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Programmed biodegradation capability of bio-based materials and products, validated in specific environments

MAGICBIOMAT

Manufacturing Guiding Tool for Circular and Programmed Biodegradable Materials Under Open Environment Conditions

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Acronyms

ACDV	Association Chimie du Végétal
ALCA	Attributional Approach
ANSES	Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail
CBA	Cost Benefit Analysis
CLCA	Consequential Approach
CO_2	Carbon Dioxide
CTP	Climate Tipping Potential
EF	Environmental Footprint
ELCC	Environmental Life Cycle Costing
EU	European Union
FU	Functional Unit
GA	Grant Agreement
GHG	Greenhouse gas
GTP	Global Temperature change Potential
GWP	Global Warming Potential
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LUC	Land Use Change
MarILCA	Marine Impacts in Life Cycle Assessment
MFA	Material Flow Analysis
NPV	Net Present Value
OEF	Organisation Environmental Footprint
PEF	Product Environmental Footprint
PE	Polyethylene
PEFCR	Product Environmental footprint category rules
PET	Polyethylene therephlate
PLA	Polylactic acid
PHA	polyhydroxyalkanoates
SB	System boundaries
SDG	Sustainable Development Goals
SHDB	Social Hotspots Database
S-LCA	Social Life Cycle Assessment
WP	Work Package

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1. Executive Summary

Deliverable D7.1 outlines the proposed methodology for evaluating the sustainability performance of the two case studies under investigation in the MAGICBIOMAT project: paper-based coated packaging and mulching film. The selected framework is Life Cycle Sustainability Assessment (LCSA), which integrates three key pillars of sustainability, namely, environmental, economic, and social. Each pillar will be assessed using a distinct but complementary method:

- Environmental impacts will be measured through Life Cycle Assessment (LCA), following ISO 14040/44 standards. Despite limited available data on the biodegradability and development of bio-based materials, the assessment will proceed through the standard four-step LCA approach.
- Economic impacts will be evaluated using Life Cycle Costing (LCC), employing the same structure and system boundaries as the LCA to ensure coherence.
- Social impacts will be assessed via Social Life Cycle Assessment (S-LCA), using and adapting the UNEP Guidelines to the specific context of MAGICBIOMAT.

The full definition of the goal and scope will be detailed in Deliverable D7.2. Data collection will be carried out in collaboration with project partners through regular meetings to ensure accurate and consistent input across the assessments.

2. Introduction

The objectives and ambitions of the MAGICBIOMAT project are to ensure a well-informed and holistic approach to environmental, economic and social dimensions of the proposed solutions of bio-based materials with programmed biodegradability in open environments.

Life Cycle Sustainability Assessment (LCSA) is a comprehensive methodology that evaluates the environmental, economic and social impacts and benefits of products, processes, or services throughout their entire life cycle. LCSA integrates three main approaches: Environmental Life Cycle Assessment, Life Cycle Costing, and Social Life Cycle Assessment, to provide a holistic perspective on sustainability performance. By considering all three pillars of sustainability, LCSA helps decision-makers identify trade-offs, prioritize improvements, and make informed choices that support more sustainable production and consumption patterns. This approach enables organizations and stakeholders to better understand the full range of impacts associated with their activities, ultimately fostering more responsible innovation and value chain management.

The aim of the deliverable D7.1 is to (i) explain the methodology for each pillar, (ii) data collection procedure, and (iii) risks for data collection limitations and their mitigations.

The goals and scope of the LCSA study will be defined in the deliverable D7.2, planned for M18.

3. Problem statement

Plastic pollution and uncontrolled waste littering in open environments remain critical environmental challenges, particularly in agriculture and packaging sectors. Conventional plastic materials, while functional, persist in natural ecosystems and contribute significantly to environmental degradation. The MAGICBIOMAT project addresses this issue by developing a portfolio of circular, bio-based materials—specifically for agricultural mulching films and paper-based coated packaging—with programmed biodegradability across soil, freshwater, and marine environments in diverse EU climates. However, the introduction of biodegradable alternatives raises an essential question: do these materials represent a truly sustainable solution, or do they simply shift the environmental burden? This deliverable aims to define the methodological approach for assessing the sustainability of these innovations, using two case studies for evaluation.

3.1. Case-study 1: Paper-based Packaging

Packaging accounts for 40% of global plastic waste generation and is currently one of the biggest sources of waste littering worldwide (1). Offering biodegradable materials for specific packaging applications can therefore be environmentally relevant to avoid plastic pollution.

The case study will be a paper tray coated with a durable biodegradable acrylics coating. Paper-based packaging is often considered more environmentally friendly than plastics, however, paper-based packaging is the main packaging waste material with 16.1 million tonnes (2). According to the National Litter Pollution Monitoring System in Ireland, paper-based packaging is responsible for 7.3% of litter in 2022 (3). Furthermore, paper-based packaging does not inherently possess certain required packaging properties, such as moisture resistance, durability, etc. Therefore, plastic coating is often applied to the surface of the paper-based packaging to enhance the packaging properties, with non-biodegradable polymers, such as polyethylene (PE), fluorocarbons, polyolefins, and biodegradable materials with slow biodegradation, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA). These coatings present a problem where, although the paper packaging decomposes, the non-biodegradable coating remains, contributing to plastic pollution (4). MAGICBIOMAT aims to develop biodegradable acrylic coating for paper-based packaging with controlled biodegradability to suit specific degradation requirements (short term).

The formulation of the coating is carried out by Task 1.4 from M1 to M16, its development on the paper tray corresponds to WP5 from M17 to M48. The environmental, social and economic impacts of this innovative solution will be compared with a conventional tray (petroleum-based and non-biodegradable). The biodegradation of the packaging tray will be tested in a short-term period (less than 6 months).

3.2. Case-study 2: Mulching film

Mulching is an agricultural practice commonly used for crop production since the mid-1950s with among other benefits: weed control, soil moisture conservation soil moisture conservation and soil temperature regulation.

The consequences for the plant growth are an increased survival after planting and an enhanced vigour, which drive to higher fruiting yields. In the case of vineyard, an extra advantage provided by mulching is to reach grapes bearing age one year earlier. Even if less often used than for short-term crops, mulching films made of PE have also been used for decades in long-term crops such as vineyards. However, non-biodegradable plastic mulch films ended up degrading in the field and progressively broke up into small pieces that are not recoverable at the end of the crop cycle and consequently led to an irreversible and detrimental environmental contamination. Hence, biodegradable polymer films are more and more considered as eco-friendly alternatives to PE (5).

Building upon this growing interest in sustainable mulching solutions, the MAGICBIOMAT project focuses on developing agricultural mulching films with programmed slow biodegradability suitable for open environmental conditions. These films are based on polyester composites selected for their degradation performance using advanced digital tools. Their environmental behaviour will be evaluated through a combination of accelerated aging in laboratory settings and long-term field testing across multiple European bioclimatic zones. These studies will monitor key environmental and material parameters to better understand the degradation processes, including the potential formation of micro and nano plastics. The resulting data will contribute to a comprehensive sustainability assessment, integrated into AI-based modelling tools, to support the development of truly circular and eco-compatible mulching materials.

4. Sustainability Assessment Methodology in MAGICBIOMAT

Since sustainability gains importance for decision making in policy and business cycles, interest in sustainability assessment tools is growing. In order to deal with the three pillars of sustainability, namely environment, economy and society, different assessment tools have been developed (6).

To evaluate the sustainability performance of the two case studies presented in the previous chapter, the Life Cycle Sustainability Assessment (LCSA) methodology will be adopted. LCSA offers a comprehensive and systemic approach by integrating environmental, economic, and social dimensions throughout the entire life cycle of the materials—from resource extraction and production through distribution and use to end-of-life. This integrated perspective is particularly relevant for the MAGICBIOMAT project, where innovative bio-based and biodegradable materials are being developed and evaluated for complex applications. A more detailed definition of the system boundaries, objectives, and assumptions will be provided in Deliverable D7.2.

The LCSA framework was first introduced by Klöpffer and Renner to address the need for multidimensional sustainability assessment in product and process evaluation (7). It combines three distinct and complementary methodologies:

- Life Cycle Assessment (LCA) to quantify environmental impacts,
- Life Cycle Costing (LCC) to assess economic performance across the life cycle, and
- Social Life Cycle Assessment (S-LCA) to evaluate social and societal impacts on stakeholders.

While LCA is the most mature and widely applied of the three pillars, integrating it with LCC and S-LCA enables a more holistic and forward-looking evaluation—particularly important when assessing emerging technologies and materials. The conceptual framework proposed by Guinée et al. (8), which provides methodological structure for integrating the three dimensions, will serve as a key reference for structuring the sustainability assessment within MAGICBIOMAT.

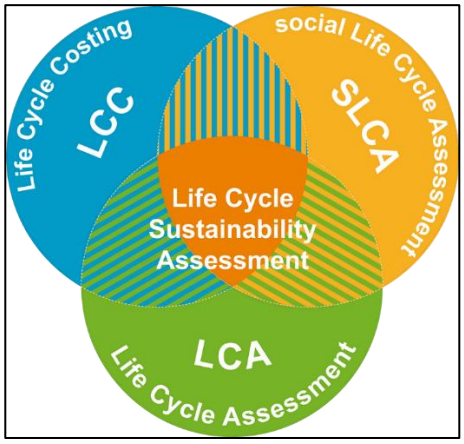


Figure 1: LCSA Framework

5. Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a methodological tool used to assess the environmental aspects and potential impacts associated with a product, process, or service throughout its entire life cycle—from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. Through such a systematic perspective, the transfer of potential environmental burdens between different stages of the life cycle or between particular processes can be identified and avoided.

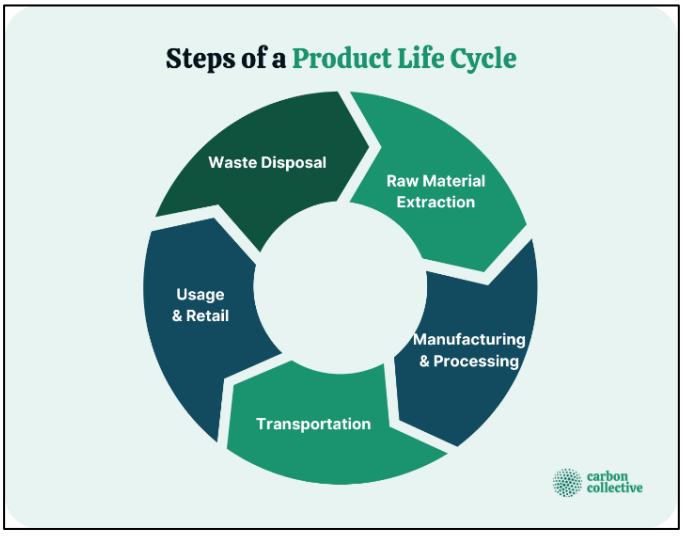


Figure 2: Life Cycle of a product (9)

The LCA methodology is governed by the ISO 14040 and ISO 14044 standards (10) (11). LCA is defined as compilation and assessment of the inputs, outputs and potential environmental impacts of a product system over its life cycle. It's a multi-stage, multi-indicator, multi-system and iterative approach. According to ISO 14040 and ISO 14044 standards, an LCA must be carried out in four interrelated phases:

1. Goal and Scope Definition
2. Life Cycle Inventory (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Results and Interpretation

LCA is an iterative methodology, allowing for continuous refinement of the analysis. If any phase yields unexpected or incomplete results, it can be revisited—along with preceding steps—to ensure consistency and robustness. This characteristic is particularly valuable in the context of MAGICBIOMAT, as it enables us to adapt the analysis if certain data or requirements are missing, ensuring that the evaluation remains as comprehensive and reliable as possible.

