ManuREfinery

D4.1.- LCA_DL

Detailed LCA at Design Level

Circular Bio-based Europe Joint Undertaking

Bio-based Industries Consortium

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LIST OF ABBREVIATIONS

ABBREVIATION	FULL NAME
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
EF	Environmental Footprint
FU	Functional Unit
LHV	Lower Heating Value
GVL	Gas Valorisation Line
LVL	Liquid Valorisation Line
SVL	Solid Valorisation Line
CF	Capacity Factor
RER	Europe
RoW	Rest of World
GLO	Global
BF	Biogas Fermenter
AD	Anaerobic Digester
NPR	Nitrogen and Phosphorous Recovery
CA	Caproic Acid

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EXECUTIVE SUMMARY

This report presents the Detailed Life Cycle Assessment (LCA) at Design Level for the MANUREFINERY project (Grant Agreement No. 101157679), covering the evaluation of innovative modular biorefining technologies for manure valorization. The study, conducted by the University of Florence, adopts a cradle-to-gate approach to quantify the environmental performance of three primary valorization pathways: the Gas Valorisation Line (GVL), the Liquid Valorisation Line (LVL), and the Solid Valorisation Line (SVL). Methodological Framework The assessment is compliant with ISO 14040 and 14044 standards. The Environmental Footprint 3.1 (EF 3.1) methodology was selected for the Life Cycle Impact Assessment (LCIA), utilizing 16 midpoint impact categories. Primary data collected from project partners were supplemented by the ecoinvent 3.10 database for background inventory modelling. The Functional Unit (FU) is defined as 1 kg of bioproduct for all lines, employing mass-based allocation for multi-output processes and system expansion to account for energy recovery credits (e.g., biogas and syngas).

The results of the LCA (Life Cycle Assessment) for the MANUREFINERY project demonstrate that modular biorefining of manure is a promising solution for the circular economy, though certain technical challenges remain for future optimization.

Based on the evaluation of the three valorization pathways—Gas (GVL), Liquid (LVL), and Solid (SVL)—the following general conclusions can be drawn:

- Positive Climate Impact: All three lines show significant potential to reduce impacts on Climate Change (CC) compared to conventional industrial benchmarks. This benefit is primarily driven by the recovery of nutrients (which replaces chemical fertilizers) and the production of energy (biogas and syngas).
- The Importance of Renewable Energy: The integration of Photovoltaic (PV) systems is a decisive factor across all scenarios. Utilizing renewable energy drastically lowers the carbon footprint and improves performance in energy-intensive categories like Resource Use (Fossils) and Freshwater Eutrophication.
- Critical Resource Challenges: A major common weakness is high Water Use (WU). In many scenarios, water consumption is significantly higher than conventional processes, highlighting a critical need for advanced water recirculation strategies in the next design phases

The MANUREFINERY biorefinery concept demonstrates strong potential for greenhouse gas mitigation and resource recovery compared to conventional industrial processes. While the design-level LCA confirms the benefits of nutrient and energy circularity, future optimization should prioritize reducing material-related toxicity in the construction phase and minimizing direct water consumption to enhance the overall environmental performance of the modular units

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INTRODUCTION

1. BRIEF INTRODUCTION

The present report describes the activities carried out during the first 18 months of work within Task WP4. Specifically, it presents the life cycle assessment (LCA) conducted at the design level of the technologies proposed within the framework of the Manurefinery project. The model developed and the results obtained are the outcome of the work performed by the University of Florence, which collected primary data directly from all project partners involved, and subsequently processed and assessed them within the LCA framework.

This report follow the framework proposed by the ISO 14040 and ISO 14044 standards. The LCA methodology is structured into four sequential and iterative phases showed in Figure 1. The first phase, ***Goal and Scope Definition***, establishes the purpose of the study, the functional unit, the system boundaries, and the assumptions and limitations adopted. This phase determines the overall framework within which the subsequent analysis is conducted. The second phase, ***Life Cycle Inventory (LCI)***, involves the collection and quantification of all input and output flows (including raw material consumption, energy use, emissions to air, water, and soil, and waste generation) associated with the system under study throughout its entire life cycle. The third phase, ***Life Cycle Impact Assessment (LCIA)***, translates the inventory results into potential environmental impacts by associating the quantified flows with specific impact categories through characterisation factors. This phase may also include optional steps such as normalisation and weighting, aimed at facilitating the interpretation of results. The fourth and final phase, ***Interpretation***, involves the systematic evaluation of the results obtained from the LCI and LCIA phases in relation to the goal and scope of the study. This phase includes the identification of significant issues, sensitivity and uncertainty analyses, and the formulation of conclusions and recommendations.

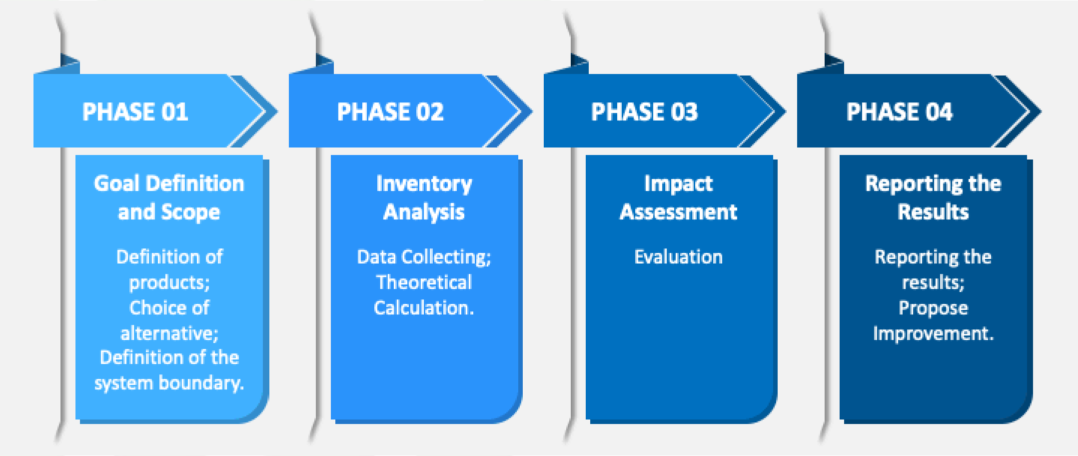

Figure 1: LCA Framework proposed by ISO14040 and 14044

For the purpose of this study, the LCIA methodology selected is the Environmental Footprint 3.1 (EF 3.1), as proposed by the European Commission. This methodology provides 16 midpoint environmental impact categories, spanning a wide range of environmental concerns including, among others, acidification, climate change, ecotoxicity, human toxicity, and resource consumption. A comprehensive overview of all impact categories included in the methodology is reported in Table 1. In addition, EF 3.1 provides a normalisation and weighting set, which can be applied to evaluate the relative contribution of each impact category and to aggregate the results into a Single Score,a composite environmental indicator that synthesises the information across all impact categories into a single dimensionless value, thereby facilitating the overall comparison and interpretation of results.

Table 1: Environmental Footprint Indicator and Normalization and weighting set

Indicator	Unit	Acronym	Normalization Factor	Weighting Factor
Acidification	mol H+ eq	AC	55.56954	0.062
Climate change	kg CO2 eq	CC	7553.083	0.2106
Ecotoxicity freshwater	CTUe	Ecf	56716.59	0.0192
Eutrophication freshwater	kg P eq	Euf	1.606852	0.028
Eutrophication marine	kg N eq	Eum	19.54518	0.0296
Eutrophication terrestrial	mol N eq	Eut	176.755	0.0371
Human toxicity cancer	CTUh	Htc	1.73E-05	0.0213
Human toxicity non-cancer	CTUh	Htnc	1.29E-04	0.0184
Ionising radiation (human health)	kBq U235 eq	IR	4220.163	0.0501
Land use	dimensionless (pt)	LU	819498.2	0.0794
Ozone depletion	kg CFC11 eq	OD	0.052348	0.0631
Particulate matter	disease incidence	PM	5.95E-04	0.0896
Photochemical ozone formation	kg NMVOC eq	Pof	40.8592	0.0478
Resource use fossils	MJ (net calorific)	Ruf	65004.26	0.0832
Resource use minerals and metals	kg Sb eq	Rumm	0.063623	0.0755
Water use	m3 world eq	WU	11468.71	0.0851

The ecoinvent 3.10 database was employed as the primary source of background inventory data, providing the life cycle inventory datasets necessary to model the upstream and downstream processes associated with the systems under assessment. In addition, ecoinvent 3.10 serves as the source for the conventional and industrial process inventories representing the reference products against which the Manurefinery valorisation pathways are compared in the comparative assessment.

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2. GOAL AND SCOPE DEFINITION

The LCA conducted within the present work pursues multiple objectives and is presented separately for each of the three valorisation pathways considered in their respective dedicated sections 2.1 Gas Valorisation Line, 2.2 Liquid Valorisation Line, 2.3 Solid Valorisation Line.

The analysis is structured into several sequential methodological steps. First, the environmental impacts associated with the production of bioproducts are quantified and presented across all 16 impact category indicators defined by EF 3.1 methodology. Subsequently, in order to identify the impact categories of greatest relative significance, the normalisation set provided by EF 3.1 is applied. This allows results to be compared on a common scale and priority indicators to be selected for interpretation. For these indicators, a contribution analysis is carried out, aimed at identifying the processes that have a predominant influence on each impact category considered.

In parallel, the environmental impacts generated by each valorisation pathway are compared with those of conventional industrial processes available on the market for the production of the same product. This comparison allows the net environmental advantage or disadvantage associated.

The methodological approach adopted and the definition of the Functional Unit (FU) is set for all pathways to one kilogram of bioproduct (1 kg bioproduct). These are described in detail in the following sections, as they presents specific characteristics for each pathway. Finally, for each valorisation line, the parameters exerting the greatest influence on environmental impacts are identified, and a parametric sensitivity analysis is conducted on selected indicators, in order to illustrate their influence and to define the plausible range of variation of the associated impacts. Finally, adopting a system expansion approach, the results obtained for each impact category indicator are presented in net terms, as the difference between the total environmental impacts generated by each valorisation line and the environmental credits attributable to the substitution of conventional products by the respective bioproducts. This allows to determine whether the Manurefinery valorisation line results in a net environmental burden or, conversely, yields a net environmental credit relative to the conventional reference system.

The following sections provide a detailed description of each valorisation line, including the system boundaries, the FU, the allocation approach adopted, the main scenarios for the comparison, and the most significant parameters influencing the environmental performance of the system.

2.1. Gas Valorisation Line

Gas Valorisation Line (GVL) is based on a gas biofiltration unit, designed to achieve complete recovery of NH_3 from air emissions, converting it into $NaNO_3$ for subsequent use in fertiliser production. The underlying technology is based on the gas-liquid mass transfer of gaseous NH_3 into a recirculating $NaHCO_3$ solution trickling over a nitrifying bacteria biofilm, which biologically oxidises NH_3 to nitrate through nitrification. The system is expected to produce **approximately 395 kg/year of $NaNO_3$ in the 1 m^3 demonstration plant**, which will be validated at two dedicated demo sites, namely a swine farm (SwF) and a poultry farm (PoF), both located in Romania.

