FertiCovery

Assessment of environmental aspects of technologies

Publish Date: March 2026

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Technical References

Project Acronym	FertiCovery
Project Title	BEST AVAILABLE TECHNIQUES TO RECOVER OR RECYCLE FERTILISING PRODUCTS FROM SECONDARY RAW MATERIALS
Project Coordinator	Martijn Vis, BTG Biomass Technology Group B.V.
Project Duration	36 months

Deliverable No.	3.2
Dissemination level [1]	PU
Work Package	WP3–Analysis of nutrient recovery and bio-based fertiliser production technologies
Task	**3.2. Environmental impacts and resource efficiency assessment**
Lead beneficiary	Fundación Cartif (CTF)
Contributing beneficiary(ies)	BTG, NTUA
Due date of deliverable	31 March 2026
Actual submission date	23 September 2026

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RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for members of the consortium (including the Commission Services)

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Document history

Version	Date	Beneficiary	Author
V1	17/02/26	Fundación Cartif (CTF)	F.Verdugo /F.Corona
V1.1	17/03/26	Fundación Cartif (CTF)	F.Verdugo / F.Corona Martijn Vis / Sterre Van der Voort
V1.2	23/03/26	Fundación Cartif (CTF)	F.Verdugo / F.Corona Martijn Vis / Sterre Van der Voort Maria Kyriazi / Roula Klemp
V.2	26/03/26	Fundación Cartif (CTF)	F.Verdugo / F.Corona Martijn Vis / Sterre Van der Voort Maria Kyriazi / Roula Klemp
V.3	22/09/26	Fundación Cartif (CTF)	F.Verdugo / F.Corona Martijn Vis / Sterre Van der Voort Maria Kyriazi / Roula Klemp

Summary of Deliverable

This deliverable presents a review of the environmental aspects to be considered in the assessment of nutrient recovery (NR) and bio-based fertiliser (BBF) production technologies within the FertiCovery project. Its main objective is to identify and justify a set of Environmental Assessment Indicators (EAIs) suitable for supporting the subsequent environmental comparison of the technologies addressed in the project, particularly in Task 3.3 and in the multicriteria decision analysis (MCDA) foreseen in WP6.

To achieve this objective, the work combines evidence from three complementary sources: recent scientific literature, Product Category Rules (PCRs), and documentation from European research projects. The scientific literature provides methodological insight into how Life Cycle Assessment (LCA) is currently applied to nutrient recovery and bio-based fertiliser systems. The PCRs offer a structured and harmonised reference on functional units, system boundaries and mandatory impact categories for product groups relevant to this study. European project documentation contributes practical evidence from pilot, demonstration and applied research contexts, showing how environmental assessment is currently implemented in innovation-oriented settings.

The review highlights that, although environmental assessment practices are broadly aligned, important methodological differences remain across sources. In particular, functional units vary according to the objective of the study and may be based on the amount of waste treated, the quantity of fertiliser produced, the amount of nutrient recovered, or the agricultural function delivered. System boundaries also differ, with cradle-to-gate being the most common approach, while cradle-to-grave and gate-to-gate perspectives are also applied depending on the purpose of the assessment. These differences are especially relevant because they directly affect the comparability of environmental results across technologies and studies.

The review also shows that several life cycle impact assessment methods are used in the analysed sources. ReCiPe and CML appear prominently in the scientific literature, while European projects frequently apply ReCiPe, Product Environmental Footprint (PEF), Impact World+ and, in some cases, complementary modelling approaches adapted to agricultural systems. This methodological diversity confirms that the reported environmental results are influenced not only by the technologies assessed, but also by the selected impact assessment framework and its characterisation factors.

Despite this methodological variability, the analysed evidence converges around a relatively stable group of environmental impact categories. Climate change, eutrophication and acidification were identified as the most consistently reported categories across the reviewed sources. Resource use and water use also appeared frequently and were considered particularly relevant in the context of circular nutrient management and bio-based fertiliser production. Based on this integrated review, these five categories were selected as the core EAIs for the subsequent stages of the project.

Overall, this deliverable provides a transparent and evidence-based review of the environmental aspects most relevant for the evaluation of NR and BBF technologies in FertiCovery. It not only identifies the impact categories to be prioritised in subsequent tasks, but also highlights the importance of carefully considering functional units, system boundaries and impact assessment methods in order to ensure fair, transparent and robust comparisons between technologies in later stages of the project.

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1 Introduction

The assessment of environmental impacts has become an essential component in the development and deployment of innovative technologies, particularly those aimed at supporting sustainable nutrient management and bio-based fertiliser production. As Europe moves towards more resource-efficient and circular economic models, it is increasingly important to understand not only the technical performance of emerging solutions but also their potential environmental consequences. This deliverable contributes to this broader objective by establishing a clear and coherent basis for evaluating the environmental performance of the technologies studied within the project.

The work presented here builds on the activities conducted in earlier project stages, especially the selection and description of the technologies carried out in Tasks 2.2 and 2.3. By drawing on this foundational knowledge, the present deliverable focuses on defining appropriate indicators and impact categories that can capture the most relevant environmental aspects associated with nutrient recovery and bio-based fertiliser production. This preparatory step is essential for ensuring that forthcoming assessments are both robust and aligned with the characteristics and operating conditions of each technology.

The main objective of this deliverable is to identify and justify a set of Environmental Assessment Indicators that are suitable for evaluating the technologies under consideration. To achieve this, the work combines an extensive review of established methodologies, including Life Cycle Assessment and Environmental Impact Assessment, with an examination of scientific literature and outcomes from European research initiatives. This approach ensures that the selected indicators are grounded in recognised methodological frameworks while remaining relevant to the specific systems addressed in the project.

Along with indicators, the deliverable defines the environmental impact categories that will guide the assessment in future tasks. Selecting these categories requires careful consideration of both scientific relevance and the availability of meaningful data. It also involves ensuring consistency across technologies so that they can be compared in a fair and transparent manner. Establishing these categories at this stage therefore sets the foundation for an effective and coherent environmental evaluation process.

A further objective is to determine an appropriate functional unit that will serve as a reference for all assessments conducted later in the work package. The definition of the functional unit is a critical step, as it ensures that comparisons across different technologies are meaningful and reflect their intended purpose and scale. The process described in this deliverable aims to ensure that the selected unit is practical, scientifically sound, and consistent with standard practice in environmental assessment.

Together, these elements create a solid methodological framework that will support the detailed environmental analysis to be carried out in subsequent tasks, particularly the comparative study developed in Task 3.3. By clearly establishing indicators, impact categories, and methodological principles, this deliverable ensures that future evaluations are transparent, traceable, and aligned with recognised best practices. As such, it represents an important milestone in the project's efforts to assess and improve the environmental performance of nutrient recovery and bio-based fertiliser production technologies.

