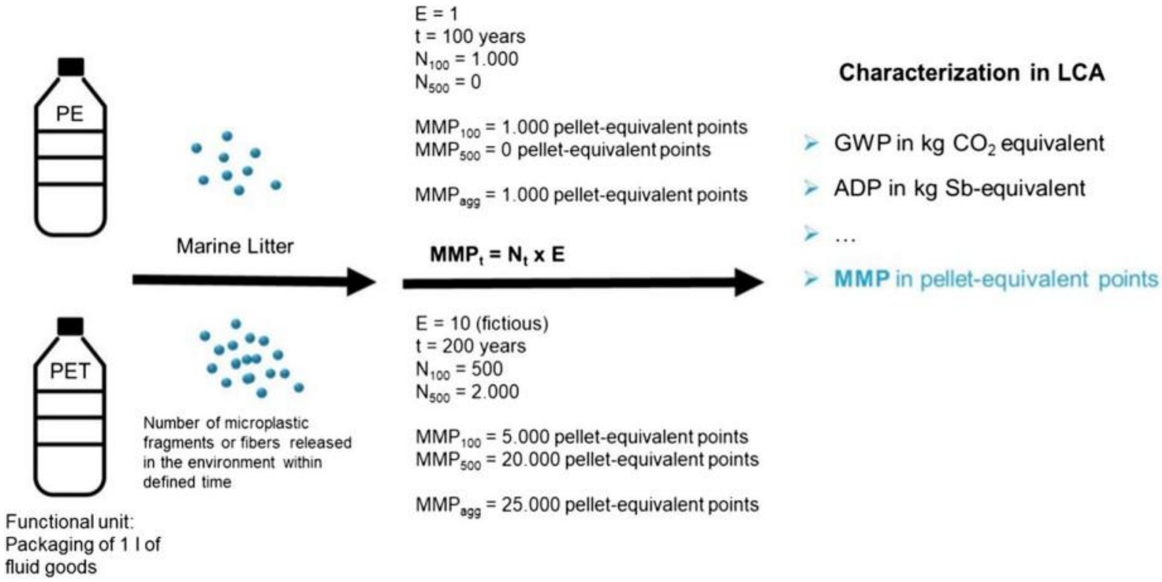


*Figure 4. Proposed methods for toxicity calculation of microplastics in marine environment with Microplastics in Marine Environment from [14]*

As a summary of different approaches for characterization factors for microplastics it is worth mentioning the results of the MarILCA international working group. These CFs quantify the physical effects on biota from emissions to aquatic environments, which represents only a part of the potential impact of plastics on biodiversity as described in the MarILCA framework [18]. The scope of the CFs is highlighted in green in the figure below. While the work mainly focuses on the characterization factors for marine plastic litter impacts, it can be useful also for freshwater plastic litter impact assessment.


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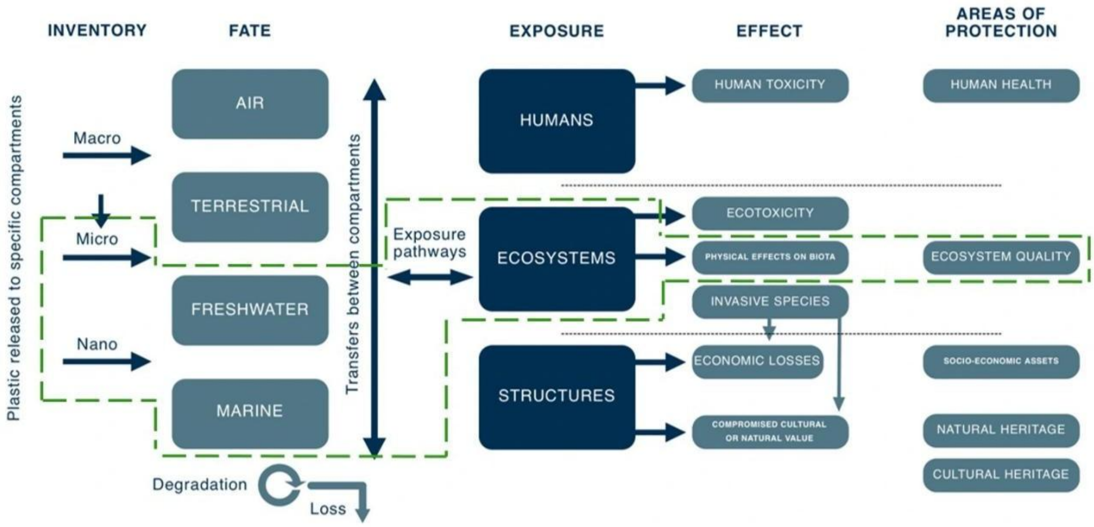


*Figure 5. Simplified MarILCA framework with the scope of the developed CFs highlighted in green [17]*

CFs were developed for eleven (11) different polymers (EPS, PS, PP, HDPE, LDPE, PET, PVC, PLA, PHA, PA and TRWP), three (3) shapes (microbead/unspecified, cylinder/microfiber, microplastic film fragments) and five (5) sizes (1, 10, 100, 1000, 5000 µm). The fate, exposure and effect factors are combined following the USEtox model approach and requirements. They also provide this database [19]. with two (2) sets of units are available to use with Impact World + methodology (PDF.m$^2$.yr/kg) and for the upcoming GLAM methodology (PDF.yr/kg). Also, the uncertainty parameter values are provided.

Sample CF values from the Marine LCA database for freshwater, the PET microplastic polymer for bead, fibre, film are presented in Table 5-7.

*Table 5. CF values for PET polymer beads*

| | *Midpoint CF [PAF*m3*day/ kgemitted]* | | | | | *Endpoint CF [PDF*m2*year/ kgemitted]* | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Polymer type* | *Size - initial sphere diameter [µm]* | *Recommended CF (geometric mean)* | *Geometric st.dev.* | *Lower limit 95% CI* | *Upper limit 95% CI* | *Recommended CF (geometric mean)* | *Geometric st.dev.* | *Lower limit 95% CI* | *Upper limit 95% CI* |
| *PET* | *5000* | *3,07E+07* | *3,36E-01* | *2,72E+06* | *3,48E+08* | *8,46E+02* | *4,16E-01* | *4,89E+01* | *1,46E+04* |
| *PET* | *1000* | *2,16E+07* | *3,73E-01* | *1,55E+06* | *3,00E+08* | *5,93E+02* | *4,52E-01* | *2,90E+01* | *1,21E+04* |
| *PET* | *100* | *6,98E+06* | *5,24E-01* | *2,55E+05* | *1,91E+08* | *1,92E+02* | *6,07E-01* | *5,22E+00* | *7,06E+03* |
| *PET* | *10* | *1,07E+06* | *7,07E-01* | *2,14E+04* | *5,34E+07* | *2,94E+01* | *7,96E-01* | *4,64E-01* | *1,86E+03* |
| *PET* | *1* | *9,70E+04* | *7,95E-01* | *1,53E+03* | *6,13E+06* | *2,67E+00* | *8,89E-01* | *3,38E-02* | *2,11E+02* |



