FertiCovery

Comparison of environmental and resource efficiency of nutrient recycling and bio based fertiliser production technologies with conventional technologies

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Summary of Deliverable

Deliverable D3.3 presents the comparison of the environmental impacts and resource efficiency of selected nutrient recycling and bio-based fertiliser production technologies with conventional fertiliser production systems. The assessment focuses on the technologies shortlisted in previous project tasks and evaluates their performance using Environmental Assessment Indicators (EAIs) defined within Work Package 3.

The assessment considers both emission-related environmental impacts and resource-related pressures. Climate change, acidification and eutrophication are used to reflect the main environmental burdens associated with emissions to air, water and soil. In parallel, fossil resource use and mineral and metal resource use are included to capture pressure on non-renewable resources. Water use is also considered due to its relevance in treatment and fertiliser production processes.

The methodology was developed using the best available information from three complementary sources: primary data from technology providers, scientific literature and LCA databases. Primary data were used to understand the specific characteristics of the selected technologies and to identify relevant unit processes. Literature data were used to identify environmental hotspots, comparable studies and possible proxy values. LCA databases were used mainly for conventional fertiliser reference systems, background processes and selected proxy datasets.

Due to the heterogeneity and incompleteness of the available data, the assessment does not constitute a full harmonised LCA for all technologies. Instead, it provides a structured and transparent comparative approach. Environmental values were assigned at unit-process level where possible, aggregated at technology level, normalised through a common five-point scale and weighted to obtain an overall EAI classification.

The results provide a relative classification of the assessed technologies and conventional references. This classification helps identify technologies with potentially favourable environmental and resource-related performance, as well as technologies where higher impacts or data uncertainty require further attention. The outcomes of this deliverable provide a transparent basis for the subsequent Multi-Criteria Decision Analysis in WP6.

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1 Abbreviations and acronyms

Table 1. Abbreviations and acronyms

Abbreviation	Meaning
AD	Anaerobic digestion
ADf	Abiotic depletion potential – fossil resources
ADmm	Abiotic depletion potential – minerals and metals
AP	Acidification potential
BBF	Bio-based fertiliser
CMC	Component Material Category
DM	Dry matter
EAI	Environmental Assessment Indicator
EF	Environmental Footprint
EPf	Eutrophication potential – freshwater
EPm	Eutrophication potential – marine
FU	Functional unit
GWP	Global warming potential
HORECA	Hotels, restaurants and catering
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision-Making
N.G.	Natural gas
NPK	Nitrogen, phosphorus and potassium
NR	Nutrient recycling
OFMSW	Organic fraction of municipal solid waste
PFC	Product Function Category

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Table 1. Abbreviations and acronyms

Abbreviation	Meaning
RO	Reverse osmosis
Sb	Antimony
TAI	Technical Assessment Indicator
TRL	Technology Readiness Level
FU	Functional unit
WU	Water use

2 Introduction

The FertiCovery project aims to identify, assess and promote technologies capable of recovering and recycling fertilising products from secondary raw materials. In this context, bio-based fertilisers and nutrient recycling technologies are considered potential alternatives or complements to conventional mineral fertilisers, contributing to circular economy objectives, reduced dependence on primary raw materials and improved management of organic waste streams.

Deliverable D3.3 focuses on the comparison of the environmental impacts and resource efficiency of selected nutrient recycling and bio-based fertiliser production technologies with conventional fertiliser production systems. The deliverable builds on the shortlist of technologies defined in previous project tasks and provides an environmental assessment framework suitable for comparing diverse technologies on a common basis.

The assessment is based on EAIs defined within Task 3.2. These indicators cover key environmental impact categories, including climate change, acidification, eutrophication, fossil resource use, mineral and metal resource use and water use. This selection allows the comparison to address both environmental burdens and resource-related performance, which are central aspects of the task.

A key challenge of the assessment is the diversity of the technologies considered. The selected technologies include biological processes, such as anaerobic digestion and composting; physicochemical recovery routes, such as precipitation, membrane separation and stripping; hydrolysis processes; thermochemical routes; and innovative technologies such as plasma-based treatment. These technologies differ in feedstocks, process boundaries, product outputs, maturity and data availability. For this reason, a direct environmental screening based only on primary data was not feasible.

To address this limitation, the methodology combines several data sources. Primary data from technology providers were used to understand the process configuration and operational characteristics of each technology. Scientific literature was reviewed to identify published LCA evidence and methodological references. LCA databases were used to obtain values for conventional fertiliser references, background processes and selected proxies. This combined approach was necessary because no single source provided complete, consistent and directly comparable data for all technologies.

The comparison was therefore carried out through a stepwise methodology. First, the unit processes included in each technology were identified. Second, environmental values were assigned to each relevant EAI using the most representative available source. Third, the contributions of each unit process were combined to estimate the total environmental profile of each technology. Finally, the results were normalised, weighted and translated into a five-point classification scale.

The results presented in this deliverable should be interpreted as a comparative environmental and resource-related screening under the available data conditions. The assessment was not designed as a full methodological LCA for each case. Instead, it follows life cycle thinking principles to provide a structured and transparent comparison based on the data sources, assumptions and system boundaries available at this stage of the project.

Finally, It should also be noted that this deliverable does not aim to assess all parameters that may determine the final suitability of a BBF product or technology for a specific end use. Aspects such as nutrient concentration, product quality, agronomic function, regulatory end-use conditions, market acceptance and practical application requirements are outside the direct scope of this environmental and resource-related screening. These aspects will be considered in subsequent project tasks when defining the final set of parameters to be included in the MCDA.

3 Data sources used for the EAIs

The selected EAIs were defined to cover both emission-related impacts and resource-related pressures. Climate change, acidification and eutrophication were included to reflect the main environmental burdens associated with emissions to air, water and soil. In parallel, fossil resource use and mineral and metal resource use were included to capture the demand for non-renewable resources linked to each technology. Water use was also considered due to its relevance in treatment and fertiliser production processes. Together, these categories provide a common basis for comparing environmental impacts and resource-related performance across the assessed technologies and the conventional fertiliser references.

The environmental and resource efficiency comparison was developed using the best available information collected within the project and from external sources. The approach follows life cycle thinking principles, but it should not be interpreted as a full LCA performed with harmonised primary data for all technologies. Three main data sources were considered to support the assignment of EAI values. Three main data sources were considered.

First, primary data were collected from **technology providers** through a dedicated questionnaire developed within the project. This questionnaire was designed to obtain technical, operational, environmental and product-related information for the selected nutrient recovery and bio-based fertiliser production technologies.

Second, a **scientific literature review** was carried out to identify published LCA studies dealing with nutrient recovery, bio-based fertiliser production technologies and conventional fertiliser production systems. This review was used to complement the primary data and to understand how these technologies have been assessed in previous studies.

Third, **LCA databases**, mainly Ecoinvent and Agribalyse, were reviewed to identify available datasets for conventional fertilisers, background processes and, where possible, processes similar to some of the selected technologies. These databases were also considered as possible sources for modelling energy, chemicals, transport, waste treatment and other background inputs.

3.1 Primary data from technology providers

The primary data used in this assessment were collected through a dedicated questionnaire developed within Task 2.3 by the project partners. The questionnaire was designed to capture the main technical, operational, environmental and product-related information considered relevant for subsequent project activities. It was distributed to the technology providers corresponding to the technologies identified during Task 2.2.

For the environmental assessment, two possible uses of these data were considered. The first was the direct use of environmental or LCA-related information reported by the providers. This route was intended to obtain technology-specific environmental values where available. The second was the indirect calculation of simplified environmental indicators using operational data reported in the questionnaire. In principle, this route would have allowed the construction of a more homogeneous inventory under a

common modelling framework. However, the information available was not complete or specific enough to apply either route consistently across all selected technologies.

The indirect calculation route was also limited. Although several providers reported data on energy consumption, water use, chemical consumption, waste generation, plant capacity and operating conditions, the level of detail was not sufficient to calculate complete and technology-specific EAIs for all cases. Some data were reported as qualitative descriptions rather than numerical values. For example, water use was often described as “recycled”, “minimal” or “no external water use”, without enough information to quantify actual consumption. Chemical use was sometimes reported only as the type of chemical used, without dosage. In other cases, energy consumption was reported without specifying the energy source, electricity mix, share of electricity and heat, or whether the value referred to the whole plant or only to one process step.

The level of detail also varied between technology groups. More established processes, such as anaerobic digestion and composting, generally provided more operational information. In contrast, emerging or more specialised technologies, such as plasma-based and some thermochemical processes, had more limited data availability. Applying a full quantitative calculation to all technologies under these conditions would have introduced bias and false precision.

For this reason, primary data were not used as the only basis for a direct quantitative EAI ranking. Instead, they were used to describe the selected technologies, identify their main unit processes, understand key operational and resource requirements, identify potential environmental hotspots and support the interpretation of values obtained from literature and LCA databases.

3.2 Scientific literature review

The scientific literature review presented in this work is built on the methodological framework established in D3.2. While the review performed in D3.2 was mainly aimed at identifying and selecting the Environmental Assessment Indicators (EAIs), the review developed in this document focused on the selected technologies and on the identification of published LCA studies dealing with nutrient recovery, bio-based fertiliser production technologies and conventional fertiliser production systems. The review was also used to identify representative studies and potential proxy data and to understand how these technologies had been assessed in previous studies, with particular attention to the functional units, system boundaries, LCIA methods and impact categories applied. This information was used to support the selection of environmental values that were as comparable and representative as possible for the subsequent assessment of the technologies.