2 Methodology

The methodological approach adopted in this task was designed to build a coherent and well-supported foundation for assessing the environmental impacts of nutrient recovery (NR) and bio-based fertiliser (BBF) technologies. Because these technologies involve diverse feedstocks, treatment routes and system scales, it was necessary to construct the assessment framework using a wide and complementary set of information sources. The aim was not only to identify relevant environmental indicators and functional units (FUs), but also to ensure that the evidence reflects both scientific knowledge and current industrial practice.

To achieve this, the methodology followed a structured but flexible workflow, combining scientific studies, environmental declarations, and project-level evidence developed under recent European research initiatives. Each source type contributes a distinct perspective and level of detail, and their integration helps avoid biases associated with using a single form of evidence. Three major groups of sources were consulted:

- **Scientific literature**. Scientific publications were systematically searched using targeted keyword combinations related to life-cycle assessment, nutrient recovery technologies and bio-based fertilisers. These articles provide transparent methodological descriptions, detailed life-cycle inventories and explicit functional units. As such, they offer the most rigorous foundation for understanding how environmental impacts have been historically assessed in comparable systems. Their inclusion ensures alignment with state-of-the-art LCA practice and captures methodological trends emerging over the last five years.
- **Environmental Product Declarations (EPDs).** EPDs were included when relevant to fertiliser products derived from waste or bio-based materials. Although these documents are less detailed than academic studies, they follow harmonised Product Category Rules (PCRs) and ISO standards. This means they offer reliable, industry-grounded environmental profiles that reflect real-world production systems rather than laboratory or pilot scales. They therefore help bridge the gap between scientific assumptions and operational practice.
- **European project deliverables and reports (H2020 / Horizon Europ**e). Outputs from European research and innovation projects were also reviewed, including initiatives such as LEX4BIO, RUN4LIFE, FER-PLAY, NUTRI2CYCLE, NOVAFERT, SYSTEMIC and SEA2LAND. These projects often evaluate nutrient recovery and bio-fertiliser systems at pilot or demonstration scale, using LCA approaches aligned with EU guidance frameworks (e.g., ILCD, PEF, JRC recommendations). They frequently provide harmonised datasets, practical inventory assumptions and broader system insights that are not available in scientific literature or commercial declarations. Their inclusion ensures coherence with EU methodological expectations and policy priorities.

3 Findings of the Literature Review

This section presents the findings of the literature review and document analysis conducted for Task 3.2. The results are organised into three subsections corresponding to the main categories of sources consulted: peer-reviewed scientific articles, Environmental Product Declarations (EPDs), and deliverables from European research projects. Each subsection summarises the key observations derived from the evidence base, including the types of technologies assessed, the functional units employed, the environmental impact indicators reported, and the methodological approaches adopted by the respective studies.

3.1 Insights from the Scientific Literature Review

Scientific literature provides the most rigorous methodological foundation for understanding how environmental impacts are evaluated in nutrient recovery (NR) and bio-based fertiliser (BBF) systems. Peer-reviewed Life Cycle Assessment (LCA) studies typically include clearly defined system boundaries, transparent inventory assumptions, and explicit functional units, making them an essential reference for identifying established environmental assessment practices.

Within the context of this deliverable, the review of scientific literature aims to identify the environmental impact categories most applied in the environmental evaluation of technologies related to:

- Nutrient recovery from organic residues and waste streams,
- Production of bio-based fertilisers,
- Manure and organic waste treatment systems.

To ensure a robust and representative evidence base while maintaining methodological clarity, the analysis focused on two recent review articles addressing the environmental assessment of fertiliser production from secondary raw materials. Review papers provide a comprehensive synthesis of numerous individual studies and therefore allow broader methodological trends to be identified.

The objective of this section is therefore not to compare environmental results across technologies, but rather to extract methodological insights from the literature, particularly regarding:

- The types of technologies evaluated,
- The functional units used in environmental assessments,
- The system boundaries typically adopted,
- The environmental impact categories most frequently reported.

These observations provide an essential scientific reference for defining the Environmental Assessment Indicators used later in this deliverable.

3.1.1 Scope of the Reviewed Studies

The scientific literature considered in this task was synthesised through two recent review articles that provide complementary perspectives on the environmental assessment of nutrient recovery and bio-based fertiliser systems. Together, these reviews offer a broad methodological basis for identifying the environmental impact categories most frequently applied in Life Cycle Assessment studies relevant to the scope of FertiCovery.

The first review addresses nutrient circularity from waste and wastewater to fertiliser and examines **128 papers covering more than 300 scenarios**, with a particular focus on the waste/wastewater–agriculture nexus. It includes a wide range of circular economy pathways, from direct land application to established and emerging nutrient recovery technologies. Its scope is broad and cross-sectoral, covering **municipal, agricultural and industrial streams**, although municipal systems account for the largest share of the analysed scenarios.

The second review focuses more specifically on the **production of biofertilisers from agricultural waste** and analyses **98 references** published between 2018 and 2024. This review is particularly useful for characterising the technological and methodological profile of recent studies, since it provides structured information on feedstocks, technology types, technological maturity, system boundaries, functional units and impact categories.

Nutrient circularity from waste to fertilizer: A perspective from LCA studies [1]

128 studies; >300 scenarios (1998-2021)

Feedstocks: Municipal (organic solid waste and WWTP), agricultural and industrial streams

Technologies: Biological processes (Anaerobic digestion, composting) and direct application

Impact categories: Global Warming Potential (GWP), Eutrophication, Acidification

Functional units: Input and output base FUs

Life Cycle Assessment of the Production of Biofertiliser from agriculture waste [2]

98 studies (2018-2024)

Feedstocks: Manure and Organic wastes, Crop residues, others

Technologies: Biological processes (Anaerobic digestion, composting) and Thermochemical (incineration, pyrolysis and gasification)

Impact categories: Global Warming Potential (GWP), Eutrophication, Acidification and Ozone depletion

Functional units: Input and output base FUs

Taken together, the two reviews cover a wide variety of feedstocks and technological pathways relevant to nutrient recovery and fertiliser production. The reviewed studies include animal manures, crop residues, food and organic waste, sewage-related streams, digestates, sludge and other biomass-based side streams. From a technological perspective, the literature is dominated by **anaerobic digestion and composting**, while other pathways such as precipitation, ammonia recovery, thermochemical treatment and mechanical processing appear less frequently but are also represented.