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*Table 6. CF values for PET polymer fibers*

| | Midpoint CF [PAF*m3*day/ kg emitted] | | | | | Endpoint CF [PDF*m2*year/ kg emitted] | | | |
|---|---|---|---|---|---|---|---|---|---|
| Polymer type | Size - initial fiber diameter [μm] | Recommended CF (geometric mean) | Geometric st.dev. | Lower limit 95% CI | Upper limit 95% CI | Recommended CF (geometric mean) | Geometric st.dev. | Lower limit 95% CI | Upper limit 95% CI |
| PET | 5000 | 3,19E+07 | 3,34E-01 | 2,86E+06 | 3,56E+08 | 8,77E+02 | 4,13E-01 | 5,13E+01 | 1,50E+04 |
| PET | 1000 | 2,35E+07 | 3,63E-01 | 1,79E+06 | 3,09E+08 | 6,46E+02 | 4,42E-01 | 3,31E+01 | 1,26E+04 |
| PET | 100 | 8,40E+06 | 4,99E-01 | 3,37E+05 | 2,09E+08 | 2,31E+02 | 5,82E-01 | 6,83E+00 | 7,82E+03 |
| PET | 10 | 1,40E+06 | 6,88E-01 | 2,94E+04 | 6,61E+07 | 3,84E+01 | 7,77E-01 | 6,36E-01 | 2,32E+03 |
| PET | 1 | 1,34E+05 | 7,88E-01 | 2,16E+03 | 8,34E+06 | 3,69E+00 | 8,81E-01 | 4,76E-02 | 2,87E+02 |

*Table 7. CF values for PET polymer films*

| | Midpoint CF [PAF*m3*day/ kg emitted] | | | | | Endpoint CF [PDF*m2*year/ kg emitted] | | | |
|---|---|---|---|---|---|---|---|---|---|
| Polymer type | Size - initial film thickness [μm] | Recommended CF (geometric mean) | Geometric st.dev. | Lower limit 95% CI | Upper limit 95% CI | Recommended CF (geometric mean) | Geometric st.dev. | Lower limit 95% CI | Upper limit 95% CI |
| PET | 5000 | 3,32E+07 | 3,32E-01 | 3,02E+06 | 3,66E+08 | 9,14E+02 | 4,11E-01 | 5,41E+01 | 1,55E+04 |
| PET | 1000 | 2,60E+07 | 3,51E-01 | 2,11E+06 | 3,21E+08 | 7,16E+02 | 4,31E-01 | 3,86E+01 | 1,33E+04 |
| PET | 100 | 1,07E+07 | 4,67E-01 | 4,90E+05 | 2,33E+08 | 2,94E+02 | 5,48E-01 | 9,78E+00 | 8,83E+03 |
| PET | 10 | 2,00E+06 | 6,59E-01 | 4,61E+04 | 8,72E+07 | 5,51E+01 | 7,47E-01 | 9,88E-01 | 3,08E+03 |
| PET | 1 | 2,10E+05 | 7,77E-01 | 3,48E+03 | 1,27E+07 | 5,77E+00 | 8,69E-01 | 7,64E-02 | 4,36E+02 |

As we can observe there are some slight differences between similar sizes but different shapes, so based on the available data on the demo sites regarding polymer types and their shapes and sizes and the effluent after treatment we can access some of the ecotoxicity values with the proposed CFs.

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## 2.2 Fate models for biodegradable plastics

As Task T4.3 establishes the links between the technological solutions developed within the project and its quantifiable environmental effects, the LCA on WP2 technologies must be addressed following sustainability principles. In this context, the LCA assessment of the solutions developed in UPSTREAM is key to improve their sustainability and circularity performances with respect to their fossil-based counterparts, focusing on minimising the drivers of climate change while maximising circularity and reducing the use of harmful products, applying robust evaluation methods. Within this task, Novamont is evaluating MPs pollution and prevention solutions from the design to the manufacturing of new bio-based biodegradable materials.

The definition of a “bio-based” product establishes a direct link between the biomass and the product, as further detailed in the Deliverable 2.1. The word “bio-based” is intrinsically related to the carbon source from which the product comes from: carbon-based monomers from renewable sources (i.e. byproducts from the agroindustry, biomass from agricultural sector, organic waste or sewage sludge) as specified in the European standard CEN/TC 411 - Bio-based products. The term "bio-based" therefore strictly refers to the renewable origin of raw materials (carbon source). Test method EN16640:2017 allows us to determine the renewable carbon content in bio-based polymers and materials. Moreover, bio- based materials can also be biodegraded meaning that they can be broken down by living organisms, such as bacteria, in the presence of oxygen to carbon dioxide, water, mineral salts and new biomass, or in the absence of oxygen to carbon dioxide, methane, mineral salts and new biomass, closing the carbon cycle.

Biodegradability is an intrinsic property as it refers to the inborn potentiality for biodegradation, not considering the extrinsic properties. The biodegradability of a material is deduced by studying a biodegradation process under controlled and predefined conditions. From the results obtained, it can be concluded whether the material is biodegradable based on a standardized assessment methodology.

High levels of conversion to $CO_2$, equal to those achieved by generally recognized as biodegradable substances (like cellulose), indicate that a plastic material is biodegradable. Cellulose is frequently used as reference material in laboratory test methods, because biodegradation of cellulosic biomass represents an important part of the carbon cycle within the biosphere. Microorganisms can completely degrade cellulose in $CO_2$, water and microbial biomass under aerobic conditions. Therefore, cellulose does not accumulate in the environment, and it can be considered as totally biodegradable in any environment, independently from the environmental conditions.

Biodegradation rate is strongly connected to specific environmental conditions: temperature, presence of microorganisms, presence of oxygen, macronutrients availability and free water are some of the key parameters in a biodegradation process.

A recent study, focusing on **marine environment**, highlighted the performance of different bioplastics to biodegrade if directly exposed to different marine environments, in mesocosm and laboratory conditions. UConn marine sciences researchers demonstrated that the starch-based polymer produced by Novamont, degraded by nearly 50% over nine months in a marine environment [20]. Additionally, they found that the rate of degradation increased during warmer months. These findings could have meaningful implications for reducing plastic pollution in aquatic environments. According to these studies, biodegradable materials demonstrated to biodegrade also in natural environment poor nutrients and microorganisms [21]. In addition, [22] published a relevant analysis related to the potential ability of microorganisms to attack and metabolize biodegradable polyesters in every natural environment as they can be considered ubiquitous.

The intrinsic **biodegradability** of the targeted **biobased materials** is therefore paramount in mitigating microplastic pollution, although future research should focus on expanding experimental data to different polymers and environments, integrating biological effects to enhance the accuracy of impact assessments. Recent studies on polymer biodegradability in WWTP or freshwater are difficult to find, and UPSTREAM project can help to obtain useful data set on new biopolymer formulations that have as end-of-life scenario the WWTP and fresh water (rivers) if accidental release will happen.

On the other hand, the more general and uncontrolled release of non-biodegradable plastic into the environment is of great relevance to public opinion worldwide and some actions to reduce this phenomenon have already been implemented. A relevant initiative to mention is the "Plastic Leak Project"1 [23] [21], which seeks to find the type and amount of macro plastics and primary microplastics released as an environmental emission of a product.