The review covered biological, physical, physicochemical, thermochemical, hydrolysis and plasma-based technologies, as well as synthetic fertiliser production systems used as conventional references. In total, 42 article records were included in the updated review database.

The literature review confirmed that there is a broad evidence base on the environmental assessment of nutrient recovery and bio-based fertiliser technologies. However, the information is highly heterogeneous. The reviewed studies use a wide range of functional units, including the amount of final product obtained, the amount of waste or secondary raw material treated, the fertilised area, the amount of nutrient recovered, the volume of wastewater treated and the amount of conventional fertiliser produced. This variability limits the direct comparison of values between studies.

System boundaries are also not fully aligned. The reviewed studies include cradle-to-gate, cradle-to-grave, gate-to-gate, gate-to-grave and study-specific approaches. This is relevant because the inclusion or exclusion of upstream processes, waste treatment, transport, agricultural application, credits and avoided burdens can significantly affect the final environmental result.

The LCIA methods also differ between studies. Most studies use either the ReCiPe or CML method families. Although these methods may report similar impact categories, their characterisation factors and modelling assumptions are not always equivalent. In addition, not all studies report the same impact categories, and some categories are expressed using different units.

For these reasons, the literature review was not used as a single homogeneous dataset for a direct numerical ranking of all technologies. Instead, it was used to support the selection of representative LCA data, check the consistency of results obtained from other sources and define the level of confidence of the assessment. Direct quantitative use of literature values was only considered when the functional unit, system boundary, LCIA method and impact category were sufficiently aligned with the assessment.

3.3 LCA databases

LCA databases were considered as an additional source of information for the environmental assessment of the selected nutrient recycling and bio-based fertiliser production technologies. These databases provide life cycle inventory data for a wide range of processes, including energy production, transport, chemical production, waste treatment, agricultural systems and conventional fertiliser production.

In practical terms, LCA databases are used through specialised LCA software tools, such as SimaPro, GaBi or openLCA. These tools allow the user to select datasets, connect them with foreground data, define system boundaries and calculate environmental indicators using life cycle impact assessment methods.

The databases most relevant for this type of assessment include general background databases, such as Ecoinvent, and agricultural or agri-food databases, such as AGRIBALYSE and Agri-footprint. General databases are useful for modelling common background processes, such as electricity, heat, fuels, transport, chemicals and waste treatment. Agricultural and agri-food databases are more useful for processes linked to biomass, manure, compost, agricultural residues and fertiliser use.

In this context, the LCA databases available through SimaPro were reviewed as a complementary data source to support the assignment of environmental values. Their role was to identify whether representative datasets were available for the selected BBF technologies, conventional fertiliser production systems and relevant background processes.

This review showed that LCA databases can provide useful and consistent data for conventional fertiliser production, energy, transport, chemicals and waste treatment. However, their coverage is more limited for several specific or emerging BBF technologies, such as struvite recovery, hydrolysis, plasma-based technologies and some thermochemical routes.

Table 2 presents the LCA database datasets selected for the comparison and indicates their role in the assessment.

Table 2. LCA datasets selected for the EAI assessment

Assembly	Database	Technology Covered
A. Compost, of green waste	AGRYBALISE 3.0	Tech_8; Tech_10
A. Compost, of biowaste and green waste	AGRYBALISE 3.0	Tech_1; Tech_2; Tech_3: Tech_9
A. Compost, of biowaste	AGRYBALISE 3.0	Tech_7
F. Average digestate, from manure and slurry	AGRYBALISE 3.0	Tech_1; Tech_2; Tech_3; Tech_6; Tech_11
F. Average agricultural digestate	AGRYBALISE 3.0	Tech_4; Tech_5; Tech_19

Table 2. LCA datasets selected for the EAI assessment

Assembly	Database	Technology Covered
F. Solid fraction of digestate 90%DM, from manure and crops, ammonia stripped, thermally dried	AGRYBALISE 3.0	Tech_4; Tech_19; Tech_21; Tech_22
F. Mineral concentrate, from liquid fraction of digestate, from manure and crops, ammonia stripped	AGRYBALISE 3.0	Tech_4; Tech_19; Tech_21; Tech_22
F. K fertiliser, from liquid fraction of digestate, from manure and crops, ammonia stripped	AGRYBALISE 3.0	Tech_4; Tech_19; Tech_21; Tech_22
Heat, central or small-scale, other than natural gas {RoW}| heat and power co-generation, biogas, gas engine | APOS, U	Ecoinvent 3	Tech_1; Tech_2; Tech_3; Tech_5; Tech_6; Tech_20
Heat, district or industrial, natural gas {Europe without Switzerland}| heat and power co-generation, natural gas, 1MW electrical, lean burn | APOS, U	Ecoinvent 3	Tech_1; Tech_2; Tech_3; Tech_5; Tech_6; Tech_20
Charcoal {GLO}| charcoal production | APOS, U	Ecoinvent 3	Tech_23; Tech_24; Tech_25
Water, ultrapure {RER}| water production, ultrapure | APOS, U	Ecoinvent 3	Tech_4; Tech_19; Tech_20; Tech_22
NPK (15-15-15) fertiliser | NPK (15-15-15) fertiliser production | APOS, U	Ecoinvent 3	Conventional NPK fertiliser
Inorganic phosphorus fertiliser, as P2O5 | nutrient supply from triple superphosphate | APOS, U	Ecoinvent 3	Conventional P fertiliser
Inorganic phosphorus fertiliser, as P2O5 | nutrient supply from phosphate rock, beneficiated | APOS, U	Ecoinvent 3	Conventional P fertiliser
Inorganic phosphorus fertiliser, as P2O5 | nutrient supply from NPK (26-15-15) fertiliser | APOS, U	Ecoinvent 3	Conventional P fertiliser
Inorganic phosphorus fertiliser, as P2O5 | nutrient supply from NPK (15-15-15) fertiliser | APOS, U	Ecoinvent 3	Conventional P fertiliser
kg Inorganic phosphorus fertiliser, as P2O5 | nutrient supply from monoammonium phosphate | APOS, U	Ecoinvent 3	Conventional P fertiliser
Inorganic phosphorus fertiliser, as P2O5 | nutrient supply from diammonium phosphate | APOS, U	Ecoinvent 3	Conventional P fertiliser
Inorganic phosphorus fertiliser, as P2O5 | nutrient supply from ammonium nitrate phosphate | APOS,	Ecoinvent 3	Conventional P fertiliser
Urea | urea production | APOS, U	Ecoinvent 3	Conventional Urea fertiliser

Table 2. LCA datasets selected for the EAI assessment

Assembly	Database	Technology Covered
Inorganic potassium fertiliser, as K2O | nutrient supply from potassium sulfate | APOS,	Ecoinvent 3	Conventional K fertiliser
Inorganic potassium fertiliser, as K2O | nutrient supply from potassium nitrate | APOS,	Ecoinvent 3	Conventional K fertiliser
Inorganic potassium fertiliser, as K2O | nutrient supply from potassium chloride | APOS, U	Ecoinvent 3	Conventional K fertiliser
Inorganic potassium fertiliser, as K2O | nutrient supply from potash salt | APOS, U	Ecoinvent 3	Conventional K fertiliser
Inorganic potassium fertiliser, as K2O | nutrient supply from NPK (26-15-15) fertiliser | APOS, U	Ecoinvent 3	Conventional K fertiliser

APOS: Allocation at the Point of Substitution;

U: unit process dataset.

The prefixes "A." and "F." correspond to the nomenclature used in the AGRIBALYSE database for Amendment and Fertiliser respectively

4 Methodological procedure for assigning environmental values

After the identification of the available data sources, a structured procedure was applied to assign environmental values to each impact category and technology. The aim of this procedure was to ensure that the values used in the comparison were as transparent, representative and consistent as possible, considering the limitations of the available information.

Given the diversity of the technologies assessed, the products obtained also differ in their composition and agronomic characteristics. Accordingly, the functional units used in the assessment were defined according to the final product generated by each technology and the information available from the selected data sources. Where the functional unit is expressed as 1 kg of fertiliser, this refers to 1 kg of the final fertilising product. It does not imply an equivalent fertilising function, since the products obtained from the different technologies may differ in their N, P and K contents, organic matter content and other agronomic characteristics. These product-related characteristics are assessed separately within the project and will be considered together with the environmental indicators in the subsequent MCDA.

4.1 Step 1. Identification of unit processes included in each technology

The first step consisted of identifying the unit processes included within the overall process chain of each selected technology. This step was necessary because several of the technologies assessed do not correspond to a single isolated process, but to a combination of different unit operations required to produce the final bio-based fertiliser. For example, a given technology may include one or more of the following unit processes: anaerobic digestion, membrane separation, stripping, pyrolysis, composting, hydrolysis, plasma treatment or precipitation. In these cases, the environmental performance of the technology cannot be represented correctly by considering only one process step. This process mapping allowed the assessment to define the technical scope of each technology before assigning environmental values.

The unit processes assigned to each selected technology are summarised in Table 3, which provides the basis for the subsequent selection of representative data sources and environmental values.