The scope of the reviewed studies is also broad in terms of assessment scale and application context. The literature includes both pilot and full-scale systems, although full-scale applications are more common in the agricultural waste review, while the broader nutrient circularity review captures a larger diversity of technological maturity and system configurations. Geographically, the literature is strongly centred on Europe, although studies from Asia, North America and other regions are also included.

This combined scope is particularly valuable for the objectives of this deliverable. The broader review helps identify common assessment practices across nutrient circularity systems, while the more targeted agricultural waste review provides a detailed picture of how biofertiliser-related technologies are currently assessed in practice. Their joint use therefore strengthens the identification of the environmental impact categories most consistently applied in the scientific literature.

3.1.2 Methodological Characteristics of LCA Studies

Life Cycle Assessment studies evaluating nutrient recovery and bio-based fertiliser production systems show a considerable diversity in methodological choices. This variability is mainly related to the definition of the functional unit, the system boundaries adopted in the assessment, and the life cycle impact assessment (LCIA) methods used to translate inventory data into environmental indicators. Although these methodological differences may limit direct comparability between studies, they also provide useful insights into current assessment practices in the scientific literature.

One of the most important methodological elements in LCA is the definition of the functional unit, as it establishes the reference against which environmental inputs and outputs are normalised. The reviewed literature shows that functional units are defined according to different perspectives depending on the

objective of the study. In some cases, the functional unit refers to the quantity of waste or feedstock treated, for example one tonne of manure or organic waste processed. In other cases, the functional unit is based on the amount of fertiliser produced, such as one tonne of bio-based fertiliser. Some studies instead focus on the recovery of specific nutrients and therefore define the functional unit in terms of the amount of nitrogen or phosphorus recovered. Energy-based functional units are also occasionally used when the system includes energy recovery processes, such as biogas production. This diversity reflects the multifunctional nature of many nutrient recovery systems, which may simultaneously perform waste treatment, fertiliser production and energy generation.

Another important methodological aspect concerns the system boundaries considered in the environmental assessment. The literature shows that several types of system boundaries are applied depending on the scope and objectives of the study. The cradle-to-gate approach is the most used framework, covering the stages from raw material extraction and feedstock collection to the production of the fertiliser product at the plant gate. This approach is often preferred because it allows researchers to focus on the production stage while avoiding uncertainties associated with the use phase and end-of-life management. Other studies adopt a cradle-to-grave perspective, which also includes fertiliser application and potential emissions during the use phase. Less frequently, gate-to-gate assessments are used to evaluate the environmental performance of specific treatment steps within a broader system.

The choice of Life Cycle Impact Assessment methodology also varies across studies. Several commonly used LCIA methods appear in the literature, including ReCiPe, CML, TRACI and climate-specific indicators derived from the IPCC methodology. These methods convert inventory flows such as emissions to air, water and soil, or resource consumption, into environmental impact indicators. Because each methodology includes its own set of impact categories and characterisation factors, the selected LCIA framework directly influences the environmental indicators reported in each study. For example, widely used methods such as ReCiPe and CML typically include categories related to climate change, eutrophication and acidification, which explains why these indicators appear consistently across many LCA studies assessing nutrient recovery systems.

Despite the methodological diversity observed across studies, a common pattern emerges regarding the environmental aspects that are considered most relevant. Indicators associated with greenhouse gas emissions, nutrient losses to aquatic environments and atmospheric emissions are consistently reported, reflecting the main environmental pressures associated with waste management and fertiliser production systems. Consequently, the LCIA methods applied in the reviewed literature tend to include categories addressing climate change, eutrophication and acidification as core environmental indicators.

3.1.3 Summary of Key Findings from the Scientific Literature

The review of the scientific literature provides a clear overview of the methodological approaches commonly used to evaluate nutrient recovery and bio-based fertiliser systems through Life Cycle Assessment. Although the analysed studies differ in technological focus and methodological choices, several consistent patterns can be identified.

First, the literature shows a high degree of variability in the definition of functional units and system boundaries. This reflects the multifunctional nature of many nutrient recovery systems, which may simultaneously perform waste treatment, fertiliser production and energy recovery. As a result, studies adopt different reference units and system configurations depending on the specific objective of the assessment.

Second, despite these methodological differences, a relatively stable set of environmental impact categories is repeatedly used across studies. Indicators related to climate change, eutrophication and acidification appear particularly frequently, reflecting the main environmental pressures associated with waste management and nutrient recovery processes. Their recurrent use is also linked to the LCIA methodologies most applied in the literature, such as ReCiPe and CML.

Overall, the literature review highlights both the diversity of methodological practices and the convergence around a core group of environmental indicators. These findings provide a useful scientific reference for identifying the environmental impact categories that are most relevant for the assessment of nutrient recovery technologies within the FertiCovery project.

Table 1.Key methodological requirements from literature review

Methodological element	Description	Findings from literature review
Functional unit	Reflects different system functions and assessment objectives	Waste treated (e.g., 1 tonne manure), fertiliser produced (e.g., 1 tonne product), nutrient recovered (e.g., 1 kg N or P), energy produced (e.g., 1 kWh)
System boundaries	Determines which life-cycle stages are included in the analysis	Cradle-to-gate (most common), cradle-to-grave, gate-to-gate
LCIA methodology	Defines the environmental indicators and characterisation factors	ReCiPe, CML, TRACI, IPCC
Impact categories commonly associated with these methods	Indicates the environmental pressures typically assessed in nutrient recovery systems	Climate change, eutrophication, acidification, ozone depletion, resource use

3.2 Information from Product Category Rules (PCRs) for EPD Development

Product Category Rules (PCRs) represented a particularly coherent source of information within this review. Their high level of internal consistency derives directly from the methodological framework under which the Environmental Product Declaration are based on.

Each PCR prescribes the functional unit, system boundaries, allocation procedures, mandatory impact indicators and reporting format that must be followed. Consequently, EPDs belonging to the same product category show a degree of comparability that is seldom found in scientific literature or in EU project deliverables, where methodological choices are far more variable.

To illustrate the specific methodological features that underpin this homogeneity, Table 2. summarises the functional units, methodological references and impact categories established in the three PCRs relevant to this study. Within this framework, several clear patterns emerged from the EPDs reviewed.

