Simplified LCA models preliminary version

Deliverable D3.3

INNOVATIVE DECISION-MAKING TOOL FOR DEFINING THE MOST SUITABLE MANURE MANAGEMENT STRATEGIES TO ACHIEVE A SUSTAINABLE LIVESTOCK FARMING SYSTEM DURING THE WHOLE VALUE CHAIN

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NUTRITIVE

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TABLE OF CONTENTS

1. Executive summary

It is acknowledged that livestock farming has non-negligible impacts on the environment due to emissions of compounds to the air, soil, and water along the value chain. There are mature and emerging technologies that allow the management of these compounds to decrease their release to the environment. The aim of NUTRITIVE is to develop a decision-making tool to identify the most efficient manure management strategies/technologies (S/T) with the best performance not only from an environmental aspect but also from an economic and social perspectives, which are the three pillars of sustainability.

These environmental, social, and economic assessments of manure management S/T are performed in the Work Package (WP) 3 of the NUTRITIVE project using life cycle principles. To do so, Life Cycle Assessment (LCA) has been selected in this project, which is a valuable and widely accepted methodology that follows the ISO 14040 and 14044 standards.

The first task on LCA in WP3 is Task 3.2 *Environmental assessment through prospective and dynamic LCA models* lead by the Universidad de Santigo de Compostela (USC). The aim of this task is to develop LCA models of the S/T chosen in NUTRITIVE considering the evolution of the system in the future (prospective approach) and their inherent variations (dynamic approach). USC being the leader of Task 3.2, ARMINES/MinesParis-PSL is the first contributor to the dynamic approach, which will be described in this deliverable. Besides, the models developed in Task 3.2 will be the basis of Task 3.3 *Sensitivity analysis and simplified LCA models*, which is the second focus of this deliverable, with two main objectives. The first objective is to perform a sensitivity analysis to determine aspects influencing the most the LCA results but also to identify the focus points for improvements of the technology or processes. The models developed during Task 3.2 can be complex and difficult to utilize by non-LCA experts. Therefore, the second objective of Task 3.3 is to tackle this problem through the generation of simplified LCA models. These are simple mathematical equations that will be generated for quick and easy evaluation of the environmental impacts of the systems by anyone with low skills in LCA.

The goal and scope definition is the first step of the LCA methodology according to the standards and its application to manure management systems is presented in this deliverable. In this step, the functional unit and system boundaries among other assumptions and methodological choices necessary for the environmental evaluation are presented.

2. Introduction

The European Union (EU) is pushing for enhanced efforts to address pressing environmental issues, including climate change, pollution, loss of biodiversity, and the depletion of resources. This involves improving monitoring, reporting, and prevention measures, as well as remediation strategies, to mitigate the impact of pollution on air, water, soil, and consumer safety. To do so the EU Action plan: "Towards Zero Pollution for Air, Water and Soil" (European Commission, 2021) has been communicated by the European Commission. This plan aims to reduce pollution in air, water, and soil to safe levels, protecting human health and preserving the natural balance of ecosystems. By doing so, it seeks to respect the planetary boundaries and create a healthy environment, free from toxic substances.

Within this context, the NUTRITIVE project aims to help identify the most efficient and sustainable manure management S/T in livestock farming. The latter has been identified as important contributor to air, water, and soil pollution.

To select these manure management S/T, environmental, social and economic assessments are needed to evaluate their whole sustainability (Ciroth et al., 2011; Valdivia et al., 2021; Zamagni et al., 2013).

Life Cycle Assessment (LCA) is a systematic approach used to identify, quantify, and characterize the environmental impacts associated with a product or service, encompassing all stages of its life cycle, thereby facilitating the development of environmentally conscious decision-making (ISO 14040, 2006; ISO 14044, 2006). The scope of LCA has broadened to encompass social and economic considerations, through the development of Social Life Cycle Assessment (Andrews et al., 2009; UNEP 2020, 2020) and Life Cycle Costing (Ciroth et al., 2008) enabling a more comprehensive understanding of a product's or service's overall sustainability performance. Considering the potential environmental, social, and economic consequences of a product or service throughout its life cycle provides a holistic understanding of its sustainability performance. Besides, it makes sure that no burden shifting happens when comparing different options with each other, and informs strategic decision-making at various levels, from organizational to national.

Therefore, life cycle-based approaches have been selected to evaluate the sustainability of manure management S/T in the NUTRITIVE project. But only the environmental dimension is tackled in this deliverable corresponding to the contribution of ARMINES/MinesParis-PSL to Task 3.2 on dynamic modeling and the Task 3.3.

3. Methodology

LCA evaluates the environmental impacts of products or services along its entire life cycle from the acquisition of raw materials until its end-of-life (ISO 14040, 2006; ISO 14044, 2006). This systemic approach assesses a system's environmental impacts by considering direct and indirect emissions, across multiple stages and impact categories. It involves four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

Each of these four steps is briefly described in Section 3. Then, the Goal and scope definition of the systems in NUTRITIVE is presented in Section 5. Finally, preliminary conclusions and future work are presented in Section 7.

3.1. Goal and scope definition

The goal and scope definition is a very important step in the application of LCA as it drives the whole study. In this step, the intended application of the study and to whom the results of the study will be disclosed are provided (ISO 14040, 2006; ISO 14044, 2006). The study should clearly define its objective, target audience, and the temporal, geographical, and technological coverage, along with key methodological choices such as the functional unit, system boundaries, data requirements, and the method used to address system multifunctionality.

The functional unit (FU) acts as a reference frame, quantifying a product's performance characteristics and providing a basis for relating inputs and outputs flows. This enables accurate analysis and comparison (ISO 14040, 2006). It is essential that the FU accurately represents the function of the product or service being evaluated and consistent with the goal of the study. A well-chosen FU ensures that the results are comparable across different alternatives, enabling informed decision-making.

The system boundaries determine which unit processes are included in the analysis. Ideally, the product system should be modeled to have clear boundaries, with inputs and outputs that are elementary flows. However, it's not necessary to quantify every details, and resources can be focused on the most significant aspects that drive the overall conclusions of the study (ISO 14040, 2006).

There are different approaches to define the system boundaries defining the processes included. The ideal approach is called from “cradle-to-grave”, in which all processes to deliver the reference flow defined by the functional unit are considered from the acquisition of raw materials until the end-of-life of the system. A more constrained approach to define the system boundaries is from “cradle-to-gate”, in which processes happening after the gate of the system such as transportation, use phase, and end-of-life are excluded from the analysis. This means that cut-off criteria can be established to exclude stages or unit processes with minimal impact on the results. The chosen criteria should be well justified as it significantly affects the results. The system can be divided into two categories:

- **Foreground system**: This includes the unit processes that are directly influenced by the study and can be controlled by decision-makers. These processes are typically under the direct management of the organization or individual conducting the assessment.