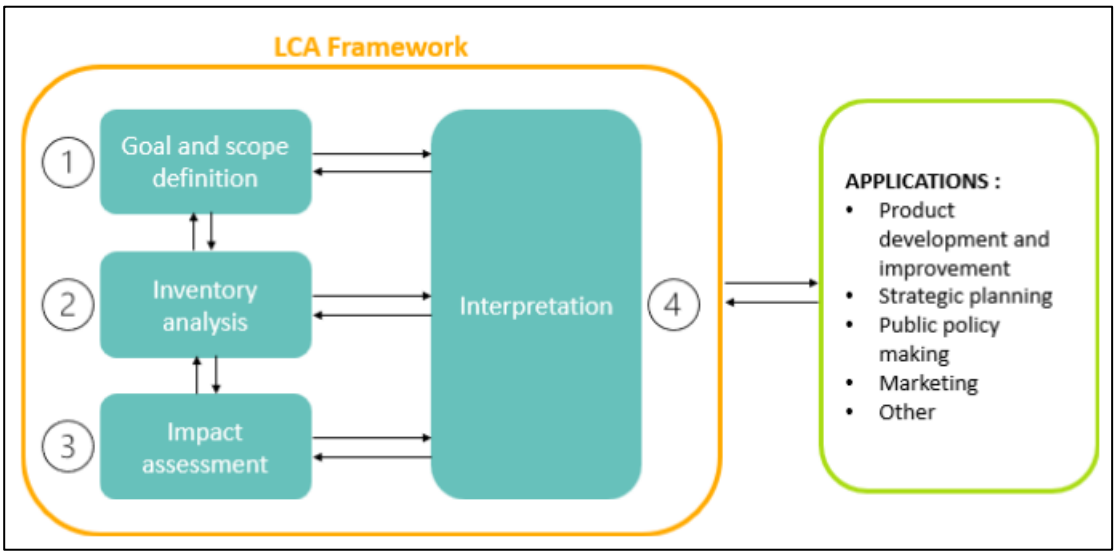


Figure 3 : Stages in the LCA process

Different LCA approaches exist depending on the purpose and context of the assessment. The two main types are: attributional and consequential.

According to the UNEP Guidelines for LCA, the Attributional Approach (ALCA), this method looks at how much of the total environmental impact can be attributed to a specific product throughout its life cycle. It uses existing data and focuses on describing the current situation by assigning a share of global environmental burdens to the product (12).

The Consequential Approach (CLCA): This approach focuses on the environmental consequences of a decision, such as an increase or decrease in demand for a product. It models how systems change in response to that decision, considering only the processes directly affected.

Both consequential and attributional studies can be prospective or retrospective (13), (14), (15). Prospective LCA deals with technologies in the future, whereas retrospective studies deal with products in the past, regardless of other modelling approaches (16).

Given the early-stage nature of the technologies developed in MAGICBIOMAT, a prospective ALCA might be adopted. This method is well-suited for assessing emerging innovations, as it allows for the integration of future scenarios—such as anticipated developments in production processes, energy systems, and end-of-life treatments. This forward-looking perspective is essential for evaluating technologies that are not yet commercially deployed. However, this will be better clarified in D7.2.

5.1. Goal and scope definition

In MAGICBIOMAT, the goal and scope definition phase provide the foundation for conducting a robust and transparent LCA. It establishes the purpose of the study, identifies the intended audience, and outlines how the results will support decisions related to material development, biodegradation testing, and overall environmental

evaluation. This phase also defines the product system—its function, the key life cycle stages, and the core processes to be analysed. A central component is the functional unit (FU), which ensures consistency and comparability across all scenarios assessed. A product system is defined based on a FU of a product, specified in relation to the nature of a system, geographical, and time boundary. The main role of a FU is to be used as a reference to quantitatively connect inputs and outputs of an LCI. In this way, LCA results of the same FU can be compared between one another provided that, among other things, the system boundaries are similar, and the scales are normalized. A proper FU that positively reflects the reality is very important in LCA studies. This is important since different choices of FUs from the same system may result in different outcomes when compared to each other (17).

A critical element of this phase is the determination of system boundaries. For bio-based materials, this is particularly important due to the unique treatment of biogenic carbon flows across the life cycle. In line with ISO 14044, the primary objective of MAGICBIOMAT is to adopt a cradle-to-grave perspective, covering all stages from raw material extraction to end-of-life treatment. However, given that some experimental data (e.g., related to biodegradation or downstream impacts) may still be under development, an initial cradle-to-gate approach may be used as a starting point for preliminary assessments. The goal remains to extend this boundary as more comprehensive data becomes available.

The choice of system boundary plays a significant role in the interpretation and comparability of results. For example, cradle-to-gate studies often omit downstream emissions, which can result in an overestimation of the environmental benefits of bio-based materials. These considerations—as well as related modelling approaches—are further discussed in the Annex A, section 9.1.1.

Overall, the goal and scope definition serve as the structural basis of the LCA and will be further refined in Deliverable 7.2, due in Month 18 of the project.

5.2. Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) phase is a core component of the LCA, involving the systematic collection and quantification of inputs and outputs across all processes in the product system. These include raw materials, energy, water, and auxiliary substances as inputs, and products, co-products, emissions, waste, and by-products as outputs. LCI data typically comes from two sources:

- Primary data, collected directly from partners, manufacturers, or pilot operations (the example template is shown in Table 1);

Table 1: LCA example data collection template

Input	Unit

Raw materials, chemicals	Mass/volume
Energy	Energy unit
Water	Mass/volume
Duration of the operation	Time
Any additional input	Depends on the input
Output	**Unit**
Final product	Depends on the products and on the defined FU
By products	Depends on the products and on the defined FU
Waste	Mass/Volume
Emissions	Mass/Volume

- Secondary data, drawn from established databases (e.g., Ecoinvent), literature, or industry reports when primary data is unavailable.

In MAGICBIOMAT, the LCI will play a central role in assessing the environmental performance of the two case studies. This phase—covered in WP8 between Month 18 and Month 36—will involve gathering and validating material and energy flow data for the developed bio-based products. Given the experimental and evolving nature of these materials, some data gaps and uncertainties are expected. To address this, technical coordination meetings with project partners will be held regularly to collect updated information, clarify system conditions, and jointly validate assumptions. This collaborative and iterative process will help ensure the LCI reflects both the current development stage and realistic scenarios, supporting a robust and context-sensitive LCSA.

A key element within this phase is the definition of allocation and cut-off rules, which affect how multi-output systems and small flows are treated. Although allocation is not the preferred approach, it is sometimes necessary, especially for bio-based systems with multiple co-products. Following ISO 14044 and Product Environmental Footprint (PEF) guidance, the following hierarchy is recommended:

- Subdivision, to avoid allocation by separating processes;
- System expansion, to account for the benefits of co-product substitution;
- Physical allocation (mass or energy-based);

- Economic allocation, based on market value when prices are stable and relevant.

In the case of MAGICBIOMAT, economic or mass allocation may be appropriate depending on data availability and system characteristics. When dealing with biogenic carbon dioxide (CO_2) flows, allocation based on carbon content should also be considered to ensure fair attribution of impacts.

Cut-off rules define which flows may be excluded from the system boundary. According to NF EN 16760 (18) and PEF (19) recommendations, exclusions may be justified if:

- The flow accounts for <1% of product mass or energy;
- The flow is deemed environmentally insignificant.

However, the total exclusions must not exceed 3% of total environmental impact. As noted by Bishop et al., even small flows such as additives can significantly influence results—particularly for bio-based plastics—and should therefore be included whenever possible (20).

To ensure the transparency and robustness of the LCI phase, all assumptions related to allocation and cut-off choices must be well-documented and tested through sensitivity analysis. Additional information is available in the Annex A, section 9.1.1.

5.3. Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) phase translates inventory data into environmental impact indicators. It begins by classifying emissions and resource use into specific categories (e.g., CO_2 emissions under climate change), followed by characterization, which quantifies their potential effects using scientifically established models—such as converting greenhouse gas emissions into CO_2 equivalents. Optional steps such as normalization, grouping, and weighting may support interpretation, although weighting should be applied with caution due to its subjectivity.

Among the various LCIA methods, the Environmental Footprint (EF) methods (21)—developed by the European Commission (EC)—provides a comprehensive and harmonized framework. Specifically, the PEF is designed for product-level assessment and includes 16 impact categories listed in covering key environmental concerns.

Table 2: Impact Categories included in the PEF method.

Impact Category	Impact Category Indicator (unit of measure)	Description
Climate change, total	Radiative forcing as global warming potential – GWP100 (kg CO_2 eq)	Increase in the average global temperature resulting from greenhouse gas emissions (GHG)
Ozone depletion	Ozone Depletion Potential – ODP (kg CFC-11 eq)	Depletion of the stratospheric ozone layer protecting from hazardous ultraviolet radiation
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	Impact on human health caused by absorbing substances through the air, water, and soil. Direct effects of products on humans are not measured
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh)	Impact on human health caused by absorbing substances through the air, water, and soil. Direct effects of products on humans are not measured
Particulate matter	Impact on human health (disease incidence)	Impact on human health caused by particulate matter emissions and its precursors (e.g. sulfur and nitrogen oxides)
Ionising radiation, human health	Human exposure efficiency relative to U-235 (kBq U-235 eq)	Impact of exposure to ionising radiations on human health
Photochemical ozone formation, human health	Tropospheric ozone concentration increase (kg NMVOC eq)	Potential of harmful tropospheric ozone formation ('summer smog') from air emissions
Acidification	Accumulated Exceedance – AE (mol H^+ eq)	Acidification from air, water, and soil emissions (primarily sulfur compounds) mainly due to

		combustion processes in electricity generation, heating, and transport
Eutrophication, terrestrial	Accumulated Exceedance – AE (mol N eq)	Eutrophication and potential impact on ecosystems caused by nitrogen and phosphorous emissions mainly due to fertilizers, combustion, sewage systems
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (kg P eq)	Eutrophication and potential impact on freshwater ecosystems
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (kg N eq)	Eutrophication and potential impact on marine ecosystems
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	Impact of toxic substances on freshwater ecosystems
Land use	Soil quality index (Dimensionless – pt)	Transformation and use of land for agriculture, roads, housing, mining or other purposes. The impact can include loss of species, organic matter, soil, filtration capacity, permeability
Water use	Weighted user deprivation potential (m^3 world eq)	Depletion of available water depending on local water scarcity and water needs for human activities and ecosystem integrity
Resource use, minerals and metals	Abiotic resource depletion – ADP ultimate reserves (kg Sb eq)	Depletion of non-renewable resources and deprivation for future generations
Resource use, fossils	Abiotic resource depletion, fossil fuels – ADP-fossil (MJ)	Depletion of fossil resources and energy for future generations

In the context of MAGICBIOMAT, the goal is to follow the PEF framework as a reference to ensure methodological consistency and comparability. However, given the innovative nature of the materials and the uncertainty around data availability and system requirements, we do not commit to strict adherence to PEF. Instead, we will adopt a

flexible and case-sensitive approach, selecting impact categories and methodological elements based on their relevance to the case studies and robustness of the available data.