Table 2. Key methodological requirements defined in the PCRs relevant to this study

PCR	FU	Required impact categories
Fertilisers (PCR 2010:20, v4.0.0) [3]	1 tonne of fertiliser	Climate Change; Ozone Depletion; Acidification; Eutrophication; Photochemical Ozone Creation; Abiotic Resource Use; Water Use; Waste indicators

Table 2. Key methodological requirements defined in the PCRs relevant to this study

PCR	FU	Required impact categories
Biochar (PCR 2021:07, v1.0) [4]	1 tonne of biochar	Climate Change; Acidification; Eutrophication; Photochemical Ozone Formation; Resource Use; Water Use; Land Use; Biogenic carbon reporting
Biostimulants (PCR 2025:02, v1.0.0) [5]	1 gram of product (including CFU/g for microbial products)	Climate Change; Acidification; Eutrophication; Water Use; Resource Use; Photochemical Ozone Formation; Particulate Matter; Ionising Radiation; Human Toxicity; Freshwater Ecotoxicity

First, functional units were fully consistent within each product category. Fertiliser and biochar EPDs uniformly reported results per tonne of product, whereas biostimulant EPDs consistently used a gram-based functional unit, as required by their respective PCRs. This contrasts markedly with the wide variety of functional units identified in the scientific literature, where differences in study design and research objectives often lead to incompatible metrics.

Second, system boundaries were applied in the same manner across all EPDs, reflecting the cradle-to-gate or cradle-to-grave structure mandated in the PCRs. The division of the life cycle into upstream, core and downstream stages was consistent across documents, ensuring that production processes, transport, packaging, use and end-of-life stages were handled in a comparable way for all products within the same category.

Finally, the environmental impact categories reported were identical for all products governed by the same PCR, since these categories are prescribed directly in the PCR and must be included in every EPD issued under that rule. This eliminates the methodological divergence observed in other sources and ensures that climate change, acidification, eutrophication, resource use and other mandatory indicators are calculated using the same conventions and characterisation methods.

Together, these findings explain the high level of internal coherence observed in the EPDs reviewed. Their structure, imposed by the PCRs, guarantees comparable functional units, harmonised system boundaries and consistent impact indicators, making EPDs a particularly reliable and stable reference point within the broader evidence base used for this task.

3.3 Results from EU-Funded Project Documentation

3.3.1 LEX4BIO

The **LEX4BIO [6]** project seeks to strengthen the sustainability of nutrient management in Europe by promoting the use of bio-based fertilisers (BBFs) produced from secondary raw materials and reducing dependence on conventional mineral fertilisers. Its work focuses on understanding the environmental performance of BBFs derived from a wide variety of feedstocks, such as crop residues, animal by-products, sewage sludge, poultry litter, sunflower husk ash and other residual biomasses.

These materials are transformed through several technological pathways that include biological treatments like fermentation and hydrolysis, chemical precipitation processes, thermal treatments, solid–liquid separation, drying steps and systems integrating biochar production. Together, these technologies represent the most mature and relevant nutrient-recovery routes currently being developed within the

European context, delivering both phosphorus-based and nitrogen-based fertilising products in different physical and chemical forms.

To assess their environmental performance, LEX4BIO applies a harmonised methodological framework grounded in ISO 14040/44, supported by the Ecoinvent 3.9.1 database and using ReCiPe 2016 Midpoint (H) as the life-cycle impact assessment method. The evaluation includes the following **impact categories**: a) Climate change, b) Fine particulate matter formation, c) Terrestrial, Freshwater and Marine Ecotoxicity, d) Freshwater and Marine e) Eutrophication, f) Human toxicity (cancer and non-cancer), g) Terrestrial acidification and h) Stratospheric ozone depletion. Because the products differ greatly in composition and nutrient concentration, the study adopts nutrient-based **functional units** to ensure comparability across technologies: 1 kg of P_2O_5 for phosphorus-based BBFs and 1 kg of N for nitrogen-based BBFs. Conventional mineral fertilisers are used as reference flows to contextualise substitution effects. The **system boundary** is consistently defined as cradle-to-gate, incorporating all upstream and conversion stages, from feedstock sourcing and preparation to biological, chemical or thermal processing and final product conditioning, while excluding land-application emissions, which are addressed separately.

3.3.2 RUN4LIFE

The **RUN4LIFE** [7] project investigates decentralised and source-separated wastewater management as a way to increase nutrient recovery and produce fertilising products from domestic waste streams. Its central idea is to separate blackwater, greywater and food waste at source so that each fraction can be treated with technologies best suited to its characteristics. Across several demonstration sites, the project applies combinations of anaerobic and aerobic treatment, membrane processes and nutrient recovery operations such as struvite precipitation and ammonium stripping, with the aim of closing nutrient loops and reducing reliance on conventional centralised wastewater treatment.

For the environmental assessment, RUN4LIFE follows the Life Cycle Assessment framework defined by ISO 14040/44, uses Ecoinvent as the main background database and applies ReCiPe 2016 as impact assessment method. The categories actually used to express the results are explicitly listed in the study and comprise eight midpoint indicators: Global warming, Stratospheric ozone depletion, Ozone formation (terrestrial ecosystems), Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Mineral resource scarcity and Water consumption. This focused set of indicators provides a balanced view of climate-related, air- and water-quality impacts, as well as resource use, in the comparison between decentralised and conventional systems.

The functional units employed vary according to the function being analysed. When the objective is to evaluate the overall sanitation service provided by source separation, the functional unit is defined as “the management of one capita yearly load of food waste, blackwater and greywater, including collection, treatment and disposal”, capturing the full service delivered to a person over one year. In other comparisons, especially when the water-treatment function is emphasised, flow-based functional units such as cubic metre of wastewater treated per day are used. For the specific case where decentralised and centralised systems are compared on the basis of phosphorus recovery, a nutrient-based functional unit of 1 kg P_2O_5 is applied, allowing a direct comparison of systems with very different configurations but the same fertilising output.

System boundaries are adapted to the research question but remain clearly defined in all cases. At sanitation-system level, the boundary encompasses collection (often via vacuum toilets), transport of separated streams, treatment of blackwater, greywater and food waste, and subsequent nutrient recovery, typically following a cradle-to-gate approach that includes all processes up to the production of recoverable fertiliser products. In scenarios where the aim is to investigate the benefits of fertiliser substitution or energy recovery, the boundary is expanded to incorporate credits for avoided mineral fertiliser production or displaced energy from biogas use. For unit-process analyses focused on individual technologies, gate-to-gate boundaries are also applied to isolate the contribution of specific treatment steps.

3.3.3 FER-PLAY

The **FER-PLAY [8]** project addresses the development and uptake of "circular fertilisers" produced from secondary raw materials across Europe. It starts from a broad mapping of existing and emerging products and value chains and then narrows the analysis to seven representative circular fertilisers: struvite recovered from urban waste water, struvite from industrial waste water, stabilised sewage sludge, composted bio-waste from food and green waste, feather meal fertiliser, solid fraction of digestate (from food waste, sewage sludge and manure) and spent mushroom substrate.