- **Background system**: This comprises the processes that supply energy and material flows to the foreground system but are not directly controlled by the decision-maker. These processes are often external to the organization or individual and come from the market.

Another important aspect to define in the goal and scope is the method to deal with a multifunctional system. A system or process is considered multifunctional when it serves multiple purposes, generating multiple products and/or providing multiple services. In reality, these additional products and services often contribute to increased economic revenue. However, this can create complexity when trying to allocate environmental impacts, as the system or process is linked to other product systems. This can make it challenging to accurately assign environmental responsibility, as the impacts may be shared across multiple products or services (Hauschild et al., 2018). Multifunctionality in LCA is typically addressed using one of four methods: subdivision, system expansion, substitution, or allocation (Heijungs et al., 2021; ISO 14044, 2006) .

- **Subdivision** is complete when it enables separate modeling of a unit process's product and co-product, improving data accuracy.
- **System expansion** adds functions by combining single-function products. This is usually used when considering all products as the main products to compare their performances with systems providing the same products.
- In **substitution**, the system's total impact is assigned to the main product, and the impacts of equivalent co-products from alternative processes are deducted.
- **Allocation**, by contrast, distributes the system's total impact among products based on physical or economic properties.

Subdivision is rarely applied because it is often difficult to clearly separate the subprocesses that generate each product. For allocation or partitioning, energy content or mass is usually preferred, as these properties remain stable over time, unlike economic value, which varies over time.

A fourth important aspect to consider in the goal and scope definition is the data quality requirements. The accuracy of LCA results heavily relies on the quality of the data used. Therefore, it's essential to establish clear requirements for data collection in the early stages of the study. This involves defining the scope of the data, including temporal, geographical, and technological. Additionally, the sources of data need to be identified such as primary data from on-site measurements or invoices and secondary data from process simulations, literature, databases among others.

The goal and scope of an LCA study should be clearly defined from the start, but it's also important to know that the iterative nature of the methodology allows adjustments to the scope as new information becomes available.

This deliverable is mainly focused on the goal and scope definition phase. In the following section are described the functional unit, system boundaries, method to deal with the multifunctionality of a system, data quality requirements in the context of NUTRITIVE. The other three phases of LCA are briefly described in the following sub-section to have an overview of how they are conducted to obtain the full results of the assessment.

3.2. Inventory analysis

This phase involves gathering data to quantify the inputs and outputs of mass and energy for the system. The outcome is a comprehensive list of elementary flows that cross the system boundaries, known as the Life Cycle Inventory (LCI). The LCI is the foundation for the impact assessment phase. Notably, this stage is often the most resource-intensive and time-consuming part of an LCA, as it requires detailed data collection.

Data collection encompasses energy and raw material inputs, as well as outputs such as products, co-products, waste, and emissions to air, soil, and water. This data can be obtained through direct measurement or estimation, and transparent calculation procedures should be used to ensure accuracy.

3.3. Impact assessment

The third phase of an LCA involves the Life Cycle Impact Assessment (LCIA), where relevant impact categories are selected and evaluated. This phase assesses the potential environmental impacts of the system, depending on its nature and the goals and scope of the analysis.

LCIA involves two mandatory steps including classification of elementary flows determined during LCI into impact categories, then conversion into an equivalent amount of a reference substance. This is achieved through characterization factors, which translate the impacts into a common unit allowing for comparison and evaluation.

Optional steps in LCIA include normalization and weighting. Normalization involves multiplying LCIA results by normalization factors, which represent the impacts corresponding to a reference point, such as a country or sector. During weighting, normalized LCIA results may be summed directly across impact categories or multiplied by value-based weighting factors before being aggregated across categories. Even when optional steps are performed, the results from the mandatory steps must still be reported to ensure full transparency of the information.

3.4. Interpretation

In this final phase of the LCA, key issues are identified based on the LCI and LCIA results. The study's completeness, consistency, and sensitivity to uncertainties must be assessed, and the suitability of earlier methodological choices such as functional unit and system boundaries is re-examined alongside the study's limitations. Final conclusions and recommendations consistent with the goal and scope are then formulated and communicated to decision-makers.

The results of an LCA can be obtained using parameterized models that are valuable tools for complex computation. Parameterized models are built upon input parameters and their mathematical relationships to simulate the operation of each of the unit processes of the system under study. These equations quantify material, energy, and emission flows across the system. The same parameterized structure can be used for Impact Assessment through Python-based LCA libraries such as Brightway2 (Mutel, 2017) and lca_algebraic (Jolivet, 2020), which convert exchanges into impact results. Parameterized models enable scenario evaluation across multiple parameters sets.

4. Application of LCA methodology to NUTRITIVE

4.1. Dynamic modeling

As already mentioned before, a dynamic approach of LCA is targeted in NUTRITIVE in Task 3.2. This approach aims to consider the inherent variations of the S/T and their subsequent effects on the environmental performance. In fact, in the example of microalgae systems, their cultivation is done in open ponds that are directly exposed to the external environment, which affects the performance of the microalgae. Their ability to use nutrients and degrade harmful compounds in manure will vary, potentially impacting the environmental performance of the system. Like the microalgae system, the inherent variations specific to each selected strategy/technology (S/T) to treat manure from livestock farming will be considered. The dynamic modeling approaches to consider these inherent variations is further described in more details in the following paragraphs.

In NUTRITIVE, the consideration of inherent variations will be done through dynamic LCI meaning that the timing of the input and output flows is considered instead of a static average value as commonly done in the literature. Then, a dynamic LCIA will be performed, in which the timing of the emissions is considered. Two python libraries specific to LCA modeling can be used namely *bw_timex* (Müller et al., 2025) and *edges* (Sacchi et al., 2025).

bw_timex allows to (i) account for the timing of exchanges and emissions of processes by giving them temporal distribution, (ii) account for the timing of processes throughout the supply chain such as the end-of-life that occurs 30 years after construction, (iii) account for the evolution of supply chains and technologies over time or prospective modeling, and (iv) do dynamic impact assessment by considering the emission timing.

edges allows applying characterization factor directly on the exchanges between suppliers and consumers to consider (i) geographical region of the production and consumption, (ii) the magnitude of flows, and (iii) scenario-based parameters such as changing atmospheric conditions. The latter is the added value of *edges* compared to *bw_timex*, which does not consider the evolution of the global concentration of GHG in the atmosphere over time for example. This aspect helps in performing dynamic LCIA considering more realistic aspect of environmental mechanisms such as the fate of an emission after release.

4.2. Sensitivity analysis and simplified LCA models

The Task 3.3 of the WP3 of NUTRITIVE is performed in the interpretation phase of LCA including (1) sensitivity analysis to identify the most influencing parameters to the LCA results and to identify focus points for improvements of the technology/processes, and (2) propose simplified LCA models to ease the environmental assessment by no-LCA expert.