An innovative method that allows us to measure one of the main hazards associated to plastic materials is the **release of microplastics in the environment**, particularly relevant in the case of UPSTREAM. The problem of pollution from plastics released in the environment is a highly relevant topic in the project, as well as in numerous studies and legislation initiatives at international level. In particular, the microplastics that are produced from the partial degradation of dispersed plastic items exposed to the environment arise particular concern for their tendency to accumulate, for the impossibility of being collected and therefore the risk that they may encounter living beings (e.g. marine biodiversity), with consequences that to date are still not well known. This potential ecological hazard of plastic materials can be assessed by using the **Microplastics Emission Potential (MPEP)** metric [24], which is useful for characterizing and classifying plastic materials from the point of view of their potential for emitting microparticles (MPs) and their tendency to persist in the environment in case of leakage. The Microplastic Emission Potential (MPEP) is a parameter designed to evaluate the environmental impact of polymeric materials in terms of microplastic generation and persistence [24]. Therefore, assuming the same number of microplastics emitted, the ecological hazard is related to the life of the particles. The Microplastic Emission Potential (MPEP) could be described as:

$$MPEP = Nmp \times t_d$$

Where *Nmp* is the standard number of MPs for all types of polymers and td is the time required for biodegradation expressed in years. However, the MPEP only determines the overall level of potential emission and permanence of MPs by a polymeric item, and it does not consider the biological effects caused by the MPs. To determine the environmental impact, it is in fact necessary to account for both the emission and the biological effect. The potential impact can be determined from the MPEP by adding the effect factor (E) - where *E* could be subdivided into the effects caused by physical factors (*Ep*) and those caused by chemical-physical factors (*Ec*)- thus obtaining the Microplastic Impact Potential

(MPIP): $MPIP = MPEP \times E$. [18]

This approach could provide a robust framework for understanding the environmental impact of biobased materials.

Literature data report that comparing three materials such as cellulose (a natural polymer), biobased biodegradable polymer (as for the case of NVMT starch-based biodegradable polymers), and polyethylene (a conventional, non-biodegradable polymer), -polyethylene exhibits an MPEP 1,827 times higher than cellulose and NVMT starch based biodegradable polymer. This difference is attributed to the significantly longer time required for HDPE to fully degrade—548 years—compared to an average of 0.3 years for the biodegradable materials. While polyethylene releases microplastics more slowly due to lower fragmentation rates, these MPs persist for centuries, leading to cumulative ecological risks. In contrast, NVMT starch based biodegradable polymer and cellulose rapidly fragment and biodegrade, minimizing their environmental persistence despite a higher initial fragmentation rate. Simulations showed that polyethylene microplastics persist for hundreds of years, while those from NVMT starch based biodegradable polymer disappear within a year in line with legislative priorities, such as the EU's Single-Use Plastics Directive, which seeks to reduce persistent plastic waste [21].

The activities foreseen in UPSTREAM will support the refining of the model and enhance its applicability, expanding the availability of data and consolidating the evaluation of biobased and biodegradable materials of different nature addressing the life cycle assessment as cosmetic ingredients and moving bed bioreactor (MBBR) fillers. In this context, NVMT has initiated data collection and preliminary analyses, to establish a framework to evaluate the environmental performance of the solutions target of UPSTREAM, the results will be presented and discussed later in the project.

## 2.2 LCA study for wastewater treatment plants

As majority of the demo sites (excluding one) are sites which utilize some form of wastewater treatment it is also recommended to check the available LCA studies and their Life Cycle Inventory building for a Waste Water Treatment Plant (WWTP). One of the largest meta studies on the LCA assessment of WWTPs was made in 2013 by [25] where they compared 45 papers published up to that date. Their analysis of these papers has shown that within the constraints of the ISO standards, there is variability in the definition of the functional unit and the system boundaries, the selection of the impact assessment methodology and the procedure followed for interpreting the results. Hence, there they conclude there is need to develop standardized guidelines for the wastewater treatment field to ensure the quality of the application of the LCA methodology. For functional units the studies mainly used (1 $m^3$, 1 PE, 1L 1PE per y etc up to 10000 PE) with some using declared assessment methodologies but due to older timeframe of course non with the new ReciPe2016 one. One more recent study of LCAs done on WWTP is one published by [26] where the authors used the ProKnow-C systematic review methodology for paper selection and 111 studies were analysed. In this systematic review of LCA applied to WTTP, most of the shortcomings identified relate to the disclosure of important information, which can increase transparency. A diversity of impact methodologies and categories were identified as well as many different systems and configurations. Some papers presented a very careful and well-thought discussion. However, they concluded many methodological aspects are still divergent and there is a lack of comparability on the works. The most significant challenge identified was data quality and availability, which leads to uncertainties and the use of databases that may not represent well regional data. Furthermore, the quality of the data used in the studies must be related to its timeline and the experiments must be conducted according to a detailed methodology. The definition of how to allocate resources and how to account for the avoided impacts in the system is also a common problem. Moreover, the creation and adoption of LCIA methodologies that can show the environmental impacts locally can benefit future studies. The results demonstrate the need for the creation of a specific protocol for LCA of urban WWTPs to guarantee comparability between studies and increase transparency

One of the earliest studies which used the previous methodology of ReciPe was done in dissertation [27] where he claims that the inventory data is a very data demanding and the most challenging stage as it requires a technical study on the nature of wastewater treatment system. Despite the basic parameter such as BOD, COD and plant capacity, the construction and equipment fabrication phase also need to be considered as the life cycle assessment is a study from beginning toward the end-of-life process. The laboratory research required to be done to evaluate the wastewater content in each treatment stage, influent and effluent. The background function such as electricity consumption and amount of raw chemical material used in plant operations also the important parameter needs to be collected as well. The impact analysis showed that the largest impact of wastewater toward the environment was fossil depletion which was coming from the energy consumption of machines in WWTP. The second highest impact of wastewater treatment plant toward the environment was the impact category climate change connected with the overall GHG emissions. The third largest impact of wastewater treatment plants toward the environment is human toxicity. Human toxicity was calculated by considering the time-integrated fate, exposure of a unit mass of chemical released into the environment. The assessment of effects related to the human toxicity impact category was focused on effect resulting from direct exposure to chemicals. Secondary and tertiary treatment system (subsystem 2) has the highest contribution toward human toxicity due to the present of high dosage of sodium percarbonate as the surfactant agent for cleaning purposes and detergent in wastewater treatment plant. The other possible factors which were identified by the authors were lime (CaO) which present in detergent during cleaning process and high voltage of electricity consumption in wastewater treatment plant.

Due to these factors the newly developed cleaning technologies for microplastics from freshwater need to be energy efficient and to use the minimal amount of potentially harmful chemicals.