These products are all derived from waste streams such as municipal and industrial effluents, manures, bio-waste and organic by-products, which enter the system as recovered materials rather than as primary resources. The central objective of the environmental work is to compare the life-cycle impacts of these circular fertilisers with those of conventional non-renewable fertilisers delivering an equivalent nutrient function, so that the contribution of circular options to climate and pollution objectives can be assessed in a consistent way.

For the environmental pillar of the life cycle sustainability assessment, FER-PLAY applies the **Product Environmental Footprint (PEF) 3.1 method** as the common life cycle impact assessment framework. For each of the seven value chains the report specifies the N, P, K and C content per tonne of product, distinguishing between dry- and wet-basis formulations, so that impacts can be related both to mass of product and to nutrient delivery. **System boundaries** follow a cradle-to-gate-to-grave perspective, covering all processes from extraction and production of auxiliary raw materials, through waste treatment and fertiliser manufacturing, to packaging, distribution and final application on agricultural land. Because all circular fertilisers are based on waste inputs, the study applies a zero-burden assumption: environmental impacts associated with generating the waste are attributed to the original product system, and the recovered material enters the fertiliser system without upstream environmental loads. The analysis distinguishes between the production (cradle-to-gate) and use (gate-to-grave) segments in order to reflect different levels of data uncertainty in these two parts of the life cycle, while maintaining a consistent overall boundary definition.

Within this framework, FER-PLAY calculates the full set of PEF 3.1 midpoint **impact categories** for all circular and conventional fertiliser systems. These include climate change (with separate indicators for total, fossil, biogenic and land-use-change-related greenhouse gas emissions), acidification, terrestrial, freshwater and marine eutrophication, freshwater ecotoxicity, human toxicity (cancer and non-cancer effects), particulate matter, photochemical ozone formation, ionising radiation (human health), ozone depletion, land use, water use, and resource use for fossils and for minerals and metals. Although all categories are calculated to respect the PEF method, the narrative discussion focuses particularly on climate change, freshwater eutrophication and resource use (minerals and metals), since these indicators are most directly linked to nutrient cycling, pollution control and the substitution of mined fertiliser raw materials. The project also applies PEF normalisation and weighting to derive single-score results, and subsequently uses monetisation factors derived from the Environmental Prices Handbook and recent literature to explore external environmental costs in monetary terms, while keeping the methodological basis transparent.

3.3.4 NUTRI2CYCLE

The **Nutri2Cycle [9]** project focuses on improving nutrient management in European agriculture by closing nitrogen, phosphorus and carbon loops at farm level. Its aim is to identify technological solutions that can reduce emissions, recover nutrients from animal and crop residues and support more circular farming systems. Within this framework, the project evaluates a broad set of innovations that reflect the diversity of nutrient flows and agricultural practices across Europe.

The technologies assessed in Nutri2Cycle cover different types of nutrient recovery and manure treatment options. Among the solutions studied are ammonia stripping and scrubbing systems; evaporation and membrane-based concentration of liquid manure fractions; phosphorus recovery through crystallisation; several digestate-based treatments; acidification of manure during storage; low-temperature ammonia recovery; the production of alternative bedding materials; insect rearing on organic waste streams; and the use of aquatic plants grown on diluted manure. These technologies generate a wide range of products, including ammonium sulphate, ammonium nitrate, nutrient-rich concentrates, recovered phosphorus minerals such as struvite, processed digestate fractions, organic fertiliser materials, alternative bedding and protein-rich biomass.

The environmental evaluation uses Life Cycle Assessment (LCA) based on the principles of the **Product Environmental Footprint (PEF).** Inventory data are built from primary measurements provided by partners, experimental results generated within the project, agricultural modelling and background processes taken from the Ecoinvent database. This approach ensures that all technologies are assessed through a consistent methodological frame while still capturing the practical variation associated with different farm systems and waste streams.

The **functional unit** depends on the type of technology being assessed. For manure and digestate treatments, the most common unit is one tonne of liquid or solid fraction treated, reflecting the service of reducing emissions or recovering nutrients from manure. For nutrient recovery processes, the functional unit refers to the fertiliser product delivered, often one tonne of product or, in some cases, a nutrient-based unit depending on the formulation. For technologies producing non-fertiliser outputs, such as bedding or protein biomass, the unit is adapted to the nature of the product and its function.

Finally, the **system boundaries** include all processes required to operate each technology, generally following a cradle-to-gate approach. This covers inputs and transport of raw materials, energy use, operation of the treatment system and emissions to air, water and soil. When the recovered product substitutes a mineral fertiliser or another conventional material, the system boundary is extended to include the avoided production of the displaced product. For solutions that require field application or influence nutrient losses, downstream emissions and changes in fertiliser requirements are also incorporated when relevant. In the case of precision technologies, where no physical processing takes place, the boundary focuses on changes in nutrient flows and emissions within the farming system rather than on a stand-alone process.

3.3.5 NOVAFERT

NOVAFERT [10] is a European project focused on improving the sustainability of fertilising products by assessing a wide range of alternative and recovered materials. The work reviewed in this document maps existing methodological approaches for evaluating these products and identifies the requirements needed to build a harmonised environmental assessment framework. The project considers a large portfolio of fertilising materials produced from different secondary raw materials, including manures, digestates, food waste, sewage-derived streams and other biomass residues, but does not assess specific technologies in detail at this stage.

The LCA methodology explored in the project is based on a comparison of existing standards and guidelines, with particular emphasis on the Product Environmental Footprint (PEF) framework, the International EPD System and ISO 14040/44. The document highlights the need for consistent methodological rules for bio-based fertilisers, especially because no dedicated PEF Category Rules currently exist for this product group.

The discussion of impact assessment focuses on the full PEF 3.1 set of 16 midpoint categories, which the project identifies as the most appropriate basis for future harmonised assessments. These include climate change, acidification, freshwater and marine eutrophication, particulate matter, photochemical ozone formation, ionising radiation, ozone depletion, land use, water use, ecotoxicity, human toxicity (cancer and

non-cancer), and resource use (fossils and minerals/metals). The deliverable contrasts this comprehensive list with the narrower sets more commonly used in the scientific literature.

Functional units are reviewed from a methodological perspective rather than through specific examples. The project notes the lack of a unified FU definition for fertilisers and discusses the limitations of mass-based units for products whose fertilising effect depends strongly on local conditions. The report therefore identifies FU definition as a key methodological challenge for future assessments.

System boundaries are also analysed in conceptual terms. The document reviews the implications of using cradle-to-gate, cradle-to-grave, or waste-entry system boundaries and stresses the need to clearly define how upstream burdens are allocated to recovered materials. The report highlights that most existing BBF studies adopt cradle-to-gate boundaries and that inconsistent treatment of upstream and end-of-life processes remains a major source of variability across LCAs.