To do so, detailed parameterized models are constructed during the Inventory Analysis phase, which supports the subsequent sensitivity analysis, a crucial step for developing simplified models.

The detailed and simplified models are developed following the protocol described in (Padey, 2013) and (Douziech et al., 2021), which consists of five main steps: (i) defining the scope of the study, (ii) constructing the detailed model, (iii) identifying key input variable parameters per impact category, (iv) deriving a simplified model for each impact category, and (v) specifying the applicability domain of the simplified models. A brief description of each step is provided as follows:

- Scope definition: the characteristics of the system to be modeled—technology, geographical context, and temporal aspects—are established. This is identical to the first phase of LCA described in subsection 3.1.
- Detailed model construction: input and output flows are inventoried for each stage of the system using fixed and variable parameters and their mathematical relationships. A probability distribution function (PDF) is assigned to each variable parameter to represent its range of variation. Results of the detailed model are then compared with literature values.
- Identification of key parameters: A Global Sensitivity Analysis (GSA) using the Sobol method (Sobol, 2001) is performed to determine which input parameters exert the greatest influence on model outputs. Sobol indices, computed via Monte Carlo sampling, are used to identify the most influential parameters (Saltelli et al., 2008).
- Simplified model generation: for each impact category, a simplified model is developed using only the key parameters. All other parameters are fixed at the median of their PDFs. Background processes are replaced by their impact scores, and terms contributing less than 1% of the total impact are removed. The resulting model consists of analytical equations whose outputs are compared with those of the detailed model for validation.
- Applicability domain: the valid range of use for each simplified model is specified, potentially involving parameter redefinition or adjustment of variability ranges.

5. Goal and Scope definition of NUTRITIVE

This section is the core of this document in which the goal and scope of the LCAs performed in NUTRITIVE is defined.

5.1. Goal and functional unit

In NUTRITIVE, the goal is to develop a "*Decision-making tool to define most efficient and sustainable manure management strategies for a given livestock farm limiting manure air emissions and soil and water contaminants*". Therefore, the main function of the system would be the treatment of manure from livestock farms, thus, the FU can be "treatment of 1kg of manure", which is weight-based as suggested by the EN 16760: 2015 Bio-based products - Life Cycle Assessment guidelines (European Committee for standardization, 2015). This will allow the comparison of different S/T considered in the project.

NUTRITIVE covers the entire manure management chain, from livestock housing to yarding, grazing, storage, and field application (

Figure 1). Since different S/T act at different points in this chain, they change the manure's nutrient content in different ways. As a result, comparing systems based on "treatment of 1 kg of manure" is not meaningful, since the amount of nutrients applied to the field can vary a lot. This affects fertilization needs, crop yields, and the use of additional mineral fertilizers, which in turn increases related emissions. A more accurate FU for a fair comparison between the systems is "treatment of

1 kg of manure so that it meets crop nutrient needs at application for optimal yields with minimal reliance on commercial fertilizers". This will allow assessing how well each system treats 1 kg of manure and reducing the need for extra fertilizers.

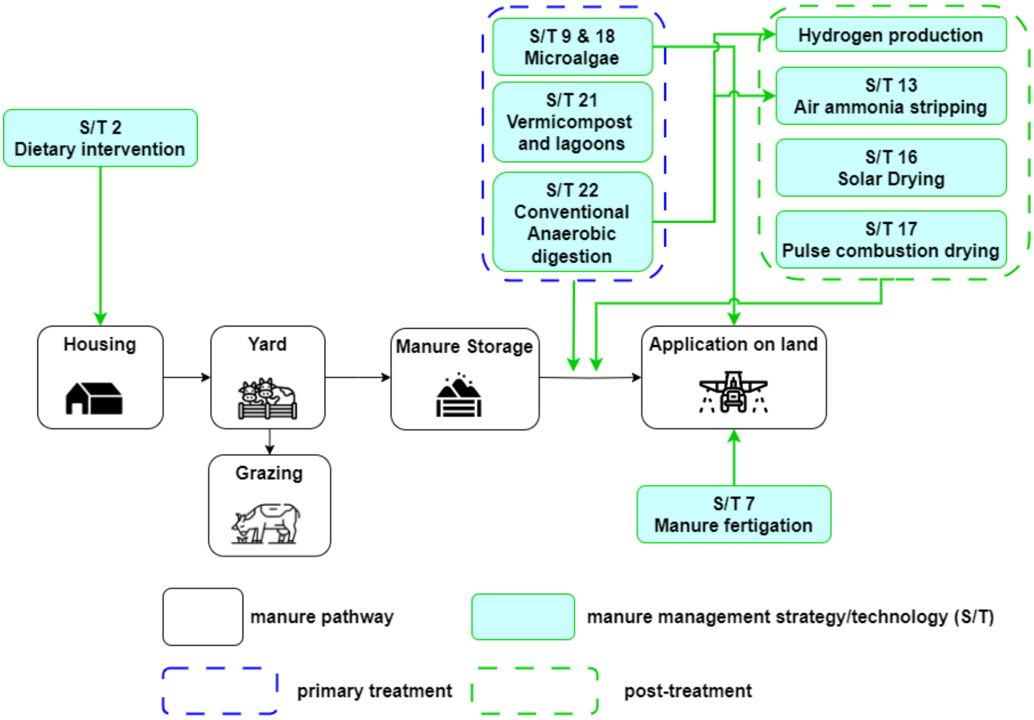


Figure 1 Common manure pathways and management systems selected for LCA

Considering the aim of NUTRITIVE, the targeted audience of the LCA results will be livestock farmers, local community, and policy makers. The geographical coverage of the studied S/T will include four climate zones namely Atlantic, Mediterranean, Continental, and Alpine.

5.2. Selection of strategies/technologies for LCA

In NUTRITIVE, 22 strategies/technologies were considered but only a selection of them will be evaluated through LCA in WP3 as depicted in

Figure 1. The motivation behind the selection of some strategies/technologies out of the 22 proposed in NUTRITIVE is that by experience LCA modeling is time-consuming especially when using parameterized LCA model. Depending on the complexity of the system, the knowledge on it, and data availability, the modeling can take approximately from few weeks to one year or more. And NUTRITIVE only lasts for 4 years.

The S/T have been selected to satisfy the following criteria:

- the whole manure management is covered including housing level, primary treatment, post treatment, and soil application.
- all manure-derived pollutants mitigations targeted in NUTRITIVE are covered namely emissions reduction, nutrients recovery, and pollutants removal.
- consider circularity
- experiments conducted by the partners are quite advanced at this stage of the project

Considering these four criteria, the following S/T were selected:

At housing level:

1. S/T 2 Dietary interventions aiming to NH3 emissions reduction through the modification of the diet of the animal. This will include the modification of the level of protein, the source of the protein and a mix of isoacids to increase the efficiency of protein absorption and reduction of nitrogen excretion.