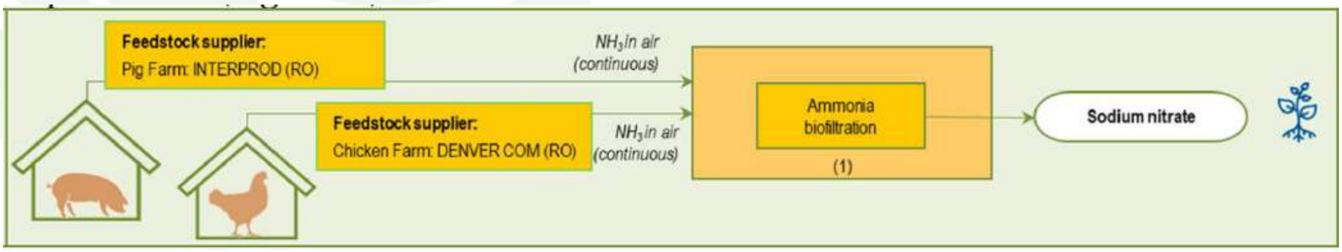

Figure 2: Gas Valorisation Line Layout

The FU of GVL is defined as 1 kg of sodium nitrate ($NaNO_3$) produced. Based on the data currently available, the annual production of $NaNO_3$ is subject to variability, and two reference values have been considered: 0.4 kg/day and 1.1 kg/day. Accordingly, two distinct scenarios are defined for the comparative assessment, Scenario 1 and Scenario 2, corresponding respectively to the two aforementioned bioproduct production rates. A detailed overview of all scenarios is provided in Table 2. For this line, as it is a single-product process, no allocation approach is applied.

Within the model, the two farm configurations differ in a single aspect: the PoF has an existing photovoltaic (PV) system with an installed capacity of 200 kW. Given that this system serves the overall electricity demand of the farm, it has been assumed, for the purposes of this analysis, that the PV contribution is allocated exclusively to the electrical consumption associated with the ventilation system responsible for conveying the treated airstream to the GVL. Based on a PV capacity factor of 0.11[1] and the electrical consumption of the inlet compressor feeding the GVL, it is estimated that the photovoltaic system covers approximately 73% of the total electrical energy demand of the GVL.

Two additional key parameters are the capacity factor (CF) and the liquid flow rate within the biotrickling filter. CF is defined as the ratio between the operating hours at nominal capacity and the total number of hours in one year, and therefore represents an indicator of the effective productivity level of the system. Based on estimates derived from primary data provided by the project partners, CF is expected to vary between 0.4 and 0.6. For this reason, a parametric analysis was carried out over this range.

A further variable parameter is the liquid flow rate within the biotrickling filter, which depends on the residence time of the air stream inside the filter. As this parameter has a significant influence on the results, it was included in a combined parametric analysis together with CF. All the parameters associated with the different scenarios are reported in Table 2.

Table 2 – Main Parameter and Scenario definition for GVL

Unit	Parameter	SwF - 1	SwF - 2	PoF - 1	PoF - 2
h/h	Capacity Factor (CF)	0.5 (0.4 – 0.6)	0.5 (0.4 – 0.6)	0.5 (0.4 – 0.6)	0.5 (0.4 – 0.6)
g/d	NaNO3 production	401	1100	401	1100
%	Renewable	0	0	73	73
l/d	Daily flow GVL	15 (5-25)	15 (5-25)	15 (5-25)	15 (5-25)

The system boundaries encompass the construction, maintenance, and operational phases of all mechanical devices installed within the GVL. In addition, the direct emissions of the system, the photovoltaic system, the electricity grid, and all chemical and water consumption required for operation are accounted for. The following aspects are excluded from the system boundaries: transportation of machinery to the farm and control devices.

The reference system adopted for the comparative assessment is the conventional production of $NaNO_3$ as retrieved from the ecoinvent database, considering two distinct market scenarios: the European market (RER) and the Rest of the World market (RoW). The ecoinvent dataset providers are reported below:

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[1] IRENA, Statistical Profile (www.irena.org/Data/Energy-Profiles)

- SN_RER = sodium nitrate production – RER
- SN_RoW = sodium nitrate production – RoW

2.2. Liquid Valorisation Line

Raw manure is processed in a thermophilic anaerobic digester designed to maximise the conversion of biodegradable organic matter into biogas, to mineralize organic nitrogen into ammonia (NH_3) for subsequent recovery via stripping, and to achieve partial hygienization of the substrate. The output of the anaerobic digester are two: Digestate and Biogas. The first one is a mixture of solid and liquid that is separated and the liquid fraction is treated in the subsequent process, while the solid fraction is sent to Solid Valorisation Line. While for the secondo output a fraction of the of the biogas produced is used to convert the methane into microbial protein with efficiencies exceeding 90% using a pressurized gas-phase bioreactor. A non-pathogenic *Methylococcus* inoculum is employed. The anaerobic digester effluent is centrifuged with the aid of coagulants to enhance phosphorus recovery. The liquid fraction is stored and-periodically treated through an innovative ammonia stripping process capable of fixing CO_2 in the form of ammonium bicarbonate (NH_4HCO_3), enabling nitrogen recovery for fertiliser production. The treated water, still containing residual nitrogen and phosphorus, will be reused for on-farm fertigation to support grass production. The initial grass pretreatment based on extrusion with lime was found to be not scalable due to technical and economic limitations. Alternative approaches using different substrates and lactic acid bacteria were therefore investigated; however, protein extraction methods proved to be too costly and treatment-intensive. As a result, an alternative strategy based on static fermentation of ensiled grass was explored. This approach represents a simpler and more robust process and was shown to achieve the target lactic acid concentrations, with further improvements expected through process optimization. Grass proteins is separated from the juice by thermal treatment, while the remaining sugar-rich liquid is biologically converted into caproic acid for use as a prebiotic in pig nutrition. The extracted grass protein is mixed with the grass press cake to produce animal feed. Caproic acid is recovered from the fermentation broth by means of electrochemical extraction. The valorisation line consisted of fixed units, including the thermophilic anaerobic digester coupled with the biogas fermenter, and mobile units dedicated to ammonia recovery, grass extrusion and fermentation, grass protein separation, and caproic acid extraction. These mobile units were periodically deployed on-farm depending on the availability of liquid digestate and grass biomass. Per tonne of wet manure treated (dry matter is 48 kg/ton), the system generated **13–15 kg of NH_4HCO_3, 2.5–3.8 kg of microbial protein, 0.14–0.16 kg of protein-rich grass biomass, and 0.39–0.47 kg of caproic acid, depending on the animal species**. At maximum operating capacity, the demonstration plant, comprising a 20 m^3 anaerobic digester, a nitrogen stripping unit with a capacity of 1 $m^3\ h^{-1}$ (total plant volume of 19 m^3), a 1 m^3 biogas fermenter, and a 0.5 m^3 granular caproic acid fermenter. The system produce annually 4,956 kg of NH_4HCO_3, 274 kg of microbial protein, 2,737 kg of protein-rich grass biomass, and 8,760 kg of caproic acid. The valorisation line is implemented at a pig farm located in Spain.

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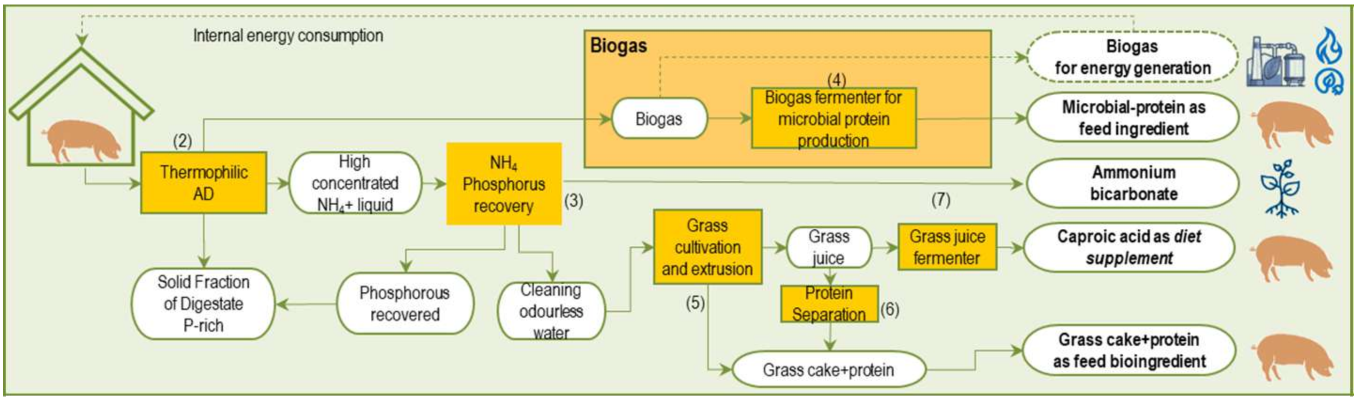

Figure 3: Liquid Valorisation Line Layout

This production line represents a multi-product process, specifically generating four bioproducts:

- Microbial protein
- Ammonium bicarbonate
- Caproic acid
- Grass cake and proteins
- Biogas

Due to the multi-product nature of the system, an allocation approach is applied to distribute environmental impacts. For the first three bioproducts, a physical allocation based on mass is used, considering the annual production of each. As a result, the functional unit is defined as 1 kg of bioproduct exiting the system.

For biogas, since it is not directly comparable in the same unit as the other products, a system expansion approach is applied. Here, the biogas is assumed to be converted into electricity (2 kWh/m^3) and heat (2.5 kWh/m^3), treated as an avoided product, thereby generating environmental credits.

Due to the lack of literature data for grass cake, proteins, and caproic acid, the comparative analysis is conducted exclusively against conventional protein feed for animals and ammonium bicarbonate production. However, the benefits associated with the additional products are included in the allocation phase.

The system boundaries for this line are defined in the same way as for the previous line. The system boundaries for the LVL production line include the construction, maintenance, and operational phases of all installed equipment across the process. In addition, direct emissions from the system, electricity supply, and all chemical and water inputs required for operation are accounted for. The following aspects are excluded from the system boundaries: transportation of equipment to the facility and monitoring/control devices. Moreover, the analysis is applied to the Spanish case study; therefore, electricity flows are sourced from the Spanish national grid. Various scenarios of renewable energy integration are considered, with PV shares of 0% (baseline), 50%, and 100%.

The comparison is carried out with protein feed (the same as those reported in Section 2.3, Solid Valorisation Line). For ammonium bicarbonate, the reference processes are taken from ecoinvent as follows:

- ammonium bicarbonate production – RER
- ammonium bicarbonate production – RoW

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2.3. Solid Valorisation Line

The Solid Valorisation Line (SVL) use the solid manure fraction of the digestate obtained after centrifugation. It is continuously dried using on-site residual heat. This phosphorus- and potassium-rich solid fraction is stored and subsequently gasified into synthesis gas (syngas), which is further biologically converted into acetate in a U-loop fermenter configuration. An acetogenic microbial consortium, selected for its high acetate productivity, is employed as inoculum. The biogenic acetic acid produced is subsequently converted into microbial protein via aerobic microbial fermentation using *Cupriavidus necator* for feed applications. The ash generated during the gasification process, characterized by high phosphorus and potassium contents, is recovered and reused as a raw material for fertiliser production. This valorisation pathway consisted of a fixed processing unit (digestate dryer) and mobile units, including a digestate gasifier, a syngas fermentation reactor, and a microbial protein production unit. These mobile units are deployed on-farm when sufficient quantities of dried digestate became available. On a mass basis, the process yield **3.5–6.2 kg of microbial protein and 10–17 kg of ash per tonne of manure treated**. At the scale of the demonstration plant, equipped with a gasifier with a nominal capacity of 50 kg h^{-1}, a 1 m^3 syngas fermenter, and a 0.5 m^3 acetate fermenter, annual production **amount to 1,588 kg of microbial protein and 4,285 kg of ash.** Based on the physicochemical properties of these gaseous streams, the operational requirements for combined heat and power (CHP) generation are determined, enabling the definition of suitable engine models, sizes, and configurations in accordance with farm-specific energy demands.