3.3.6 SYSTEMIC

SYSTEMIC [11] is a European project focused on demonstrating nutrient recovery and recycling (NRR) technologies integrated into large-scale anaerobic digestion (AD) plants. Its aim is to evaluate how NRR systems influence environmental performance and to compare AD plants with and without NRR solutions. The project assesses five full-scale demonstration plants, each operating under different feedstock, technology and market conditions. These technologies produce both biogas (converted to electricity, heat or upgraded fuels) and nutrient-rich fertilising products such as ammonium sulphate, concentrated liquid fractions and solid organic amendments.

The LCA follows ISO 14040/44 principles and uses a comparative approach, assessing each plant with and without its NRR systems. Inventory data were collected directly from the plants and complemented with ecoinvent and GaBi datasets. Environmental impacts are quantified using **ReCiPe 2016 Midpoint (H),** chosen for consistency and comparability across plants and with the wider literature.

The **impact categories** assessed are: fossil depletion, climate change, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity (cancer and non-cancer), freshwater ecotoxicity, marine ecotoxicity and terrestrial ecotoxicity. These indicators cover energy use, nutrient losses and potential toxicity effects and provide a broad picture of environmental performance.

Two **functional units** are defined, reflecting the dual role of AD plants. From the energy perspective, the functional unit is 1 m^3 of methane produced. From the waste management perspective, the functional unit is 1 tonne of substrate treated. Both are applied across all plants to enable a consistent comparison.

Considering the **system boundaries** are defined as gate-to-gate, including transport from the point of waste generation and transport to product destinations. All AD operations and NRR processes fall within the boundaries: digester operation, biogas upgrading, nutrient separation steps, evaporation, filtration, chemical additions and logistical transport of both substrates and products. Downstream field emissions are excluded to avoid distortion due to high variability in use-related emissions. When recovered products substitute mineral fertilisers or energy carriers, these avoided burdens are included using reference flows based on Ecoinvent datasets.

3.3.7 SEA2LAND

The **SEA2LAND [12]** project focuses on producing bio-based fertilising products (BBFs) from fishery and aquaculture side streams generated in several European regions. These side streams include fish waste, shells, sludge and mixed organic residues, which are transformed into different BBFs using processes such as enzymatic hydrolysis, fermentation, separation, drying, composting, pyrolysis and blending. The

project evaluates these BBFs both at pilot scale and under upscaled industrial conditions.

The environmental assessment uses a two-step LCA. In the first step, a cradle-to-factory-gate LCA is carried out to quantify the impacts of BBF production. In the second step, the fertilisers are assessed from cradle to farm gate using the FarmLCA model to account for impacts related to agricultural use, including nutrient substitution and field emissions. Inventory data are based on measured pilot-scale performance and complemented by an internal upscaling procedure that reflects expected industrial-scale operation.

The LCA method applied for production impacts is Impact World+ version 2.0, as explicitly stated in the document. For agricultural use, FarmLCA is applied, which incorporates standard characterisation models for emissions and nutrient flows.

The impact categories reported in the production LCA correspond to the midpoint indicators provided by Impact World+. These include climate-related impacts, nutrient-related impacts (freshwater and marine eutrophication), acidification, ecotoxicity and resource-related categories (as reflected in the tables and figures comparing pilot and industrial scales). For the use phase, FarmLCA calculates climate change and nutrient-emissions-related indicators relevant for agricultural systems.

Because the project handles different types of BBFs with different nutrient contents, SEA2LAND does not define a single universal functional unit for production. Instead, the assessment considers the production of each BBF as modelled in each case study and expresses agricultural use in terms of crop output, typically 1 kg of wheat grain or 1 kg of harvested rye grass, following the functional units identified in the use-phase modelling.

The system boundaries are clearly defined. For production, the boundary is cradle-to-factory-gate, including all upstream flows (collection and transport of side streams), processing operations (hydrolysis, fermentation, pyrolysis, separation, drying), energy use, chemicals and transport within the production system. For use, the boundary expands to cradle-to-farm-gate, incorporating fertiliser application, nutrient substitution and the emissions modelled in FarmLCA. Capital goods are excluded, in line with standard LCA practice.

4 Integrated Interpretation of the Findings

The analysis presented in the previous sections combines evidence from three complementary sources: scientific literature, Environmental Product Declarations (EPDs), and documentation from European research projects. Each source provides a different perspective on the environmental assessment of nutrient recovery and bio-based fertiliser systems. Scientific studies offer methodological depth and transparency, EPDs reflect standardised industrial reporting practices, and European projects provide applied evidence from pilot and demonstration-scale implementations. Taken together, these sources form a coherent knowledge base for identifying the environmental impact categories that are most relevant for the assessment of nutrient recovery technologies within the FertiCovery project.

The review of Environmental Product Declarations revealed a particularly high level of methodological consistency. This coherence stems from the Product Category Rules that govern their development, which define mandatory functional units, system boundaries and impact indicators. As a result, EPDs belonging to the same product category report environmental impacts using identical methodological conventions. Across the fertiliser, biochar and biostimulant PCRs examined, several impact categories appear systematically as core indicators. These include climate change, eutrophication, acidification, photochemical ozone formation, resource use and water use. The repeated presence of these indicators across different product categories highlights their importance in the environmental evaluation of fertilising products derived from secondary raw materials.