While climate change will remain a central focus of the LCIA, other categories commonly assessed in bioplastic LCAs—such as land use, water use, eutrophication, and acidification—may also be included where appropriate. Additional details on LCIA practices and impact category selection can be found in Annex A, sections 9.1.3 and 9.1.4.

5.4. Results and Interpretation

The interpretation phase is the final step of the LCA, where the results from the inventory analysis and impact assessment are examined to drive conclusions aligned with the study's objectives. This phase begins with the identification of key contributors and environmental hotspots, followed by a critical evaluation of the study's completeness, sensitivity, and consistency to ensure methodological robustness. Based on this evaluation, conclusions are drawn and, where relevant, recommendations for improvement are formulated. Transparency is essential at this stage; therefore, all limitations, assumptions, and uncertainties must be clearly documented. If the results are intended for public disclosure or comparative assertions, an independent critical review, as required by ISO 14044, must be conducted to ensure the credibility and reliability of the findings. Overall, this phase plays a vital role in translating complex life cycle data into meaningful insights to support informed and responsible environmental decision-making.

5.5. Literature review of LCAs for bioplastics and End of Life (EoL)

While general LCA frameworks and methodologies are well established, there is currently a lack of sector-specific guidance tailored to bio-based and biodegradable materials—particularly those relevant to the solutions being developed in the MAGICBIOMAT project. As a result, existing LCAs in this field often vary significantly in terms of scope, assumptions, and modelling choices. This lack of harmonization limits the comparability of studies and makes it challenging to draw robust conclusions about the environmental advantages of bio-based materials over their petrochemical counterparts.

To support the development of a suitable LCA framework for MAGICBIOMAT, a targeted literature review was conducted. Studies were selected based on the following criteria: (i) they assess the environmental performance of bio-based and/or biodegradable products in comparison with fossil-based alternatives, preferably in applications such as packaging or mulch film; (ii) they follow established LCA standards (ISO 14040 and ISO 14044); and (iii) they were published from 2000 onwards.

Among the key references, three comprehensive reviews provide a valuable overview of methodological practices and recurring challenges in the LCA of bio-based products:

- Bishop et al. (2021) (20): Synthesized findings from 44 LCAs of bioplastics, emphasizing gaps in data transparency and biodegradability modelling.
- Spierling et al. (2018) (22): Reviewed 29 LCAs (including LCC and S-LCA) on bio-based products, highlighting the variability in system boundaries, impact categories, and allocation choices.
- Xue Leping (2022) (23): Focused on 26 LCAs comparing PLA with fossil-based plastics, identifying key sensitivities in modelling assumptions.

A recurring issue in the literature concerns how the end-of-life (EoL) phase of biodegradable plastics is modelled. Many LCAs assume complete aerobic mineralization of the material, meaning 100% of its carbon content is converted into CO_2 (22). While this simplifies modelling, it does not always reflect real-world conditions where degradation may be partial or context dependent. The European Commission's Joint Research Centre (24) recommends using this assumption as a conservative estimate when no specific data is available, but it also stresses the importance of integrating material -and environment- specific degradation data to improve reliability.

This approach aligns with the concept of carbon neutrality, where the net impact is represented as (0;0). An alternative is the temporary storage approach (−1;+1), which incorporates the time dynamics of carbon fluxes. In this method, a negative impact (−1) is assigned to the CO_2 uptake during biomass growth, and a corresponding positive impact (+1) is applied when the CO_2 is eventually released at the end of life. This framework acknowledges the climate benefit of delaying emissions, offering a more nuanced and time-sensitive perspective for modelling carbon impacts. More details are provided in the Annex A, section 9.1.3

Although several experimental and theoretical models exist to describe the biodegradation of plastics across various conditions (e.g., home composting, in-situ soil degradation), few LCA studies integrate these models in a consistent and robust manner. The lack of alignment between biodegradation science and life cycle modelling further limits the comparability of existing studies. A detailed overview of available biodegradation models and their relevance for LCA is presented in Annex A, section 9.1.5.

Further methodological support is provided by the technical report FD CEN/TR 16957 *"Bio-based products – Guidelines for Life Cycle Inventory (LCI) for the end-of-life phase"*, which outlines how to build life cycle inventories for various EoL scenarios, including reuse, recycling, incineration, landfilling, and environmental release. This is particularly relevant for MAGICBIOMAT, where understanding the biodegradation pathways—especially in soil and home compost—will be key to generating accurate and context-sensitive environmental impact assessments.

5.6. Challenges to perform LCA on innovative emerging technologies

The Life Cycle Inventory (LCI) phase is arguably the most challenging step of the assessment, as it requires extensive collaboration with various stakeholders to gather accurate and comprehensive data. One major limitation is the lack of direct access to on-site operations, which makes it difficult to fully understand which

processes and flows are most relevant for the analysis. To address this, the LCI will rely on the specific knowledge of project partners involved in each phase of the life cycle.

To manage uncertainty and improve data quality, an iterative data collection strategy will be used. This involves gathering an initial dataset, reviewing and refining it through documented assumptions or substitutions, and then validating the results with the relevant partners. This process will be repeated as many times as needed to ensure a consistent and realistic representation of the systems under study.

Another constraint lies in the availability of secondary data. Although databases like Ecoinvent provide a wide range of background processes, they often lack the specificity required to model innovative or emerging technologies such as those developed in MAGICBIOMAT. Consequently, additional assumptions and expert input will be necessary.

Finally, as previously noted, there is a lack of robust and standardized research on bio-based materials and biodegradation models. This gap further complicates the LCI, as the modelling of EoL scenarios and degradation behaviour remains uncertain. These limitations highlight the need for a cautious, transparent approach, which will be complemented by methodological insights provided in Annex A.

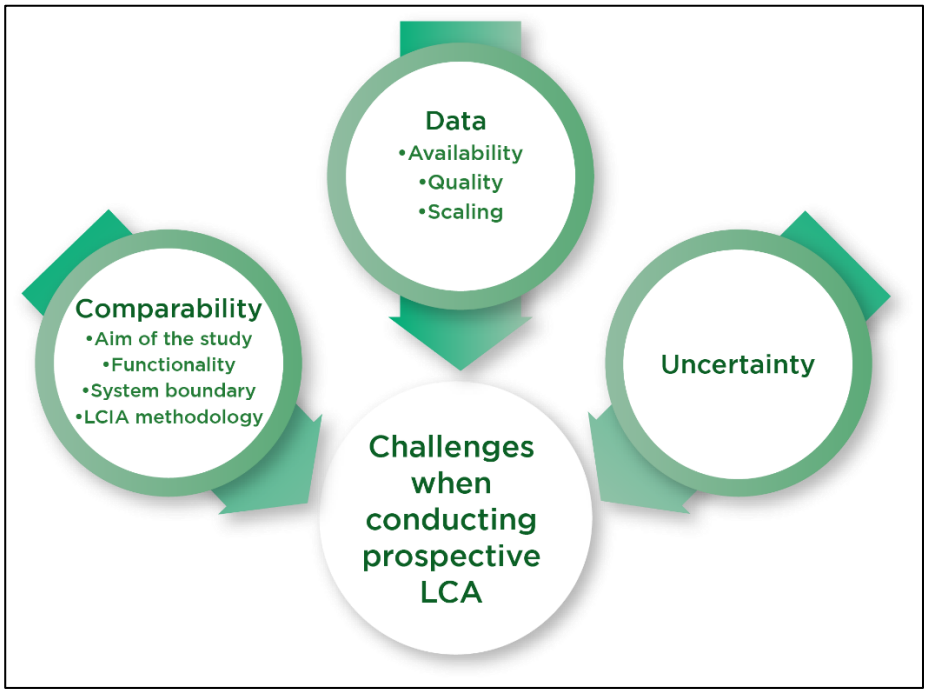


Figure 4: Challenges in performing LCA

6. Life Cycle Costing (LCC)

Life Cycle Costing (LCC) assesses the economic performance of a product or a service over its lifetime. The LCC analysis balances the initial financial investment with the long-term ownership and operational investments. In

other words, the methodology of performing LCC consists of estimating the total cost of a product or service, considering its whole life cycle, direct and external costs (e.g., material acquisition, annual costs of operations & maintenance, decomposition costs at the EoL cycle) (25). Businesses and Governments often perform LCC analysis to select the most cost-effective (i.e., least cost) approach among various product alternatives to achieve the lowest long-term cost of ownership (26). This is evident in the public tendering prospect of the EU. Under the 2014 EU procurement rules, a contract must be awarded based on the most economically advantageous tender (27).

Different types of LCC exist and summarised in the Table 3: Differences between the three LCC types presented in the Environmental Life Cycle Costing book (28): Conventional LCC, Environmental LCC and Societal LCC.

Table 3: Differences between the three LCC types (28)

Aspect	Conventional LCC	Environmental LCC	Societal LCC
Value added compared to conventional LCC	—	Consistent environmental assessment (LCA) at the same time and consistent approach for sustainability assessments of products	Opportunity costs or credits considered
Product system (model)	Life cycle, without EoL phase (and sometimes use phase) if not borne by main actor	Complete life cycle	Complete life cycle
System boundaries	Only internal costs	Internal costs, plus external costs expected to be internalized	Internal plus all (costs of) externalities
Perspectives: actors	Mainly 1 actor, either the manufacturer or the user or consumer	One or more actors connected to the product life cycle, mainly manufacturers, supply chain, and end user or consumer	Society overall, including governments
Reference unit	Item or product	Functional unit	System
Cost categories	Mainly acquisition costs (R&D and investment costs) and ownership costs (operating costs, disposal costs)	Mainly costs of development, materials, energy, machines, labour, waste management, emission controls, transport,	Mainly costs of construction, maintenance, and environmental damages; taxes and subsidies have no net cost effect

		maintenance and repair, liability, taxes, and subsidies	
Cost model	Generally quasi-dynamic model	Steady-state model	Generally quasi-dynamic model
Discounting of result of LCC	Recommended (but usually not applied)	Inconsistent and not recommended	Recommended
Discounting of cash flows for calculation	Recommended	Recommended	Recommended
LCA according to ISO14040/44 (2006)	No	Yes	Not recommended due to risk of double counting and inconsistencies
Use in life cycle management (LCM)	Mostly internal decision making to private organization and supply chain considerations	Mostly internal decision making of producer or user of product, but also for external communication (similar to LCA)	Mostly internal to public organizations

According to the table, the most suitable approach for MAGICBIOMAT is the Environmental Life Cycle Costing. The following section provides a more in-depth investigation of the methodology and its potential application to the project.

For a more detailed explanation of the different types of LCC, please refer to the Annex B, section 9.2.1

6.1. Life Cycle Costing (LCC) in MAGICBIOMAT

Following the Environmental Life Cycle Costing (ELCC) approach proposed by Hunkeler (28), the scope of analysis is organized around a conceptual framework that reflects the physical life cycle of a product. This framework includes five key stages:

1. Research and development
2. Production of materials or components
3. Manufacturing
4. Use and maintenance
5. EoL management

Within this structure, two main categories of costs are identified:

- Internal costs: These are costs incurred directly by actors involved in the product system — such as producers, transporters, consumers, or EoL operators. “Internal” indicates that these costs are borne within the economic system and can be linked to specific business expenditures or revenues. They may occur either within or outside an individual organization, depending on the scope and stakeholder perspective.
- External costs (externalities): These refer to costs that are already expressed in monetary terms and are expected to be internalized in the foreseeable future (e.g., via regulations or market mechanisms). Importantly, ELCC does not attempt to convert environmental impacts into monetary units; instead, it maintains a clear distinction between economic and environmental assessments to avoid double counting. External costs included in LCC must not overlap with those assessed separately in the complementary LCA.