Primary treatment:

2. S/T 9 microalgae for nutrients recovery, in which microalgae will be used to utilize the raw manure or its anaerobic digestate to grow. Then, the harvested biomass will be used as fertilizer.
3. S/T 21 Vermicompost and lagoons for heavy metals and other contaminants removal. Here, the manure is separated into solid and liquid fractions. The solid part is treated by vermicomposting using red earthworms to stabilize organic matter and improve nutrient availability, while the liquid fraction is treated in pilot-scale lagoons to assess the removal of heavy metals and other contaminants.
4. S/T 22 conventional anaerobic digestion (AD) for antibiotic residues removal and pathogens, and Antibiotic resistance bacteria and antibiotic resistance genes abatement. With this technology, mesophilic one-stage AD will be upgraded aiming at maximizing antibiotic residues removal and pathogens, and Antibiotic resistance bacteria and antibiotic resistance genes abatement.

Post treatment:

5. Hydrogen production from methane obtained via anaerobic digestion of manure for nutrients recovery. It should be noted that this system was added to NUTRITIVE. With this technology, biogas obtained from the anaerobic digestion of manure will further undergo steam methane reformer to obtain hydrogen.
6. S/T 13 Air ammonia stripping for nutrients recovery from liquid manure or digestate by transferring ammonia from the liquid to the gas phase and capturing it in an acidic solution. This produces nitrogen-rich fertilizer salts while reducing ammonia levels in the treated effluent.
7. S/T 16 Solar drying for nutrient recovery by reducing water content of manure or manure-derived digestate as well as to facilitate improved fertilizing products. The system features a drying line that comprises a solar dryer, an air blower, and a biofilter, and also includes a turning machine that helps to distribute the material evenly and prevent crusting.
8. S/T 17 Pulse combustion drying for nutrients recovery is another thermal drying technology applied to manure or digestate to remove water. In this technology, water is removed from a substrate using energy generated by intermittent combustion.

Soil application:

9. S/T 7 Manure fertigation for GHG and air pollutants reduction through traditional spread or injection of manure into the soil.
10. S/T 18 Fertilizers based on S/T 9 microalgae for GHG and air pollutants reduction

5.3. Common system boundaries as basis

In waste management, a cradle-to-gate approach is often applied, leaving out the use of bio-based fertilizers. However, land application of these fertilizers can substantially contribute to impacts such as global warming and eutrophication (Maga, 2017)(Glover et al., 2023). For this reason, excluding the fertilizer application stage must be clearly justified. Moreover, in comparative assessments—such as those carried out in NUTRITIVE—the system boundaries should extend from cradle-to-grave meaning from the acquisition of raw materials until the end-of-life. When infrastructures differ, accounting for the end-of-life phase is essential to avoid overlooking impacts that arise at the construction and dismantling stages.

It is worth noting that the inventory of emissions across the manure pathway will be modeled following the Tier 2 approach of the European Monitoring and Evaluation Programme of the European Environmental Agency (EMEP/EEA) air pollution inventory guidebook (European Environment Agency, 2023). This approach allows us to account for all pollutants including nitrogen, phosphorus, non-methane volatile organic compounds and methane. The Tier 2 approach provides different equations to do the mass balance of these compounds so that improvements from a management system applied at any stage of the pathway can be evaluated.

Because each S/T can act at different points in the manure pathway, the common system boundaries for their LCAs are defined along this pathway while also including infrastructure and end-of-life considerations, as illustrated in Figure 2.

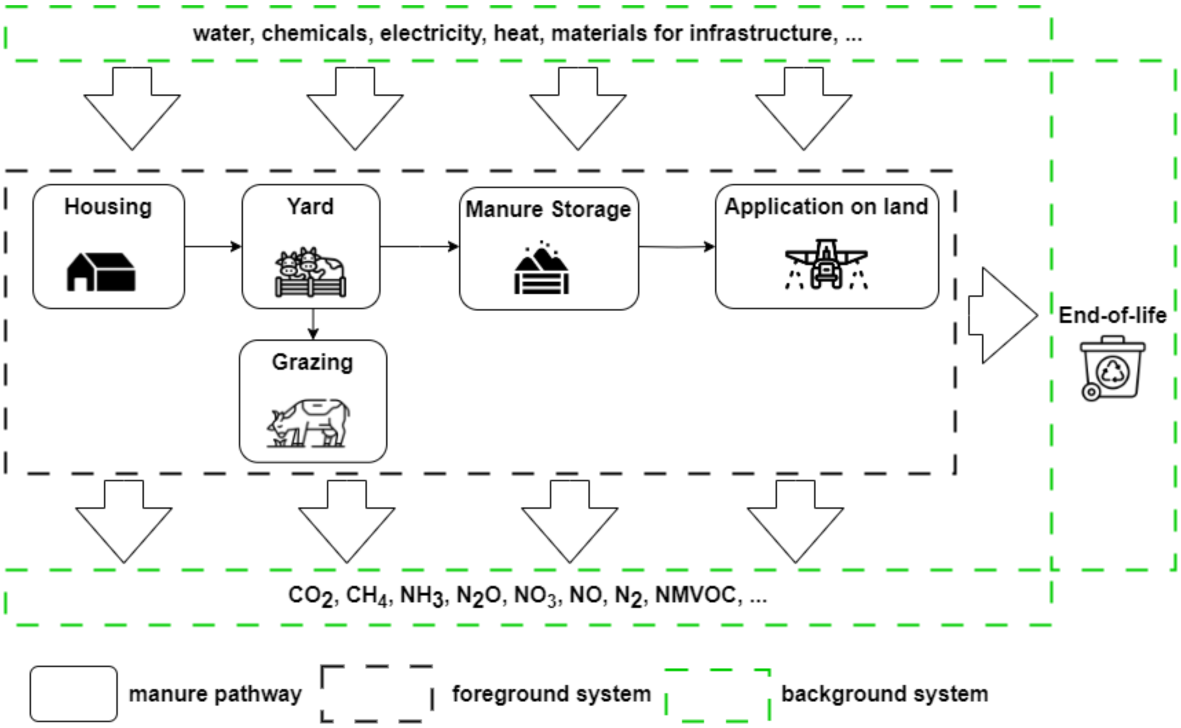


Figure 2 Common system boundaries and elementary flows as basis for each strategies/technologies in NUTRITIVE

At this stage of the project, the systems currently modeled for LCA, out of the 10 selected, are S/T 9 microalgae and harvested biomass as fertilizer in S/T 18, and hydrogen production. Their system boundaries are described in the following subsection.

5.4. System boundaries of S/T 9 and S/T 18

The system boundaries of the microalgae system are integrated in the manure pathway as presented in Figure 3.