One of the recent studies used LCA calculation for revamping WWTP by focusing on energy efficiency. In a recent study by [28] where three different scenarios were analyzed: a baseline scenario that considers a conventional activated sludge treatment technology exploiting data from an existing plant located in central Italy, a second scenario that involves the implementation of MBR technology applied to the baseline scenario, and finally a third scenario that consists of the addition of an anaerobic digester that allows energy recovery from biogas production, followed by a photovoltaic plant capable of supplying the plant energy demand. Global warming potential, eutrophication, and acidification are the environmental categories considered most relevant to emissions. The results showed that the effluent had the highest impact in terms of $CO_2$ equivalent in all three situations due to the presence of $N_2O$. Since emissions from biological processes, transportation, and wastewater are almost similar in all three scenarios, it is preferable to focus on the environmental impacts associated with energy consumption. The third scenario involved careful resource management and the use of treatment technologies that allow for a reduction in the use of non-renewable energy sources in favour of renewable ones. Their functional unit was 1 $m^3$/d of influent. The results showed that from three studied scenarios it was affirmed that scenario B, while it is expected to give good removal efficiencies with the use of MBR technology, has high impacts due to high energy consumption to power the used technology. The treatment technology under scenario C involves careful resource management and the introduction of treatment technologies that allow for a decrease in the consumption of non-renewable energy sources, in favour of renewable ones. Another more recent study focused on the geographical relevance of LCAs for WWTP [29]. Since the majority of microplastics are transferred into sludge at wastewater treatment plants, sludge treatment, disposal, and effective decision-making are critical to protecting the environment from microplastic (re)contamination. Therefore, supportive policy measures coupled with effective wastewater treatment plant designs are important for minimizing microplastic-related pollution. Plastic-related chemicals and biofilms with attached pathogens are other factors to consider. As the release of toxic chemicals from microplastics has not been studied in detail, reconciling the limitations of analytical capabilities requires continued work [30].

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## 2.3 Integration of microplastics influence in LCIA models and frameworks

So how to integrate the different demo sites in the Upstream project with different technological setups and cleaning technologies as well as one demo site which is not a water treatment facility but a biodegradable plastics producer?

There is some general guidance on how to set up an LCA study for wastewater treatment [25] for the application of LCA in the context of municipal wastewater management (treatment plants, technologies, and planning decisions) so it may not fit for purpose on all demo sites, and some modifications will be needed. But to acquire a common nominal value or functional unit to assess the efficiency of the different water cleaning technologies it is recommended to adopt a functional unit which reflects pollutant loads in the influence and defines an operation target. The operation target establishes WWTP goals beyond a volumetric quantity treated and is important in addressing the system performance (i.e., treatment efficacy) aspect of the functional unit. This criterion includes water quality objectives – either as contaminant treatment requirements (e.g., abatement of nitrogen load) or effluent/product water 14 standards (e.g., effluent ammonia less than 5 mg-N·L -1 328) [28]. For WWTPs which are designed to remove COD, N, and P, a functional unit which reflects eutrophication potential reduction (i.e., kg $PO_4^{3-}$ 330 as P removed) is recommended [32].

Based on this recommendation we can adapt part of the LCIA framework which defines water quality and has already been established at that is the WW LCI (Wastewater LCI) (2.-0 LCA consultants) which is now part of the SimaPro company. The WW LCI framework offer several aspects of handling wastewater LCA calculations as it accounts for:

- The fate of substances in WWTPs and downstream in the environment (air, water, soil).
- Direct and indirect emissions from wastewater collection and treatment at different WWTP levels (primary, activated sludge, lagooning, tertiary treatment), taking into account local climatic conditions.
- Domestic sanitation through septic tanks, latrines and open defecation.
- Wastewater reuse in agriculture.
- Sludge disposal through composting, landfarming, incineration, controlled landfilling and uncontrolled landfilling.
- Greenhouse-gas and other indirect emissions from degradation of substances in the environment, in the case they are not degraded in a WWTP or subject to treatment at all.
- It has a database with country-specific data on wastewater management for more than for 100 countries and two regions (see figure 2): connection to sewer, WWTP treatment levels, sludge disposal practices, discharges to freshwater/seawater, capacity of operating WWTPs, availability of anaerobic digestion and cogeneration, etc.
- It also has Inventories linked to Ecoinvent as background system, in an easy format for export to LCA software (SimaPro, GaBi).

The overall LCIA buildup is presented in Figure 6.

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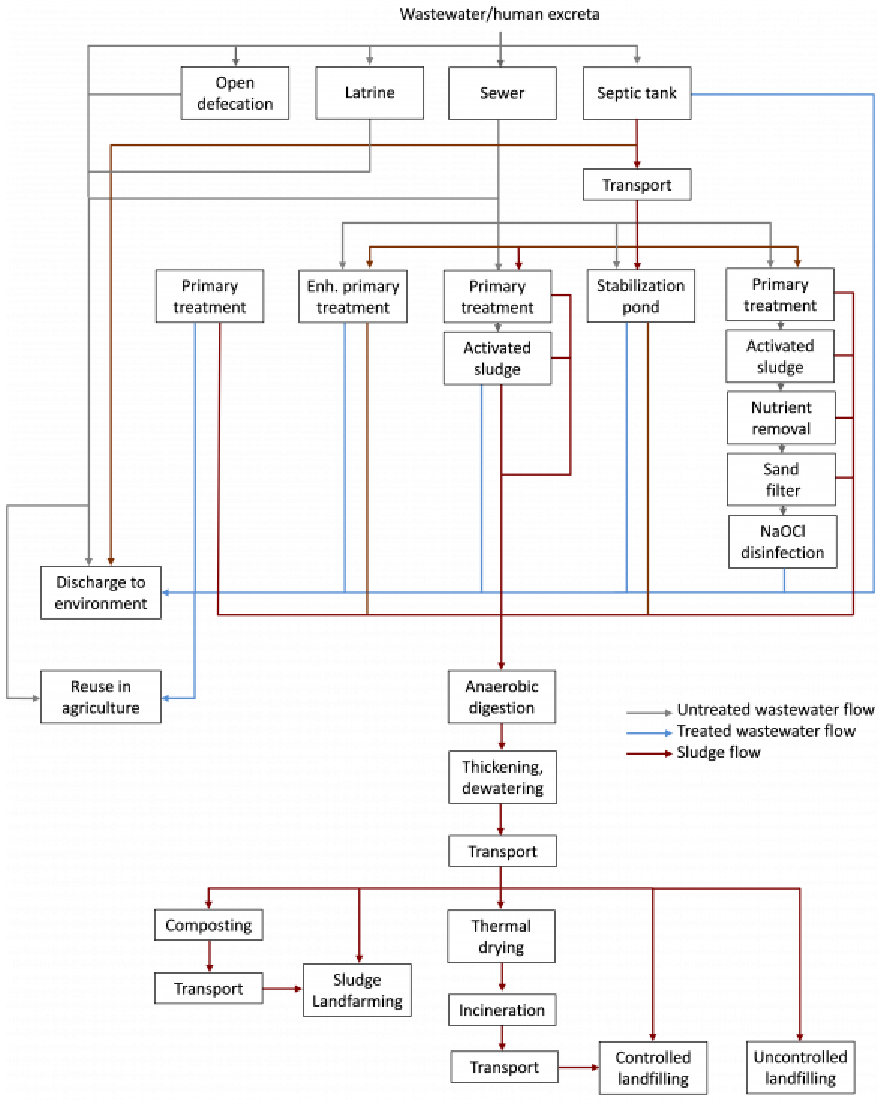


*Figure 6. Waste Water (WW) LCI framework*

For demo site based on the recommended chemical substances which can be found in the influent river freshwaters we have developed an Excel questionnaire for collecting potential data from the demo sites regarding water effluent quality after cleaning/filtration applied.