Given the lack of a formally defined and widely standardized framework for LCC—unlike LCA, which is governed by ISO 14040 - 14044—it is common practice to apply the same ISO structure as a reference, adapting it to a cost perspective. This alignment ensures methodological coherence, especially when LCA and LCC are performed together, as is the case in MAGICBIOMAT.

In this context, the LCC methodology for MAGICBIOMAT will follow a structured, iterative process composed of seven main steps. These steps support a comprehensive and consistent economic assessment across the product’s life cycle:

1. Problem Definition: Clearly identify the issue to be addressed.
2. Cost Elements Definition: Determine all relevant cost factors.
3. Data Collection: Gather necessary data for analysis.
4. System Modelling: Create a model to represent the cost system.
5. Cost Profile Development: Develop a detailed cost profile.
6. Evaluation: Assess the cost profile against objectives.
7. Result Reporting: Present findings and recommendations.

Each of the above steps can be further broken down into sub-steps realising a concept map (shown in Figure 5) of the LCC assessment that MAGICBIOMAT will undertake.

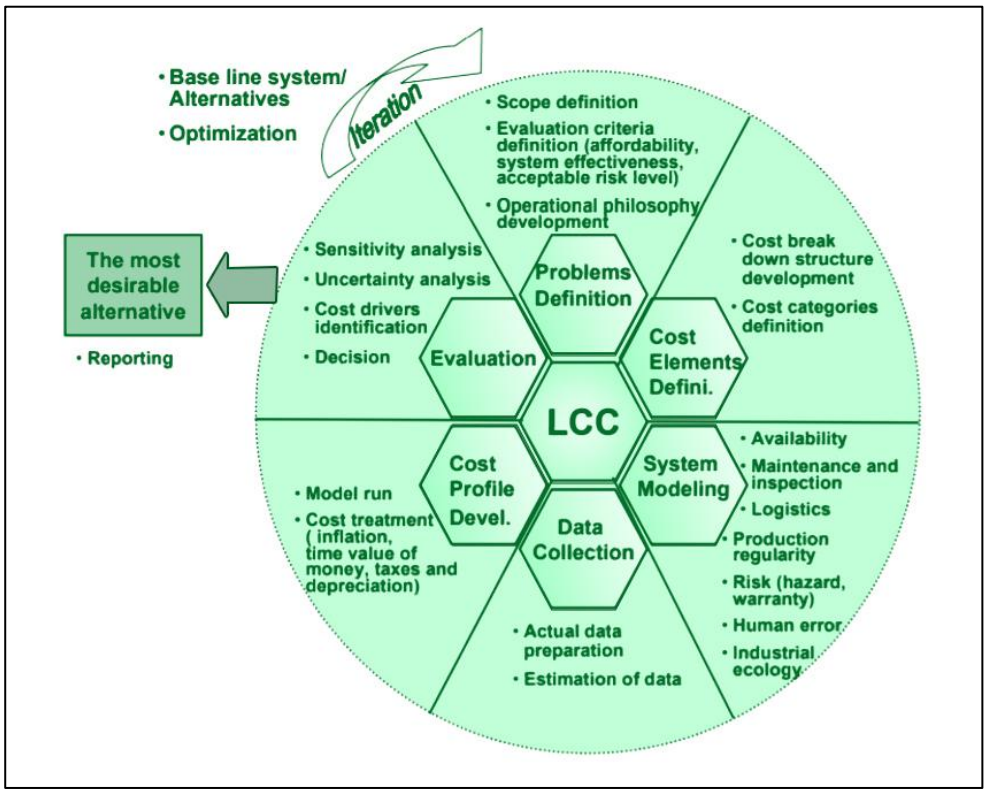


Figure 5: Overall concept map of LCC detailing each step

In the MAGICBIOMAT project, the LCC assessment will be conducted in parallel with the LCA, aiming to systematically collect economic data corresponding to each specific life cycle stage of the product. As with the LCA, stakeholder engagement will be essential; therefore, a series of structured meetings will be organized with project partners and other relevant actors to obtain cost-related information. To support data collection and ensure consistency, a generic cost template may be used as a starting point. This structure will be progressively refined as the project advances and as more detailed knowledge regarding process flows, inputs, and outputs becomes available.

Table 4: LCI sample data collection template

LCI Template Field	Adaptation for Cost Data (Manufacturing Example)
Process Name	Process Name
Material Input (kg)	Material Input (kg) + Material Cost ($/kg)
Energy Input (kWh)	Energy Input (kWh) + Energy Cost ($/kWh)
Labor Hours	Labor Hours + Labor Cost ($/hour)
Equipment	Equipment Type + Depreciation/Lease Cost
Waste Output (kg)	Waste Output (kg) + Disposal Cost ($/kg)
References	References for all cost data sources
Uncertainty Assessment	Cost data uncertainty (range, confidence, pedigree score)
Comments/Notes	Cost assumptions, calculation methods, special conditions

6.2. Differences with Cost-Benefit Analysis

It is particularly interesting to explore why LCC is often adopted in place of—or alongside—Cost–Benefit Analysis (CBA) in sustainability assessments. While both tools aim to evaluate economic aspects, their underlying assumptions, analytical focus, and methodological approaches differ significantly. Understanding these distinctions can help clarify when and why LCC might be the more appropriate choice, especially in product-based evaluations where alignment with environmental and social assessments (e.g., LCA and S-LCA) is crucial.

Hoogmartens et al. address the increasing complexity and confusion in sustainability assessments stemming from the proliferation of tools such as LCA, LCC, and CBA (6). The authors propose a framework to clarify the distinctions, overlaps, and complementarities among these methodologies, with the goal of supporting their more coherent and integrated application.

LCA, as introduced earlier, focuses on evaluating the environmental impacts of products or processes over their entire life cycle, in accordance with ISO 14040/44 standards. LCC, while following a similar life cycle approach, shifts the lens to economic costs incurred throughout the life span of a product, including acquisition, operation, maintenance, and end-of-life phases.

In contrast, CBA adopts a broader evaluative scope by assessing the total net benefits—economic, environmental, and social—of a project or policy. It does so using discounted cash flow techniques to compute the net present value (NPV), placing particular emphasis on the time value of money and societal welfare.

While all three tools contribute valuable insights to sustainability assessment, they diverge in several fundamental ways:

- Analytical Focus: LCA and LCC are product-centered, often used to compare alternative products or systems. CBA, however, is typically project- or policy-oriented, evaluating whether an intervention yields positive societal returns.
- Scope and System Boundaries: LCA and LCC consider the full product life cycle, including upstream and downstream processes. CBA is usually bounded by the duration of a project and its direct impacts, which may result in different assumptions, particularly regarding infrastructure and capital goods.
- Use of Reference Scenarios: LCA and LCC are inherently comparative, requiring a baseline or alternative product for meaningful analysis. CBA, by contrast, can be applied to a single intervention without comparison, focusing instead on its standalone costs and benefits.
- Treatment of Time (Discounting): CBA relies heavily on discounting future costs and benefits to present value terms, which can influence how long-term environmental or social impacts are valued. LCA and LCC may apply discounting to some extent in economic assessments but are less dependent on it conceptually.
- Valuation of Labor: Labor is treated differently across these tools. In social LCA and social LCC, labour may be seen as a social benefit (e.g., job creation), while in social CBA, labour is often treated as a cost to society. This distinction reflects underlying assumptions about labour markets and social welfare.
- Handling of Scarcity: LCA generally interprets resource scarcity as a societal concern and supports strategies like resource efficiency or recycling. CBA assumes that scarcity is reflected through market prices, although this presumes that markets function efficiently and discount rates align with societal preferences—assumptions that may not always hold.

Despite these differences, the tools share some conceptual intersections. LCA and LCC are frequently used in tandem to assess the environmental and economic aspects of the same system. LCC and CBA both involve monetary valuation, albeit with differing scopes and time treatment. Environmental Impact Assessment (EIA)

concepts underpin both LCA and CBA. Moreover, all three tools can address aspects of social inequality, though different lenses.

To support integration and reduce fragmentation, Hoogmartens et al. propose a harmonized framework that aligns key methodological elements across tools—such as metrics, data structures, scope definitions, discounting practices, and valuation techniques (6). In doing so, they highlight as a promising unifying approach. LCSA merges the strengths of LCA and LCC while incorporating social dimensions, offering a comprehensive framework for assessing environmental, economic, and social sustainability.

7. Social Life Cycle Assessment (S-LCA)

Sustainability relies on a three-pillar approach encompassing environmental, economic, and social dimensions. To address the social pillar, Social Life Cycle Assessment (S-LCA) extends the life cycle perspective by integrating human and ethical considerations into sustainability assessments. In MAGICBIOMAT, a structured S-LCA framework—aligned with UNEP/SETAC guidelines—will be applied to evaluate social impacts across the product and service life cycles. Unlike the more quantitative LCA, S-LCA adopts a qualitative lens, focusing on the socio-economic effects on stakeholders throughout the value chain.

7.1. S-LCA Standards and Guidelines

The recently published ISO 14075:2024 standard formalizes the methodological framework for conducting S-LCA of products, expanding the ISO 14000 family's coverage of sustainability assessments beyond environmental impacts. Rooted in the life cycle perspective, ISO 14075:2024 provides the foundational structure for applying S-LCA by defining requirements and guiding principles across its four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. Unlike the more prescriptive ISO standards for environmental LCA (e.g., ISO 14040 and ISO 14044), ISO 14075 adopts a flexible approach, reflecting the evolving nature of social indicators and methodological diversity in S-LCA practice. This standard builds upon earlier conceptual developments, notably the UNEP/SETAC Guidelines (2009; 2020), which emphasize stakeholder-centred analysis and the evaluation of socio-economic impacts across the entire value chain. ISO 14075 reinforces the alignment of S-LCA with international sustainability goals, such as the UN Sustainable Development Goals (SDGs), by promoting assessments that highlight both positive and negative social impacts (29). As noted by Traverso et al., the standardization of S-LCA is a critical step toward mainstreaming social considerations in product sustainability assessments and ensuring greater methodological consistency (32). Nevertheless, ISO 14075 deliberately refrains from dictating specific impact pathways or indicators, allowing practitioners to tailor assessments to sectoral and regional contexts—an approach particularly relevant in innovative projects like MAGICBIOMAT, where stakeholder engagement and contextual sensitivity are essential (30), (31), (32).

Although ISO 14075:2024 now provides an internationally recognized framework for conducting S-LCA, its practical implementation remains limited, as the standard is still in its early stages of adoption. Currently, there are no publicly available case studies that fully apply ISO 14075 as the methodological foundation for a complete S-LCA. As a result, most practitioners continue to rely on the well-established UNEP/SETAC Guidelines (2009; updated 2020), which offer more detailed procedural guidance and indicator sets. These guidelines have served as the de facto reference for S-LCA applications over the past decade and remain the most widely used and validated approach (31). In the context of the MAGICBIOMAT project, adopting the UNEP Guidelines therefore represents the most robust and reliable strategy, ensuring methodological consistency while aligning with internationally

accepted practices. At the same time, the structure and principles introduced in ISO 14075 can inform and complement the assessment, particularly as the standard becomes more widely implemented in future studies.