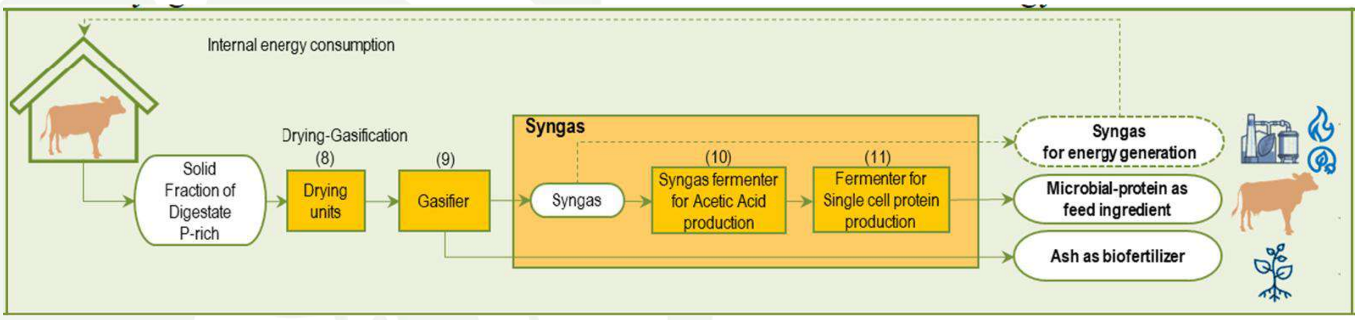

Figure 4: Solid Valorisation Line Layout

Considering that this process is a multi-product process, there are three bioproducts:

- Microbial-protein
- Biofertilizer
- Syngas

Given the multi-output nature of the system, a combined methodological approach was adopted to handle co-product allocation. For the two primary bioproducts, a mass-based allocation approach was applied, whereby the environmental burdens associated with the production processes are distributed among the co-products in proportion to their respective mass flows (kg). For the third bioproduct, syngas, system expansion was adopted Under this approach, syngas is treated as an avoided product, on the assumption that it substitutes a conventional energy source. Specifically, the volume of syngas produced is converted into its equivalent energy content, and the corresponding amount of energy is credited to the system by offsetting it against the total energy consumption of the valorisation pathway. This results in net environmental credits that reduce the overall environmental burden attributed to the system, effectively accounting for the avoided impacts associated with the displacement of conventional energy production.

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Based on the methodological approach described above, the FU is defined as 1 kg of bioproduct, referring either to 1 kg of microbial protein or to 1 kg of biofertilizer, depending on the specific output considered in the assessment. Specifically, given an annual production of 4,285 kg/year of biofertilizer and 1,588 kg/year of microbial protein, the resulting mass-based allocation factors are 72.96% for biofertilizer and 27.04% for microbial protein, respectively.

For this demo site, five distinct scenarios were investigated, each reflecting a progressively higher level of renewable energy integration through the installation of a photovoltaic (PV) system, with incremental steps of 25%.

The parametric analysis was primarily focused on syngas-related parameters, given their substantial influence on the overall environmental results. First, since a reliable fixed estimate of syngas production is not yet available, a plausible productivity range of 0–40 m³/h was adopted. Second, the lower heating value (LHV) of syngas was considered as a key variable, as it is strongly dependent on the operational conditions of the production process; accordingly, it was assumed to vary within a range of 10–20 MJ/m³. Third, the efficiency of syngas conversion into electrical energy via conventional systems was also included in the parametric analysis, with an assumed variability range of 20–30%.

Table 3 – Main Parameter and Scenario definition for SVL

Unit	Parameter	SVL - 1	SVL - 2	SVL - 3	SVL - 4	SVL - 5
%	Renewable	0	25	50	75	100
h/h	Capacity Factor	0.5				
m^3/h	Syngas production	20 (0-40)				
MJ/m^3	LHV	15 (10-20)				
%	Efficiency conversion	25 (20-30)				

The system boundaries encompass the construction, maintenance, and operational phases of all mechanical devices installed within the SVL. In addition, the direct emissions of the system, the electricity grid, and all chemical and water consumption required for operation are accounted for. The following aspects are excluded from the system boundaries: transportation of machinery to the farm and control devices.

Regarding the reference products selected for the comparative assessment, multiple options were considered, as the ecoinvent database provides several datasets comparable to the two bioproducts under investigation. With respect to the biofertilizer, four reference products were selected, representing both nitrogen-based and phosphorus-based fertilisers, each available in either inorganic or organic form. For the inorganic fertilisers, a market average was computed at the European level, aggregating data across multiple countries, leveraging the broad dataset availability within the ecoinvent library. While for organic is at global level. The specific ecoinvent dataset providers are reported below:

- Inorganic Ferilizer N: market for inorganic nitrogen fertiliser, as N (Germany, Spain, France, Italy, Romania, Slovenia)
- Inorganic Ferilizer P: market for inorganic phosphorus fertiliser, as P2O5 (Spain, France, Italy, Romania, Slovenia)
- Organic Fertilizer N: market for organic nitrogen fertiliser, as N - GLO
- Organic Fertilizer P: market for organic phosphorus fertiliser, as P2O5

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With respect to microbial protein, all protein-based substances available in the ecoinvent library applicable to animal feed were selected as reference products, on the basis that they can perform the same functional role as the Manurefinery bioproduct. The specific ecoinvent dataset providers considered are reported below:

- PF1: market for protein feed, 100% crude
- PF2: market for protein pea production, organic
- PF3: market for wheat bran to generic market for energy feed
- PF4: market for tofu production | protein feed, 100% crude
- PF5: market for soybean meal to generic market for protein feed
- PF6: market for sugar beet pulp to generic market for energy feed

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3. LIFE CYCLE INVENTORY

3.1. Gas Valorisation Line

GVL, as described in paragraph 2.1, is the least complex valorization line within Manurefinery. In fact, it consists of a single section. The process is based on a biotrickling filter (BTF) for the biological treatment of ammonia-laden air originating from poultry or swine farms. The air is fed into the system by a blower and, after preliminary removal of solid particles, is introduced into the intermediate module of the BTF, where it comes into contact with the nitrifying biofilm developed on the packing material.

The nutrient solution, prepared in a dedicated tank by dissolving sodium bicarbonate and nutrients in tap water, is fed to the lower module of the BTF and continuously recirculated by a pumping system, trickling down through the packed bed from top to bottom. The main biological reaction occurring in the system is nitrification, whereby ammonia is oxidized to nitrate, with bicarbonate consumed as an inorganic carbon source. The resulting product is a sodium (or potassium) nitrate solution, which is separated from the biomass by filtration and collected in a storage tank for subsequent use.

The construction and maintenance phase, that is called Commissioning, for each component involves the following list:

- Agitating Tank [IBC-101]
- Pump [P-101]
- Air Compressor [C-101]
- Air Filter [F-101]
- Biotrickling Filter [BTF-101]
- Pump [P-102]
- Pump [P-103]
- Bag Filter[F-102]
- Final Product Tank [IBC-102]
- Vessel Storage [V-101]
- Pump [P-104]
- Pipilines Liquid [L1-L6]
- Pipelines Gas [G1-G5]

3.2. Agitating Tank [IBC-101]

BC-101 is a cylindrical vessel with a horizontal disposition, featuring an internal diameter of 2 m and a total height of 1.515 m, corresponding to a cross-sectional surface of 3.14 m² and a total volume of 4.76 m³. The tank is constructed in polypropylene, the wall thickness is set at 10 mm, while the base, which rests directly on the floor, is reinforced with a thickness of 15 mm. A dedicated pipeline connection for tap water supply is also installed on the side of the vessel. Accounting for these connections and auxiliary components, the overall height of the tank, inclusive of all fittings, reaches 2.12 m.

3.3. Pump [P-101]

P-101 is a centrifugal pump responsible for transferring the nutrient solution from IBC-101 to the lower module of BTF-101, handling a flow rate of 0.15 m³/h through pipeline L2. The pump is designed to deliver a discharge pressure of 3.59 bar (359 kPa), corresponding to a gauge pressure of 2.59 barg, sufficient to overcome the pressure drops across the pipelines and the packed bed. An efficiency of 80% is assumed for the mechanical design of the unit. The pump is design in polypropylene, but

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for the LCI modelling, due to the lack of specific dimensional data for the pump, a proxy process from the ecoinvent database was adopted: “pump production, 40W”. This process was decomposed into the material flows provided for the entire life cycle as reported in the database, and only the construction materials were considered as reference flows. The process was subsequently scaled with respect to the actual power size of the pump, which amounts to 18.7 W.

3.4. Air Compressor [C-101]

C-101 is a blower responsible for extracting the ammonia-laden indoor air from the farm facilities and conveying it through the biotrickling filter BTF-101, providing the necessary pressure to overcome the resistance of the packed bed and the associated pipelines. The unit has a rated power of 0.186 kW and is constructed in AISI 316 stainless steel, selected for its good chemical resistance to all components present in the gas stream. For the life cycle assessment modelling, a proxy process from the ecoinvent database was adopted as a reference: ”air compressor production, screw-type compressor, 300kW”. This process was decomposed into its material flows as provided by the database, and only the construction materials were considered. The process was subsequently rescaled with respect to the actual power size of the blower, expressed in kW

3.5. Air Filter [F-101]

F-101 is a particle filter installed in the gas inlet line, upstream of the biotrickling filter BTF-101. Its function is to retain solid particles, including dust and microorganisms, that may be present in the ammonia-laden air stream extracted directly from the farm facilities, preventing their introduction into the packed bed and protecting the integrity of the biofilm. The filter and all its components are entirely constructed in AISI 316 stainless steel. The maximum flow treatable is 500 m3/h, no other specific size data for this unit are available. For the modelling phase, a reference process available in the ecoinvent database library was selected: "air filter production, central unit, 600 m3/h“. This process was analysed and decomposed into the life cycle stages as reported in ecoinvent. Only the materials involved in the construction phase were selected and subsequently scaled with respect to a reference unit, namely the treated flow rate.

3.6. Biotrickling Filter [BTF-101]

BTF-101 is the core unit of the process, where the biological capture and conversion of ammonia into nitrate takes place. The vessel has a cylindrical geometry with a flat base, an internal diameter of 0.8 m and a total height of 4.81 m, corresponding to a cross-sectional surface of 0.5 m^2. The tower is divided into three distinct modules, each serving a specific function within the process. The lower module, with a height of 1.543 m and a volume of 0.776 m^3, acts as a liquid sump where the mineral salt medium is stored, with a total liquid hold-up of 500 L. From this module, the liquid is recirculated to the upper part of the tower. The intermediate module, with a height of 1.4 m and a volume of 0.704 m^3, hosts the packing material on which the nitrifying biofilm develops. The packing consists of 2" polypropylene Pall rings, selected for their high specific surface area and low pressure drop characteristics. The upper module, where the recirculation inlet is located at a height of 3.2 m, houses the spraying system and the droplet separator. The spray nozzle, is a full cone PVC nozzle with a nominal size of 1" and a spray angle of 120°, ensuring uniform liquid distribution over the packed bed. The droplet separator, model DV 270, consists of polypropylene modules with dimensions of 100×100 mm and a usable surface of 0.08 m^2, preventing liquid entrainment in the treated gas stream, which exits the tower at a height of 4.79 m. The entire vessel is constructed in polypropylene, with a uniform wall thickness of 15 mm, ensuring chemical resistance to the biological and chemical environment of the process

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3.7. Pump [P-102]

P-102 is a centrifugal pump located in the liquid recirculation line of BTF-101, responsible for pumping the mineral medium stored in the lower module of the biotrickling filter and conveying it to the upper module. The pump handles a flow rate of 0.15 m^3/h and is designed to deliver a discharge pressure of 4.25 bar (425 kPa), corresponding to a gauge pressure of 3.25 barg. An efficiency of 80% is assumed for the mechanical design of the unit. The pump is constructed in polypropylene, ensuring chemical compatibility with the recirculated nutrient solution.For the life cycle assessment modelling, the same approach adopted for P-101 was applied. The ecoinvent proxy process pump production, 40W was used as a reference, decomposed into its material flows and rescaled with respect to the actual power size of the pump of 22.14 W.