Table 3. Unit processes considered for each selected technology

Tech. number	Technology name	Anaerobic Digestion	Membrane	Stripping	Pyrolysis	Composting	Hydrolysis	Plasma	Precipitation
Tech 1	Integrated AD and tunnel composting for household, HORECA, and green biowaste streams	X				X			
Tech 2	Integrated dry AD for biowaste and composting of dewatered digestate	X				X			
Tech 3	Integrated wet AD of biowaste and composting of dewatered digestate	X				X			
Tech 4	Integrated valorisation of pig manure through AD and nutrient recovery from digestate by membrane filtration	X	X	X					
Tech 5	Production of fertilizers and biomethane via wet anaerobic co-digestion of multiple feedstocks	X							
Tech 6	Integrated valorisation of biowaste through AD for biomethane, biogenic CO2 and stable soil amendment	X							
Tech 7	Tunnel composting combined with pre-treatment and refining					X			
Tech 8	Open windrow composting for green waste					X			

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Table 3. Unit processes considered for each selected technology

Tech. number	Technology name	Anaerobic Digestion	Membrane	Stripping	Pyrolysis	Composting	Hydrolysis	Plasma	Precipitation
Tech 9	Composting system using semi-permeable membrane and forced aeration					X			
Tech 10	Semi-covered windrow composting for green waste					X			
Tech 11	Turning local industrial wastes into nutrient-rich fertilizer via AD	X							
Tech 12	Biothermal treatment for efficient biosolids processing						X		
Tech 13	A physical-chemical hydrolysis process for the treatment of biosolids and organic waste						X		
Tech 14	Hydrolysis of keratin waste						X		
Tech 15	Hydrolysis of anaerobic digestate						X		
Tech 16	Plasma-based technology converting livestock slurry and biogas digestate into fertilizing products							X	

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Table 3. Unit processes considered for each selected technology

Tech. number	Technology name	Anaerobic Digestion	Membrane	Stripping	Pyrolysis	Composting	Hydrolysis	Plasma	Precipitation
Tech 17	Crystallizer for struvite production from nutrient-rich liquid streams								X
Tech 18	Fluidized bed reactor for struvite production from municipal and industrial wastewater								X
Tech 19	Integrated solid-liquid separation, evaporation and reverse osmosis (RO) treatment for digestate valorisation	X	X	X					
Tech 20	Liquid digestate valorisation through biological treatment and ultrafiltration technologies	X	X						
Tech 21	Stripping and scrubbing system for ammonia recovery from wastewater streams			X					
Tech 22	Membranes and stripping technologies: transforming livestock manure and digestate		X	X					
Tech 23	Pyrolysis of biomass residues for biochar production				X				

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Table 3. Unit processes considered for each selected technology

Tech. number	Technology name	Anaerobic Digestion	Membrane	Stripping	Pyrolysis	Composting	Hydrolysis	Plasma	Precipitation
Tech 24	Biowaste to biochar and energy: integrated pyrolysis and biological methanation				X				
Tech 25	Pyrolysis of wood chips for the production of biochar				X				

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4.2 Step 3. Calculation of the total environmental contribution of each technology

Once the unit processes included in each technology had been identified, the next step consisted of assigning environmental values to each Environmental Assessment Indicator (EAI) defined in Task 3.2. These indicators included, among others, climate change, acidification, eutrophication, fossil resource use, mineral resource use and water use.

Different data sources were considered for this assignment, including primary data from technology providers, scientific literature and LCA databases. The selection of values followed a consistent and critical procedure, with the aim of ensuring that the comparison was as fair and representative as possible. For each potential value, the process represented by the data source was reviewed, together with its system boundaries, functional unit and methodological assumptions.

Particular attention was paid to whether the data source represented the same process as the unit process being assessed. In LCA terms, this meant checking whether the dataset or study covered only a single unit operation, a wider treatment chain, or a complete fertiliser production system. This distinction was necessary to avoid assigning values from a partial process to a complete technology, or vice versa.

The system boundaries were also considered when selecting values. Results from studies or datasets with different boundaries, such as gate-to-gate, cradle-to-gate or cradle-to-grave, were not treated as directly equivalent unless the comparison was technically justified. Similarly, the functional unit was reviewed to assess whether the value referred to the amount of waste treated, the amount of product produced, the amount of nutrient recovered, the fertilised area or another reference basis.

This screening allowed the most suitable value or proxy to be selected for each EAI and unit process. Where a direct and representative value was available, it was prioritised. Where only partially comparable information was available, the value was used with caution and documented as a proxy. Where no sufficiently representative value was available, the data gap was retained rather than forcing an unsupported numerical assignment.

Based on the procedure described above, the environmental values assigned to each technology are presented in the following tables. The functional units reported correspond to the mass of the final product considered in each case and should therefore be interpreted together with the specific characteristics of the resulting fertilising product.

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Table 4. EAI data sources and values assigned to Tech 1

Tech 1	Integrated AD and tunnel composting for household, HORECA, and green biowaste streams			
FU	1 kg Compost			
Comments	1 tonne of manure to produce 350 kg of compost Biogas and heat from biogas has been considered Credits from N.G heat has been included			
EAI	AD	Composting	Total	Units
AP	3.30E-03	2.22E-03	6.62E-03	mol H+ eq.
GWP	6.81E-02	5.72E-02	1.83E-01	kg CO2 eq.
EPm	1.12E-03	5.97E-06	1.82E-03	kg N eq.
EPf	1.35E-04	9.50E-05	1.59E-04	kg P eq.
ADmm	4.19E-07	1.14E-07	7.91E-07	kg Sb eq.
ADf	5.35E-01	3.78E-01	1.23E+00	MJ
WU	8.43E-01	6.62E-03	1.15E+00	m3 depriv.

Table 5. EAI data sources and values assigned to Tech 2

Tech 2	Integrated dry AD for biowaste and composting of dewatered digestate			
FU	1 kg Compost			
Comments	1 tonne of manure to produce 350 kg of compost Biogas and heat from biogas have been considered Credits from N.G heat has been included			
EAI	AD	Composting	Total	Units
AP	3.30E-03	2.22E-03	6.62E-03	mol H+ eq.
GWP	6.81E-02	5.72E-02	1.83E-01	kg CO2 eq.
EPm	1.12E-03	5.97E-06	1.82E-03	kg N eq.
EPf	1.35E-04	9.50E-05	1.59E-04	kg P eq.
ADmm	4.19E-07	1.14E-07	7.91E-07	kg Sb eq.
ADf	5.35E-01	3.78E-01	1.23E+00	MJ
WU	8.43E-01	6.62E-03	1.15E+00	m3 depriv.

Table 6. EAI data sources and values assigned to Tech 3

Tech 3	Integrated wet AD of biowaste and composting of dewatered digestate			
FU	1 kg Compost			
Comments	1 tonne of manure to produce 350 kg of compost Biogas and heat from biogas have been considered Credits from N.G heat has been included			
EAI	AD	Composting	Total	Units
AP	3.30E-03	2.22E-03	6.62E-03	mol H+ eq.
GWP	6.81E-02	5.72E-02	1.83E-01	kg CO2 eq.
EPm	1.12E-03	5.97E-06	1.82E-03	kg N eq.
EPf	1.35E-04	9.50E-05	1.59E-04	kg P eq.
ADmm	4.19E-07	1.14E-07	7.91E-07	kg Sb eq.
ADf	5.35E-01	3.78E-01	1.23E+00	MJ
WU	8.43E-01	6.62E-03	1.15E+00	m3 depriv.

Table 7. EAI data sources and values assigned to Tech 4

Tech 4	Integrated wet AD of biowaste and composting of dewatered digestate				
FU	1 kg Potassium fertiliser				
Comments	Biogas and heat from biogas have been considered Credits from N.G heat has been included Subproduct: Phosphorous fertiliser. Credits due to its production not considered				
EAI	AD	Membrane	Stripping	Total	Units
AP	1.10E-02	2.00E-04	2.41E-02	3.53E-02	mol H+ eq.
GWP	3.28E-01	3.93E-02	1.56E+00	1.93E+00	kg CO2 eq.
EPm	2.11E-03	3.70E-05	7.56E-03	9.70E-03	kg N eq.
EPf	1.15E-03	3.54E-05	6.08E-04	1.79E-03	kg P eq.
ADmm	3.38E-06	1.20E-07	5.13E-06	8.63E-06	kg Sb eq.
ADf	5.51E+00	9.01E-01	2.72E+01	3.36E+01	MJ
WU	8.57E+00	1.73E-02	2.37E+00	1.10E+01	m3 depriv.

Table 8. EAI data sources and values assigned to Tech 5

Tech 5	Production of fertilizers and biomethane via wet anaerobic co-digestion of multiple feedstocks		
FU	1 kg manure digestate		
Comments	Biogas and heat from biogas have been considered Credits from N.G heat has been included		
EAI	AD	Total	Units
AP	1.12E-03	1.12E-03	mol H+ eq.
GWP	2.31E-02	2.31E-02	kg CO2 eq.
EPm	3.80E-04	3.80E-04	kg N eq.
EPf	4.58E-05	4.58E-05	kg P eq.
ADmm	1.43E-07	1.43E-07	kg Sb eq.
ADf	1.82E-01	1.82E-01	MJ
WU	2.87E-01	2.87E-01	m3 depriv.