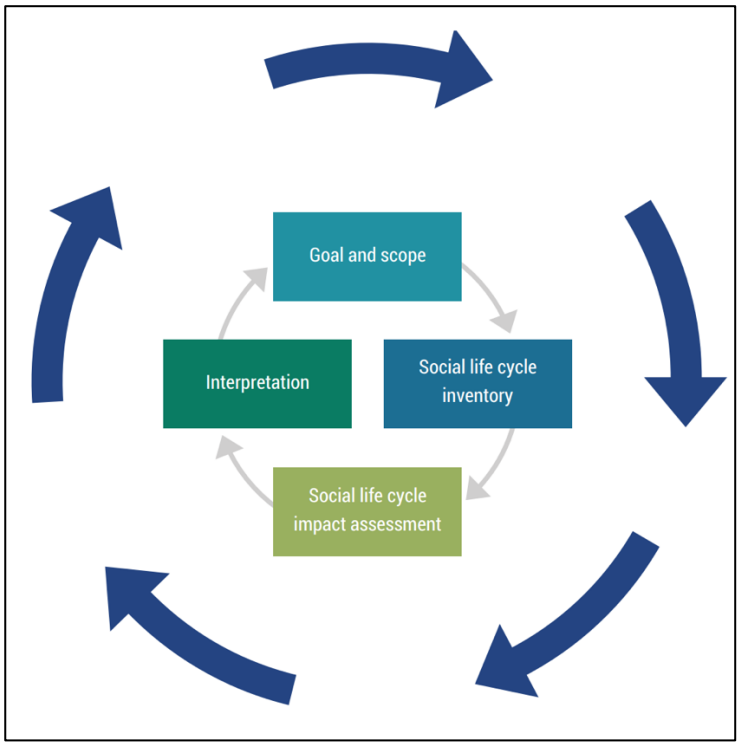


Figure 6: S-LCA iterative phases (31).

7.2. S-LCA in MAGICBIOMAT

The S-LCA within the MAGICBIOMAT project will follow the ISO 14075 framework, operationalized through the UNEP/SETAC Guidelines (2009; 2020) (31). This methodological structure defines social impacts as the outcomes of interactions occurring throughout a product's life cycle—whether during production, use, or end-of-life stages, or as a result of proactive or preventive stakeholder actions (e.g., the implementation of workplace safety standards).

The core structure of the S-LCA is built on two interrelated dimensions:

1. Stakeholder Categories – Identifying who is affected by the product system (e.g., workers, local communities, consumers, value chain actors, and society at large).
2. Impact Categories – Clarifying what types of social consequences are being assessed (e.g., working conditions, human rights, access to basic needs, and community well-being).

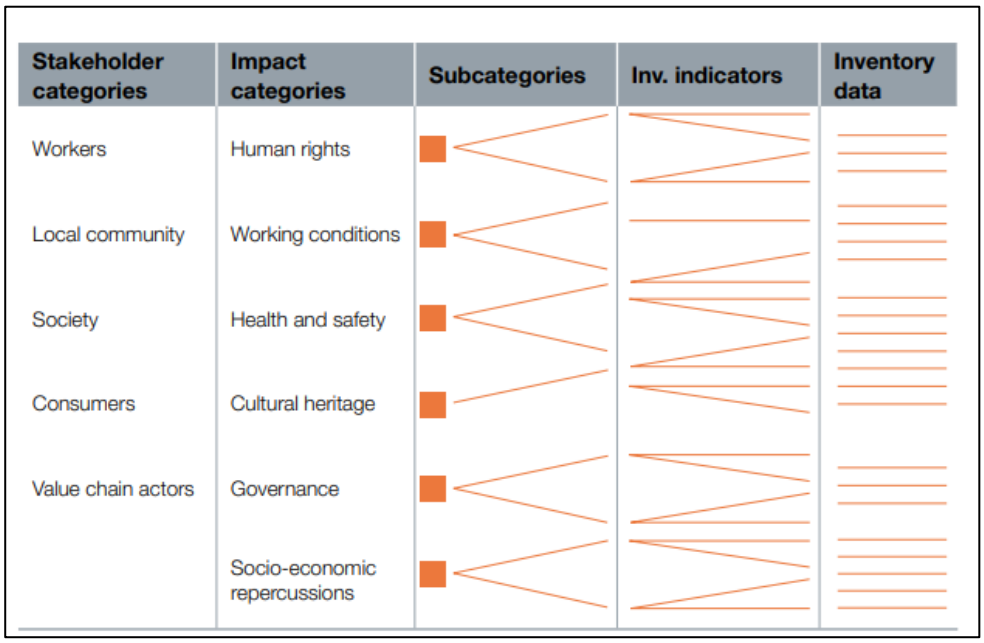


Figure 7: Assessment system from categories to unit of measurements, from the UNEP Guidelines 2020 (31)

At the intersection of these dimensions lie subcategories, which reflect specific social issues such as fair salary, child labour, or social security. These subcategories form the foundation of the inventory phase, guiding the development of indicators and ensuring thematic and stakeholder relevance (31).

In the MAGICBIOMAT context, this structure will be used to define relevant social aspects after the goal and scope are formally established in Deliverable D7.2. The operational sequence will be as follows:

1. Hotspot Identification – Social hotspots will be identified using secondary data and preliminary engagement with stakeholders. The Social Hotspots Database (SHDB) can be used with their online Risk Mapping Tool for the secondary data acquisition. The Risk Mapping Tool enables the identification and assessment of potential risks according to the activity sectors and countries involved in the supply chain. This tool supports identifying the highest social risks (country, sector) and which issues are the most concerning (impact categories). It graphically illustrates the data from the SHDB database. More accessible than raw data analysis, the Risk Mapping Tool makes it easier to identify and prioritize risk areas of the project.
2. Framework Orientation – Based on hotspot findings, the study will adopt either a stakeholder-focused or impact-focused orientation, depending on which better aligns with the project scope.
3. Indicator and Questionnaire Development – Tailored questionnaires will be developed based on identified subcategories and directed to relevant project partners and stakeholders.

The expected outcome is a qualitative analysis that integrates into the broader LCSA of the project, offering a people-centred view of the socio-economic impacts linked to the novel materials and systems developed within MAGICBIOMAT.

7.3. Complementary Tools to the UNEP Guidelines for Operationalizing S-LCA

Although most current research relies heavily on the UNEP Guidelines for Social Life Cycle Assessment (S-LCA), there are additional resources that build upon these guidelines with the aim of providing a more operational and application-oriented framework. These resources could be particularly relevant for the MAGICBIOMAT project in the implementation of S-LCA, as they align with UNEP's foundational approach while offering more practical tools. Among these are:

1. The Handbook for Product Social Impact Assessment, which offers methodological guidance for assessing social impacts at the product level and operationalizing social indicators (33);
2. Social Life Cycle Metrics for Chemical Products, which tailor social life cycle assessment methodologies specifically for the chemical sector, offering metrics and indicators applicable to material innovations such as those developed within MAGICBIOMAT (34).

These sources may serve as valuable complements to the UNEP Guidelines, helping translate their broader principles into more actionable procedures suitable for our case studies.

8. Conclusion

The MAGICBIOMAT LCSA methodology is designed to support the continuous improvement of the products and processes developed in the project by providing a comprehensive sustainability assessment across environmental, economic, and social dimensions. This integrated approach will help evaluate and enhance the performance of innovations throughout their development lifecycle. However, the application of LCSA in a research and innovation context like MAGICBIOMAT also presents several challenges and risks, particularly related to data availability, consistency, and quality, which must be carefully managed to ensure credible and useful results.

1. Challenges in Data Collection: One of the most significant risks in applying LCSA in a research context is the limited availability of reliable, site-specific data. In many cases, primary data may not be accessible due to the early-stage nature of the technologies involved, or because activities are outsourced to third parties. Where data exists, it may reflect only laboratory-scale conditions, which complicates extrapolation to real-world applications. These limitations often necessitate the use of secondary datasets or estimates, reducing the overall robustness and accuracy of the assessment.
2. Risks to Data Quality and Consistency: Another challenge concerns the variability and inconsistency of data across different sources. Data gathered under lab conditions may not be directly comparable to industrial-scale scenarios, while novel processes often lack sufficient representation in existing secondary databases. Differences in formats, units, and system boundaries further complicate integration, making the assessment time-consuming and increasing the risk of misinterpretation.

To address these challenges, MAGICBIOMAT will adopt a flexible and adaptive approach to data management. While the specific data landscape will only become clear during the development of Deliverable 7.2 (Goal and Scope Definition), the project will follow internationally recognized standards (e.g., ISO 14040/44, UNEP), incorporate early-stage validation procedures, and apply data quality audits throughout the LCSA process. In this context, a data quality audit refers to a systematic internal review of the data used in the assessment, evaluating key criteria such as technological, geographical, and temporal representativeness, as well as completeness, consistency, transparency, and reliability. This review helps identify potential gaps, uncertainties, or inconsistencies and supports decisions on data use or substitution. By setting up a transparent and structured review process, MAGICBIOMAT aims to ensure that the LCSA remains a credible and decision-supportive tool for guiding sustainability performance across the project lifecycle.

9. Annexes

9.1. Annex A: LCA Literature review

9.1.1. System boundaries

The choice of system boundaries in LCA significantly influences the results, particularly for bio-based products, where biogenic carbon modelling approaches play a central role.

The fundamental principle of LCA is based on a life cycle approach, aiming to capture the environmental impacts associated with all stages of the product. As such, a "cradle-to-grave" system boundary is generally preferred, as it accounts for the entire life cycle, including the end-of-life phase. However, the feasibility of this approach depends on the availability and quality of data (10).

In practice, for comparative LCAs between fossil-based and bio-based materials, the distribution and use phases are often excluded, either due to data gaps or under the assumption that these stages are functionally equivalent across materials (22).

Many studies, particularly those conducted or commissioned by raw material producers, adopt a "cradle-to-gate" approach, covering the extraction and processing phases but excluding downstream life cycle stages. Within this boundary, the temporary carbon storage model (-1; +1) often promotes bio-based products, since only the carbon uptake during biomass growth (-1) is accounted for, while the CO_2 release at EoL(+1) is outside the modelled scope. As a result, this approach can overestimate the climate benefits of bio-based materials compared to fossil-based alternatives (22), (23) (35).

Conversely, the carbon neutrality model (0; 0), as recommended in the PEF methodology, does not assign any credit or burden to biogenic carbon flows, thereby neutralizing any temporary storage benefits. Depending on the environmental impacts of biomass production, this may result in impact transfer between fossil and bio-based products, often preventing clear conclusions on global impact environmental (19), (23).

Finally, depending on methodological choices (such as allocation rules, EoL modelling, or inclusion of avoided burdens) system boundaries can significantly influence the interpretation of LCA results. These aspects must therefore be aligned with the study’s goal and level of detail (19).