3.8. Pump [P-103]

P-103 is a centrifugal pump installed in the biofilter outlet line, responsible for conveying the sodium nitrate laden liquid from the lower module of BTF-101 to the final product storage tank IBC-102. The pump handles a flow rate of 0.15 m^3/h and is designed to deliver a discharge pressure of 3.93 bar (393 kPa), corresponding to a gauge pressure of 2.93 barg, sufficient to overcome the pressure drops along the outlet pipeline. An efficiency of 80% is assumed for the mechanical design of the unit. The construction material selected for P-103 is polypropylene. For the life cycle assessment modelling, the same approach adopted for P-101 and P-102 was applied. The ecoinvent proxy process pump production, 40W was used as a reference, decomposed into its material flows and rescaled with respect to the actual power size of the pump, which amounts to 15.26 W.

3.9. Bag Filter[F-102]

F-102 is a bag filter installed in the liquid outlet line of BTF-101, designed to separate the biomass present in the liquid stream prior to its collection in the product storage tank. The retained biomass accumulates on the filtering surface and remains stored within the bag until periodic removal. The filter body and clamp are constructed in AISI 316 stainless steel, ensuring chemical resistance to the liquid media handled. The unit is rated for a maximum flow rate of 9 m^3/h. The filter bag has a total volume of 2.6 L, a height of 0.257 m and a diameter of 0.1143 m.

3.10. Final Product Tank [IBC-102]

IBC tank where the solution containing the final product is stored after the NH_3 nitrification process and biomass separation in the bag filter. IBC-102 is the product storage tank, designed to collect the sodium nitrate solution obtained after biomass separation. The vessel has a cylindrical geometry with a horizontal disposition, featuring an internal diameter of 1.262 m and a total height of 0.8 m, corresponding to a cross-sectional surface of 1.251 m^2. As for IBC-101, the construction material is polypropylene, chosen for its chemical compatibility with the nitrate solution stored within. The lateral wall thickness is 10 mm, while the base thickness is increased to 15 mm

3.11. Vessel Storage [V-101]

V-101 is the storage tank for the basic solution, sodium hydroxide (NaOH), used for pH control within BTF-101. The vessel has a cylindrical geometry, with an internal diameter of 0.6 m and a total height of 0.7 m, corresponding to a cross-sectional surface of 0.41 m^2 and a total volume of 0.2 m^3 (200 L). This capacity was selected to ensure a storage autonomy of approximately one

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month of operation. The construction material is polypropylene, chosen for its good resistance to water and acceptable chemical compatibility with both sodium and potassium hydroxide solutions. The lateral wall thickness is set at 10 mm, while the base thickness is increased to 15 mm to withstand the mechanical loads of the floor-supported vessel

3.12. Pump [P-104]

P-104 is a centrifugal pump installed in the pH control line of BTF-101, responsible for conveying the basic solution (NaOH or KOH) from the storage tank V-101 to the lower module of the biotrickling filter, where it is dosed for pH regulation of the mineral medium. The pump handles a flow rate of 0.15 m^3/h and is designed to deliver a discharge pressure of 3.43 bar (343 kPa), corresponding to a gauge pressure of 2.43 barg. An efficiency of 80% is assumed for the mechanical design of the unit. The construction material selected for P-104 is polypropylene, ensuring chemical compatibility with the corrosive nature of the basic solutions handled. For the life cycle assessment modelling, the same approach adopted for P-101, P-102 and P-103 was applied. The ecoinvent proxy process pump production, 40W was used as a reference, decomposed into its material flows and rescaled with respect to the actual power size of the pump, which amounts to 12.6 W

3.13. Pipelines

Piping system is divided into three groups according to the fluid conveyed: liquid lines (L1–L6), gas lines (G1–G5), and recirculation lines (R1–R2). All pipelines are designed according to Schedule 40, with a wall thickness of 3.375 mm, including a 3 mm corrosion overthickness. The liquid lines (L1, L2, L3, L4, L5 and L6) share identical dimensions, with an internal diameter of 0.01 m and an external diameter of 0.0137 m. Their lengths vary between 2 and 3 m: L1 and L3 have a length of 3 m, while L2, L4, L5 and L6 are 2 m long. The gas lines (G1, G2, G3, G4 and G5) are sized for a significantly higher volumetric flow rate, resulting in larger dimensions, with an internal diameter of 0.077 m and an external diameter of 0.0807 m. Lines G1 through G4 have a length of 2 m, while G5 extends to 3 m. The recirculation lines (R1 and R2) have an internal diameter of 0.034 m and an external diameter of 0.0377 m, with a length of 2 m each. The material usd for all of them is Polypropylene.

3.14. Whole LCI of Construction phase

Table 4: LCI Commissioning GVL

Material / Energy flows	Amount	Unit	Note
Input			
market for polypropylene, granulate | polypropylene, granulate | Cutoff, S - GLO	172.5	kg	IBC-101
Pump*	0.01869792	kW	P-101
Compressor*	0.186	kW	C-101
Air Filter*	500	m3/h	F-101
market for polypropylene, granulate | polypropylene, granulate | Cutoff, S - GLO	31.66	kg	BTF-101
market for polypropylene, granulate | polypropylene, granulate | Cutoff, S - GLO	2	kg	

market for polypropylene, granulate | polypropylene, granulate | Cutoff, S - GLO	83.3	kg	
PVC	0.06	kg	
Pump*	0.02213542	kW	P-102
Pump*	0.01526042	kW	P-103
Air Filter*	9	m3/h	F-102
market for polypropylene, granulate | polypropylene, granulate | Cutoff, S - GLO	63.2	kg	IBC-102
market for polypropylene, granulate | polypropylene, granulate | Cutoff, S - GLO	12.9	kg	V-101
Pump*	12.6	kW	P-104
market for polypropylene, granulate | polypropylene, granulate | Cutoff, S - GLO	2.09	kg	Pipelines [G1-G5]
market for polypropylene, granulate | polypropylene, granulate | Cutoff, S - GLO	0.868	kg	Pipelines [L1-L6]
market for polypropylene, granulate | polypropylene, granulate | Cutoff, S - GLO	1.68	kg	Pipelines [R1-R2]
Output			
Gas Valorisation Line	1	item	Commissioning

* The LCI model for these flows is shown in Annex 1.

3.15. Operation And Maintenance phase

The **operation phase** of the system considered in GVL includes the energy and material inputs associated with continuous plant operation. Specifically, the electricity consumption of pumps P-101, P-102, P-203, P-104, and compressor C-101 is accounted for. Regarding reagents, the salts used in unit IBC-101 are modeled as a single representative flow classified under *chemical, inorganic*. Within the same chemical group, the amount of sodium hydroxide (NaOH) required to sustain the reaction in the biotrickling filter is also included. Additionally, the daily water consumption is considered as an input to the system, contributing to the overall environmental inventory during the operational phase. The inventory presented in the table refers to one hour of system operation. For the parametric analysis, these values are subsequently scaled by the total annual operating hours and by the corresponding capacity factor.

Table 5: LCI Operation GVL

Material / Energy flows	Amount	Unit	Note
Input			
market for chemical, inorganic - GLO	46.815	g/h	Salt
Electricity for Manurefinery*	0.018	kWh	P-101
Electricity for Manurefinery*	0.022	kWh	P-102
Electricity for Manurefinery*	0.015	kWh	P-103
Electricity for Manurefinery*	0.012	kWh	P-104

Electricity for Manurefinery*	0.18	kWh	C-101
market for sodium hydroxide, without water, in 50% solution state - RER	384	g/h	
market for deionised water - Europe without Switzerland	15	kg/h	
Output			
Gas Valorisation Line	1	h	Operation

* The LCI model for these flows is shown in Annex 1.

3.16. Liquid Valorisation Line

The LVL of the Manurefinery system includes a sequence of biochemical and thermochemical processes aimed at converting the liquid fraction of manure into energy carriers and value-added products. The line consists of four process units: anaerobic digestion, nutrient recovery from digestate, biogas fermentation for microbial growth, grass extrusion, protein precipitation, and fermentation for caproic acid production.

For each process unit, the life cycle inventory (LCI) distinguishes between two main stages: (i) the construction stage, which accounts for the materials and infrastructure required for plant manufacturing and installation, and (ii) the operational and maintenance (O&M) stage, which includes all material and energy inputs, direct emissions, consumables, and component replacements occurring during the plant lifetime.

3.17. Anaerobic Digestion

The construction stage includes the digester reactor, internal mixing systems, pumps, heat exchangers, and piping. Material quantities are estimated based on reactor volume and scaled according to the design capacity of the plant. A background process available in the ecoinvent database was adopted as a reference for the anaerobic digester infrastructure “anaerobic digestion plant construction, agriculture, with methane recovery“. The original dataset was modified to reflect the specific design capacity of the system under study. In particular, input flows were rescaled according to the actual reactor volume, assuming proportional scaling between material demand and digester size.

Table 6: LCI Commissioning LVL - AD section

Material / Energy flows	Amount	Unit	Note
Input			
market for alkyd paint, white, without solvent, in 60% solution state - RER	0.75	kg	Buffer Tank
market for pitch - Europe without Switzerland	20.625	kg	
market for steel, low-alloyed, hot rolled - GLO	78	kg	
Pump*	0.55	kW	Feed Pump 1
market for alkyd paint, white, without solvent, in 60% solution state - RER	0.6	kg	Mixing Tank
market for pitch - Europe without Switzerland	16.5	kg	
market for steel, low-alloyed, hot rolled - GLO	62.4	kg	
Pump*	1.5	kW	Feed Pump 2
market for copper, cathode - GLO	9	kg	Anaerobic digester

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market for glued laminated timber, MUF-glue - RER	1.44	m3	
market for glued laminated timber, PUR-glue - RER	1.44	m3	
market for polyethylene, high density, granulate - GLO	6.12	kg	
market for polystyrene, high impact - GLO	20.52	kg	
market for polyvinylidenchloride, granulate - RER	11.88	kg	
market for steel, chromium steel 18/8 - GLO	46.8	kg	
market for synthetic rubber - GLO	43.2	kg	
Output			
Anaerobic Digester section	1	item	Commissioning

* The LCI model for these flows is shown in Annex 1.

During operation, the inventory includes the input of liquid manure, electricity consumption for mixing and pumping, and thermal energy required to maintain the operating temperature. In addition, molasses is assumed to be dosed into the digester in order to enhance biogas production. According to the process design, molasses supplementation is foreseen only for short-term testing periods (4–6 months), depending on the biogas demand of the downstream biogas fermenter. In the present study, a conservative assumption of six months of molasses dosing per year was adopted. The addition of molasses affects the yields, resulting in different quantities of biogas and digestate compared to operation without molasses supplementation. The inventory data reported in Table 7 refer exclusively to the operational stage and reflect the corresponding output flows under the assumed operating conditions.

The biogas generated in the digester is first directed to a condensate trap for moisture removal and subsequently conveyed to a second pilot plant, where methane is converted into microbial protein. Any excess biogas not required for the downstream fermentation process is treated in a biofilter.

In addition to material and energy flows, land occupation associated with the installation of the main units was included in the inventory. The area required for the manure reception tank, equipment room, anaerobic digester, biogas fermenter, and biofilter was estimated based on the pilot plant layout and modelled using the flow ”Occupation, industrial area“. The occupied surface was expressed in m^2·year and allocated over the assumed operational lifetime of the system (105 m^2·20 years).

The digestate overflows into a buffer tank connected to stripping pilot plant. Subsequently, the digestate is processed in a centrifuge to separate it into a liquid and a solid fraction. The liquid fraction is directed to downstream nitrogen recovery, whereas the solid fraction is intended for gasification and phosphorus recovery, following a preliminary phosphorus concentration step via coagulation–flocculation.