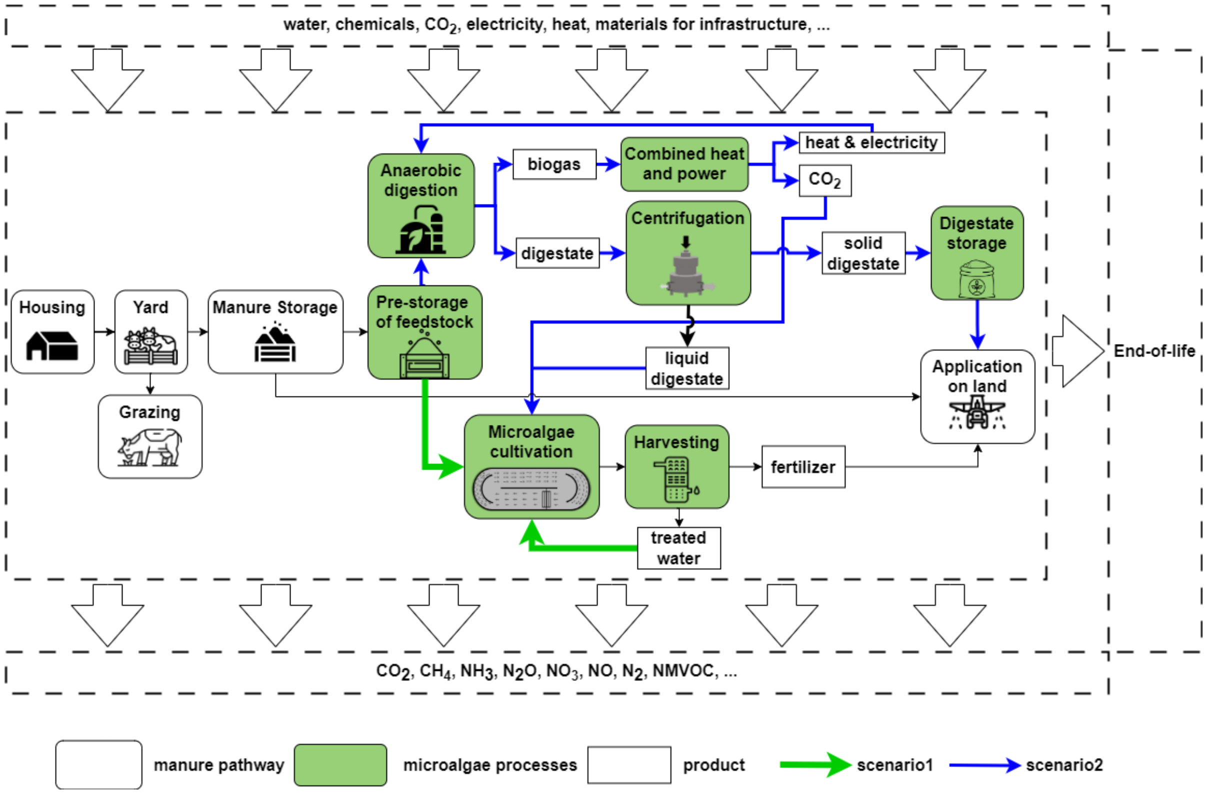


Figure 3 System boundaries of the S/T9 and S/T18 microalgae

As shown in Figure 3, the processes of the microalgae system evaluated in NUTRITIVE, in green, are integrated right after the storage in the manure pathway. Two scenarios have been considered.

5.4.1. First scenario

The first scenario is related to a microalgae system as primary treatment meaning that raw manure is directly used to cultivate microalgae, mainly *nannochloropsis* strain in open raceway ponds and in continuous mode. Then, the harvested biomass will be used as fertilizers while the recovered water will be reused in the cultivation.

5.4.2. Second scenario

The second scenario is related to a microalgae system as post treatment, in which raw manure goes first to anaerobic digestion producing biogas and digestate. The biogas is burnt in a combined heat and power engine to produce heat and electricity that are used onsite. The digestate is centrifuged to separate the liquid from the solid fraction. The solid digestate will be used as fertilizers, while the liquid digestate will be used to cultivate microalgae. Like in the first scenario, the harvested biomass will be used as fertilizer, too.

5.5. System boundaries of hydrogen production

The system boundaries of hydrogen production are integrated in the manure pathway as presented in Figure 4.

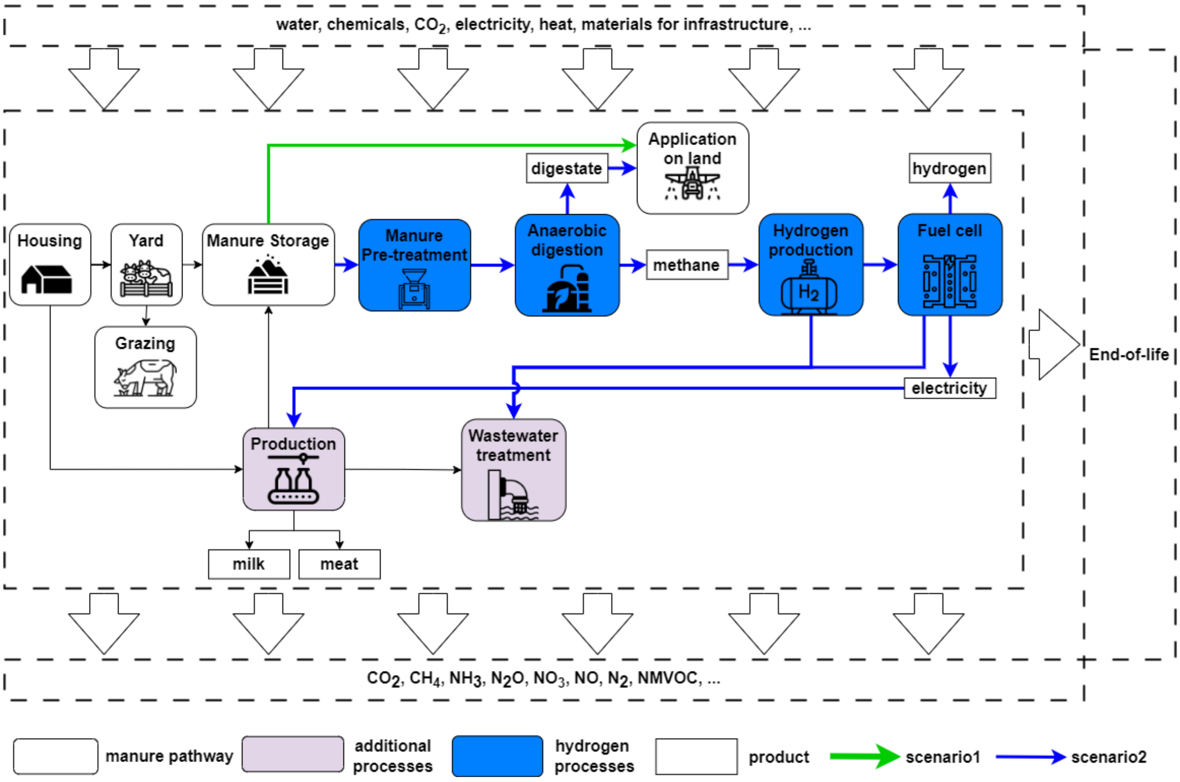


Figure 4 System boundaries of the hydrogen production

For the hydrogen production system two scenarios are considered:

- **Scenario 1,** based on the manure pathway, includes additional milking and farming processes, generating milk and meat, and wastewater treatment activities. The manure is directly applied on land.