9.1.2. Allocation Methods and Inventory Assumptions

The choice of allocation method in LCA can significantly influence the distribution of environmental impacts, especially in systems involving co-products, which are frequently encountered in the production of bio-based materials. Allocation refers to the process of assigning environmental impacts to the various outputs of a system that produces multiple co-products. The choice of allocation method is especially important for bio-based co-products, as it affects the calculation of biogenic CO_2 storage.

According to ISO 14044 and the PEF, there are several methods for allocating environmental impacts, listed in order of priority, each with specific advantages depending on the characteristics of the system and the co-products.

- Subdivision: This method involves splitting the studied process into two distinct sub-processes, effectively avoiding the presence of a process generating co-products within the life cycle of the product under study. This approach is useful when it is possible to clearly define and separate the functions of each co-product, eliminating the need for allocation.
- System Expansion: In this approach, the system is expanded by incorporating additional functions related to the co-products. The key concept here is substitution, which involves subtracting the impacts of the functions avoided through the valorisation of co-products from the total environmental impacts of the process. This method is widely recommended when co-products are used in other applications and their environmental benefits can be quantified and integrated into the system's impact.
- Physical Mass Allocation: This method assigns environmental impacts based on the mass of the products and co-products. While widely applicable to material products, it does not account for the differences in value between the primary product and co-products. This method is often used when the co-products have similar material or functional characteristics.
- Physical Energy Allocation: This method is used when the energy content of the products is a significant differentiator, reflecting their value and content. It assigns environmental impacts based on the energy content of the products and co-products.
- Economic Allocation: This approach assigns impacts based on the market values of the products and co-products and is most applicable when stable and reliable market prices are available. This method becomes particularly relevant when the market values of the co-products differ significantly, reflecting their economic importance and demand.

Furthermore, the *Association Chimie Du Végétal* (36) highlights a specific recommendation for bio-based products: when applying mass allocation, the dry matter content of the co-products should be considered. An additional consideration pertains to biogenic carbon storage. Regardless of the chosen allocation method, it is essential to conduct a specific allocation based on the carbon content of the products and co-products. This is particularly important to avoid skewing the results related to carbon sequestration and climate change impact indicators. In all allocation methods, sensitivity analysis is essential to account for uncertainties in the assumptions and choices made during the allocation process.

The variability of environmental impact results depending on the allocation method is clearly illustrated in the study by Spierling et al., which compares different allocation strategies applied to a system producing ethanol and lignin from biomass (22).

The authors highlighted significant differences in the results depending on the allocation method used. For instance, when applying mass allocation, the environmental impact per unit of ethanol was higher than with economic allocation, the latter considering the market value of ethanol and lignin. The system expansion approach, which considers the benefits of using lignin as a co-product in other sectors, resulted in the lowest impact per unit of ethanol by effectively "offsetting" the environmental burdens through the valorisation of the co-product.

In conclusion, the choice of allocation method depends on several factors, including the structure of the system, the economic characteristics of the products, and the types of environmental impacts being assessed. Each method has its strengths and limitations, and the allocation process must always be transparent, well-justified, and supported by sensitivity analyses to ensure reliable and robust results.

The application of cut-off rules in LCA is a critical factor for ensuring the completeness, consistency, and robustness of results, particularly in the context of bio-based products, which often involve a wide range of secondary inputs (e.g. additives, fillers, processing aids).

According to normative framework, with NF EN 16760, all elementary flows and Technosphere processes should, in principle, be included in the system boundaries. If certain elements are excluded, such exclusions must be justified using three criteria:

- Mass criterion: best estimate of the total mass of excluded components, expressed as a percentage of the total product mass;
- Energy criterion: best estimate of the energy consumption related to the excluded inputs, expressed as a percentage of the total product energy consumption;
- Environmental relevance criterion: exclusions should be based on relevant environmental impact information, such as data from Safety Data Sheets (SDS), emission declarations, or regulatory documentation.

In addition, some methodological recommendations, such as the ACDV methodological guide (36) aligned with the PEF methodology (European Commission Recommendation 2013/179/EU), recommends avoiding cut-off rules whenever possible. Nevertheless, the PEF allows for the exclusion of flows and processes that cumulatively contribute less than 3% to the total environmental impact (single score). Accordingly, the ACDV recommends that the inventory should cover at least 97% of all mass and energy flows, corresponding to a maximum cut-off threshold of 3%.

The review by Bishop et al. highlights practical limitations associated with cut-off practices, particularly regarding additives in bio-based materials. Out of 44 studies reviewed, only 7 explicitly accounted for additives. A 1% mass-based cut-off rule was found to lead to the omission of 2.6% to 7.5% of the total environmental impacts. The

authors therefore recommend the systematic inclusion of additives in the inventory to ensure that the environmental performance of bio-based products is accurately represented (20).

To conclude, the reviewed sources converge in emphasizing the importance of minimising the use of cut-off rules and adopting a transparent, documented, and impact-relevant approach. This is particularly crucial for bio-based products, where even small flows may contribute significantly to overall impacts.

9.1.3. Impact category: Climate change

The selection of impact categories to be assessed is a critical step in LCA, as it determines which environmental issues are most relevant for the system under study. This choice is even more crucial for bio-based products, as their environmental profiles often differ significantly from those of fossil-based alternatives.

9.1.3.1. Climate change

Climate change refers to long-term shifts in temperature and weather patterns, mainly caused by the build-up of greenhouse gases (GHGs). Its impacts are categorized based on the source of emissions and their interaction with the carbon cycle, which is crucial for bio-based products with different carbon dynamics compared to fossil systems.

In LCA, the impacts on climate change are quantified using models that convert GHG emissions into a common metric, enabling comparison of their contribution to global warming. Various methodological approaches have been developed to account for the distinct atmospheric behaviours and lifespans of different GHGs (20).

Among these, the Global Warming Potential (GWP) over a 100-year time horizon (GWP100) remains the most widely adopted. Created and recommended by GIEC (37), GWP100 quantifies the cumulative radiative forcing of a unit mass of a GHG over 100 years, relative to that of CO_2. This metric is not only central to LCA standards, but also underpins major international climate policies such as the Paris Agreement, and forms the default basis for characterization in frameworks like the EF3.1 (38).

Alternative approaches exist and offer different perspectives on climate impact. The Global Temperature Change Potential (GTP), for instance, estimates the temperature response at a given point in the future (e.g., 50 or 100 years) following an emission event. The GWPbio method addresses the specific dynamics of biogenic CO_2, accounting for biomass regrowth and the temporal delay between emission and reabsorption. Another approach, the Climate Tipping Potential (CTP), is inspired by the planetary boundaries framework and evaluates the proximity of emissions to climate system thresholds based on concentration-driven temperature increases (20).

Despite the many methodologies, GWP100 remains the recommended default in both academic practice and LCA software tools. For example, SimaPro includes multiple time horizons for GWP (20, 100, 500 years), yet explicitly identifies GWP100 as the standard, in line with the Global Guidance for Life Cycle Impact Assessment Indicators and Methods (GLAM) (39).

The GWP100 disaggregates the climate change impact into four subcategories: fossil, biogenic, land-use change (LUC) and CO_2 uptake; and the four are then simply added together to form the “Climate Change” impact.

The widespread preference for GWP100 is grounded in its balanced treatment of short- and long-lived GHGs. For example, methane, which has a relatively short atmospheric lifetime (~12 years), exerts a strong but brief warming effect, while CO_2 can persist for centuries. The 100-year time frame thus offers a pragmatic compromise, aligning policy relevance, scientific robustness, and comparability across studies.

9.1.3.1.1. Climate change – fossil

Fossil climate change, as defined by the GWP100 method, is a key indicator in the assessment of environmental impacts. It measures the influence of GHG emissions from fossil sources on climate change. The method is based on the GWP over a 100-year time horizon (GWP100), which quantifies the radiative forcing effect of various GHGs over 100 years, relative to carbon dioxide (CO_2), used as the reference gas.

Fossil climate change only accounts for emissions resulting from the combustion or extraction of fossil resources, such as oil, coal, and natural gas. The gases typically included are CO_2, methane (CH_4), and nitrous oxide (N_2O), but only when they are derived from fossil origins. These emissions are then converted into CO_2-equivalents using GWP100 factors.

In practice, the impact category "climate change" is often used to refer specifically to the fossil component. Fossil resources remain widely used across the globe, making the fossil climate change indicator systematically included in all LCAs. It remains a critical and unavoidable metric, as it is directly linked to the most significant anthropogenic GHG emissions and thus to international climate policy frameworks. As a result, it serves as a universal reference point for comparing the environmental performance of products, processes, and services.

Fossil resources are also widely used for biomass production, so this indicator remains essential even in the context of an LCA of a bio-based product.

9.1.3.1.2. Climate change – biogenic

The biogenic climate change impact refers to the exchange of carbon between biomass and the atmosphere. It includes both:

1. The emission of GHG (such as CO_2, CO, and CH_4) resulting from the transformation, degradation, or combustion of biomass through oxidation or reduction processes; and
2. The uptake of atmospheric CO_2 through photosynthesis during the growth phase of plants.

Two primary methodological approaches are used to model these biogenic carbon fluxes:

- Carbon neutrality approach (0;0)

This approach assumes that biogenic CO_2 emissions and absorptions cancel each other out over the life cycle of the product. The CO_2 captured during the growth of biomass is assigned a characterization factor of zero, as the CO_2 is released at the end of life (e.g., through combustion or biodegradation). This simplified modelling assumes the carbon cycle is closed over a short timeframe and is widely adopted in major LCA databases such as Ecoinvent, and recommended within the PEF methodology promoted by the European Commission. The GWP100 method used by EF3.1 calculates climate change from biogenic carbon, taking into account only biogenic methane, with a characterization factor of 27, compared with 29,8 for fossil methane.

According to COWI & Utrecht University, this approach was historically favoured in order to simplify modelling and due to the limited availability of time-sensitive emissions data. However, it is increasingly debated due to its inability to reflect the actual climate benefit or delay effects of biogenic carbon (40).

Xue provides a comprehensive review of LCA standards and highlights how the (0;0) method remains dominant in many LCAs of biobased products due to its inclusion in databases and PEF guidance, despite criticism over its limited temporal sensitivity (23).

Spierling et al., in their review of 44 LCAs of biobased plastics, show that many studies rely on the (0;0) assumption (22). However, the authors also point out a lack of transparency and harmonization regarding how biogenic carbon is treated, which hinders comparison between studies.

- Temporary carbon storage approach (−1;+1)

This method accounts for the time dynamics of carbon fluxes, assigning a negative impact (−1) for the uptake of CO_2 during the biomass growth phase and a corresponding positive impact (+1) when the CO_2 is released back into the atmosphere at the end of life. This approach captures the potential climate benefit of delayed emissions and provides a more refined and time-sensitive modelling framework.

This method is explicitly supported by internationally recognized standards such as ISO 14067 (41) and EN 15804 (42), which advocate for temporal differentiation of emissions in carbon footprint calculations.

The guidelines from ACDV (36) for bio-based products, recommends the temporary storage method for products with delayed biodegradation or long storage phases, emphasizing its importance for communicating true environmental benefits.

Nessi et al. (35) and Vural Gursel et al. (43) applied this method in their comparative LCA of bio-based vs. petrochemical plastics, showing how delayed biogenic carbon release influences overall climate impact scores.

To conclude, the carbon neutrality method remains prevalent for its simplicity, while the growing literature and standardization efforts increasingly highlight the need for dynamic carbon accounting in environmental assessments. The results of a “cradle-to-gate” LCA may vary according to the method used. However, for a “cradle-to-grave”, whatever the method used, the results must be equivalent.