Table 7: LCI Operation LVL - AD section

Material / Energy flows	Amount	Unit	Note
Input			
Electricity*	2.2	kWh	Shredder
Electricity*	0.035	kWh	Pump feed
Heat	3.7	kWh	Heat tracing
Electricity*	2.2	kWh	General agitator

molasses, from sugar beet - S	65	kg/d	
Electricity*	0.045	kWh	Pump feed
Output			
Operation phase AD	1	h	
Biogas production (with molasses)	1.29	m^3/h	Output biogas
Biogas production (w/o molasses)	0.39	m^3/h	Output biogas
Digester sludge production (with molasses)	36.33	kg/h	Output sludge
Digester sludge production (w/o molasses)	37.58	kg/h	Output sludge

* The LCI model for these flows is shown in Annex 1.

3.18. Biogas fermenter for microbial protein production

In this section, biogas is further valorised through fermentation processes aimed at microbial biomass production. The biogas fermenter is modelled as a pressurised bubble column fermenter with internal gas recirculation, designed to convert methane into microbial protein under aerobic conditions. Biogas from the anaerobic digester is injected at the base of the reactor and mixed with compressed air to supply the oxygen required for microbial growth. Gas injection induces liquid circulation and enhances gas–liquid mass transfer, promoting methane dissolution into the fermentation broth, where it is metabolised as carbon source.

At the top of the reactor, a gas–liquid separation step allows the recovery of residual gas, which can be internally recycled to improve methane utilisation efficiency. The circulating broth passes through a recirculation pump and a heat exchanger to maintain controlled flow velocity and optimal temperature. Biomass is periodically harvested and directed to ultrafiltration, where the protein-rich fraction is separated and collected, while the permeate is recycled to the fermenter.

The construction inventory of the biogas fermenter unit includes the main reactor structure, associated structural elements, and auxiliary equipment required for gas handling, aeration, liquid circulation, and process dosing. The system comprises a biogas pre-treatment section with an activated carbon filter. The biofilter for excess gas treatment is also included in the construction stage.

Material requirements for these components were estimated based on pilot-scale technical specifications. The detailed life cycle inventory for the construction phase is reported in Table 8.

Table 8: LCI Commissioning LVL - BF section

Material / Energy flows	Amount	Unit	Note
Input			
steel, chromium steel 18/8 - GLO	76.78	kg	Activated Carbon filter
activated carbon, granular - GLO	58.5	kg	
steel, chromium steel 18/8 - GLO	39.5	kg	Compressor Biogas
steel, chromium steel 18/8 - GLO	134.4	kg	Compressor Air
water pump, 22kW - GLO	0.068	Item	Feedwater pump
polypropylene, granulate - GLO	27.16	kg	Dosing Tanks
polyvinylchloride, suspension polymerised - GLO	12.8	kg	Dosing Pumps
steel, chromium steel 18/8 - GLO	17.2	kg	

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steel, chromium steel 18/8 - GLO	1603.46	kg	Biogas Fermenter piping
steel, chromium steel 18/8 - GLO	2571.98	kg	Biogas Fermenter structure
steel, chromium steel 18/8 - GLO	26.62	kg	Heat Exchanger
steel, chromium steel 18/8 - GLO	155	kg	Blower circulating air
cast iron - GLO	102	kg	Centrifugal pump recirculation
steel, chromium steel 18/8 - GLO	122.72	kg	Static Mixers
steel, chromium steel 18/8 - GLO	12.72	kg	Biogas piping line
steel, chromium steel 18/8 - GLO	35.49	kg	Air piping line
polyvinylchloride, suspension polymerised - GLO	12.72	kg	Water piping line
chromium steel pipe - GLO	2.97	kg	Dosage piping line
Output			
Construction phase BF	1	item	

The operational inventory includes biogas and water as main process inputs, together with electricity consumption associated with auxiliaries. Additional operational inputs comprise chemical dosing (antifoam, trace elements, nitrogen and phosphorus nutrients, and NaOH). The activated carbon used in the biogas pre-treatment unit is assumed to be replaced every six months and treated as hazardous waste.

Output flows comprise gas exhaust leaving the reactor via the gas–liquid separator, the protein-rich microbial biomass harvested as a purge stream following ultrafiltration, and the liquid effluent from the ultrafiltration step. It should be noted that the ultrafiltration unit is not included in the pilot and its subsequent treatment is therefore outside the scope of the present inventory.

The full operational and maintenance life cycle inventory is reported in Table 9.

Table 1: LCI of Biogas Fermenter unit in the O&M phase using Ecoinvent 3.10 reference.

Table 9: LCI Operation LVL - AD section

Material / Energy flows	**Amount**	**Unit**	**Note**
Input			
activated carbon, granular {GLO}| market for | Cut-off, S	58.5	kg***	Activated Carbon filter – every six months
Electricity*	0.75	kWh	Compressor Biogas
Electricity*	5.2	kWh	Compressor Air
calcium chloride {RER}| market for | Cut-off, S	0.177	kg/h	Antifoam+trace elements
molybdenum {GLO}| market for | Cut-off, S	0.002	kg/h	
copper sulfate {GLO}| market for | Cut-off, S	0.005	kg/h	
iron sulfate {RER}| market for | Cut-off, S	0.012	kg/h	
zinc monosulfate {RER}| market for | Cut-off, S	0.009	kg/h	
boric acid, anhydrous, powder {GLO}| market for | Cut-off, S	0.0004	kg/h	

cobalt sulfate {RoW}| market for | Cut-off, S	0.001	kg/h	
EDTA, ethylenediaminetetraacetic acid {GLO}| market for | Cut-off, S	0.006	kg/h	
manganese sulfate {GLO}| market for | Cut-off, S	0.0005	kg/h	
nickel sulfate {GLO}| market for | Cut-off, S	0.0002	kg/h	
Electricity*	0.01	kWh	Antifoam dosing pump
Electricity*	0.01	kWh	Trace elements dosing pump
sodium nitrate {GLO}| market for | Cut-off, S	0.21	kg/d**	Nitrogen/Phosphorus
phosphoric acid, industrial grade, without water, in 85% solution state {GLO}| market for | Cut-off, S	0.042	kg/d**	Nitrogen/Phosphorus
Electricity	0.01	kWh	N/P dosing pump
sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, S	16	kg/d**	NaOH
Electricity*	0.01	kWh	NaOH dosing pump
Biogas	4	m^3/h	From anaerobic digestion
water, deionised {EU w/o CH}| market for | Cut-off, S	83.4	kg/h	
Electricity*	12	kWh	Tracing blanket for heating
Electricity*	4	kWh	Blower circulating air
Electricity*	4	kWh	Centrifugal pump recirculation
Output			
hazardous waste, for incineration {EU w/o CH}| market for | Cut-off, S	58.5	kg/h	Spent activated carbon filter – every six months
carbon dioxide, biogenic	6.24	kg/h	Gas exhaust
methane, biogenic	0.08128	kg/h	Gas exhaust
Biomass purge	92	L/h	
Effluent	3.3	L/h	

* The LCI model for these flows is shown in Annex 1; ** The amount is referred to the daily total consumption; *** The amount is referred to 6 months total consumption

3.19. Nutrient recovery from digestate

The liquid fraction of digestate is treated through a sequence of coagulation–flocculation for phosphorus recovery, followed by a double-stage ammonia stripping. The NH_3-rich air is sent to an acid scrubber, where ammonia is absorbed and recovered as ammonium salts. A subsequent electrochemical membrane process converts the captured ammonia into ammonium bicarbonate (NH_4HCO_3). The recovered phosphorus follows the solid valorisation pathway of the digestate treatment system. The remaining treated liquid fraction, still containing residual nutrients, is reused for fertigation of grass cultivated downstream for caproic acid production. Since the unit operates in a closed loop, gaseous emissions are considered negligible and were not explicitly modelled.

The nutrient recovery system consists of a series of interconnected reaction and stripping chambers. In the absence of detailed information on construction materials, all process chambers and structural components were conservatively assumed to be made of stainless steel. Additional equipment components were included in the inventory when technical specifications were available. For components lacking detailed material information, no additional assumptions were introduced in order to avoid arbitrary estimations

Table 10: LCI Commissioning LVL - NPR section

Material / Energy flows	Amount	Unit	Note
steel, chromium steel 18/8 {GLO}| market for | Cut-off, S	41815.12	kg	Container
brass {RoW}| market for | Cut-off, S	1.02	kg	Spray nozzles
steel, chromium steel 18/8 {GLO}| market for | Cut-off, S	12.5	kg	Filter
steel, low-alloyed {GLO}| market for | Cut-off, S	11	kg	Circulation pump
polyvinylfluoride {GLO}| market for | Cut-off, S	4.54	Item	Dosing pump
steel, chromium steel 18/8 {GLO}| market for | Cut-off, S	66.14	kg	Boiler
polyurethane, rigid foam 18/8 {RER}| market for | Cut-off, S	9.86	kg	Boiler
cast iron {GLO}| market for | Cut-off, S	2.17	kg	Circulation pump hot boiler
Output			
NP recovery	1	item	Commissioning

During operation, the system requires the addition of sulfuric acid (H_2SO_4) for ammonia capture and ferric chloride ($FeCl_3$) for phosphorus precipitation. The liquid digestate fraction constitutes the main process input. The system generates three output stream: a phosphorous-rich fraction directed to the solid valorisation line, ammonium bicarbonate solution as a recovered nitrogen product, and a treated aqueous effluent reused for fertigation in grass cultivation.

Table 11: LCI Operation LVL - NPR section

Material / Energy flows	Amount	Unit	Note
Input			
sulfuric acid {RER}| market for | Cut-off, S	0.627708	kg/h	
iron(III) chloride, without water, in 40% solution state {GLO}| market for | Cut-off, S	0.037125	kg/h	
Electricity*	1.1	kWh	Circulation pump
Electricity*	0.37	kWh	Ventilator
Electricity*	6	kWh	Boiler
Electricity*	0.018	kWh	Circulation pump hot boiler
Output			
Operation NP recovery	1	h	
P-rich fraction	6.9	kg/h	To the solid valorisation line
N-recovery	0.28	kg/h	

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Effluent	29.63	kg/h	For fertigation in grass cultivation

* The LCI model for these flows is shown in Annex 1.

3.20. Grass extrusion, protein precipitation and fermentation for caproic acid

The treated nutrient-rich water from the digestate upgrading unit is used for fertigation of grass cultivation. Harvested grass undergoes ensiling followed by lactic acid fermentation. A subsequent solid–liquid separation step generates a protein-rich grass cake and a lactic acid-rich broth. In the present study, only the subsequent fermentation stage for caproic acid production is modelled, due to the lack of detailed data for downstream purification steps. In this section, the lactic acid-rich broth is fed to an expanded granular sludge bed (EGSB) reactor, where chain elongation occurs, leading to caproic acid formation. The fermentation effluent is then subjected to ceramic membrane ultrafiltration. The permeate, enriched in caproic acid, is considered the intermediate product of this section, while further extraction and purification of caproic acid are excluded from the current system boundaries. Accordingly, the LCI includes only the infrastructure and operational inputs and outputs associated with the caproic acid fermentation section. The resulting material inventory for the infrastructure of the caproic acid fermentation section is reported in Table 12.