Table 9. EAI data sources and values assigned to Tech 6

Tech 6	Integrated valorisation of biowaste through AD for biomethane, biogenic CO2 and stable soil amendment		
FU	1 kg biowaste digestate		
Comments	Biogas and heat from biogas have been considered Credits from N.G heat has been included Hygienisation / stabilisation steps included		
EAI	AD	Total	Units
AP	1.12E-03	1.12E-03	mol H+ eq.
GWP	2.31E-02	2.31E-02	kg CO2 eq.
EPm	3.80E-04	3.80E-04	kg N eq.
EPf	4.58E-05	4.58E-05	kg P eq.
ADmm	1.43E-07	1.43E-07	kg Sb eq.
ADf	1.82E-01	1.82E-01	MJ
WU	2.87E-01	2.87E-01	m3 depriv.

Table 10. EAI data sources and values assigned to Tech 7

Tech 7	Tunnel composting combined with pre-treatment and refining		
FU	1 kg of compost		
Comments	From LCA database Hygienisation / stabilisation steps included		
EAI	Composting	Total	Units
AP	2.22E-03	2.22E-03	mol H+ eq.
GWP	5.72E-02	5.72E-02	kg CO2 eq.
EPm	5.97E-06	5.97E-06	kg N eq.
EPf	9.50E-05	9.50E-05	kg P eq.
ADmm	1.14E-07	1.14E-07	kg Sb eq.
ADf	3.78E-01	3.78E-01	MJ
WU	6.62E-03	6.62E-03	m3 depriv.

Table 11. EAI data sources and values assigned to Tech 8

Tech 8	Open windrow composting for green waste		
FU	1 kg of compost		
Comments	From LCA database Hygienisation / stabilisation steps included		
EAI	Composting	Total	Units
AP	2.22E-03	2.22E-03	mol H+ eq.
GWP	5.72E-02	5.72E-02	kg CO2 eq.
EPm	5.97E-06	5.97E-06	kg N eq.
EPf	9.50E-05	9.50E-05	kg P eq.
ADmm	1.14E-07	1.14E-07	kg Sb eq.
ADf	3.78E-01	3.78E-01	MJ
WU	6.62E-03	6.62E-03	m3 depriv.

Table 12. EAI data sources and values assigned to Tech 9

Tech 9	Composting system using semi-permeable membrane and forced aeration		
FU	1 kg of compost		
Comments	From LCA database Hygienisation / stabilisation steps included		
EAI	Composting	Total	Units
AP	2.22E-03	2.22E-03	mol H+ eq.
GWP	5.72E-02	5.72E-02	kg CO2 eq.
EPm	5.97E-06	5.97E-06	kg N eq.
EPf	9.50E-05	9.50E-05	kg P eq.
ADmm	1.14E-07	1.14E-07	kg Sb eq.
ADf	3.78E-01	3.78E-01	MJ
WU	6.62E-03	6.62E-03	m3 depriv.

Table 13. EAI data sources and values assigned to Tech 10

Tech 10	Semi-covered windrow composting for green waste		
FU	1 kg of compost		
Comments	From LCA database		
EAI	Composting	Total	Units
AP	2.22E-03	2.22E-03	mol H+ eq.
GWP	5.72E-02	5.72E-02	kg CO2 eq.
EPm	5.97E-06	5.97E-06	kg N eq.
EPf	9.50E-05	9.50E-05	kg P eq.
ADmm	1.14E-07	1.14E-07	kg Sb eq.
ADf	3.78E-01	3.78E-01	MJ
WU	6.62E-03	6.62E-03	m3 depriv.

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Table 14. EAI data sources and values assigned to Tech 11

Tech 11	Turning local industrial wastes into nutrient-rich fertilizer via AD		
FU	1 kg biowaste digestate		
Comments	Biogas and heat from biogas have been considered Credits from N.G heat has been included		
EAI	AD	Total	Units
AP	1.12E-03	1.12E-03	mol H+ eq.
GWP	2.31E-02	2.31E-02	kg CO2 eq.
EPm	3.80E-04	3.80E-04	kg N eq.
EPf	4.58E-05	4.58E-05	kg P eq.
ADmm	1.43E-07	1.43E-07	kg Sb eq.
ADf	1.82E-01	1.82E-01	MJ
WU	2.87E-01	2.87E-01	m3 depriv.

Table 15. EAI data sources and values assigned to Tech 12

Tech 12	Biothermal treatment for efficient biosolids processing		
FU	1 kg of fertiliser		
Comments	Values from FERPLAY project		
EAI	Hydrolysis	Total	Units
AP	3.03E-04	3.03E-04	mol H+ eq.
GWP	1.24E+00	1.24E+00	kg CO2 eq.
EPm	7.98E-02	7.98E-02	kg N eq.
EPf	3.09E-02	3.09E-02	kg P eq.
ADmm	1.55E-06	1.55E-06	kg Sb eq.
ADf	1.23E+01	1.23E+01	MJ
WU	1.68E-01	1.68E-01	m3 depriv.

Table 16. EAI data sources and values assigned to Tech 13

Tech 13	A physical-chemical hydrolysis process for the reatment of biosolids and organic waste		
FU	1 kg of fertiliser		
Comments	Values from FERPLAY project		
EAI	Hydrolysis	Total	Units
AP	3.03E-04	3.03E-04	mol H+ eq.
GWP	1.24E+00	1.24E+00	kg CO2 eq.
EPm	7.98E-02	7.98E-02	kg N eq.
EPf	3.09E-02	3.09E-02	kg P eq.
ADmm	1.55E-06	1.55E-06	kg Sb eq.
ADf	1.23E+01	1.23E+01	MJ
WU	1.68E-01	1.68E-01	m3 depriv.

Table 17. EAI data sources and values assigned to Tech 14

Tech 14	Hydrolysis of keratin waste		
FU	1 kg of fertiliser		
Comments	Values from FERPLAY project		
EAI	Hydrolysis	Total	Units
AP	3.03E-04	3.03E-04	mol H+ eq.
GWP	1.24E+00	1.24E+00	kg CO2 eq.
EPm	7.98E-02	7.98E-02	kg N eq.
EPf	3.09E-02	3.09E-02	kg P eq.
ADmm	1.55E-06	1.55E-06	kg Sb eq.
ADf	1.23E+01	1.23E+01	MJ
WU	1.68E-01	1.68E-01	m3 depriv.

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Table 18. EAI data sources and values assigned to Tech 15

Tech 15	Hydrolysis of anaerobic digestate		
FU	1 kg of fertiliser		
Comments	Values from FERPLAY project		
EAI	Hydrolysis	Total	Units
AP	3.03E-04	3.03E-04	mol H+ eq.
GWP	1.24E+00	1.24E+00	kg CO2 eq.
EPm	7.98E-02	7.98E-02	kg N eq.
EPf	3.09E-02	3.09E-02	kg P eq.
ADmm	1.55E-06	1.55E-06	kg Sb eq.
ADf	1.23E+01	1.23E+01	MJ
WU	1.68E-01	1.68E-01	m3 depriv.

Table 19. EAI data sources and values assigned to Tech 16

Tech 16	Plasma-based technology converting livestock slurry and biogas digestate into fertilizing products		
FU	1 kg of fertiliser		
Comments	-		
EAI	Plasma	Total	Units
AP	1.14E-03	1.14E-03	mol H+ eq.
GWP	2.59E-01	2.59E-01	kg CO2 eq.
EPm	2.48E-04	2.48E-04	kg N eq.
EPf	8.84E-05	8.84E-05	kg P eq.
ADmm	2.00E-06	2.00E-06	kg Sb eq.
ADf	3.28E+00	3.28E+00	MJ
WU	7.63E-02	7.63E-02	m3 depriv.

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Table 20. EAI data sources and values assigned to Tech 17

Tech 17	Crystallizer for struvite production from nutrient-rich liquid streams		
FU	1 kg of struvite		
Comments	Values from FERPLAY project		
EAI	Crystallisation	Total	Units
AP	1.16E+00	1.16E+00	mol H+ eq.
GWP	2.02E-02	2.02E-02	kg CO2 eq.
EPm	6.90E-03	6.90E-03	kg N eq.
EPf	2.77E-03	2.77E-03	kg P eq.
ADmm	7.00E-06	7.00E-06	kg Sb eq.
ADf	9.52E+00	9.52E+00	MJ
WU	2.99E-01	2.99E-01	m3 depriv.

Table 21. EAI data sources and values assigned to Tech 18

Tech 18	Fluidized bed reactor or struvite production from municipal and industrial wastewater		
FU	1 kg of struvite		
Comments	Values from FERPLAY project		
EAI	Crystallisation	Total	Units
AP	1.16E+00	1.16E+00	mol H+ eq.
GWP	2.02E-02	2.02E-02	kg CO2 eq.
EPm	6.90E-03	6.90E-03	kg N eq.
EPf	2.77E-03	2.77E-03	kg P eq.
ADmm	7.00E-06	7.00E-06	kg Sb eq.
ADf	9.52E+00	9.52E+00	MJ
WU	2.99E-01	2.99E-01	m3 depriv.

Table 22. EAI data sources and values assigned to Tech 19

Tech 19	Integrated solid-liquid separation, evaporation and reverse osmosis (RO) treatment for digestate valorisation				
FU	1 kg Potassium fertiliser				
Comments	Biogas and heat from biogas have been considered Credits from N.G heat has been included Subproduct: Phosphorous fertiliser. Credits due to its production not considered				
EAI	AD	Membrane	Stripping	Total	Units
AP	1.10E-02	2.00E-04	2.41E-02	3.53E-02	mol H+ eq.
GWP	3.28E-01	3.93E-02	1.56E+00	1.93E+00	kg CO2 eq.
EPm	2.11E-03	3.70E-05	7.56E-03	9.70E-03	kg N eq.
EPf	1.15E-03	3.54E-05	6.08E-04	1.79E-03	kg P eq.
ADmm	3.38E-06	1.20E-07	5.13E-06	8.63E-06	kg Sb eq.
ADf	5.51E+00	9.01E-01	2.72E+01	3.36E+01	MJ
WU	8.57E+00	1.73E-02	2.37E+00	1.10E+01	m3 depriv.