9.1.3.1.3. Climate change – CO_2 uptake

Carbon sequestration refers to the long-term absorption of CO_2 by a material or biological system, preventing its release into the atmosphere over a significant period. The “long-term” nature of this sequestration depends on the time frame adopted, itself defined by the chosen assessment method.

For example, using the GWP 100 method, carbon is considered sequestered if the CO_2 captured is not released into the atmosphere at the end of 100 years. Other time horizons are also used depending on the context of analysis, including periods of 20 years or 500 years, each influencing the assessment of climate impact differently. The choice of time window therefore plays a decisive role in interpreting the benefits of carbon sequestration, particularly for bio-based materials or long-life-cycle products.

As part of the RE2020, the ‘dynamic and simplified’ method has been used to assess GHG emissions. This approach weights emissions according to their date of emission, with a coefficient of 1 for year 0 and 0.57 for year 50. This means that the earlier in time an emission occurs, the greater its impact is considered to be on the GWPover the period in question. This method is mainly used in LCAs of construction materials and buildings, to encourage the use of low-carbon solutions from the earliest stages of the project, and thus limit long-term environmental impacts.

The treatment of biogenic carbon storage in environmental impact assessments is subject to strict methodological rules within existing normative frameworks. According to the Product Environmental Footprint Category Rules (PEFCR) guidance (19) any temporary storage of biogenic carbon is not credited as an emission reduction. This means that if carbon is re-emitted within a defined time window after its absorption, it is considered as being emitted at the time of release, with no climate benefit during the interim.

The time window is typically set to 100 years, in line with standards such as ISO/TS 14067 (41), the ILCD Handbook (44) and PAS 2050:2011 (45). Therefore, only carbon that remains stored for more than 100 years is considered permanently removed from the atmosphere and can be credited as such in life cycle assessments.

This rule is particularly important when evaluating bio-based or biodegradable materials, which often involve short life spans and rapid degradation. The ADEME recommends not accounting for biogenic carbon sequestration when the lifetime of the product is less than 10 years, as is typically the case for bio-based packaging (46).

Consequently, both European and national guidelines align in excluding biogenic carbon storage credits for short-lived products, to prevent overestimating their climate benefits. This harmonized approach ensures that environmental performance assessments remain conservative and consistent, particularly in product categories like biodegradable plastics and single-use packaging.

9.1.3.1.4. Climate change – Land use change

Land use change (LUC) is a critical factor in the environmental assessment of bio-based materials due to its potential impact on GHG emissions, especially when land is converted from forest or grassland to agricultural use. LUC is commonly divided into two types: direct land use change (dLUC), which results from the immediate conversion of one land use type to another (e.g., forest to maize field), and indirect land use change (iLUC), which arises from broader market-driven effects.

Most studies that incorporate dLUC rely on IPCC guidelines to estimate emissions associated with changes in carbon stocks in soils and biomass (20). The French environmental agency ADEME emphasizes the importance of transparent documentation when including dLUC in LCAs. This includes detailing the geographic context, the baseline land use, and the emission factors used (whether generic or region-specific). The Ecoinvent database includes dLUC-related emissions under its climate change (GWP100) impact category. In practice, the most operational approach to account for dLUC is to use Ecoinvent's "land use change" inventories (36).

The inclusion of iLUC in LCAs remains limited and highly uncertain due to its methodological complexity and the lack of scientific consensus. iLUC is generally excluded from attributional LCAs, which focus only on directly observable impacts within a product system. However, consequential LCAs, which aim to capture broader system-level changes resulting from decisions, are theoretically more suited to include iLUC (20).

In the study of Vural Gursel et al. (43), LUC impacts were modelled to account for the additional arable land needed for sugarcane cultivation in Brazil and grain crops in the EU. While the PEFCR methodology does not explicitly address iLUC, the study adopts an alternative approach developed by the European Commission, which builds on global deforestation data and assumes land expansion (85%) and intensification (15%) as responses to increased demand. These assumptions were applied to calculate the LUC impacts associated with bio-based PET bottle production, using crop-specific dry matter yields.

The ADEME guidelines acknowledges the lack of methodological maturity in this area and do not require the quantification of iLUC in current LCA practices (46). Nevertheless, for bio-based packaging materials, the guidelines recommend the inclusion of qualitative information on iLUC: highlighting key issues, uncertainties, and potential future directions for integration into environmental assessments.

Given the significant influence of LUC on the overall environmental profile of bio-based materials, several expert bodies (such as ACDV) strongly recommend including dLUC when conducting comparative LCAs between bio-based and fossil-based products. Doing so enables more accurate and informed decision-making about sustainable alternatives.

However, the lack of harmonized methodologies and robust, context-specific data, especially for iLUC, continues to pose challenges for standardization. Future efforts should focus on refining predictive models, improving data

availability, and establishing clear guidance to ensure the comparability and credibility of LCA results across studies.

9.1.4. Others impact categories

Although the "Climate Change" impact category is widely recognized as a key reference in LCA methodologies, it is not sufficient on its own to reflect the full spectrum of environmental issues associated with a product. The EF 3.1 method, as recommended by the European Commission within the framework of the PEF, adopts a multi-criteria assessment approach based on 16 impact categories, offering a more comprehensive and nuanced evaluation of environmental impacts.

Comparisons of bio-based products with their petroleum-sourced counterparts frequently reveal impact trade-offs across multiple environmental categories, also called impact transfer. Due to their plant-based origin, bio-based materials often exhibit heightened impacts in categories directly linked to agricultural activities, such as:

- Land use, large surface area required for cultivation,
- Water consumption, particularly through irrigation,
- Eutrophication (both terrestrial and aquatic),
- Acidification, due to fertilizer and pesticide application (43).

In contrast, environmental benefits can be observed in comparison of petroleum-sourced products in categories such as:

- Depletion of fossil resources,
- Fine particulate matter formation.

To guide interpretation and ensure methodological relevance, the PEF methodology recommends focusing on the impact categories that account for at least 80% of the total single score. This threshold helps orient eco-design strategies and identify key environmental performance drivers, thereby maximizing the utility of LCA results.

A literature review by Bishop et al. (20), based on 44 LCAs conducted between 2011 and 2020, confirms the relevance of broadening the scope of environmental indicators beyond climate change. In addition, the most frequently assessed categories were:

- Acidification potential (66% of studies),
- Eutrophication potential (64%),
- Resource depletion (59%),
- Photochemical ozone formation (52%),
- Ozone layer depletion (45%),

- Ecotoxicity (43%),
- Human toxicity (39%),
- Particulate matter formation (39%),
- Energy consumption (36%),
- Water use (34%),
- Land use (32%).

These figures highlight the multidimensional nature of environmental impacts and reinforce the necessity of adopting a comprehensive, multi-indicator approach to the LCA of bio-based products.

9.1.5. Biodegradation modelling

ADEME defines a material as “biodegradable” if it can be decomposed by micro-organisms (bacteria, fungi, algae, earthworms, etc.). The result is the formation of water (H_2O), CO_2 and/or CH_4, and by-products (residues, new biomass) that are non-toxic for the environment.

Biodegradation process stages (47) :

- Biodeterioration: It is the initial stage of the plastic biodegradation process, driven by microorganisms that colonize the surface of the plastic, often forming structured communities known as biofilms. These microorganisms initiate mechanical and chemical degradation of the plastic’s surface, leading to micro-cracks, physical weakening, and the production of acidic compounds. This surface-level alteration facilitates further degradation by increasing the plastic’s surface area and making it more susceptible to enzymatic attack.
- Biofragmentation: It occurs when extracellular enzymes secreted by microorganisms begin breaking down the complex polymer structure of the plastic. These enzymes target and cleave the covalent bonds between carbon atoms in the polymer chains, reducing large macromolecules into smaller units such as oligomers and eventually monomers. This molecular size reduction is a critical step, as it makes the plastic fragments sufficiently small for microbial uptake.
- Bioassimilation: In this stage, microorganisms internalize the small degradation products resulting from biofragmentation. Only molecules with a molecular weight below approximately 600 Daltons are typically small enough to pass through the microbial cell membranes. Once inside the cell, these carbon-based compounds are metabolized and incorporated into microbial biomass or used as energy sources.
- Mineralization: The final stage, mineralization, involves the complete conversion of the organic carbon present in the plastic into inorganic forms, primarily CO_2, through microbial metabolism. For aerobic biodegradation, this process results in the release of CO_2, while anaerobic conditions may also generate

CH_4. Mineralization signifies the ultimate degradation endpoint, where the plastic-derived carbon is fully reintegrated into natural biogeochemical cycles.

Several types of biodegradations can be distinguished, depending on the presence or absence of oxygen, on the environment and human intervention (controlled biodegradation). Biodegradation under anaerobic conditions (absence of oxygen) is notably present in methanization, but is not studied in this project. For the purposes of MAGICBIOMAT, only aerobic biodegradation will be discussed here, in terrestrial environments (excluding aquatic ones) with minimal control over conditions, therefore only: biodegradation in-situ and home-compost.

The adjective “biodegradable” must always be supplemented by the environment in consideration. There is no standard for asserting that a product is biodegradable independently of the environment.

Biodegradation tests carried out in accordance with EN13432 (48) standard determine whether packaging is biodegradable in the environments mentioned above (in-situ, domestic compost and industrial compost). To be certified as biodegradable in a specific environment, according to the standard, four stages must be validated.

1. The sample must be of good quality, for example: no CMRs and no heavy metals above threshold levels.
2. Biodegradation test (ISO 14855-1) (49): the grounded sample, placed in the environment to be tested, must degrade by 90% in absolute or relative terms (compared with the environment alone, and the environment with a reference, usually cellulose). The results indicate the amount of CO_2 emitted over time throughout the evaluation period.
3. Disintegration test: the sample is placed directly in the environment to be tested. Residues present at the end of the evaluation period and greater than 2 mm must not represent more than 10% by mass of the initial weight of the sample.
4. The results of the biodegradation process must not present any ecotoxic effects on the environment. For example, vegetation planting tests are carried out in environments following biodegradation of plastics for a specific period. Then, the dry matter content of the vegetation produced is measured and compared with the reference environment (virgin and with cellulose biodegradation): it must be identical.

The certification standards require a biodegradation rate of at least 90% of testing under controlled conditions (48). However, as underlined by the French Agency for Food, Environmental and Occupational Health and Safety (50), there remains uncertainty regarding the residual fraction (potentially up to 10% of the original material) which is not subject to a formal environmental or health impact assessment. This residual matter may contain persistent or hazardous compounds that could be disseminated into the environment or accumulate in soils, especially when the compost is applied by private users as an organic soil amendment.

Moreover, ANSES underlines that, in most cases, compostable plastics do not contribute to nutrient content in compost. Since nitrogen availability is the limiting factor in compost generation, and since bioplastics do not supply nitrogen, they cannot replace other compost feedstocks (50). Furthermore, the carbon contained in biodegradable

plastics is generally less bioavailable to microorganisms than traditional biomass, often requiring the addition of more easily digestible carbon sources to maintain microbial activity (50). This limitation implies that biodegradable plastics do not enhance compost quality and, if not fully degraded, could hinder the composting process or reduce the end-product's value.