Besides taking the wastewater chemical quality parameters for calculating impact assessment, additionally the most developed model with the highest number of fate models for different sizes of micro and nano plastics the Marine LCA framework will also be combined in the final setup. The detailed methodology of the Marine LCIA concept is presented in Figure 7.

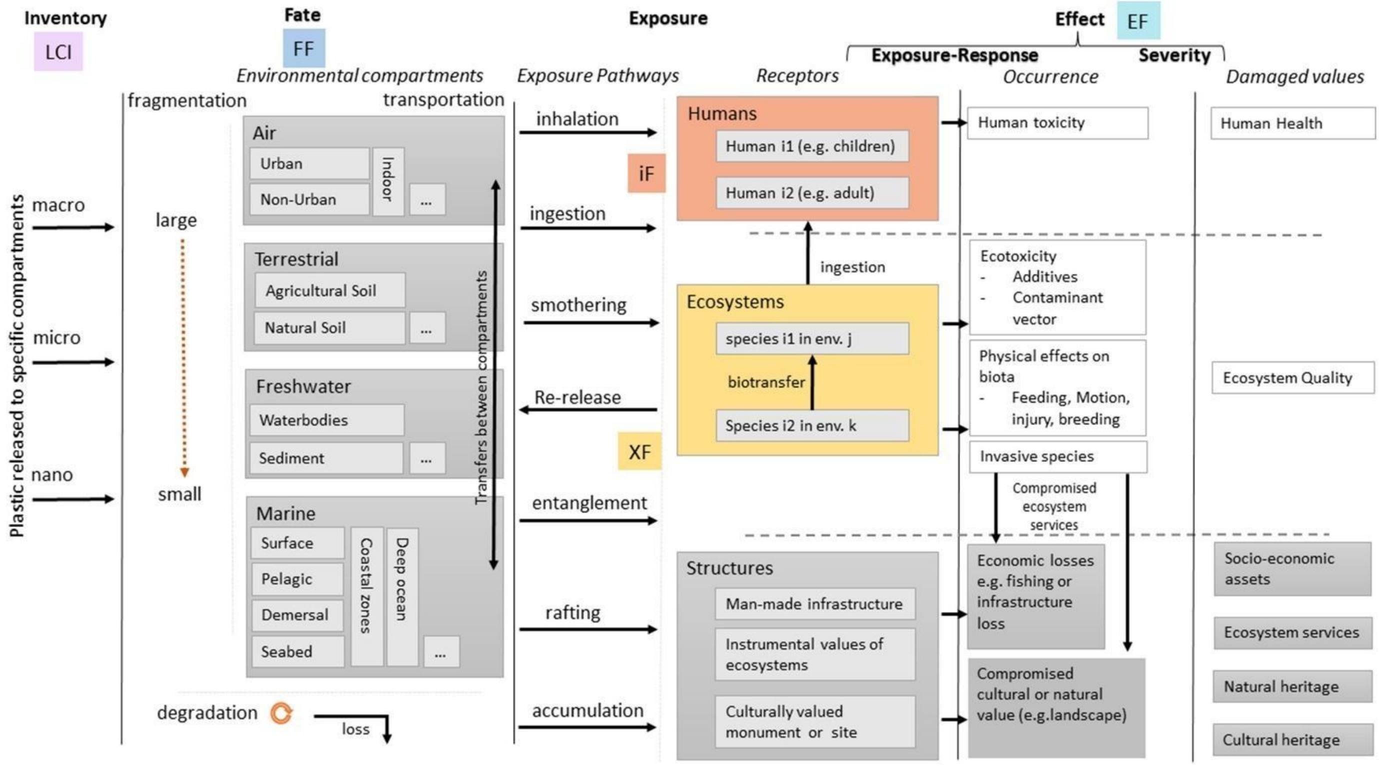


*Figure 7. Marine LCA framework for assessment of microplastics in freshwater*

So, by combining these two models and based on the acquired data for the types and quantities of microplastics, the LCA will be calculated. The proposed LCI for the model which will be used and was sent out to demo sites is presented in Table 8.

*Table 8. Influent/Effluent composition in demo site*

| Influent/Effluent composition (Parameters) | Value |
|---|---|
| *Chemical oxygen demand, total COD (mg $0_2$/L)* | |
| *COD, soluble (mg $0_2$/L)* | |
| *COD, suspended (mg $0_2$/L)* | |
| *Nitrogen, total, N (mg N/L)* | |
| *N, soluble (mg N/L)* | |
| *N, suspended (mg N/L)* | |
| *Phosphorus, total, P (mg P/L)* | |
| *P, soluable (mg P/L)* | |
| *P, suspended (mg P/L)* | |



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| | |
|---|---|
| *Suspended solids, total, TSS (mg TSS/L)* | |
| *Suspended solids, volatile, VSS (mg VSS/L)* | |
| *Suspended solids, inert, ISS (mg ISS/L)* | |
| *Metals (mg/L)* | |
| *Silver* | |
| *Aluminium* | |
| *Arsenic* | |
| *Cadmium* | |
| *Chromium* | |
| *Copper* | |
| *Mercury* | |
| *Manganese* | |
| *Nickel* | |
| *Lead* | |
| *Zinc* | |
| *Barium* | |
| *Cobalt* | |
| *Iron* | |
| *Magnesium* | |
| *Antimony* | |
| *Vanadium* | |
| *Polymers (mg/L)* | |
| *Polypropylene (PP)* | |
| *Polyethylene (PE)* | |
| *Polystyrene (PS)* | |
| *Other....* | |
| *Micro plastic polymer shapes (bead, fiber, film)* | |
| *Microplastic size distribution* | *µm* |

# 3. Social LCA

S-LCA is a methodology used to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle. Unlike traditional Life Cycle Assessment (LCA), which focuses on environmental impacts, S-LCA emphasizes the social dimensions, including human health, labour conditions, and community well-being. It classifies social impacts by impact subcategories ranging from fair salary to community engagement. This framework is particularly useful for addressing complex issues like plastic pollution especially microplastics, where the environmental and social impacts are intertwined. Social LCA follows the ISO 14040 standard developed for environmental LCA and includes the phases of goal and scope, inventory, impact assessment and interpretation.

Positive and negative impacts of plastic pollution can be assessed with a Social LCA. Social Life Cycle Assessment and Environmental Life Cycle Assessment are two of the methods considered in a Life Cycle Sustainability Assessment. Life Cycle Sustainability Assessment is often represented as the addition of Environmental LCA with Social LCA and Life Cycle Costing to provide a complete picture of the three dimensions of sustainability (people, planet, prosperity) [33].

## 3.1 Standards and guidelines

The conduct of the S-LCA studies is governed by several key documents [34], [35] UNEP (2020):

- UNEP Guidelines for Social Life Cycle Assessment of Products: Published by the United Nations Environment Programme (UNEP), these guidelines provide a comprehensive framework for conducting S-LCA. They cover methodological aspects, data collection, and impact assessment

- Global Guidance Principles for Life Cycle Assessment Databases: These principles, developed by the Life Cycle Initiative, aim to harmonize LCA databases, including those used for S-LCA. They ensure consistency and reliability in data collection and analysis

- ISO 14040 and ISO 14044: While primarily focused on environmental LCA, these ISO standards provide a methodological foundation that can be adapted for S-LCA.