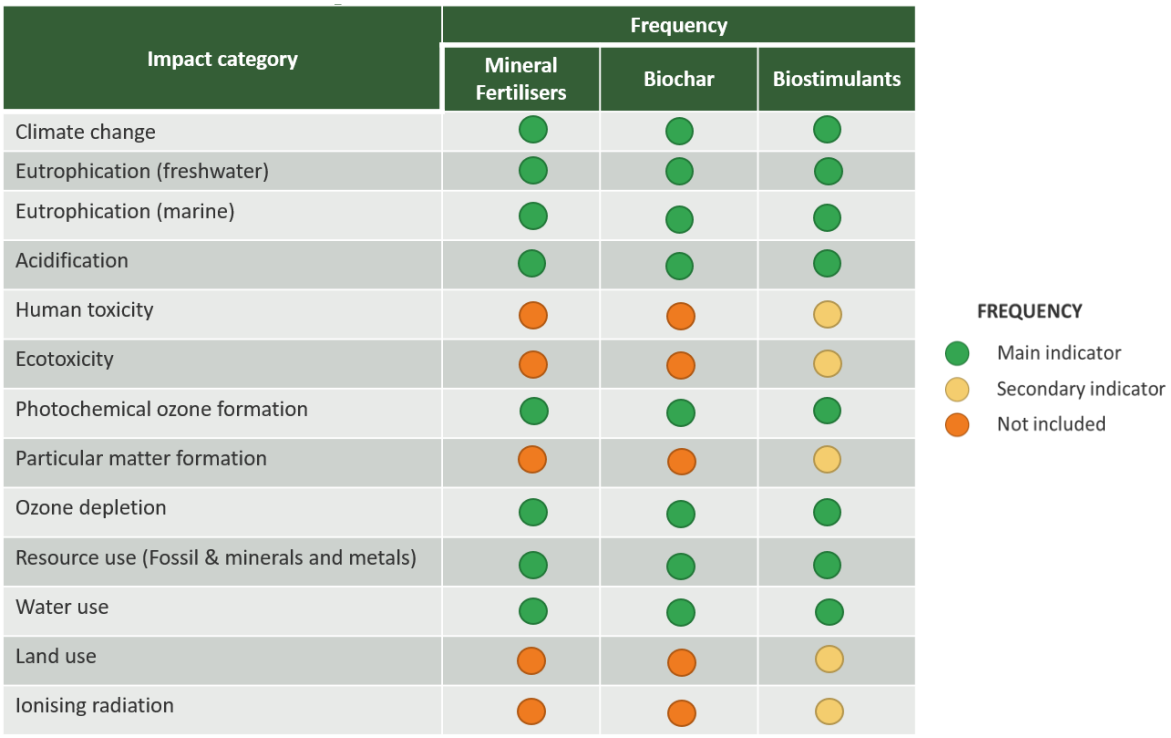


Figure 1. Frequency with which the main environmental impact categories appear across the PCRs analysed in this study.

The analysis of scientific literature provides an additional perspective on the environmental indicators commonly used in the evaluation of nutrient recovery systems. Although methodological choices vary more widely in academic studies than in EPDs, the literature nonetheless shows a clear convergence around a core set of environmental impact categories. Climate change is the most consistently reported indicator, followed by eutrophication and acidification, reflecting the environmental pressures most closely associated with nutrient management and waste treatment processes. Other categories such as photochemical ozone formation, particulate matter formation, resource use and water use also appear frequently, although with slightly lower consistency across studies.

European research projects provide a third layer of evidence by evaluating nutrient recovery technologies under practical and often pilot-scale conditions. Despite differences in project objectives, technological pathways and assessment frameworks, the environmental indicators used across projects show strong similarities. Most projects adopt internationally recognised LCA methodologies such as ReCiPe or the Product Environmental Footprint method, which leads to the consistent inclusion of categories related to climate change, eutrophication, acidification and resource use. In addition, several projects extend the analysis to categories addressing toxicity, particulate matter formation and water consumption, depending on the specific technologies assessed.

Impact category	Frequency
Climate change	●
Eutrophication (freshwater)	●
Eutrophication (marine)	●
Acidification	●
Human toxicity	●
Ecotoxicity	●
Photochemical ozone formation	●
Particular matter formation	●
Ozone depletion	●
Resource use (Fossil & minerals and metals)	●
Water use	●
Land use	●
Ionising radiation	●
Fine particular matter	●

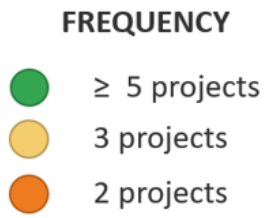


Figure 2. Environmental impact categories reported across the analysed European projects.

When the findings from these three evidence sources are considered together, a clear pattern emerges. Despite differences in methodological detail and assessment scope, a relatively stable group of environmental impact categories consistently appears across EPDs, scientific literature and European project documentation. In particular, climate change, eutrophication and acidification are systematically reported in all three sources and therefore represent the most robust indicators for assessing the environmental performance of nutrient recovery and bio-based fertiliser technologies. Other categories, such as resource use, water use and photochemical ozone formation, also appear frequently and provide complementary insights into the environmental pressures associated with these systems.

It should be noted that the purpose of this review is not to assess the quality or detailed origin of the life cycle inventory data used in each individual study. The reviewed sources were used to identify established methodological practices and the environmental impact categories most commonly applied to nutrient recovery and bio-based fertiliser systems. In LCA, impact categories are defined through the selected LCIA method rather than according to whether inventory data are primary or obtained from background databases. Primary measurements and secondary database datasets may contribute simultaneously to the same impact category, depending on the system model and data available for each study.

The frequency with which impact categories appear across the reviewed sources should primarily be interpreted as a consequence of the methodological framework applie. In LCA, impact categories are defined by the selected LCIA method, which is chosen according to the goal and scope of the study, expert judgement and, where applicable, specific methodological or regulatory requirements. This is particularly evident for EPDs, where the impact categories to be reported are prescribed by the applicable Product Category Rules. Consequently, the recurrent presence of categories such as climate change, acidification or eutrophication across the reviewed sources mainly reflects their systematic inclusion in widely applied LCIA methodologies and reporting frameworks.

The categories most frequently reported in the reviewed sources are generally those with a consolidated methodological basis and commonly available contributing inventory flows. Climate change is supported by well-established greenhouse gas characterisation factors and common inventory flows such as energy use, fuels, process emissions and transport. Acidification and eutrophication are also consistently reported in nutrient recovery and fertiliser-related studies because they are directly linked to nitrogen and

phosphorus emissions, ammonia losses and nutrient leaching, which are central environmental mechanisms in these systems.

The review also shows that resource use and water use appear frequently, although their interpretation may be more dependent on the LCIA method applied, background datasets and modelling assumptions. Their presence across the reviewed sources indicates that resource-related pressures are increasingly considered relevant in environmental assessments of fertiliser production and nutrient recovery systems, particularly where comparisons involve conventional mineral fertilisers, recovered nutrients, energy use, auxiliary materials and water demand.

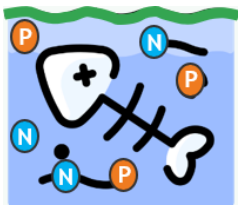
This convergence across independent sources provides strong support for the selection of a core set of Environmental Assessment Indicators to be applied in the subsequent stages of the project. By relying on indicators that are consistently used in both scientific and applied assessment contexts, the framework developed in this deliverable ensures that the environmental evaluation of the technologies considered in FertiCovery remains scientifically robust, methodologically transparent and aligned with current European assessment practices.