Certain LCA studies model the EoL phase of biodegradable plastics by assuming that 100% of the material's carbon content is converted into CO_2 emissions. This approach is often employed in scenarios where complete aerobic biodegradation is presumed, such as industrial composting or incineration.

For instance, the study by Spierling et al. note that many LCAs assume complete mineralization of biodegradable plastics, leading to the release of CO_2 equivalent to the carbon content of the material (22). This assumption simplifies the modelling process but may not always reflect real-world conditions, where biodegradation can be incomplete or vary based on environmental factors.

Similarly, the European Commission's Joint Research Centre (24) provides methodological guidance for LCA practitioners. The report suggests that, in the absence of specific data, assuming complete conversion of bio-based plastics to CO_2 at EoL is a conservative approach to estimate GHG emissions. However, it also emphasizes the importance of using material-specific degradation data when available to improve the accuracy of LCA results.

The technical report FD CEN/TR 16957 *"Bio-based products – Guidelines for Life Cycle Inventory (LCI) for the end-of-life phase"* provides recommendations on how to compile inventory data for the end-of-life stage within the LCA of bio-based products. The report addresses several EoL treatment options, including reuse, recycling, chemical and energy recovery, incineration, landfilling, release into the natural environment, and wastewater treatment.

Both industrial and home composting, is detailed in "organic recycling" section. For composted bio-based waste, key parameters include the mineralization rate and chemical composition. Specific modelling guidance for composting scenarios is provided in 9.1.5.1 and 9.1.5.2.

In the case of intentional release of bio-based products into the environment designed to biodegrade in soil (such as mulch films) the approach is treated on a case-by-case basis, provided that the principle of mass balance is maintained. This scenario refers to in-situ biodegradation, for which data on the mineralization rate, composition, and biodegradation kinetics must be documented.

To date, there is no established method or model to account for the environmental impact of non-biodegraded, and therefore persistent, microplastics in soil or in home composting systems. Nevertheless, according to the ANSES, their impact on the environment (particularly on biodiversity) is considered certain, although it remains impossible to quantify at this stage.

The MarILCA project (*Marine Impacts in Life Cycle Assessment*) is an international initiative launched in 2019 and running until 2025, aimed at better integrating the impacts of marine plastics into product LCA. Coordinated by

UNEP, in collaboration with various academic, industrial, and institutional partners, MarILCA seeks to develop robust methodologies to quantify the effects of plastic waste, particularly microplastics, on marine ecosystems within the LCA framework. The project focuses on proposing specific indicators and formulating recommendations to address current methodological gaps, taking into account the flows of plastics into the environment, their fragmentation, transport, and ecotoxicological impacts on marine biodiversity. By bridging marine plastic science and decision-making tools such as LCA, MarILCA aims to promote a more comprehensive consideration of plastic pollution issues in sustainable development strategies and public policies. This first worldwide initiative is a first step. However, it does not cover the environment studied in MAGICBIOMAT project.

To address this lack, Sadeleer et al. applied dynamically the Material Flow Analysis (MFA) methodology to model the inputs, outputs, and accumulation of microplastics in the soil compartment, depending on the type of mulch film used (biodegradable or non-biodegradable) (51). The MFA is based on a mass- and time-based approach, where the various plastic material flows are quantified annually over a 100-year time horizon. The main modelled flows include: the annual application of plastic films, their (partial or complete) degradation, post-harvest collection (with variable recovery rates depending on the scenario), and losses to aquatic environments.

Technically, the authors use simple differential equations to represent the dynamics of each flow over time. For example, for biodegradable films, an exponential degradation function is used to model the gradual disappearance of plastic mass in the soil, with a biodegradation rate based on experimental data. In parallel, the residual plastic quantity is accumulated year after year to simulate the build-up of microplastics in the soil.

The model takes into account specific parameters, such as:

- the mass of plastic film applied per hectare per year;
- the post-harvest recovery rate (for non-biodegradable films);
- the fragmentation rate into microplastics;
- the transfer rate to other compartments (e.g., erosion into surface waters);
- and the specific pedoclimatic conditions of Nordic regions (temperature, microbial activity, etc.), which strongly influence degradation rates.

Thanks to this dynamic MFA, researchers can compare different scenarios (e.g., biodegradable vs non-biodegradable films, 70% vs 100% recovery rate, etc.) and deduce the long-term trajectories of microplastic accumulation in soils. This approach does not quantify the environmental impacts linked to the presence of microplastics in soil or water but rather compares the quantity of microplastics under different materials and EoL scenarios.

9.1.5.1. Biodegradation in-situ

In-situ biodegradation takes place directly in the soil environment. The "soil" environment is considered "ordinary", less rich in nutrients and microbial activity than compost. The OK biodegradable SOIL certification from TÜV Austria ensures that a material will biodegrade directly in soil environments, such as in agricultural or natural settings. Here, the temperature can vary naturally with outdoor conditions, but testing is usually performed around 20–25°C, and materials must reach 90% biodegradation within 24 months without leaving toxic residues (52).



In-situ biodegradation occurs directly in the soil, without involving any transportation or energy consumption (such as electricity, gas, or water).

9.1.5.2. Home compost biodegradation

The OK compost HOME certification is tested in a compost environment at between 20–30°C. In this context, materials must still reach 90% biodegradation, but the evaluation period is reduced to 12 months to reflect the faster microbial activity in home composts than in natural soil (52) (TÜV Austria and NF T51-800-2015).



Home composting takes place on-site at the household level (no transportation) and requires the presence of an active composting system or compost heap maintained by the household (53). The compost does not require additional energy inputs such as electricity, gas, or water.

9.2. Annex B: LCC Literature review

9.2.1. Different types of Life Cycle Costing (LCC)

The SETAC-Europe Working Group on Life Cycle Costing has defined LCC (based on the analysis of survey results presented in Chapter 6) according to 3 types. These types are defined, independently, in the following subsections:

- Conventional LCC: The assessment of all costs associated with the life cycle of a product that are directly covered by the main producer or user in the product life cycle. The assessment is focused on real, internal costs, sometimes even without EoL or use costs if these are borne by others. A conventional LCC usually is not accompanied by separate LCA results. The perspective is mostly that of 1 market actor, the manufacturer or the user or consumer.

- Environmental LCC: The assessment of all costs associated with the life cycle of a product that are directly covered by 1 or more of the actors in the product life cycle (supplier, manufacturer, user or consumer, and/or EoL actor), with the inclusion of externalities that are anticipated to be internalized in the decision relevant future. Environmental LCC enhances conventional LCC by requiring, on the one hand, the inclusion of all life cycle stages and to-be-internalized costs in the decision-relevant future (hence, anticipated costs), and, on the other hand, separate not-monetized LCA results. A product system according to ISO 14040/44 (2006) should be used as a basis for both. The perspective is that of 1 or more given market actors, mostly manufacturers. If relevant, subsidies and taxes are included in environmental LCC.
- Societal LCC: The assessment of all costs associated with the life cycle of a product that are covered by anyone in the society, whether today or in the long-term future. Societal LCC includes all of environmental LCC plus additional assessment of further external costs, usually in monetary terms (for example, based on willingness-to-pay methods). The perspective is from society overall, nationally and internationally, including governments. Compared to environmental LCC, subsidies and taxes have no net cost effect, and hence are not included in societal LCC. All 3 types of LCC have a function-oriented systems perspective, implying a life cycle approach of some sort. The differences between conventional LCC, environmental LCC, and societal LCC are, as mentioned, categorized in Table 1.1. This book focuses on the new methodology of environmental LCC, whereas conventional LCC is well known (see Section 1.2.1) and societal LCC still suffers from not being completely defined by the scientific community (28).

9.3. Annex C S-LCA literature review

9.3.1. Sustainable Goals

The United Nations (UN) developed the action plan 'Transforming our world: the 2030 Agenda for Sustainable Development' at the General Assembly on September 25, 2015, which encompasses 17 integrated goals that combine three dimensions: economic, social, and environmental. It is to develop a fair society. The Sustainable Development Goals has a strong connection with performing S-LCA. Recent studies have shown that S-LCA indicators have direct connection with SDG for example Labor well-being, community engagement etc. S-LCA can also help on policy alignment for public procurement and sustainability innovation. The study of Backes et al. highlights the correlation between LCSA indicators and 14 out of the 17 SDGs, particularly emphasizing sustainable production, consumption, and resource management.

Also, there are international instruments involved in developing S-LCA such as European Convention on Human Rights (Article 14 – Prohibition of discrimination; Protocol 12, Art. 1 – General Prohibition of discrimination), Treaty on Plant Genetic Resources for Food and Agriculture etc.

9.3.2. UNEP Guidelines

Social impacts are understood by these Guidelines to be consequences of social relations (interactions) weaved in the context of an activity (production, consumption or disposal) and/or engendered by it and/or by preventive or reinforcing actions taken by stakeholders (ex. enforcing safety measures in a facility). When referring to the causes of social impacts, this generally implies three dimensions: behaviours, socio-economic and capitals.

Subcategories are the basis of a S-LCA assessment because they are the items on which justification of inclusion or exclusion needs to be provided. The subcategories are socially significant themes or attributes. Subcategories are classified according to stakeholder and impact categories and are assessed by the use of inventory indicators, measured by unit of measurement (or variable). Several inventory indicators and units of measurement/reporting types may be used to assess each of the subcategories. Inventory indicators and units of measurement may vary depending on the context of the study.

Social/socio-economic subcategories may be first classified by stakeholder categories as this might assist with the operationalization. It can also ensure the comprehensiveness of the framework. The purpose of the classification into impact categories is to support the identification of stakeholders, to classify subcategory indicators within groups that have the same impacts, and to support further impact assessment and interpretation. In the following figure there are the most representative stakeholder and impact categories (31).

9.3.3. Use of primary or secondary data

S-LCA is often conducted following the S-LCA Guidelines (UNEP, 2020 (31)) which defines

- primary data as “data that has been directly collected by the practitioner, via interview, survey, or participant observation for instance. (Data on aspects that are not compliant with regulations may not be voluntarily and honestly provided!)” and
- secondary data as “data that has been initially collected and manipulated by another person/institution than the practitioner or collected for another purpose than the one being currently considered or, often a mix of the two. For example, a publication, third party audit, or a database.”

Based on the S-LCA Guidelines definitions, site-specific data can be primary or secondary data (31). This differs from other definitions for primary and site-specific data, where in some cases they are considered interchangeable (e.g., EPD International, 2024 (54)) and in others all site-specific data are primary data, but not all primary data are site-specific data (55). Other definitions consider site-specific data to be one type of primary data, along with company-specific data and product-specific data (33); (21); (56); (57); (58).

The S-LCA Guidelines provide the strictest definition of what can be considered primary data, i.e., data collected directly by the practitioner. This is in contrast to the practice typically seen in environmental sustainability assessment guidelines, where site-specific data is always considered primary data, regardless of if it has been collected by the practitioner or by the company. The new ISO 14075 standard for social life cycle assessment

defines primary data in a similar manner to environmental sustainability assessments where all site-specific data is primary data. Table 1 provides an overview of existing definitions for primary, secondary, and site-specific data within social and environmental sustainability assessments. The ISO 14040/44 standards for life cycle assessment (International Organization for Standardization, 2006a, International Organization for Standardization, 2006b) were also reviewed but no explicit definitions for primary, secondary, or site-specific data are provided (10), (11), (59).

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