- In **scenario 2**, in addition to the activities in scenario 1, the manure is first pre-treated then goes through anaerobic digestion to produce biogas and digestate. The biogas is upgraded in a steam methane reformer to produce hydrogen. Part of the hydrogen is converted into electricity to meet the farm's energy demand, and the rest is supplied to the market. The digestate is used as biofertilizer that is applied on land.

5.6. Data quality

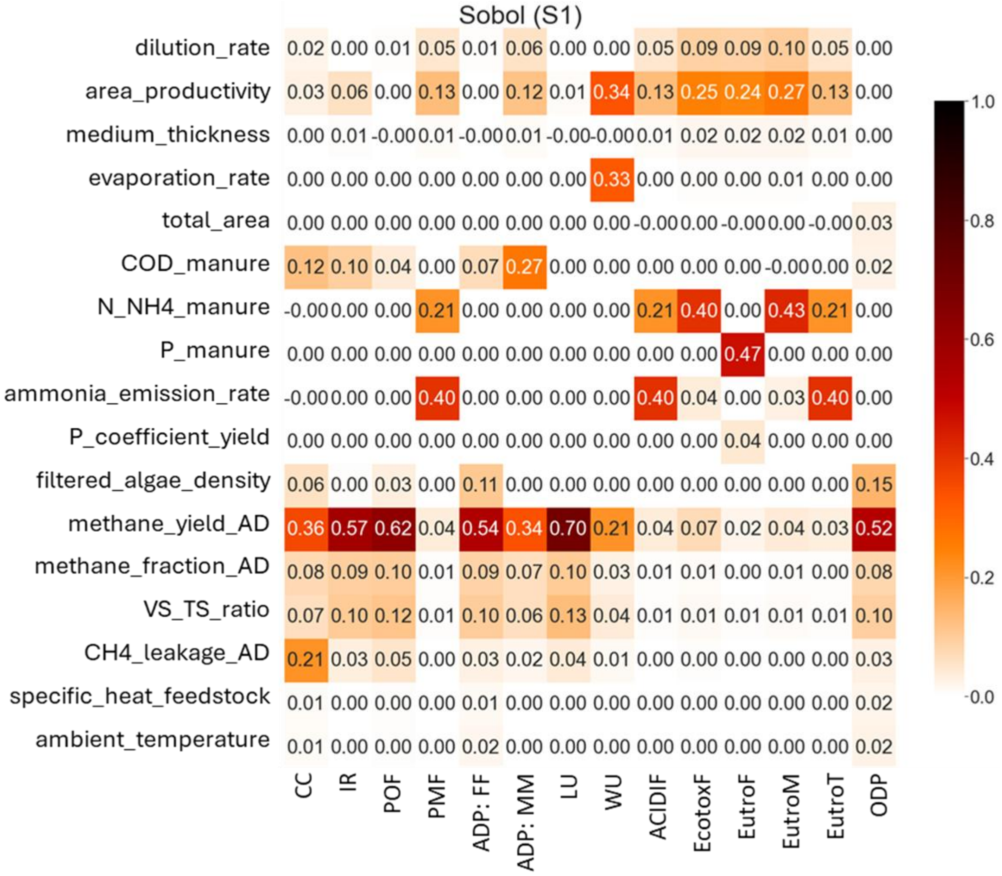
Since the LCA results are intended to be disclosed to the public and for decision making it is necessary to use high quality data. Thanks to the industrial partners in NUTRITIVE, the LCI relies mainly on primary data from experimentations in laboratory and pilot scale facilities, which will feed the foreground system. These data will be complemented by process simulation and mathematical models developed in Python, which provide the key mass and energy flow data for the system. Additional information will be gathered from scientific literature and technical reports as secondary data. Besides, existing databases such as ecoinvent (ecoinvent, 2023) and Agribalyse (Ademe, 2025) will also be used mainly for the background system.

5.7. Method to deal with the multifunctionality of the system

In manure management systems, the main product and co-products typically serve different end-uses—for example, energy from biogas and nutrients from bio-fertilizers. Substitution is therefore more appropriate, as it accounts for the distinct functions of each product. Accordingly, most waste management LCAs use substitution to credit benefits from energy recovery, wastewater treatment, and fertilizer-grade effluents (Wu et al., 2020). Therefore, the substitution method will be used in NUTRITIVE to deal with multifunctional systems, and this will ease the comparison with results from the literature.

6. Example of expected results

At the stage of the project, there are no results that can be shown. However, some examples of expected results can be displayed to have an idea on how the final results will look like. Regarding the sensitivity analysis to identify the most influencing parameters to the LCA results and to identify focus points for improvements of the technology/processes, the results will look like those presented in Figure 5.



	CC	IR	POF	PMF	ADP: FF	ADP: MM	LU	WU	ACIDIF	EcotoxF	EutroF	EutroM	EutroT	ODP
dilution_rate	0.02	0.00	0.01	0.05	0.01	0.06	0.00	0.00	0.05	0.09	0.09	0.10	0.05	0.00
area_productivity	0.03	0.06	0.00	0.13	0.00	0.12	0.01	0.34	0.13	0.25	0.24	0.27	0.13	0.00
medium_thickness	0.00	0.01	-0.00	0.01	-0.00	0.01	-0.00	-0.00	0.01	0.02	0.02	0.02	0.01	0.00
evaporation_rate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.01	0.00	0.00
total_area	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.00	0.00	-0.00	0.00	-0.00	0.03
COD_manure	0.12	0.10	0.04	0.00	0.07	0.27	0.00	0.00	0.00	0.00	0.00	-0.00	0.00	0.02
N_NH4_manure	-0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.21	0.40	0.00	0.43	0.21	0.00
P_manure	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.47	0.00	0.00	0.00
ammonia_emission_rate	-0.00	0.00	0.00	0.40	0.00	0.00	0.00	0.00	0.40	0.04	0.00	0.03	0.40	0.00
P_coefficient_yield	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00
filtered_algae_density	0.06	0.00	0.03	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15
methane_yield_AD	0.36	0.57	0.62	0.04	0.54	0.34	0.70	0.21	0.04	0.07	0.02	0.04	0.03	0.52
methane_fraction_AD	0.08	0.09	0.10	0.01	0.09	0.07	0.10	0.03	0.01	0.01	0.00	0.01	0.00	0.08
VS_TS_ratio	0.07	0.10	0.12	0.01	0.10	0.06	0.13	0.04	0.01	0.01	0.01	0.01	0.01	0.10
CH4_leakage_AD	0.21	0.03	0.05	0.00	0.03	0.02	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.03
specific_heat_feedstock	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
ambient_temperature	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02