Table 12: LCI Commissioning LVL - CA section

Material / Energy flows	Amount	Unit	Note
steel, chromium steel 18/8 {GLO}| market for | Cut-off, S	53.73	kg	Tubular reactor
aluminium, wrought alloy {GLO}| market for | Cut-off, S	6	kg	Feed pump
aluminium, wrought alloy {GLO}| market for | Cut-off, S	8	kg	Recirculation pump
polyvinyl fluoride {GLO}| market for | Cut-off, S	3	kg	HCl dosing pump
aluminium, wrought alloy {GLO}| market for | Cut-off, S	7	kg	Effluent pump
polyethylene, high density, granulate {GLO}| market for | Cut-off, S	48	kg	Buffer tank + Feed tank
steel, chromium steel 18/8 {GLO}| market for | Cut-off, S	22.4	kg	Filter feed pump
steel, chromium steel 18/8 {GLO}| market for | Cut-off, S	13	kg	Ceramic filter
aluminium oxide, non-metallurgical { IAI Area, EI27 EFTA}| market for | Cut-off, S	3	kg	Ceramic filter
tetrafluoroethylene {GLO}| market for | Cut-off, S	0.37	kg	Piping
tetrafluoroethylene {GLO}| market for | Cut-off, S	0.15	kg	Piping
tetrafluoroethylene {GLO}| market for | Cut-off, S	0.47	kg	Piping
steel, chromium steel 18/8 {GLO}| market for | Cut-off, S	4.77	kg	Piping
Output			
Grass extrusion commissioning	1	item	Commissioning

During operation, the system requires the input of lactic acid-rich broth as substrate and electricity for reactor operation, pumping, mixing, and ultrafiltration. The main output of the section is the caproic acid-rich permeate; in addition, a minor biogas stream is generated during anaerobic fermentation. Operational inputs and outputs included in the life cycle inventory are summarised in Table 13.

Table 13: LCI Operation LVL - CA section

Material / Energy flows	Amount	Unit	Note
Input			
Lactic acid-rich broth	4.8	L/h	
hydrochloric acid, without water, in 30% solution state {RER}| market for | Cut-off, S	20	L/h	
Electricity*	0.1	kWh	Feed pump
Electricity*	0.1	kWh	Recirculation pump
Electricity*	0.1	kWh	HCl dosing pump
Electricity*	0.1	kWh	Effluent pump
Electricity*	1.1	kWh	Filter feed pump
Output			
Operation Grass extrusion	11.7	L/h	Biogas outlet
carbon dioxide, biogenic	11.7	L/h	Biogas outlet
methane, biogenic	1.18	L/h	Biogas outlet
Permeate	31.88	L/h	

* The LCI model for these flows is shown in Annex 1.

3.21. Solid Valorisation Line

The SVL line is structured into three distinct sections: the drying unit, the gasification unit for syngas production and ash recovery as biofertilizers, and the acid fermenter section for microbial protein production.

The drying unit begins with a storage tank for wet solid digestate, from which the material is conveyed to a belt dryer via a transport conveyor. The belt dryer is connected to a compressor and a heat exchanger, which supply hot air to the drying chamber, where the wet solid digestate is dried by forced convection. The dried material leaving the belt dryer is then transferred through a second conveyor belt to a dried solid digestate storage tank, from which it is directly fed to the gasification unit. The gasification section begins with a dried solid digestate storage tank and a rectangular box containing sand, which is added to the biomass as a bed material. Both material streams are fed to the gasifier via a conveyor belt. The gasifier is heated by an electric steam generator, providing the thermal energy required for the thermochemical conversion of the dried biomass into syngas and solid residues. The solid outlet stream from the reactor, consisting of char and sand, is collected and transported away by a dedicated conveyor belt. The syngas produced is extracted from the upper section of the gasifier and undergoes a two-stage filtration process for particulate removal. In the first stage, the gas stream passes through a cyclone filter, which separates the coarser solid residues, collected in an adjacent tank. In the second stage, the gas stream is directed to a ceramic filter, where complete removal of the remaining particulate matter is achieved. Finally, the cleaned syngas is collected in a buffer tank, which splits the stream into two outlets: a liquid condensate stream containing tars and water, and a clean syngas stream directed to the subsequent processing unit.

The final section is the fermentation train. It receives a designated fraction of the syngas stream, which undergoes preliminary cooling in a recirculated water heat exchanger prior to entering the U-loop bioreactor. The U-loop configuration represents an established platform for the bioconversion of hydrophobic gaseous substrates, exploiting forced flow recirculation through a closed loop equipped with internal static mixers to maximize gas–liquid mass transfer and promote turbulent mixing conditions. Within this reactor, CO, CO_2, and H_2 present in the syngas are biologically converted to acetate by acetogenic microorganisms operating under strictly anaerobic conditions.

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The effluent from the Uloop reactor is directed to a centrifuge, which achieves phase separation between the harvested biomass and the residual liquid fraction. This unit remove residual cells and particulate matter, yielding a clarified permeate that serves as the carbon and energy source for downstream aerobic fermentation.The clarified liquid phase is collected in a dedicated buffer tank prior to further processing or recirculation, ensuring stable and continuous operation of the Acetic fermenter which produced the single cell protein biomass.

3.22. Drying Unit Construction phase

The components included in this section are listed below:

- Wet SD Storage Tank
- Belt Conveyor (Wet SD Feed)
- Belt Dryer
- Screw Conveyor (Dried SD Discharge)
- Dried SD Storage Tank
- Internal Screw Conveyor (Dried SD Tank Discharge)
- Inclined Screw Conveyor (Gasifier Feed)
- BLR-02 Centrifugal Compressor
- FTH-01 Fine Tube Heat Exchanger
- BLR-01 Positive Displacement Compressor

Wet SD Storage Tank: The wet sewage digestate storage tank has a total volume of 6 m^3, sized to ensure a 24-hour operational buffer capacity. In the absence of primary data regarding the construction phase of this component, the unit was modelled by adopting the material composition reported in the reference process "liquid storage tank production, chemicals, organics", scaling the material quantities proportionally to the actual tank dimensions.

Belt Conveyor (Wet SD Feed): A belt conveyor inclined at 45° with a total length of 3 m transfers wet sewage digestate from the storage tank to the belt dryer, feeding the material from above. The unit is driven by a three-phase electric motor rated at 0.37 kW, with the low power rating being consistent with the very high gear ratio and correspondingly low belt speed. The construction phase of this component was modelled using the material composition reported in the reference process "conveyor belt production" available in the ecoinvent database, scaled proportionally to the actual conveyor length. The resulting Life Cycle Inventory (LCI) is reported in the Annex n.1.

Belt Dryer: The belt dryer has a total internal volume of 24 m^3 (6 m length × 2 m width × 2 m height). Three independent conveyor belt stages are each driven by a dedicated three-phase electric motor rated at 0.09 kW. The low motor ratings are consistent with the high gear ratio and correspondingly low belt speed design. The construction phase of this unit was modelled as a combination of two sub-components: the conveyor belt system, modelled using the reference process "conveyor belt production" from the ecoinvent database scaled to the actual belt length, and the external enclosure, modelled as a steel box structure with material quantities estimated based on the actual machine dimensions.

Screw Conveyor (Dried SD Discharge): A screw conveyor inclined at 45° with a total length of 3.5 m transfers dried sewage digestate from the belt dryer outlet to the top of the dried SD storage tank. The unit is driven by a three-phase electric motor rated at 1.1 kW. Analogously to the belt conveyor described above, the construction phase of this component was modelled using the material composition reported in the reference process "conveyor belt production" available in the ecoinvent database, scaled proportionally to the actual conveyor length.

Dried SD Storage Tank and Gasifier Feed System: The dried SD storage tank has a total volume of 6 m^3, providing approximately 14 hours of operational buffer capacity. The reduced buffer duration compared to the wet SD tank is a direct consequence of

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the significantly lower bulk density of dried SD (approximately 150 kg/m^3). A larger 10 m^3 tank capable of providing a 24-hour buffer is not recommended due to mechanical constraints and cost considerations. The tank is equipped with two screw conveyors: an internal horizontal screw conveyor (2.5 m length) for tank discharge, and an inclined screw conveyor (45°, 3.5 m length) feeding dried SD from above into the gasifier.

Compressor and Fine Tube Heat Exchanger: The drying air supply is provided by the centrifugal compressor, selected for its high volumetric air flow capacity of 150 m^3/min and high operational efficiency, with a rated output of 5.5 kW. Il Blower è stato modellato allo stesso modo per i compressori nella linea GVL scalandolo rispetto alla sua taglia. The associated fine tube heat exchanger is a custom-designed unit with a heat transfer surface of 1500 × 1500 mm, sized to deliver the 120 kW thermal output required for the drying process.

Table 14: LCI Commissioning SVL – Drying unit

Material / Energy flows	Amount	Unit	Note
Input			
market for alkyd paint, white, without solvent, in 60% solution state - RER	1.5	kg	Tank wet SD
market for pitch - Europe without Switzerland	41.25	kg	
market for steel, low-alloyed, hot rolled - GLO	156	kg	
Conveyor belt*	3	m	Conveyor Belt
Conveyor belt	18	m	Belt Dryer
market for steel, low-alloyed- GLO	1705	kg	
Conveyor belt	3.5	m	Dryed SD tank
market for copper, cathode - GLO	0.5	kg	
market for glued laminated timber, MUF-glue - CH	0.08	m^3	
market for glued laminated timber, PUR-glue	0.08	m^3	
market for polyethylene, high density, granulate - GLO	0.34	kg	
market for polystyrene, high impact - GLO	1.14	kg	
market for polyvinylidenchloride, granulate- RER	0.66	kg	
market for steel, chromium steel 18/8 - GLO	2.6	kg	
market for synthetic rubber - GLO	2.4	kg	
Compressor	5.5	kW	Compressor
market for aluminium, cast alloy- GLO	2.57	kg	Heat Exchanger
market for copper, cathode - GLO	38.38	kg	
sheet rolling, aluminium - RER	2.57	kg	
market for steel, chromium steel 18/8 - GLO	8.85	kg	
wire drawing, copper - RER	38.38	kg	
Compressor	5.5	kW	Compressor
Output			
Drying Unit	1	item	Commissioning

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* The LCI model for these flows is shown in Annex 1.

3.23. Gasifier Unit Construction phase

The components included in this section are listed below:

- Tank for Biomass
- Tank for Sand
- Conveyor Belt
- Gasifier
- Cyclone Filter and storage tank
- Ceramic Filter System
- Compressor
- Inertia Tank
- Electric steam Generator

Tank for Biomass and for Sand: A silo with an approximate capacity of 6 m³, located at the KIS farm, is used as the primary storage unit for the solid feedstock. This silo provides buffer storage and ensures availability of material for downstream processing units. The same material are used for a rectangular feeding box for sand with a total volume of 24 L (dimensions: 40 × 1500 × 400 mm) is installed above the screw conveyor inlet.

Conveyor Belt: Solid material transport is performed by several inclined screw conveyors, each dedicated to a specific material stream. From the dried solid feedstock tank, a screw conveyor with a length of 3.5 m and an inclination of 45° transfers material to the upper knife valve. This conveyor is driven by a 0.55 kW three-phase electric motor. From the sand storage tank a second screw conveyor with a length of 2.5 m and an inclination of 60° conveys material to the same upper knife valve. This unit is driven by a 0.25 kW three-phase electric.

Gasifier: The system includes a gas handling volume of approximately 400 m³, associated with a cylindrical structure of approximately 0.5 m in diameter and 2 m in height, designed to accommodate the process gas flow and associated pressure and temperature stabilization.

Cyclone Filter and storage tank: Primary particulate separation is achieved by means of a cyclone separator with an approximate volume of 30 L, coupled to a solid residue collection tank with a volume of approximately 20 L. The cyclone and collection tank are connected by a pipe equipped with a ball valve, allowing periodic discharge of the separated solids. The overall footprint of this assembly is approximately 0.5 m³ (2 m × 0.5 m × 0.5 m). This unit provides preliminary mechanical removal of coarse particulate matter from the process gas.

Ceramic Filter System: Downstream of the cyclone, a valve system directs the gas either to a flare for safe combustion or to a ceramic filter system for advanced particulate removal. The ceramic filter unit consists of two filters arranged in parallel and operated alternately. This configuration enables continuous gas cleaning without process interruption during filter regeneration, thereby increasing overall plant availability.