Table 23. EAI data sources and values assigned to Tech 20

Tech 20	Liquid digestate valorisation through biological treatment and ultrafiltration technologies			
FU	1 kg of biostimulat			
Comments	Biogas and heat from biogas have been considered Credits from N.G heat has been included Assumed 5% solid content in Liquid digestate			
EAI	AD	Membrane	Total	Units
AP	2.58E-02	1.56E-06	2.58E-02	mol H+ eq.
GWP	5.32E-01	6.83E-04	5.33E-01	kg CO2 eq.
EPm	8.75E-03	2.83E-07	8.75E-03	kg N eq.
EPf	1.05E-03	1.00E-07	1.05E-03	kg P eq.
ADmm	3.28E-06	5.44E-09	3.28E-06	kg Sb eq.
ADf	4.18E+00	4.35E-03	4.19E+00	MJ
WU	6.59E+00	1.54E-04	6.59E+00	m3 depriv.

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Table 24. EAI data sources and values assigned to Tech 21

Tech 21	Stripping and scrubbing system for ammonia recovery from wastewater streams		
FU	1 kg of fertiliser		
Comments	-		
EAI	Stripping	Total	Units
AP	2.41E-02	2.41E-02	mol H+ eq.
GWP	1.56E+00	1.56E+00	kg CO2 eq.
EPm	7.56E-03	7.56E-03	kg N eq.
EPf	6.08E-04	6.08E-04	kg P eq.
ADmm	5.13E-06	5.13E-06	kg Sb eq.
ADf	2.72E+01	2.72E+01	MJ
WU	2.37E+00	2.37E+00	m3 depriv.

Table 25. EAI data sources and values assigned to Tech 23

Tech 22	Membranes and stripping technologies: transforming livestock manure and digestate			
FU	1 kg of fertiliser			
Comments	-			
EAI	Stripping	Membrane	Total	Units
AP	1.55E+00	1.79E-02	2.41E-02	mol H+ eq.
GWP	1.55E+00	5.71E-05	1.56E+00	kg CO2 eq.
EPm	7.53E-03	1.34E-05	7.54E-03	kg N eq.
EPf	6.01E-04	1.12E-05	6.12E-04	kg P eq.
ADmm	5.08E-06	8.66E-08	5.16E-06	kg Sb eq.
ADf	2.33E+01	3.02E-01	2.36E+01	MJ
WU	2.33E+00	6.47E-03	2.34E+00	m3 depriv.

Table 26. EAI data sources and values assigned to Tech 22

Tech 23	Pyrolysis of biomass residues for biochar production		
FU	1 kg of biochar		
Comments	From Ecoinvert database		
EAI	Pyrolysis	Total	Units
AP	1.91E-03	1.91E-03	mol H+ eq.
GWP	1.54E+00	1.54E+00	kg CO2 eq.
EPm	5.86E-04	5.86E-04	kg N eq.
EPf	9.46E-05	9.46E-05	kg P eq.
ADmm	5.82E-07	5.82E-07	kg Sb eq.
ADf	3.31E+00	3.31E+00	MJ
WU	8.64E-01	8.64E-01	m3 depriv.

Table 27. EAI data sources and values assigned to Tech 24

Tech 24	Biowaste to biochar and energy: integrated pyrolysis and biological methanation		
FU	1 kg of biochar		
Comments	From Ecoinvent database		
EAI	Pyrolysis	Total	Units
AP	1.91E-03	1.91E-03	mol H+ eq.
GWP	1.54E+00	1.54E+00	kg CO2 eq.
EPm	5.86E-04	5.86E-04	kg N eq.
EPf	9.46E-05	9.46E-05	kg P eq.
ADmm	5.82E-07	5.82E-07	kg Sb eq.
ADf	3.31E+00	3.31E+00	MJ
WU	8.64E-01	8.64E-01	m3 depriv.

Table 28. EAI data sources and values assigned to Tech 25

Tech 25	Pyrolysis of wood chips for the production of biochar		
FU	1 kg of biochar		
Comments	From Ecoinvert database		
EAI	Pyrolysis	Total	Units
AP	1.91E-03	1.91E-03	mol H+ eq.
GWP	1.54E+00	1.54E+00	kg CO2 eq.
EPm	5.86E-04	5.86E-04	kg N eq.
EPf	9.46E-05	9.46E-05	kg P eq.
ADmm	5.82E-07	5.82E-07	kg Sb eq.
ADf	3.31E+00	3.31E+00	MJ
WU	8.64E-01	8.64E-01	m3 depriv.

After assigning environmental values to the unit processes, the total environmental contribution of each technology was calculated. This step was carried out by combining the process mapping defined in Step 1 with the EAI values assigned to each unit process in Step 2.

For each technology, all unit processes included in its process chain were considered. Then, for each EAI, the values assigned to the corresponding unit processes were added together. Therefore, the total value of a given EAI for a technology was calculated as the sum of the values of that same EAI across all unit processes involved in the technology.

This approach allowed the environmental profile of each complete technology to be built from the contribution of its individual process steps. It was particularly relevant for integrated technologies

This additive approach provided a transparent and reproducible way to estimate the total environmental burden associated with each technology. However, it also required that all values used in the calculation referred to compatible functional units and system boundaries. Where this condition was not fully met, the result was interpreted with caution and documented as having lower comparability. Table 29 shows the final results for each EAI for all the technologies

Table 29. Total EAI values calculated for each technology

Tech num.	EAI						
	AP (mol H+ eq.)	GWP (kg CO2 eq.)	EPf (kg P eq.)	EPm (kg N eq.)	ADmm (kg Sb eq.)	ADf (MJ)	WU (m^3 eq.)
Tech. 1	5.52E-03	1.25E-01	1.41E-04	1.21E-03	5.33E-07	9.12E-01	8.50E-01
Tech. 2	5.52E-03	1.25E-01	1.41E-04	1.21E-03	5.33E-07	9.12E-01	8.50E-01
Tech. 3	5.52E-03	1.25E-01	1.41E-04	1.21E-03	5.33E-07	9.12E-01	8.50E-01
Tech. 4	3.53E-02	1.93E+00	1.79E-03	9.70E-03	8.63E-06	3.36E+01	1.10E+01
Tech. 5	1.12E-03	2.31E-02	4.58E-05	3.80E-04	1.43E-07	1.82E-01	2.87E-01
Tech. 6	1.12E-03	2.31E-02	4.58E-05	3.80E-04	1.43E-07	1.82E-01	2.87E-01
Tech. 7	2.22E-03	5.72E-02	5.97E-06	9.50E-05	1.14E-07	3.78E-01	6.62E-03
Tech. 8	2.22E-03	5.72E-02	5.97E-06	9.50E-05	1.14E-07	3.78E-01	6.62E-03
Tech. 9	2.22E-03	5.72E-02	5.97E-06	9.50E-05	1.14E-07	3.78E-01	6.62E-03
Tech. 10	2.22E-03	5.72E-02	5.97E-06	9.50E-05	1.14E-07	3.78E-01	6.62E-03
Tech. 11	1.12E-03	2.31E-02	4.58E-05	3.80E-04	1.43E-07	1.82E-01	2.87E-01
Tech. 12	3.03E-04	1.24E+00	2.25E-02	7.98E-02	1.55E-06	1.23E+01	1.68E-01
Tech. 13	3.03E-04	1.24E+00	3.09E-02	7.98E-02	1.55E-06	1.23E+01	1.68E-01
Tech. 14	3.03E-04	1.24E+00	3.09E-02	7.98E-02	1.55E-06	1.23E+01	1.68E-01
Tech. 15	3.03E-04	1.24E+00	9.00E-01	7.98E-02	1.55E-06	1.23E+01	1.68E-01
Tech. 16	1.14E-03	2.59E-01	8.84E-05	2.48E-04	2.00E-06	3.28E+00	7.63E-02
Tech. 17	2.02E-02	1.16E+00	2.77E-03	6.90E-03	7.00E-06	9.52E+00	2.99E-01
Tech. 18	2.02E-02	1.16E+00	2.77E-03	6.90E-03	7.00E-06	9.52E+00	2.99E-01
Tech. 19	3.53E-02	1.93E+00	1.79E-03	9.70E-03	8.63E-06	3.36E+01	1.10E+01
Tech. 20	2.58E-02	2.58E-02	1.05E-03	8.75E-03	3.28E-06	4.19E+00	6.59E+00
Tech. 21	2.41E-02	1.56E+00	6.08E-04	7.56E-03	5.13E-06	2.72E+01	2.37E+00
Tech. 22	2.41E-02	1.56E+00	6.12E-04	7.54E-03	5.16E-06	2.36E+01	2.34E+00
Tech. 23	1.91E-03	1.54E+00	9.46E-05	5.86E-04	5.82E-07	3.31E+00	8.64E-01

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Table 29. Total EAI values calculated for each technology

Tech num.	EAI						
	AP (mol H+ eq.)	GWP (kg CO2 eq.)	EPf (kg P eq.)	EPm (kg N eq.)	ADmm (kg Sb eq.)	ADf (MJ)	WU (m^3 eq.)
Tech. 24	1.91E-03	1.54E+00	9.46E-05	5.86E-04	5.82E-07	3.31E+00	8.64E-01
Tech. 25	1.91E-03	1.54E+00	9.46E-05	5.86E-04	5.82E-07	3.31E+00	8.64E-01

In addition to the environmental profiles calculated for the selected technologies, conventional mineral fertilisers were included as reference systems, see Table 30. These references provide representative environmental profiles for conventional N, P and K fertiliser production and were subsequently considered together with the assessed technologies during the normalisation and classification procedure.