S-LCA employs some of the modelling capabilities and systematic assessment processes of Environmental Life Cycle Assessment (E-LCA) combined with social sciences methods. The impact categories and subcategories assessed in S-LCA are those that may directly affect stakeholders positively or negatively during the life cycle of a product. They are largely defined by the international community through its policy frameworks and other social responsibility references, and in respect to the best available science. S-LCA can either be applied on its own or in combination with E-LCA and/or Life Cycle Costing (LCC). It differs from other social impact assessment techniques by its object: products or services and their life cycle; by its scope: the entire life cycle; and its systematic nature: systematic process of collecting and reporting about social impacts and benefits across the life cycle [35] . In recent years, Social Organizational Life Cycle Assessment (SO-LCA) methodology has been developed. It builds on S-LCA methodology, but its object of study differs: SO-LCA focuses on organizations, and their impacts.

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## 3.2 Selection and inventory of social life cycle assessment indicators

Selecting and inventorying indicators for Social Life Cycle Assessment (S-LCA) involves several key steps to ensure that the assessment is comprehensive and relevant. The selection involves several steps:

- Identifying Stakeholders: Determine the relevant stakeholders affected by the product or service, such as workers, local communities, consumers, and society at large.
- Defining Impact Categories: Choose social impact categories that reflect the concerns of the identified stakeholders. Common categories include labour rights, health and safety, community well-being, and socio-economic repercussions.
- Selecting Indicators: Choose specific indicators within each impact category. Indicators should be measurable and relevant to the stakeholders and impact categories. Examples include working hours, wage levels, access to education, and community engagement.

Choosing the right stakeholder in complex social systems is important as the stakeholder categories are at the basis of an S-LCA assessment because they are the items on which the justification of inclusion or exclusion in the scope needs to be provided. Linked to the stakeholder categories are the impact subcategories that comprise socially significant themes or attributes. These subcategories are assessed using impact indicators, of which inventory indicators link directly with the inventory of the product life cycle.

For example, the UNEP [35] guide provides this list of the stakeholders and impact categories that are shown in Table 9.

*Table 9. UNEP List of stakeholder categories and impact subcategories*

| Stakeholder categories | Worker | Local community | Value chain actors (not including consumers) | Consumer | Society | Children |
|---|---|---|---|---|---|---|
| Subcategories | 1. Freedom of association and collective barganing<br>2. Child lbor<br>3. Fair salary<br>4. Working hours<br>5. Forced labor<br>6. Equal opportunities/discrimination<br>7. Health and safety<br>8. Social benefits/social security<br>9. Employment relationship<br>10. Sexual harassment<br>11. Smallholders including farmers | 1. Access to material resources<br>2. Access to immaterial resources<br>3. Delocalization and migration<br>4. Cultural heritage<br>5. Safe and healthy living conditions<br>6. Respect of indigenous rights<br>7. Community engagement<br>8. Local employment<br>9. Secure living conditions | 1. Fair competition<br>2. Promoting social responsibility<br>3. Supplier relationships<br>4. Respect of intellectual property rights<br>5. Wealth distribution | 1. Health and safety<br>2. Feedback mechanism<br>3. Consumer privacy<br>4. Transparency<br>5. End-of-life responsibility | 1. Public commitments to sustainability issues<br>2. Contribution to economic development<br>3. Prevention and mitigation of armed conflicts<br>4. Technology development<br>5. Corruption<br>6. Ethical treatment of animals<br>7. Poverty alleviation | 1. Education provided in the local community<br>2. Health issues for children as consumers<br>3. Children concerns regarding marketing practices |

Another example from an S-LCA study recently published focusing on flexible plastic packaging which has a potential for litter and microplastic pollution in [36] provides another Table of potential stakeholders and impact categories:

*Table 10. S-LCA stakeholder list*

| *Stakeholder* | *Impact subcategory* | *Indicator* | *Units* |
|---|---|---|---|
| *Consumer* | *EoL responsibility* | *• Existence of extended producer responsibility (EPR) policy* | *y/n* |
| | | *• Existence of clear information about EoL options on the packaging* | *y/n* |
| | *Feedback mechanism* | *• Existence of a reporting system for consumer suggestions* | *y/n* |
| *Worker* | *Child labor* | *• Existence of record of proof of age* | *y/n* |
| | *Equal opportunities/discrimination* | *• Existence of formal policy against discrimination* | *y/n* |
| | | *• Percentage of male/female employees* | *%* |

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| *Stakeholder* | *Impact subcategory* | *Indicator* | *Units* |
|---|---|---|---|
| | *Fair salary* | • *Percentage of workers who are paid a living wage or above* | *%* |
| | *Freedom of association and collective bargaining* | • *Percentage of workers identified who are members of labour unions or similar* | *%* |
| | *Health and safety* | • *Extent of safety training* | *h/y* |
| | | • *Percentage of accident/injury in the organization* | *%* |
| | | • *Existence of health risk assessments regarding toxicity* | *y/n* |
| *Local community* | *Access to material resources[a]* | • *Existence of certified environmental management system* | *y/n* |
| | *Local employment* | • *Percentage of local suppliers* | *%* |
| | | • *Percentage of workforce hired locally* | *%* |
| | *Safe and healthy living conditions* | • *Existence of corporate social responsibility reporting* | *y/n* |
| | | • *Existence of risk monitoring by waste collection and processing company or local government* | *y/n* |
| *Society* | *Contribution to economic development[b]* | • *Extent of job creation potential* | *# FTE* |
| | *Technology development* | • *Existence of research and development department* | *y/n* |
| *Value chain actors* | *Suppliers' relationship* | • *Percentage of suppliers from countries with high estimated proportion of modern slavery* | *% suppliers (monetary)* |

The study concludes that a combination of a literature review and two cycles of MCDA resulted in a materiality ranking of 19 social indicators specifically tailored to circular flexible plastic packaging. For the prioritization of indicators, a threshold was established to guide the selection for an entry-level assessment, aiming to ensure the accessibility of S-LCA for non-experts with limited resources. This threshold refers to the selection of the nine most relevant, achievable, and easily interpretable indicators including:

- Existence of record of proof of age,
- Percentage of workers who are paid a living wage or above,
- Existence of certified environmental management system,
- Existence of research and development department,
- Percentage of accident/injury in the organization,
- Extent of safety training,
- Existence of health risk assessments regarding toxicity,
- Percentage of male/female employees,
- and Existence of extended producer responsibility (EPR) policy.

Based on the conclusion of the authors these nine prioritized indicators serve as the basis for the collection of inventory data, which can subsequently be utilized for an entry-level S-LCA while allowing for potential expansion in subsequent assessments.

## 3.4 Challenges with the social LCA

Thes S-LCA challenges include the need to identify complementarities between LCA and S-LCA [37], as there is an observed overlap in the areas of protection (AoP), which are defined to organize all primary impacts [38]. LCA focuses on ecosystem health and natural resources [39-41] alongside human health. The latter is also partially considered by S-LCA [41], besides social or human well-being [35] [42]. Another challenge is the difficulty in using a consistent unit of measurement as endpoint level [42], such as quality adjusted life years [34]. Additionally, there are overlaps and divergences between different general guidelines, such as the UNEP guidelines and PSIA handbook, e.g., regarding the terminology concerning affected stakeholders [40], which should be considered systematically when performing S-LCA [44].