Compressor, Inertia tank and Steam generator: An air compressor unit is required to supply compressed air for auxiliary system operations, including filter regeneration and process support functions. The unit is selected based on a required air flow rate of approximately 6 m³/h and a maximum operating pressure of 1.5 bar(g). The estimated electrical power demand of the compressor is in the range of 1 to 3 kW. A cooling and inertia tank have an estimated volume between 300 and 500 L and will act as a passive thermal reservoir, increasing system inertia Steam required for system preheating and process conditioning is supplied by an electric steam generator. The unit has a maximum steam production capacity of 16 kg/h at a pressure of 0.5

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bar(g), corresponding to a steam temperature range of 105–120 °C. The generator operates using two electric resistance heaters rated at 6 kW each, resulting in a total installed electric power of 12 kWel. The compact design of the unit (500 × 500 × 700 mm) and its relatively low empty weight (80 kg).

Table 15: LCI Commissioning SVL – Gasifier unit

Material / Energy flows	Amount	Unit	Note
Input			
market for alkyd paint, white, without solvent, in 60% solution state - RER	1.5	kg	Tank wet SD
market for pitch - Europe without Switzerland	41.25	kg	
market for steel, low-alloyed, hot rolled - GLO	156	kg	
market for alkyd paint, white, without solvent, in 60% solution state - RER	1.5	kg	Tank sand
market for pitch - Europe without Switzerland	41.25	kg	
market for steel, low-alloyed, hot rolled - GLO	156	kg	
Conveyor belt	6	m	Conveyor belt*
Conveyor belt	3	m	Conveyor belt*
market for aluminium, cast alloy - GLO	5.34	kg	Gasifier
market for aluminium, wrought alloy - GLO	11.35	kg	
market for copper, cathode - GLO	41.73	kg	
market for steel, low-alloyed, hot rolled - GLO	417.39	kg	
market for steel, low-alloyed - GLO	138	kg	Cyclone Filter and Tank
Tank for sand	0.02	m^3	
market for silicon carbide | silicon carbide | Cutoff, S - GLO	2750	kg	Ceramic Filter
market for steel, low-alloyed | steel, low-alloyed | Cutoff, S - GLO	741	kg	
Compressor	1.3	kW	Compressor
hot water tank production, 600l	0.5	m^3	Inertia tank
market for cast iron | cast iron | Cutoff, S - GLO	80	kg	Electric steam generator
Output			
Gasifier Unit	1	item	Commissioning

* The LCI model for these flows is shown in Annex 1.

3.24. U-loop reactor and Acetic ferment construction phase

The components included in this section are listed below:

- Syngas blower [b8]
- Heat exchangers
- Recirculation blower

- U-loop reactor
- Recirculation pump
- Acid dosing pump
- Feeding pump
- Inlet IBC
- Centrifuge
- Buffer IBC
- Feeding pump to reactor
- Base dosing pump
- Fermenter
- Recirculation pump to centrifuge

Syngas blower: The syngas blower is equipped with an electric motor rated at 1.1 kW and is designed to handle a volumetric flow rate of 5 Nm^3/h at a pressure head of 500 mbar. This unit ensures controlled extraction and transport of syngas within the process line.

Heat exchanger: The heat exchanger has a nominal thermal capacity of 7.5 kW. As a reference, the heat exchanger used in unit 07_02 is adopted, specifically the 400 × 400 mm model, which provides a thermal power of 10.44 kW with a total weight of 6.5 kg. This reference configuration is used to ensure adequate heat transfer performance for the present application.

Recirculation blower: The recirculation blower is driven by a 4 kW electric motor and operates with a nominal flow rate of 60 Nm^3/h at a pressure head of 600 mbar. Its function is to maintain continuous gas recirculation within the system, contributing to stable operating conditions.

U-loop reactor: The U-loop reactor has a total internal volume of 1000 L and is constructed from AISI 316L stainless steel. The material density is assumed to be 8000 kg/m^3.

Recirculation pump: The recirculation pump is rated at 7.5 kW and provides a nominal flow rate of 36 Nm^3/h with a hydraulic head of 17 m of water column (m.c.a.). This pump is responsible for maintaining continuous liquid circulation within the process loop.

Acid dosing pump: The acid dosing pump is driven by a 0.18 kW electric motor and is designed for a dosing capacity of 20 L/h at a head of 17 m of water column (m.c.a.). It enables controlled and precise injection of acid into the process for pH regulation and chemical conditioning

Feeding pump: The feeding pump is driven by a 1.5 kW electric motor and is designed to operate at a nominal flow rate of 4 Nm^3/h with a hydraulic head of 17 m of water column (m.c.a.). This unit ensures controlled transfer of liquid streams between upstream storage and downstream process units.

Inlet IBC: The inlet intermediate bulk container (IBC) has a nominal volume of 1000 L and is manufactured from high-density polyethylene (HDPE). It serves as a buffer storage unit for incoming liquid feedstock prior to further processing.

Centrifuge: The centrifuge operates with a nominal flow rate in the range of 500–1000 L/h and is referenced to sludge treatment conditions corresponding to Agribalyse data for dewatered sludge (23% dry matter) from wastewater treatment, processed by centrifugation (processing level 4). The construction materials are mainly cast iron (approximately 99%) with a minor fraction of unalloyed steel (approximately 1%). This unit is responsible for solid–liquid separation downstream of the biological process.

Buffer IBC: The buffer intermediate bulk container (IBC) has a nominal volume of 1000 L and is made of HDPE. It provides intermediate storage capacity between the centrifuge and subsequent process units, contributing to flow stabilization and operational flexibility.

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Feeding pump to reactor: The feeding pump to the reactor is equipped with a 1.5 kW electric motor and operates at a nominal flow rate of 4 Nm³/h with a head of 17 m of water column (m.c.a.). It ensures continuous and controlled delivery of liquid feed into the reactor system.

Base dosing pump: The base dosing pump is driven by a 0.18 kW electric motor and provides a dosing capacity of 20 L/h at a hydraulic head of 17 m of water column (m.c.a.). It is used for controlled alkaline reagent injection to regulate the pH of the process medium.

Fermenter: The fermenter is mainly constructed of chromium steel and has a nominal volume of approximately 6.5 m³, based on reference configurations used for agricultural product fermentation. This unit constitutes the core biological reactor, where biochemical conversion of the feedstock takes place under controlled operating conditions.

Recirculation pump to centrifuge: The recirculation pump to the centrifuge is powered by a 0.75 kW electric motor and is designed to deliver a flow rate of 4 Nm³/h at a head of 17 m of water column (m.c.a.). Its function is to maintain continuous circulation of the process stream from the fermenter towards the solid–liquid separation unit.

Table 16: LCI Commissioning SVL – Uloop reactor and fermenter unit

Material / Energy flows	Amount	Unit	Note
Input			
Blower	1.1	kW	Syngas Blower
market for aluminium, cast alloy - GLO	0.325	kg	Heat Exchangers
market for copper, cathode - GLO	5.005	kg	
sheet rolling, aluminium - RER	0.325	kg	
market for steel, chromium steel 18/8 - GLO	1.17	kg	
wire drawing, copper - RER	5.005	kg	
Blower	4	kW	Recirculation Blower
market for steel, chromium steel 18/8, hot rolled - GLO	3200	kg	U-loop reactor
Pump*	7.5	kW	Recirculation pump
Pump*	0.18	kW	Acid dosing pump
Pump*	1.5	kW	Feeding pump
market for polyethylene, high density, granulate - GLO	14	kg	Inlet IBC
market for steel, low-alloyed - GLO	42	kg	
market for cast iron - GLO	3168	kg	Centrifuge
market for steel, unalloyed - GLO	32	kg	
market for polyethylene, high density, granulate - GLO	14	kg	Buffer IBC
market for steel, low-alloyed - GLO	42	kg	
Pump*	1.5	kW	Feeding pump to reactor
Pump*	0.18	kW	Base dosing Pump
market for chromium steel pipe - GLO	170	kg	Fermenter
Pump*	0.75	kW	Base dosing Pump
Output			

U-loop and acetic fermenter Unit	1	item	Commissioning

* The LCI model for these flows is shown in Annex 1.

3.25. SVL Operation phase

n this phase, the chemical flows used in the different process sections are considered, in particular the base and acid dosing in the U-loop reactor and in the fermenter, which regulate pH levels. Additionally, recycled water flows are included, both for cooling purposes and for supplying the various solution tanks. Finally, the electricity consumption of all devices mentioned during the construction phase is accounted for. The inventory refers to one hour of system operation. For the LCA analysis, these values are then scaled by the system's capacity factor and by the assumed lifetime of 20 years.

Table 17: LCI Operation SVL

Material / Energy flows	Amount	Unit	Note
Input			
chemical production, inorganic	0.4	kg/h	Base dosing pump and Acid Dosing Pump - Uloop
Electricity for Manurefinery*	0.18	kWh/h	Syngas blower - Uloop
Electricity for Manurefinery*	0.18	kWh/h	Belt Dryer - Dry Unit
Electricity for Manurefinery*	0.37	kWh/h	Conveyor Belt - Dry Unit
Electricity for Manurefinery*	0.75	kWh/h	Recirculation pump to centrifuge - Uloop
Electricity for Manurefinery*	1.5	kWh/h	Feeding pump - Uloop
Electricity for Manurefinery*	0.062	kWh/h	Downstream pump - Uloop
Electricity for Manurefinery*	1.1	kWh/h	Base dosing pump - Uloop
Electricity for Manurefinery*	0.18	kWh/h	Feeding pump to reactor - Uloop
Electricity for Manurefinery*	0.18	kWh/h	Acid dosing pump - Uloop
Electricity for Manurefinery*	7.5	kWh/h	Recirculation pump - Uloop
Electricity for Manurefinery*	4	kWh/h	Recirculation blower - Uloop
Electricity for Manurefinery*	3	kWh/h	Compressor - Gassifier
Electricity for Manurefinery*	1.5	kWh/h	Dryed SD tank - Uloop
Electricity for Manurefinery*	0.55	kWh/h	Conveyor Belt - Gassifier
Electricity for Manurefinery*	12	kWh/h	Electric steam Generator - Gassifier
Electricity for Manurefinery*	0.43	kWh/h	Conveyor Belt - Gassifier
Electricity for Manurefinery*	1.1	kWh/h	Conveyor Belt - Dry Unit
Electricity for Manurefinery*	5.5	kWh/h	Compressor - Dry Unit
Electricity for Manurefinery*	4	kWh/h	Compressor - Dry Unit
Electricity for Manurefinery*	1.5	kWh/h	Feeding Pump - Uloop
Electricity for Manurefinery*	7.5	kWh/h	Centrifuge - Uloop
Electricity for Manurefinery*	0.75	kWh/h	IBC mixer - Uloop
Electricity for Manurefinery*	9.9	kWh/h	Electric heater - Uloop

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market for deionised water - Europe	300	kg/h	Centrifuge - Uloop
market for deionised water - Europe	20	kg/h	Acid Dosing Pump - Uloop
market for deionised water - Europe	400	kg/h	Inlet IBC - Uloop
market for deionised water - Europe	20	kg/h	Base dosing pump - Uloop
market for deionised water - Europe	150	kg/h	HE water used for cooling - Uloop
Output			
SVL - operation	1	h	operation

* The LCI model for these flows is shown in Annex 1.

4. RESULTS AND INTERPRETATION

4.1. Gas Valorisation Line

The following comparison involves the poultry farm (PoF), the swine farm (SwF), and the global (RoW) and European (RER) production of sodium nitrate (SN). As shown in Figure 5, several impact categories yield favourable results for both Scenario 1 and Scenario 2, namely CC, ECf, Eum, Eut, HtC, and PM.

Conversely, the impact categories AC, HTnc, LU, OD, Pof, Ruf, and Rumm are strongly dependent on the operating conditions of the GVL. In Scenario 1, where $NaNO_3$ production amounts to 401 g/d, these categories show unfavourable environmental performance. In contrast, Scenario 2, corresponding to maximum $NaNO_3$ production, yields significant environmental benefits across all of these categories.