Figure 5 Example of sensitivity analysis results. CC-climate change, IR-ionizing radiation, POF-photochemical oxidant formation, PMF-particulate matter formation, ADP:FF/ ADP:MM-abiotic depletion potential of fossil fuels/minerals and metals, LU-land use, WU-water use, ACIDIF-acidification, EcotoxF-ecotoxicity of freshwater, EutroF/EutroM/EutroT-eutrophication of freshwater/marine/terrestrial, ODP: ozone depletion potential (Rajaonison, 2024)

Figure 5 shows the first order Sobol indices of each parameter, in vertical axis, for each impact category, in horizontal axis. The higher the value, the darker the color, and the more influencing the variation of the parameter is to the variation of the impact. As parameterized models compute the input and output flows of all unit processes within the system boundaries, identifying the most influential parameters helps pinpoint the hotspots that require improvement.

Regarding simplified models, they are mathematical equations that will look like Equation 1 for the example of climate change impact category (I_{CC}) of a microalgae system (Rajaonison et al., 2025).

$$I_{CC} = \frac{\begin{gathered} 4.6\ 10^{-2}\mathrm{x}_0\mathrm{x}_1\mathrm{x}_5 - 6.3\ 10^{-4}{\theta_{\frac{VS}{TS}}}^{0.33}\mathrm{x}_2 - 0.6{\theta_{\frac{VS}{TS}}}^{0.67}\mathrm{x}_3 \\ +\mathrm{x}_5\mu_{area}\left(4\ 10^2 - 61\mathrm{x}_0\right) - 41\theta_{\frac{VS}{TS}}\mathrm{x}_1 - 12\mathrm{x}_1\delta_{recirc} \\ +\theta_{CH_4}\left(\delta_{recirc}(17\mathrm{x}_4 + 1.4) - 7.1\ 10^2\mathrm{x}_4 - 1.7\ 10^2\right) \\ -4.6\mathrm{x}_1\mathrm{x}_5 - 1.3\ 10^4\mathrm{x}_1 - 2.5\ 10^{-4}\mathrm{x}_2 - 1.6\mathrm{x}_3 \end{gathered}}{54\mu_{area}\mathrm{x}_5\left(\mathrm{x}_0 - 10^2\right)} \quad [\text{kgCO2eq/kg\_manure}] \qquad \text{Equation 1}$$

Where

$\mathrm{x}_0 = \delta_{CH_4}\mu_{CH_4}$, $\mathrm{x}_1 = \mu_{area}\theta_{CH_4}$, $\mathrm{x}_2 = {\mu_{area}}^{0.33}\theta_{CH_4}$, $\mathrm{x}_3 = {\mu_{area}}^{0.67}\theta_{CH_4}$, $\mathrm{x}_4 = {\mu_{area}}^2$, $\mathrm{x}_5 = \theta_{VS/TS}\mu_{CH_4}$

δ_{CH_4}: methane leakage rate during anaerobic digestion [kg.(kg_CH$_4$)$^{-1}$]

μ_{CH_4}: methane yield [NmL_CH$_4$.(g_VS^{a})$^{-1}$]

μ_{area}: areal productivity of microalgae [kg_DW^{b}.(m^2.day)$^{-1}$]

θ_{CH_4}: methane fraction of biogas [%]

$\theta_{VS/TS}$: Volatile to total solid ratio of the feedstock [g_VS.(g_TS^{c})$^{-1}$]

7. Conclusions and perspectives

This deliverable introduces the LCA methodological framework to be applied for assessing the environmental impacts of the strategies/technologies considered in NUTRITIVE for manure management, in accordance with (ISO 14040, 2006) and (ISO 14044, 2006). Besides, the protocol that will be followed to do sensitivity analysis and generate simplified model for each impact category related to Task 3.3 is presented. Moreover, the approach for dynamic modeling to account for the inherent variations of systems, which may impact the results of the LCA, is also presented.

Due to time constraints, ten S/T have been selected for LCA out of the twenty two proposed in NUTRITIVE including S/T 2 dietary interventions, S/T 9 microalgae, S/T 21 vermicompost and lagoons, S/T 22 conventional anaerobic digestion, S/T 13 air ammonia stripping, S/T 16 solar drying, S/T pulse combustion drying, S/T 7 manure fertigation, S/T 18 fertilizers based on S/T 9 microalgae, and an additional hydrogen production system. At the current stage of the project, only S/T 9, S/T 18 and hydrogen production are modeled for environmental evaluation, for which the system boundaries have been presented in this document.

The main elements required in the goal and scope definition—functional unit, system boundaries, method to deal with multifunctional systems and initial data quality expectations—are outlined, as they form the basis for subsequent phases: inventory analysis, life cycle impact assessment, and interpretation, in which sensitivity analysis and simplified models generation are performed.

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[a] Volatile solid

[b] Dry weight

[c] Total solid

Currently, the parameterized models are under development with close collaboration with the Universidad de Santiago de Compostela and the industrial partners of NUTRITIVE in Task 3.2. Three questionnaires for data collection have been sent and for which responses have been received for S/T 9 microalgae, S/T 13 air ammonia stripping, and hydrogen production. For the other S/T, WP3 is in contact with WP2 to ease the connection with the industrial partners.

Despite the project being in its early stages, some examples of results from sensitivity analyses and simplified models have been shown, providing an indication of what can be expected from Task 3.3. As LCA is inherently iterative, the methodological choices presented here may be revised as new data or constraints emerge. Any updates will be reflected in Deliverable 3.4.

References

Ademe. (2025). *Agribalyse*. https://agribalyse.ademe.fr/

Andrews, E. S., Barthel, L.-P., Tabea, B., Benoît, C., Ciroth, A., Cucuzzella, C., Gensch, C.-O., Hébert, J., Lesage, P., Manhart, A., Mazeau, P., Mazijn, B., Methot, A.-L., Moberg, A., Norris, G., Parent, J., Prakash, S., Reveret, J.-P., Spillemaeckers, S., … Weidema, B. (2009). UNEP-SETAC: GUIDELINES FOR Social Life Cycle Assessment of Products. In C. Benoît (Ed.), *Environment*. United Nations Environment Programme.