## 3.5 Industry applications regarding to plastic pollution

While they are hundreds of reported actions of cleaning up plastics from rivers and seaside waterfronts engaging smaller companies and local communities, larger corporations are usually careful about engaging in such action. One example of using the social elements in plastic pollution which can be confused with real social components as basis for S-LCA calculations was the initiative started by Henkel in 2017 (Henkel's Recycling Initiatives Include Social Plastic and Partnership with TerraCycle | Plastics Technology) where they partnered with PlasticBank as an initiative to collect plastic waste and turn into currency to fight ocean plastic and help people ascend from poverty. Plastic Bank's primary focus is ocean- bound plastic waste—materials that have not been landfilled and are prone to enter waterways. Henkel collected around 200 tons of »Social Plastic« as they called it and used it in 25 to 59% ration in their plastic packaging mixtures. Similar projects with the Plastic Bank had after that also some other plastic producers or brand owners like Reckitt and Dr. Brown, but no calculated S-LCA report is available for public disclosure.

Among other publicly available case studies, one done by Freepoint [45] where the LCA covered several stages of the recycling process:

- Pyrolysis of Waste Plastics: Converting waste plastics into EcoOil. Hydro-Treatment: Purifying EcoOil to produce ethylene.
- Polymerization: Producing low-density polyethylene (LDPE) granulates from ethylene.

The Social Life Cycle Assessment (S-LCA) component focused on evaluating the social impacts of the recycling process on workers, local communities, and other stakeholders. Key social indicators included:

- Labor Conditions: Assessing the working conditions and safety measures for employees involved in the recycling process.
- Community Health: Evaluating the potential health impacts on local communities due to emissions and waste management practices.
- Economic Benefits: Analysing the economic opportunities created by the recycling facility, such as job creation and local business growth.
- Their findings in the report for the social components were grouped into three main findings:
- Labor Conditions: The study found that the recycling process at Free point Eco-Systems adhered to high safety standards, minimizing occupational hazards for workers
- Community Health: Emissions from the recycling process were within regulatory limits, reducing potential health risks for nearby communities
- Economic Benefits: The facility contributed to local economic development by creating jobs and supporting local suppliers

So, the S-LCA conducted by Freepoint Eco-Systems demonstrated that their plastic recycling process not only mitigates environmental impacts but also provides significant social benefits. Based on the findings we can see that the study stayed in their regulatory frame (with no further details on health burdening) and job creation as the »classic« economic benefit. On the other hand, a study by International Pollutants Elimination Network (IPEN) [45] which documented significant health risks to workers and nearby communities from plastic recycling activities in environments with lower health and safety standards. Their study found that workers and communities near plastic recycling sites are exposed to hazardous chemicals used in plastics. For instance, in Thailand, e-waste workers had blood levels of the toxic flame retardant Dechlorane Plus nearly 40 times higher than nearby organic farm workers. This chemical is linked to neurodevelopmental toxicity and endocrine disruption. In Kenya, the study revealed high levels of dioxin-like PCBs and other toxic chemicals in recycled plastic products and the local food chain. Free-range eggs collected from areas around plastic recycling sites contained toxic chemicals exceeding EU safety limits.

The presence of these toxic chemicals poses significant health risks, including oxidative damage and potential endocrine disruption. A very recent study on the effect of microplastics which are found in and around recycling sites can be found in [46] where several effects were identified by the authors: for reproductive outcomes (sperm quality) and digestive outcomes (immunosuppression) they rated overall body evidence as "high" quality and concluded microplastic exposure is "suspected" to adversely impact them. For reproductive outcomes (female follicles and reproductive hormones), digestive outcomes (gross or microanatomic colon/small intestine effects, alters cell proliferation and cell death, and chronic inflammation), and respiratory outcomes (pulmonary function, lung injury, chronic inflammation, and oxidative stress) they rated the overall body of evidence as "moderate" quality and concluded microplastic exposure is "suspected" to adversely impact them. We concluded that exposure to microplastics is "unclassifiable" for birth outcomes and gestational age in humans based on the "low" and "very low" quality of the evidence.

The authors of this detailed study concluded that microplastics are "suspected" to harm human reproductive, digestive, and respiratory health, with a suggested link to colon and lung cancer. They also advise future research on microplastics to investigate additional health outcomes impacted by microplastic exposure and identify strategies to reduce exposure.

These studies on human health and lack of other available data from the companies underscores the need for stronger global policies to mitigate these health threats to workers and local communities. This is one of the reasons why more detailed S-LCA studies by companies producing or recycling plastics need to be conducted and disclosed to fully evaluate all the potential environmental and social benefits and threats and negative impacts of these facilities.

## 3.6 S-LCA for water treatment facilities

The S-LCA identified potential improvements in the reduction of overtime hours in drinking water treatment plants and wastewater treatment plants; the training of personnel in a constant manner and according to the work needs; the responsibility for a mechanism for constant monitoring of workers' health.; the provision of a salary that meets the needs of workers without compensating this with overtime; and the improvement of safety conditions in the facilities to reduce the risks to health and safety. This study is limited just to workers as stakeholders and does not include wider communities. In an earlier study [47] conducted a study in wastewater treatment plants and identified the following Stakeholders and indicators (Figure 8).