Table 30. Total EAI values calculated for conventional mineral fertiliser

Tech num.	EAI						
	AP (mol H+ eq.)	GWP (kg CO2 eq.)	EPf (kg P eq.)	EPm (kg N eq.)	ADmm (kg Sb eq.)	ADf (MJ)	WU (m^3 eq.)
Inorganic (NPK)	1.38E-02	1.11E+00	3.03E-04	1.47E-03	1.60E-05	1.50E+01	6.79E-01
Inorganic (P)	2.05E-02	2.51E+00	1.36E-03	4.59E-03	6.67E-05	2.64E+01	1.39E+00
Inorganic (K)	1.87E-02	3.44E+00	1.08E-03	5.26E-03	6.43E-05	3.35E+01	1.21E+00
Inorganic (Urea)	1.05E-02	1.81E+00	5.37E-04	3.58E-03	7.95E-06	3.15E+01	1.36E+00

These reference values were derived from the selected Ecoinvent datasets described in Section 3 and were included in the subsequent percentile distribution to provide a common conventional reference within the environmental comparison.

4.3 Step 4. Normalisation of EAI results through percentile distribution

Once the total values had been calculated for each EAI and each technology, the results were normalised to allow comparison across technologies. This was necessary because each impact category is expressed in a different unit and magnitude. For example, climate change is expressed in kg CO_2 eq., while acidification, eutrophication, resource use and water use are expressed using different reference units.

For each EAI, the total values obtained for all technologies were considered together, including the values assigned to the conventional fertiliser reference systems. A percentile distribution was then calculated for each impact category. This made it possible to classify the performance of each technology in relation to the full set of assessed options.

Since the EAIs represent environmental burdens, lower values indicate better environmental performance. Therefore, technologies with the lowest impact values were assigned better scores, while technologies

with higher impact values were assigned worse scores. The percentile ranges were linked to a five-point scale, as shown in Table 31.

Table 31. Percentile-based five-point scale for EAI normalisation

Percentile	5 point scale score	Description
0,9	+2	Clear technical advantage compared with conventional fertiliser reference
0,75	+1	Partial technical advantage or comparable performance
	0	Similar performance, uncertain evidence or not clearly comparable
0,25	-1	Technical limitation compared with conventional fertiliser reference
0,1	-2	Clear technical disadvantage or high development need

This procedure provided an individual normalised score for each EAI and each technology. As a result, each technology could be assessed separately for climate change, acidification, eutrophication, fossil resource use, mineral and metal resource use and water use.

4.4 Step 5. Weighting of EAI scores and calculation of the aggregated environmental score

After obtaining the individual normalised scores for each EAI, a weighting process was applied in order to calculate a single aggregated environmental score for each technology. This step was necessary to obtain a final environmental classification that considered all selected impact categories together, while reflecting their relative importance.

The weighting factors applied were based on the Environmental Footprint method. The impact categories and weighting factors used in the assessment are shown in Table 32.

Table 32. Weighting factors applied to the EAI categories

Impcat category	E.F methodology	Stakeholders	Average
Climate change	37%	15%	26%
Acidification	11%	12%	11%
Eutrophication, freshwater	5%	16%	10%
Eutrophication, marine	5%	16%	10%
Resource use, minerals and metals	13%	14%	13%
Resource use, fossils	14%	14%	14%
Water use	15%	15%	15%

For each technology, the normalised score obtained for each EAI was multiplied by the corresponding weighting factor. The weighted values were then summed to obtain a single aggregated environmental score for each technology.

This aggregated score allowed the environmental performance of the technologies to be compared using one common value. However, the individual EAI scores were also retained, because they provide important information on the specific environmental strengths and weaknesses of each technology. For example, a technology may perform well in climate change but less favourably in water use or mineral resource use.

Once the aggregated environmental scores had been calculated, the same percentile-based procedure was applied again. The aggregated scores of all assessed technologies, including the conventional fertiliser reference systems, were distributed into percentiles and converted into the same five-point performance scale. This final step provided the overall environmental classification of the technologies.

The results of this final environmental classification are presented in Table 33.

Table 33. Normalised and weighted EAI scores by technology

Tech	GWP	AP	EPF	Epm	Admm	Adf	WU	Weighted
Tech 1	0	0	0	0	0	0	0	0
Tech 2	0	0	0	0	0	0	0	0
Tech 3	0	0	0	0	0	0	0	0
Tech 4	-2	-2	-1	-1	-1	-2	-2	-2
Tech 5	1	1	1	0	1	1	0	1
Tech 6	1	1	1	0	1	1	0	1
Tech 7	0	0	1	1	1	1	1	1
Tech 8	0	0	1	1	1	1	1	1
Tech 9	0	0	1	1	1	1	1	1
Tech 10	0	0	1	1	1	1	1	1
Tech 11	1	1	1	0	1	1	0	1
Tech 12	0	1	-1	-2	0	0	0	0
Tech 13	0	1	-2	-2	0	0	0	0
Tech 14	0	1	-2	-2	0	0	0	0
Tech 15	0	1	-2	-2	0	0	0	0
Tech 16	0	0	0	1	0	0	1	0
Tech 17	0	-1	-1	0	-1	0	0	0
Tech 18	0	-1	-1	0	-1	0	0	0
Tech 19	-2	-2	-1	-1	-1	-2	-2	-2
Tech 20	1	-2	0	-1	0	0	-2	0
Tech 21	-1	-1	0	0	0	-1	-1	-1
Tech 22	-1	-1	0	0	0	-1	-1	-1
Tech 23	0	0	0	0	0	0	0	0
Tech 24	0	0	0	0	0	0	0	0
Tech 25	0	0	0	0	0	0	0	0

For comparison purposes, the conventional fertiliser reference systems were also classified using the same normalisation and weighting procedure applied to the selected technologies.

Table 34. Normalised and weighted EAI scores by conventional mineral fertiliser

Tech	GWP	AP	EPF	Epm	Admm	Adf	WU	Weighted
Inorganic (NPK)	0	0	0	0	-2	0	0	0
Inorganic (P)	-2	-1	0	0	-2	-1	-1	-1
Inorganic (K)	-2	0	0	0	-2	-2	0	-2
Inorganic (Urea)	-1	0	0	0	-1	-1	-1	-1

4.5 Step 6. Final classification of technologies based on weighted EAI results

Finally, the technologies were grouped according to the weighted environmental scores obtained in the previous step. This classification summarises the overall environmental and resource-related performance of each technology by considering all selected EAIs together.

The grouping was based on the percentile distribution of the aggregated weighted scores. Each technology was therefore classified according to its relative position within the full set of assessed options, including the conventional fertiliser reference systems. Technologies with lower weighted environmental scores were assigned to more favourable performance groups, while technologies with higher scores were assigned to groups indicating comparatively higher environmental burdens.

The aggregated classification provides a simplified overview of the environmental performance of the assessed technologies. However, it should be interpreted together with the individual EAI scores, since the aggregated result may conceal relevant differences between impact categories. For example, a technology may obtain a favourable overall classification while still showing comparatively higher impacts for water use, mineral resource use or eutrophication. This idea is already consistent with the role assigned to the aggregated score in the current version. The final results obtained for the classification of the EAIs are presented in Table 35

Table 35. Final EAI classification of assessed technologies and conventional fertiliser references

5-point scale score	Num Tech.	Name of technology
1	Tech 5	Production of fertilizers and biomethane via wet anaerobic co-multiple feedstocks
	Tech 6	Integrated valorisation of biowaste through AD for biomethane, biogenic CO2 and stable soil amendment
	Tech 7	Tunnel composting combined with pre-treatment and refining
	Tech 8	Open windrow composting for green waste
	Tech 9	Composting system using semi-permeable membrane and forced aeration
	Tech 10	Semi-covered windrow composting for green waste
	Tech 11	Turning local industrial wastes into nutrient-rich fertilizer via AD
0	Tech 1	Integrated AD and tunnel composting for household, HORECA, and green biowaste streams

5-point scale score	Num Tech.	Name of technology
	Tech 2	Integrated dry AD for biowaste and composting of dewatered digestate
	Tech 3	Integrated wet AD of biowaste and composting of dewatered digestate
	Tech 12	Biothermal treatment for efficient biosolids processing
	Tech 13	A physical-chemical hydrolysis process for the treatment of biosolids and organic waste
	Tech 14	Hydrolysis of keratin waste
	Tech 15	Hydrolysis of anaerobic digestate
	Tech 16	Plasma-based technology converting livestock slurry and biogas digestate into fertilizing products
	Tech 17	Crystallizer for struvite production from nutrient-rich liquid streams
	Tech 18	Fluidized bed reactor for struvite production from municipal and industrial wastewater
	Tech 20	Liquid digestate valorisation through biological treatment and ultrafiltration technologies
	Tech 23	Pyrolysis of biomass residues for biochar production
	Tech 24	Biowaste to biochar and energy: integrated pyrolysis and biological methanation
	Tech 25	Pyrolysis of wood chips for the production of biochar
-1	Tech 21	Stripping and scrubbing system for ammonia recovery from wastewater streams
	Tech 22	Membranes and stripping technologies: transforming livestock manure and digestate
	Inorganic	Phosphorus
	Inorganic	Urea
-2	Tech 4	Integrated valorisation of pig manure through AD and nutrient recovery from digestate by membrane filtration
	Tech 19	Integrated solid-liquid separation, evaporation and reverse osmosis (RO) treatment for digestate valorisation
	Inorganic	Potassium

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5 Discussion and conclusions

The results obtained provide a comparative overview of the environmental and resource-related performance of the nutrient recovery and bio-based fertiliser production technologies assessed in D3.3. The classification combines the selected Environmental Assessment Indicators (EAIs) and provides a common basis for comparing technologies that differ in feedstocks, process configuration, product type and level of development.