Ciroth, A., Finkbeiner, M., Hildenbrand, J., Klöpffer, W., Mazijn, B., Prakash, Siddharth Sonnemann, G., Traverso, M., Ugaya, Cássia Maria Lie Valdivia, S., & Vickery-Niederman, G. (2011). *Towards a life Cycle Sustainability Assessment: Making informed choices on products* (S. Valdivia, C. M. L. Ugaya, G. Sonnemann, & J. Hildenbrand (Eds.)). UNEP/SETAC Life Cycle Initiative. https://doi.org/DTI/1412/PA

Ciroth, A., Huppes, G., Klöpffer, W., Rüdenauer, I., Steen, B., & Swarr, T. (2008). *Environmental Life Cycle Costing* (D. Hunkeler, K. Lichtenvort, & G. Rebitzer (Eds.); 1st ed.). SETAC-CRC. https://doi.org/10.1201/9781420054736.ch3

Douziech, M., Ravier, G., Jolivet, R., Pérez-López, P., & Blanc, I. (2021). How Far Can Life Cycle Assessment Be Simplified? A Protocol to Generate Simple and Accurate Models for the Assessment of Energy Systems and Its Application to Heat Production from Enhanced Geothermal Systems. *Environmental Science and Technology*, *55*(11), 7571–7582. https://doi.org/10.1021/acs.est.0c06751

ecoinvent. (2023). *ecoinvent database*. https://ecoinvent.org/

European Commission. (2021). Pathway to a healthy planet for all. EU action plan: “Towards zero pollution for air, water and soil.” In *COM(2021) 400 final*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0400

European Committee for standardization. (2015). *BS EN 16760:2015 Bio-based products — Life Cycle Assessment*.

European Environment Agency. (2023). *EMEP/EEA air pollutant emission inventory guidebook 2023 : technical guidance to prepare national emission inventories*. https://doi.org/10.2800/795737

Glover, C. J., McDonnell, A., Rollins, K. S., Hiibel, S. R., & Cornejo, P. K. (2023). Assessing the environmental impact of resource recovery from dairy manure. *Journal of Environmental Management*, *330*, 117150. https://doi.org/10.1016/j.jenvman.2022.117150

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (Eds.). (2018). *Life cycle assessment: Theory and Practice* (Vol. 1). Springer International Publishing AG. https://doi.org/10.17654/JPHMTFeb2015_029_042

Heijungs, R., Allacker, K., Benetto, E., Brandão, M., Guinée, J., Schaubroeck, S., Schaubroeck, T., & Zamagni, A. (2021). System Expansion and Substitution in LCA: A Lost Opportunity of ISO 14044 Amendment 2. *Frontiers in Sustainability*, *2*, 1–3. https://doi.org/10.3389/frsus.2021.692055

ISO 14040. (2006). Environmental management — Life cycle assessment — Principles and framework. *International Standards Organization*.

ISO 14044. (2006). Environmental management — Life cycle assessment — Requirements and guidelines. *International Standards Organisation*.

Jolivet, R. (2020). LCA_algebraic. In *OIE MINES Paris-PSL*. https://github.com/oie-mines-paristech/lca_algebraic

Maga, D. (2017). Life cycle assessment of biomethane produced from microalgae grown in municipal waste water. *Biomass Conversion and Biorefinery*, *7*, 1–10. https://doi.org/10.1007/s13399-016-0208-8

Müller, A., Diepers, T., Jakobs, A., Cardellini, G., von der Assen, N., Guinée, J., & Steubing, B. (2025). Time-explicit life cycle assessment: a flexible framework for coherent consideration of temporal dynamics. *International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-025-02539-3

Mutel, C. (2017). Brightway: An open source framework for Life Cycle Assessment. *Journal of Open Source Software*, *2*(12), 236. https://doi.org/10.21105/joss.00236

Padey, P. (2013). *Modèles simplifiés d ' Analyse de Cycle de Vie : cadre méthodologique et applications aux filières de conversion d ' énergie* [Ecole Nationale Supérieure des Mines de Paris]. https://pastel.archives-ouvertes.fr/pastel-01057847

Rajaonison, A. (2024). *Environmental Life Cycle Assessment of time dependent microalgal-based energy production systems* [Université Paris sciences et lettres]. https://pastel.hal.science/tel-05027392v1

Rajaonison, A., Gschwind, B., Jolivet, R., Gómez-Serrano, C., Acién Fernández, F. G., Greses, S., González-Fernández, C., Pérez-López, P., & Ranchin, T. (2025). Detailed and simplified parameterized LCA models for Early-Stage Energy Projects: A Microalgae-Based Biogas Case. *Cleaner Environmental Systems*. https://doi.org/10.1016/j.biotechadv.2020.107584

Sacchi, R., Menacho, A. H., Seitfudem, G., Agez, M., Schlesinger, J., Koyamparambath, A., Saldivar, J. S., Loubet, P., & Bauer, C. (2025). Contextual LCIA Without the Overhead: An Exchange-based Framework for Flexible Impact Assessment. *International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-025-02551-7

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., & Tarantola, S. (2008). Global sensitivity analysis: The primer. In *Global Sensitivity Analysis: The Primer*. John Wiley & Sons Ltd. https://doi.org/10.1002/9780470725184

Sobol, I. M. (2001). Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. *Mathematics and Computers in Simulation*, *55*(1–3), 271–280. https://doi.org/10.1016/S0378-4754(00)00270-6

UNEP 2020. (2020). Guidelines for Social Life Cycle Assessment of Products and Organizations 2020. In C. Benoît Norris, M. Traverso, S. Neugebauer, E. Ekener, T. Schaubroeck, S. Russo Garrido, M. Berger, S. Valdivia, A. Lehmann, M. Finkbeiner, & G. Arcese (Eds.), *United Nations Environment Programme (UNEP)*. http://www.unep.fr/shared/publications/pdf/DTIx1164xPA-guidelines_sLCA.pdf

Valdivia, S., Backes, J. G., Traverso, M., Sonnemann, G., Cucurachi, S., Guinée, J. B., Schaubroeck, T., Finkbeiner, M., Leroy-Parmentier, N., Ugaya, C., Peña, C., Zamagni, A., Inaba, A., Amaral, M., Berger, M., Dvarioniene, J., Vakhitova, T., Benoit-Norris, C., Prox, M., … Goedkoop, M. (2021). Principles for the application of life cycle sustainability assessment. *International Journal of Life Cycle Assessment*, *26*, 1900–1905.

https://doi.org/10.1007/s11367-021-01958-2

Wu, W., Cheng, L.-C., & Chang, J.-S. (2020). Environmental life cycle comparisons of pig farming integrated with anaerobic digestion and algae-based wastewater treatment. *Journal of Environmental Management*, *264*, 110512. https://doi.org/10.1016/j.jenvman.2020.110512

Zamagni, A., Pesonen, H. L., & Swarr, T. (2013). From LCA to Life Cycle Sustainability Assessment: Concept, practice and future directions. *International Journal of Life Cycle Assessment*, *18*, 1637–1641. https://doi.org/10.1007/s11367-013-0648-3