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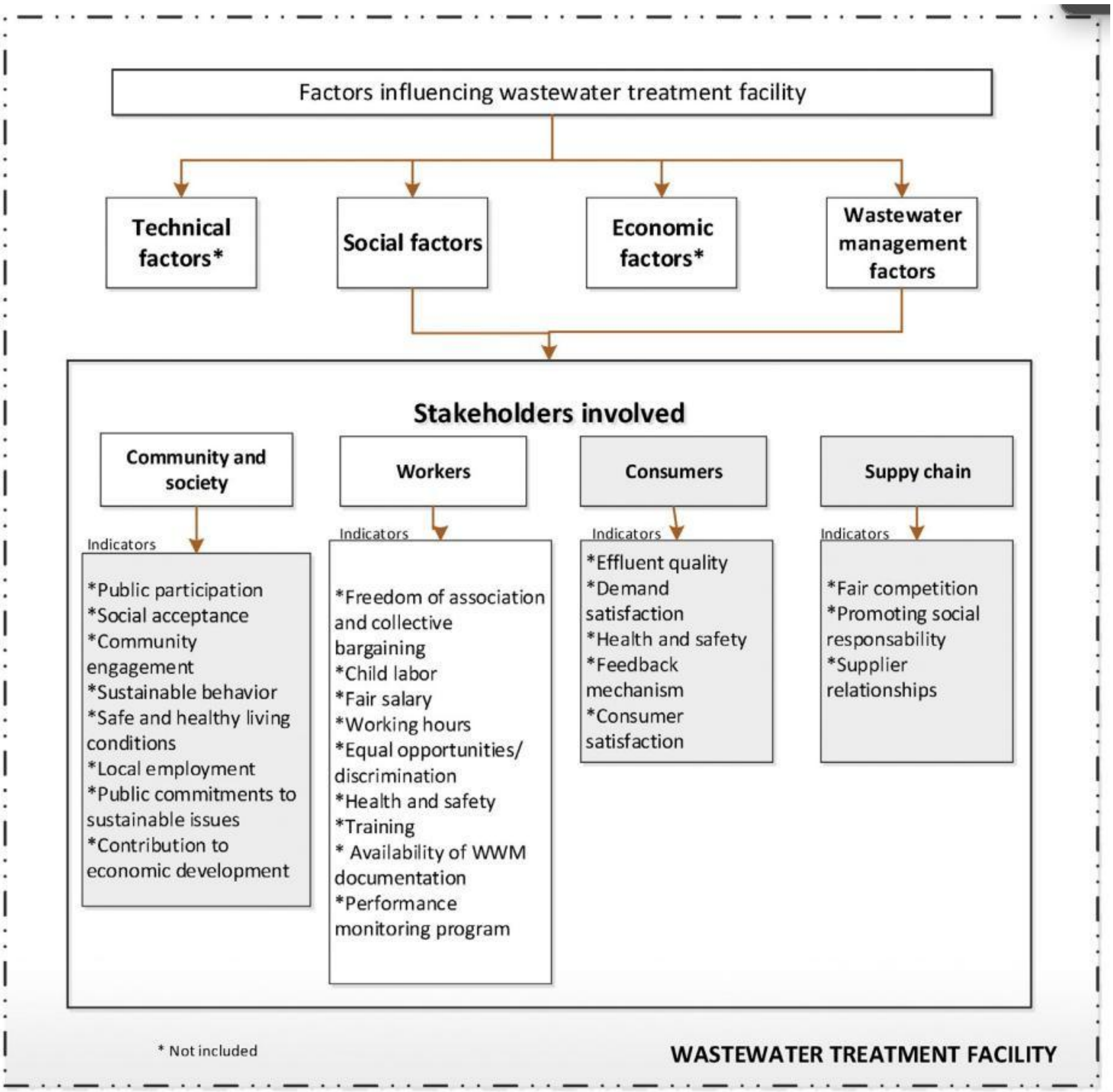


*Figure 8. S-LCA identified stakeholders in the WWTP study [47]*

In another study In the paper by Opher et al. [48], the benefits and social impacts of four alternative re-use of non-potable domestic urban water are compared: (1) central WWT, no urban re-use, the recovered water is discharged into nature; (2) central WWT and urban re-use of the tertiary effluent of the WWTP; (3) semi-distributed grey water treatment and its re-use; and (4) distributed grey water treatment and its re-use within each apartment building.

The selected subcategories and indicators useful for evaluating them are listed as: Public: water saving/equity; Local community: community engagement/local employment/urban landscape; Consumers' health: concerns (level of contact with the reclaimed water, source of the reclaimed water, trust in supplier), household expenses, convenience.

As for the case study, the re-use of distributed urban water resources had a positive impact, due to the promotion of public commitment for natural water resources conservation and the promotion of community commitment.

Of course, these findings are not directly correlated with the microplastic treatment, but similar indicators can be used with additional information to the stakeholder with the benefit and advantage that this water is free from microplastic particles. In a study by [49] they conducted a study focusing on industrial wastewater treatment plants.

For a biopolymer production facility there are almost no available studies focusing just on the S-LCA components, but some elements can be derived from the LCA analysis. Some Critics argue that LCA may not fully capture broader social implications, overlooking aspects such as social equity and socio-economic impacts [50]. The ones to be taken account one trying to do the right S-LCA assessment for biopolymer (bio-based and biodegradable ones) should investigate following areas:

- Land-Use Change: Indirect effects of land-use change, particularly in bio-based materials, are challenging to quantify in LCA.
- Ecosystem Services: Essential benefits from ecosystems may be under-addressed in LCA, neglecting impacts on water purification, pollination, and soil fertility.
- Incomplete Consideration of Externalities: Gaps in considering externalities can lead to underestimating environmental and social impacts.
- Temporal Considerations: LCA's static view might not capture dynamic ecosystem changes, especially concerning slow-release materials like plastics.
- Micro and nano-plastic creation: The consequences of plastic ingestion, as it degrades into micro and nanoparticles have been largely overlooked and underestimated in LCAs.

To overcome these studies regarding micro and nano plastic creation from biodegradable polymers show promising results.

## 3.7 Summary and proposal of S-LCA LCI and framework

As there is no clear pathways for this type of pollutants (micro and nano plastics) we shall use the General Recommendations by UNEP for the S-LCA evaluation of the products for this subcategory of the demo sites.

Another alternative approach could be the inclusion of monetized LCA results in the calculation of a social Cost-Benefit Analysis (CBA) which provided a more extensive view of the secondary environmental costs and benefits of the alternatives for biodegradable plastics (soil based) suggested by [51]. In future work this approach can be translated to water systems, but more data is needed for the biodegradation rate and cleaning efficiency of these kinds of polymers when found in water streams through the proposed wastewater cleaning technologies. This is just asserted by recent findings of [52] which claims highlighted in the recent literature surrounding microplastics and polymer persistence, composting should be adopted as a solution to avoid the generation of microplastics.

As the demo sites are not full-scale water treatment plants and during the initial stage of the value chain mapping, lot of demo sites and partners could not clearly identify the right social stakeholders, we suggest the adaptation of the 9 easy indicators presented in subchapter 3.2 which even demo sites can easily provide.

Of course, for a more detailed impact assessment in the S-LCA calculations this needs to be extended to the infrastructures where the developed demo cleaning equipment will be installed (water treatment facilities, stand-alone utilities, on river mobile utilities…).

# 4. Conclusion

A range of frameworks and methodologies as well as CF databases have been identified suitable for initial LCA and S- LCA build up that will enable assessing the impacts of the matching of Litter(L), Plastic (P) and Microplastic (MP) from demo sites to local stakeholders.

NIC has successfully mapped the LCI inventories needed and will define the scopes and goals with the demo sites after their buildup depending on their technical setup. The results from previous deliverables (mass balance flows) and identifying the stakeholder groups with the value mapping tool helped in shaping and fitting them to existing developed LCA and S-LCA frameworks and models.

Of course, some adjustments will be needed due to different technical setups, but the already developed CF databases like the Marine LCA provide a good starting point if the collected and analyzed microplastic contamination fits the developed database setup. Of course, due to different regions some variances are expected. The initial data input in the form of mass balance (the raw quantity of water treated) needs to be taken into account regarding any adjustments to the possible long-term effects of the plastic, macroplastic and microplastic littering in freshwater river streams in EU.

The social LCA will be done on a limited scope with just 9 parameters as we need to consider that these are demo sites which do not have a larger impact like industrial WWTP. Nevertheless, some suggestions will be made based on the technological setup (inside a WWTP, outside WWTP) for easier identification of future stakeholders in subsequent S-LCA studies.

Based on this analysis we can say that there have been movements in the research fields in the last few years and while there are some almost fully developed LCA frameworks like Marine LCA, the majority of studies in LCA and S-LCA are still lacking reliable data. Also, the evaluation of freshwater biodegradation of biodegradable plastics (mainly done for soil purposes, but which can precipitate in freshwater streams) are still in initial phases of research. The final deliverable (the final LCA and S-LCA assessment of the up and running demo sites) will add more information into this ever-evolving scientific field.

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