5 Conclusions and Final Selection of Environmental Impact Categories

The analysis conducted in this deliverable highlights a strong level of convergence between the different sources reviewed, namely scientific literature, Environmental Product Declarations and documentation from European research projects. Although each source applies its own methodological frameworks and assessment scope, several environmental impact categories appear consistently across the three evidence bases. Considering their recurrent presence and their relevance for systems involving nutrient recovery and bio-based fertiliser production, a set of key Environmental Assessment Indicators was identified to support the environmental evaluation of the technologies addressed in the FertiCovery project.



Climate change (Global Warming Potential) represents the potential contribution of a system to global temperature increase through the emission of greenhouse gases. Within nutrient recovery and fertiliser production systems, these emissions may arise throughout the life cycle, including material handling, energy use and the broader operation of treatment and conversion processes. As such, this indicator provides an overall measure of the contribution of a system to climate change.



Eutrophication (freshwater and marine) refers to the enrichment of aquatic environments with nutrients, particularly nitrogen and phosphorus. When excessive amounts of these nutrients reach water bodies, they can stimulate rapid algae growth, which reduces oxygen availability and negatively affects aquatic ecosystems. Because nutrient flows are central to the functioning of recovery and fertiliser systems, this category is commonly used to represent potential impacts associated with nutrient releases to water.



Acidification describes the potential of certain emissions to increase the acidity of soils and water bodies. These emissions may originate from atmospheric releases generated during the handling, treatment or transformation of organic materials. Increased acidity can affect vegetation, soil quality and aquatic environments, making this category a relevant indicator for assessing emissions to air associated with these systems.



Resource use (fossil resources, minerals and metals) reflects the extent to which processes rely on non-renewable resources. It accounts for the extraction and consumption of fossil fuels, minerals and metals required to support the functioning of the system. In the context of circular nutrient management, this indicator provides insight into the degree to which technologies may influence the demand for finite resources.



Water use represents the consumption of freshwater resources throughout the operation of a system. This includes water used directly within processing stages as well as water embedded in upstream inputs. The indicator therefore provides information on the potential influence of a process on water availability, particularly in regions where water resources may already be under pressure.

The final selection of EAIs combines two complementary objectives of Task 3.2. First, it includes emission-related categories that are consistently reported across the reviewed sources and are directly connected to the main environmental pressures of nutrient recovery and bio-based fertiliser production systems. Climate change, eutrophication and acidification address greenhouse gas emissions, nutrient losses and atmospheric emissions associated with the implementation and operation of the technologies.

Second, the selection includes resource-related categories because resource efficiency is an explicit objective of the task. Fossil resource use, mineral and metal resource use and water use allow the assessment to compare the demand for fossil energy, mineral raw materials, auxiliary materials and water across conventional, bio-based and recovered fertilising systems. Although these indicators may involve greater methodological complexity than some emission-related categories, they provide essential information for assessing pressure on resources and for supporting a direct comparison of resource efficiency between technologies.

Taken together, these impact categories capture the main environmental mechanisms typically associated with nutrient recovery and bio-based fertiliser production systems. Their consistent presence across the scientific literature, environmental product declarations and project-based assessments supports their use as a coherent and robust set of Environmental Assessment Indicators for the subsequent evaluation of the technologies considered within the FertiCovery project.

Finally, it should be noted that not all impact categories identified in the reviewed sources were ultimately prioritised for the final assessment. Although ozone depletion potential and photochemical ozone formation potential were identified in the reviewed sources, they were not prioritised in the final selection. This decision was based on the aim of focusing the assessment on impact categories expected to be more representative of the main environmental hotspots of the analysed technologies. In this context, categories related to specific atmospheric mechanisms were considered of lower priority than those more directly linked to material consumption, energy demand and the broader emissions profile of the systems. Therefore, ozone-related categories were not included in the reduced set selected for further assessment.

6 Considerations for subsequent comparative assessment tasks.

The review carried out in this deliverable is directly relevant for subsequent project activities, in particular for Task 3.3 and for the multicriteria decision analysis (MCDA) foreseen in WP6. In this sense, the present task not only supports the identification of environmental aspects and impact categories of interest, but also helps to clarify the methodological conditions under which environmental results can be interpreted and compared in a consistent manner.

According to the principles of Life Cycle Assessment (LCA), environmental impacts are quantified for a specific product, process and/or service, taking into account its characteristic input and output flows, the system boundaries defined for the study, and the corresponding functional unit. As observed in the reviewed literature and project references analysed in this deliverable, these methodological elements may vary considerably depending on the objective of the assessment and the type of technology addressed. As a consequence, the direct comparability of environmental results across different technologies or studies may be limited and, in some cases, methodologically demanding.

In addition, different life cycle impact assessment methods may be used to quantify environmental impacts, including approaches such as ReCiPe, CML and the Environmental Footprint method. Since these methods rely on different characterisation models and, in some cases, different underlying emission or conversion factors, the results obtained are not always directly equivalent, even when they refer to apparently similar environmental aspects.

For this reason, these methodological aspects should be carefully considered in subsequent project tasks. In particular, should take into account the influence of functional units, system boundaries and impact assessment methods in order to ensure that the comparison of technologies is fair, transparent and robust.

In addition to the methodological aspects described above, the review also highlights a limitation related to the scope of currently established LCIA methods. The environmental assessment frameworks identified in the reviewed literature and European projects are mainly structured around consolidated impact categories for which recognised characterisation models are available. Consequently, other environmental mechanisms that may be relevant for fertilising products derived from secondary raw materials are not necessarily represented with the same level of methodological maturity.

This is particularly relevant for soil-related effects and emerging environmental pressures such as contaminants of emerging concern (CoECs) and microplastics. These aspects become especially important when the assessment moves from the operation of the recovery technology itself to the composition, agricultural application and environmental behaviour of the resulting fertilising product. In the case of microplastics, recent developments are extending LCIA approaches by incorporating specific fate, exposure and effect mechanisms and by developing characterisation factors for different environmental compartments, including marine water and sediments [13]. However, important methodological limitations remain, including the availability of effect data and the need to consider particle-specific characteristics such as polymer type, size, shape and release pathway [13]. Recent literature also highlights remaining limitations in the consistent assessment of microplastic-related environmental effects and their potential relevance for terrestrial systems and soil quality [14].

For these reasons, soil-related impacts, CoECs and microplastics were not incorporated into the core EAI set defined in Task 3.2. Their exclusion should not be interpreted as indicating limited environmental relevance, but rather as reflecting the current scope and maturity of the assessment framework used for the comparative evaluation of the technologies. As methodologies, inventory approaches and characterisation models evolve, these aspects could become increasingly suitable for integration into LCA-based assessments. Within FertiCovery, product-specific information generated in subsequent activities, particularly D4.2, may provide the basis for considering these aspects in later environmental assessments and, where appropriate, in the MCDA.

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