A general pattern can be observed across the assessed technologies. Biological routes, particularly anaerobic digestion and composting-based systems, tend to obtain comparatively favourable classifications, which is consistent with their generally simpler treatment chains and lower dependence on intensive chemical or energy-consuming operations. Technologies within the intermediate range include hydrolysis, plasma-based treatment, struvite recovery and pyrolysis routes, whose environmental performance depends strongly on process configuration and operational requirements. Lower classifications are mainly associated with more complex liquid digestate treatment systems combining operations such as membrane separation, evaporation, reverse osmosis and stripping or scrubbing, which can involve higher energy and chemical demand.

The conventional fertiliser systems included in the assessment provide a useful reference for interpreting the results. However, this comparison should not be understood as evidence of direct substitution or full functional equivalence between bio-based and conventional fertilisers. The products may differ substantially in nutrient concentration, N, P and K composition, organic matter content, agronomic function and other relevant characteristics that are outside the direct scope of the environmental indicators considered in D3.3.

Operational scale and technological maturity also affect the interpretation of the results. Depending on the technology and data source, the environmental values may represent laboratory, pilot, demonstration or full-scale systems. These differences can influence energy and material requirements, process efficiency and the resulting EAI values. Technologies assessed at an earlier development stage may not yet reflect the optimisation, process integration or economies of scale achievable under industrial operation. Therefore, differences in maturity and operational scale should be considered when comparing environmental performance.

The robustness of the available evidence is also not the same for all technologies. The assessment combines primary information from technology providers, scientific literature and LCA databases, and differences remain in data availability, quality, process definition, functional units, system boundaries and methodological assumptions. Consequently, the results should be interpreted as a comparative environmental and resource-related screening rather than as fully harmonised LCAs. In addition, the aggregated classification should be considered together with the individual EAI results, since a favourable overall score may still conceal weaker performance in specific impact categories.

The scope of D3.3 is intentionally limited to the environmental and resource-related dimension of technology performance. Other relevant aspects, including nutrient concentration, product quality, agronomic performance, regulatory requirements, technological applicability, economic aspects and market conditions, will be considered within the broader project assessment.

In this context, D3.3 establishes a structured and transparent framework for comparing the environmental impacts and resource efficiency of the selected technologies under the available data conditions. Despite the limitations associated with data heterogeneity and differences in technological development, the results provide a common environmental basis for the subsequent integrated assessment and selection of technologies within FertiCovery.

Finally, the environmental assessment developed in D3.3 forms part of the wider FertiCovery evaluation framework. The EAI results will contribute to the subsequent Multi-Criteria Decision Analysis (MCDA), where environmental performance will be considered together with technical, agronomic, economic, regulatory and other relevant criteria. The classification presented here should therefore be understood as one input to the overall decision-making process rather than as a standalone judgement of technology suitability.

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6 Bibliography

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Saxegård, S. A., & Lyng, K.-A. (2020). *Life cycle assessment of N2 Applied technology: Introduced to a farm scale biogas plant* (Report No. OR.38.19; ISBN 978-82-7520-820-8; ISSN 0803-6659). Østfold Research.

7 ANNEX 1. LITERATURE REVIEW

Table 36. Scientific data sources

Title	Year	Technology Covered	Functional Unit	System Boundary	Method	Authors
Life cycle assessment of the integrating system of anaerobic digestion and aerobic composting for treating rural organic solid waste	2025	Anaerobic Digestion Composting	10 tons of rural organic solid waste(ROSW)	Cradle to gate	ReCiPe 2016	Peng, H., Mu, L., Song, Y., Su, H., Cheng, Z., Li, R., & Chen, G.
A comparative life cycle assessment of biofertilizer production towards sustainable utilization of anaerobic digestate	2022	Anaerobic Digestion AD+Physicochemical AD+Physical Composting	1 t of raw digestate	Gate to grave	CML 2001	Alengebawy, A., Mohamed, B. A., Jin, K., Liu, T., Ghimire, N., Samer, M., & Ai, P.
Environmental Impact Assessment of Food Waste Management Using Two Composting Techniques	2020	Composting	1 t of food waste	Cradle to grave	CML 2000 (v 2.03)	Al-Rumaihi, A., McKay, G., Mackey, H. R., & Al-Ansari, T.
Achieving circular economy through sustainable biofertilizer production from mixed municipal waste: a life cycle analysis approach	2025	Composting	1 ton of mixed municipal solid waste (MSW)	Cradle to grave	ReCiPe mid-point (H)	Ahmad, A., Javed, M. H., Musharavati, F., Khan, M. I., Al-Muhtaseb, A. A. H., Naqvi, M., ... & Nizami, A. S.
Environmental Performance in the Production and Use of Recovered Fertilizers from Organic Wastes Treated by Anaerobic Digestion vs Synthetic Mineral Fertilizers	2022	Anaerobic Digestion	1 ha maize	Cradle to grave	ReCiPe 2016	Herrera, A., D'Imporzano, G., Zilio, M., Pigoli, A., Rizzi, B., Meers, E., ... & Adani, F. (

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Table 36. Scientific data sources

Title	Year	Technology Covered	Functional Unit	System Boundary	Method	Authors
Environmental sustainability performance of a membrane-based technology for livestock wastewater treatment with nutrient recovery	2022	Physicochemical	m^3 of manure	Cradle to grave	ReCiPe method V 1.1	González-García, I., Riaño, B., Cuéllar-Franca, R. M., Molinuevo-Salces, B., & García-González, M. C.
Environmental impact of two aerobic composting technologies using life cycle assessment	2009	Composting	1 ton of organic fraction of municipal solid waste (OFMSW)	Gate to gate		Cadena, E., Colón, J., Artola, A., Sánchez, A., & Font, X.
Closing nutrient loops through decentralized anaerobic digestion of organic residues in agricultural regions: A multi-dimensional sustainability assessment	2018	Anaerobic Digestion	1 ton of dry resource-based fertilizer	Cradle to grave	CML	Vaneeckhaute, C., Styles, D., Prade, T., Adams, P., Thelin, G., Rodhe, L., ... & D'Hertefeldt, T.
Anaerobic digestion of fourth range fruit and vegetable products: comparison of three different scenarios for its valorisation by life cycle assessment and life cycle costing	2020	Anaerobic Digestion	1000 ton of mass ofr fruit and vegetable waste	Cradle to grave	CML 2 baseline 2000 V2.05	González, R., Rosas, J. G., Blanco, D., Smith, R., Martínez, E. J., Pastor-Bueis, R., & Gómez, X.
Apple pomace management by anaerobic digestion and composting: a life cycle assessment	2022	Anaerobic Digestion	1 L of apple juice	Cradle to gate	CML 2 baseline 2000 V2.05	Ampese, L. C., Ziero, H. D. D., Velásquez, J., Sganzerla, W.

Table 36. Scientific data sources

Title	Year	Technology Covered	Functional Unit	System Boundary	Method	Authors
						G., Martins, G., & Forster-Carneiro, T.
Waste Feathers Processing to Liquid Fertilizers for Sustainable Agriculture—LCA, Economic Evaluation, and Case Study	2022	Hydrolysis	1 L of hydrolysate production	Gate to gate	ReCiPe2016	Vavrova, K., Wimmerova, L., Knapek, J., Weger, J., Keken, Z., Kastanek, F., & Solcova, O. (
Evaluating biochar extraction from waste tree stumps in different pyrolysis systems using life cycle analysis	2025	Thermochemical	1 ton of biochar production	Cradle to gate	CML	Lekavičienė, K., Jotautienė, E., Grigas, A., Gaudutis, A., Paulikienė, S., & Mieldažys, R.
Life cycle assessment of sewage sludge pyrolysis environmental impacts of biochar as carbon sequestrator and nutrient recycler	2021	Thermochemical	1 kg of digested sewage sludge	Cradle to grave	ReCiPe2016	Gievers, F., Loewen, A., & Nelles, M.
Olive Oil Wastewater Revalorization into a High-Added Value Product: A Biofertilizer Assessment Combining LCA and MCI	2025	Physicochemical	1 kg of biofertilizer	Cradle to gate	ReCiPe2016	Petrucci, R., Menegaldo, G., Rocchi, L., Paolotti, L., Boggia, A., & Puglia, D.
Life Cycle Assessment of Biofertilizer Production and Use Compared with Conventional Liquid Digestate Management	2018	Physical	1 m^3 of LD from a food waste AD plant	Gate to grave	CML	Styles, D., Adams, P., Thelin, G., Vaneeckhaute, C., Chadwick, D., & Withers, P. J.

Table 36. Scientific data sources

Title	Year	Technology Covered	Functional Unit	System Boundary	Method	Authors
Life cycle assessment of struvite recovery and wastewater sludge end-use: A Flemish illustration	2022	Physical	1 kg of plant available recovered in the from of struvite		ReCiPe	Ravi, R., Beyers, M., Bruun, S., & Meers, E.
Life cycle assessment of nutrient recovery from the liquid fraction of pig manure digestate via struvite precipitation	2023	Physical	1 m3 of liquid fraction			Bedogni, F.
Environmental Impact Assessment (LCA) and Techno-Economic Assessment (TEA) of Struvite Recovery in Swine Manure	2022	Physical	volume of manure managed	Gate to grave		Aghdam, S.
Valorisation of anaerobic digestate: Environmental life cycle assessment of anaerobic digestate value chain in the UK with a digestate treatment technology	2026	Physicochemical Composting Physical	Supplying 250 kg N/ha/year.	Gate to grave	ReCiPe2016	Lin, H., Šimaitis, J., Black, M. J., & Borrion, A.
Life cycle assessment of digestate post-treatment and utilization	2022	Physical	1 kg dry matter raw digestate	Gate to grave	ReCiPe	Angouria-Tsorochidou, E., Seghetta, M., Trémier, A., & Thomsen, M.
Composting food waste or digestate? Characteristics, statistical and life cycle assessment study based on an Italian composting plant	2022	Composting	1 Mg of OFMSW compost		ReCiPe	Le Pera, A., Sellaro, M., & Bencivenni, E
Life cycle assessment of N2 Applied technology Introduced to a farm scale biogas plant	2020	Plasma	kg of N fertiliser		IPCC/CML	
At-Field and On-Demand Nitrogenous Fertilizer Synthesis	2023	Plasma	1 ha of cropland being fertilized		IPCC/CML	Butler, C., Fan, Y., Grewal, S., & Winter, L. R.
Life Cycle Assessment of sewage sludge pretreatment for biogas production, from laboratory tests to fullscale applicability	2021		treatment of 1 kg of fresh matter (FM) of		ReCiPe	Mainardis, M., Buttazzoni, M., Gievers, F.,

Table 36. Scientific data sources

Title	Year	Technology Covered	Functional Unit	System Boundary	Method	Authors
			sewage sludge through enhanced AD			Vance, C., Magnolo, F., Murphy, F., & Goi, D
Environmental impact assessment of plasma-assisted and conventional ammonia synthesis routes	2020	Plasma	1000 kg of liquid ammonia	Cradle to gate	CML 2001	Anastasopoulou, A., Keijzer, R., Patil, B., Lang, J., van Rooij, G., & Hessel, V.
Environmental impacts of phosphorus recovery from a "product" Life Cycle Assessment perspective: Allocating burdens of wastewater treatment in the production of sludge-based phosphate fertilizers	2018	Thermochemical	1 kg of P available for plants in mineral form	Cradle to gate	CML	Pradel, M., & Aissani, L.
Life cycle assessment and techno-economic analysis of nitrogen recovery by ammonia air-stripping from wastewater treatment	2023	Physicochemical	1000kg of ammonium sulfate	Gate to gate	ReCiPe	Kar, S., Singh, R., Gurian, P. L., Hendricks, A., Kohl, P., McKelvey, S., & Spatari, S.
Life Cycle Assessment and Environmental Valuation of Biochar Production: Two Case Studies in Belgium	2018	Thermochemical	Ton of biochar	Cradle to grave	IMPACT2002+	Rajabi Hamedani, S., Kuppens, T., Malina, R., Bocci, E., Colantoni, A., & Villarini, M
Life cycle assessment of sewage sludge treatment, Comparison of pyrolysis with traditional methods in two Swedish municipalities	2024	Composting Anaerobic Digestion Thermochemical Anaerobic Digestion	1 ton of dewatered sewage sludge	Gate to grave	ReCiPe	Hosseinian, A., Brancoli, P., Vali, N., Ylä-Mella, J.,

Table 36. Scientific data sources

Title	Year	Technology Covered	Functional Unit	System Boundary	Method	Authors
		+ Thermochemical				Pettersson, A., & Pongrácz, E
Toward cleaner poultry manure management in Canada: Life cycle impacts of anaerobic digestion with ammonia recovery versus traditional practices	2026	Composting Anaerobic Digestion + Hydrolysis + Physicochemical	1 ton of manure	Gate to grave	CML	Adghim, M., Sartaj, M., Strehler, B., Abdehagh, N., & Abdallah, M.
Life cycle assessment of food waste energy and resource conversion scheme via the integrated process of anaerobic digestion and hydrothermal carbonization	2024	Composting	1 ton of food waste		CML	Zhao, Z., Qi, S., Wang, R., Li, H., Song, G., Li, H., & Yin, Q.
Waste Feathers Processing to Liquid Fertilizers for Sustainable Agriculture—LCA, Economic Evaluation, and Case Study	2021	Hydrolysis	1 L of hydrolysate production		CML	Vavrova, K., Wimmerova, L., Knapek, J., Weger, J., Keken, Z., Kastanek, F., & Solcova, O
Life cycle assessment of nutrient removal technologies for the treatment of anaerobic digestion supernatant and its integration in a wastewater treatment plant	2024	Physical	1 kg PO_4^{3-} eq. removed	Cradle to grave	CML	Rodriguez-Garcia, G., Frison, N., Vázquez-Padín, J. R., Hospido, A., Garrido, J. M., Fatone, F., ... & Feijoo, G
Life cycle assessment of urea production: Environmental impact comparison of two fertilizer technologies in Northern India	2025	Synthetic	1 ton of urea production	Gate to gate	ReCiPe and EF 3.2	Katiyar, A., & Gedam, V. V
Life Cycle Assessment of Nitrate and Compound Fertilizers Production—A Case Study	2020	Synthetic	1 ton of nitrate Fertilizer	Gate to gate	ReCiPe 2008	Gaidajis, G., & Kakanis, I.

Table 36. Scientific data sources

Title	Year	Technology Covered	Functional Unit	System Boundary	Method	Authors
Environmental Impact Assessment for Animal Waste, Organic and Synthetic Fertilizers	2023	Synthetic Composting	1 kg of nitrogen	Cradle to grave	ReCiPe 2016	Litskas, V. D.
Life cycle environmental impacts of sewage sludge treatment methods for resource recovery considering ecotoxicity of heavy metals and pharmaceutical and personal care products	2019	Anaerobic Digestion Composting Thermochemical	1000 kg sludge on a dry matter basis	Cradle to grave	ReCiPe	Tarpani, R. R. Z., Alfonsín, C., Hospido, A., & Azapagic, A.
Environmental impacts of phosphorus recovery through struvite precipitation in wastewater treatment	2021	Physical	kg of struvite recovered	Cradle to grave		Sena, M., Seib, M., Noguera, D. R., & Hicks, A.
Life Cycle Environmental Impact Assessment of Sulfur-Based Compound Fertilizers: A Case Study in China	2022	Synthetic	1 ton of fertilizer	Cradle to grave		Liu, M., Li, Y., Yuan, X., Xu, Y., Qiao, L., Wang, Q., & Ma, Q.

Table 37. Eu project data sources

Title	Year	Technology Covered	Functional Unit	System Boundary	Method	Project	Number of studies
LCA study of processes and products subject to the LEX4BIO project	2024	Anaerobic digestion; Physical; Thermal; Hydrolysis	kg P2O5; kg N	Cradle to gate	ReCiPe 2016	LEX4BIO	11
Multi-assessment of impacts, trade-offs and framework conditions	2025	Physical; Anaerobic digestion; Composting; Hydrolysis	1 ton of UWW struvite; 1 ton of stabilised sludge; 1 ton of compost; 1 ton of feather meal; 1 ton of solid fraction of digestate from food waste; 1 ton spent mushroom substrate;	Cradle to grave	Environmental Footprint (PEF) 3.1	FERPLAY	7
Report on Life Cycle Assessment	2021	Anaerobic digestion	ton of substrate	Gate to gate	ReCiPe	SYSTEMIC	5
D7.2. Environmental impacts evaluation	2024	Composting; Hydrolysis; Physical; Physicochemical	1 kg of BBF	Cradle to gate	Impact World+ version 2.0	SEA2LAND	5

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Table 37. Eu project data sources

Title	Year	Technology Covered	Functional Unit	System Boundary	Method	Project	Number of studies
Report on the life cycle impact of SUSFERT fertiliser production And GHG emission reduction	2023	Physicochemical; Physical	Multiple functional units depending on fertiliser function (not specified)	Cradle to gate	Not specified	SUSFERT	4
Combining life-cycle assessment and linear programming to optimize social fertilizer costs	2024	Composting; conventional	1 ton of fertilizer	Cradle to grave	ReCiPe	RUSTICA Project	5
D.3.4 Environmental and Social Life Cycle Assessment of Selected Innovations	2022	Physicochemical; Physical	1 m3 of raw pig slurry; 1 tonne digestate; 1 t of treated liquid digestate; 1 tonne or 1 m^3 liquid fraction pig manure; 100 tons of grass production	Various	Environmental Footprint 3.0	Nutri2Cycle	6

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