The impact categories Euf and WU remain critical, showing a consistently high environmental disadvantage across all scenarios. Regarding Euf, impacts are at least 20% higher for PoF-1 and SwF-2, reaching as much as 85% for SwF-1. Results are comparable to the reference only in Scenario PoF-2. With respect to WU, a markedly high impact is observed, ranging between 80–90% for SwF and 20–25% for PoF.

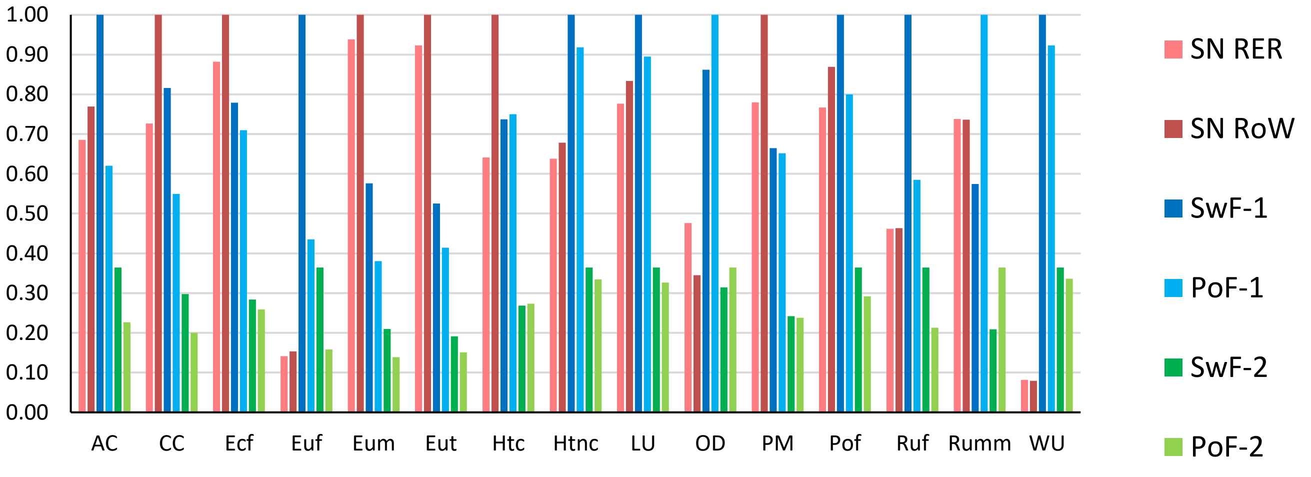

Figure 5: Impact analysis percentage comparison GVL

Following the normalisation of the results, the most relevant environmental impact categories for each scenario are identified. In Figure 6, SwF is represented by the inner circle and PoF by the outer circle. The impact percentages do not vary significantly

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between the two circles, with the exception of a few categories that are more sensitive to the use of renewable energy sources, such as EuF, which accounts for 30% of the impact in SwF and 18% in PoF.

Overall, the impact categories exceeding, or approaching, the 5% threshold are CC, Ecf, Euf, HtC, Ruf, Rumm, and WU. Among these, WU and Euf are the most relevant, and also the most critical when compared to the conventional production of sodium nitrate.

Considering the impact categories that are favourable to the GVL system, these collectively account for approximately 18% of the total impacts. In contrast, the impact categories that are critical to the manurefinery system contribute approximately 38% for PoF and 45% for SwF. The remaining share depends, as observed in the previous figure, on the operating conditions of the GVL.

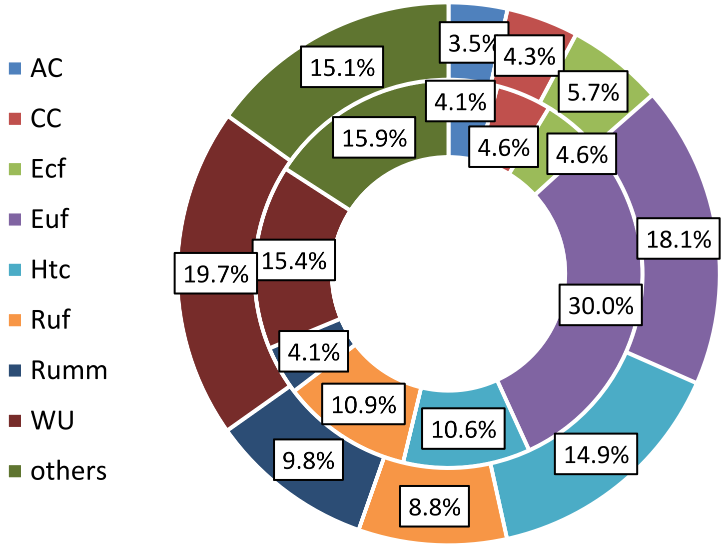

Figure 6: Normalization results GVL (SwF is represented by the inner circle and PoF by the outer circle)

Figure 7 presents the most relevant indicator, evaluated by normalization. The reported indicators are expressed at the midpoint level and refer to their specific units of measurement. Graphs highlighted with a green box identify indicators that are favorable for the GVL system. As shown for **CC**, the worst-performing scenario (SwF-1) exhibits an impact of **3.73 kg CO_2 eq**, which is approximately **12% higher** than SN-RER but still **22.5% lower** than SN-RoW. The environmental benefits observed in the other scenarios are substantially greater, reaching a maximum reduction of **72%** when comparing PoF-2 with SN-RER.

A comparable trend is observed for **Htc**, where the PoF scenario shows a significant environmental advantage of approximately **50%**. A similar pattern is found for **Ecf**, with impact reductions exceeding **68%**. Graphs highlighted with a yellow box identify indicators that are favorable for the GVL system depending on the conditions. With regard to **Ruf**, the analysis indicates that both SwF-1 and SwF-2 scenarios consistently present higher impacts than conventional processes, with increases ranging from **25% to 98%**. Conversely, in the PoF scenario, the integration of a photovoltaic system allows a substantial reduction in impacts, with relative decreases ranging from **20% (PoF-1)** to **50% (PoF-2)**.

Graphs highlighted with a red box identify indicators that are critical for the GVL system.

The last two indicators, **Euf** and **WU)** represent critical aspects. In the worst-case scenario (SwF-1), impacts increase by more than **450% for Euf** and **900% for WU** compared to conventional processes. However, a marked improvement is observed for PoF-2, which shows impacts comparable to the reference system, with only a **3% increase** relative to conventional processes.

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This highlights that optimized production combined with renewable energy integration enables the achievement of good environmental performance.
In contrast, for **Water Use**, even under the best-performing conditions, water consumption remains significantly higher, with an increase of approximately **320%** compared to conventional systems.

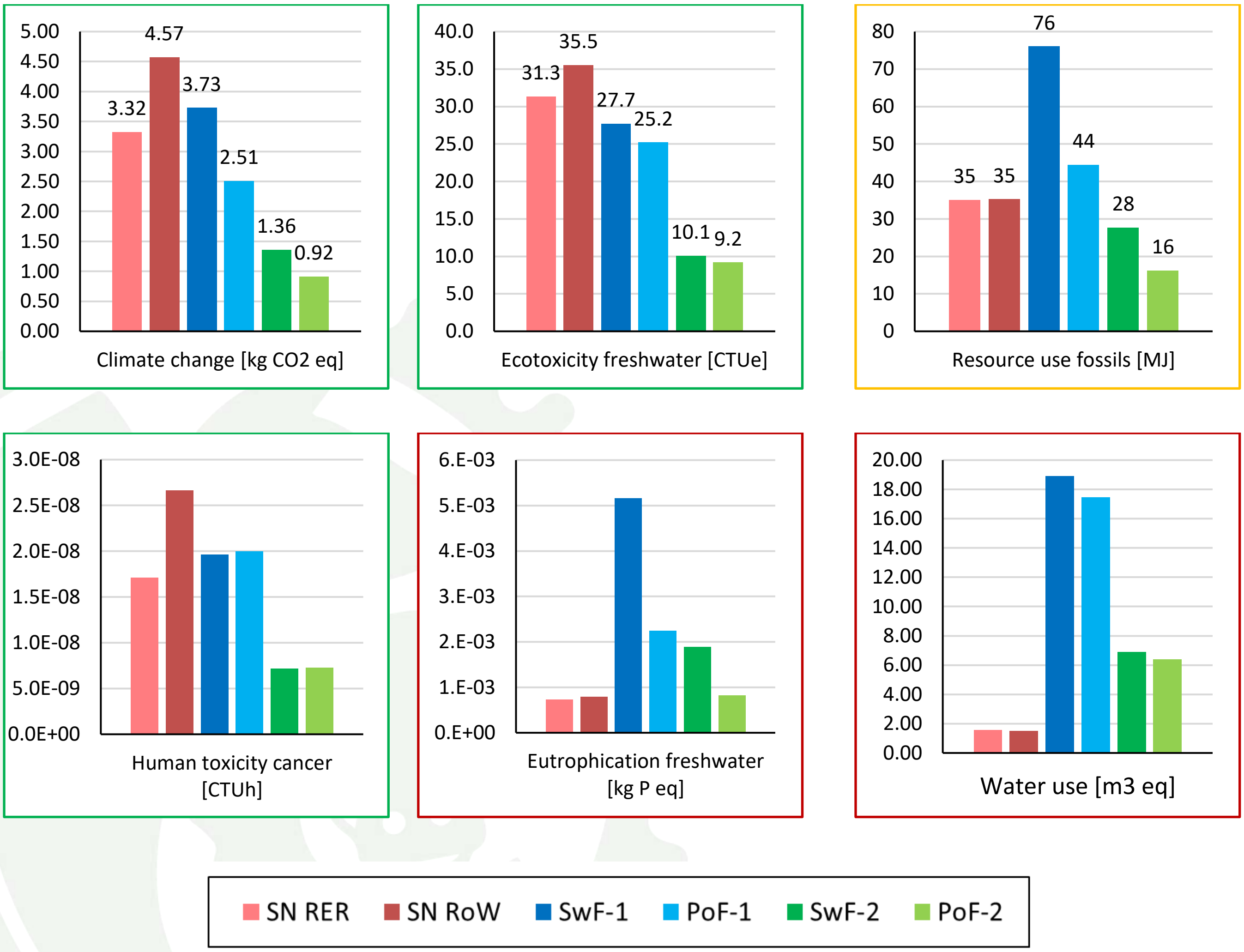

Figure 7: Impact assessment analysis, main indicator and comparison - GVL

Figure 8 presents the contribution analysis, identifying, for the same indicators discussed in the previous figure, the processes that most strongly influence the overall impacts. The main contributions are associated with the construction phase and the operational phase, the latter being subdivided into chemical inputs, energy flows, and water flows.
Focusing on the most critical indicators, particularly **Euf**, it can be observed that the majority of the impact originates from electricity consumption, accounting for **84%** and **63%**, respectively. This indicates that the impacts are not driven by direct emissions from the GVL process itself, but rather by indirect emissions related to upstream energy production processes

included in the inventory. Specifically, these emissions are associated with the Romanian electricity grid in the SwF scenario and with a combination of grid electricity and photovoltaic energy in the PoF scenario.

For **WU**, in both scenarios the impact is mainly attributable to water consumption, contributing **82%** and **89%**, respectively. In contrast to Euf, this represents a direct impact, as the amount of water required by the process is extremely high. This result highlights a critical issue within the GVL value chain, namely the need to implement an effective water recirculation system in order to substantially reduce water consumption.

For the remaining indicators, energy consumption consistently represents a significant contribution. In particular, it exceeds **50%** for **CC**, **Euf**, and **Ruf**, and remains relatively high for **Ecf**, **Htc**, and **Rumm** (in the SwF scenario).

It should also be emphasized that the second largest contribution is related to the use of chemical inputs, specifically sodium hydroxide, which is required for the production of the final bioproduct. For several indicators, including **Ecf**, **Htc**, and **Rumm**, this contribution is substantial, ranging between **50% and 60%** of the total impacts. In the PoF scenario, the contribution of chemicals is slightly lower, yet still accounts for at least **30%** of the total impacts.

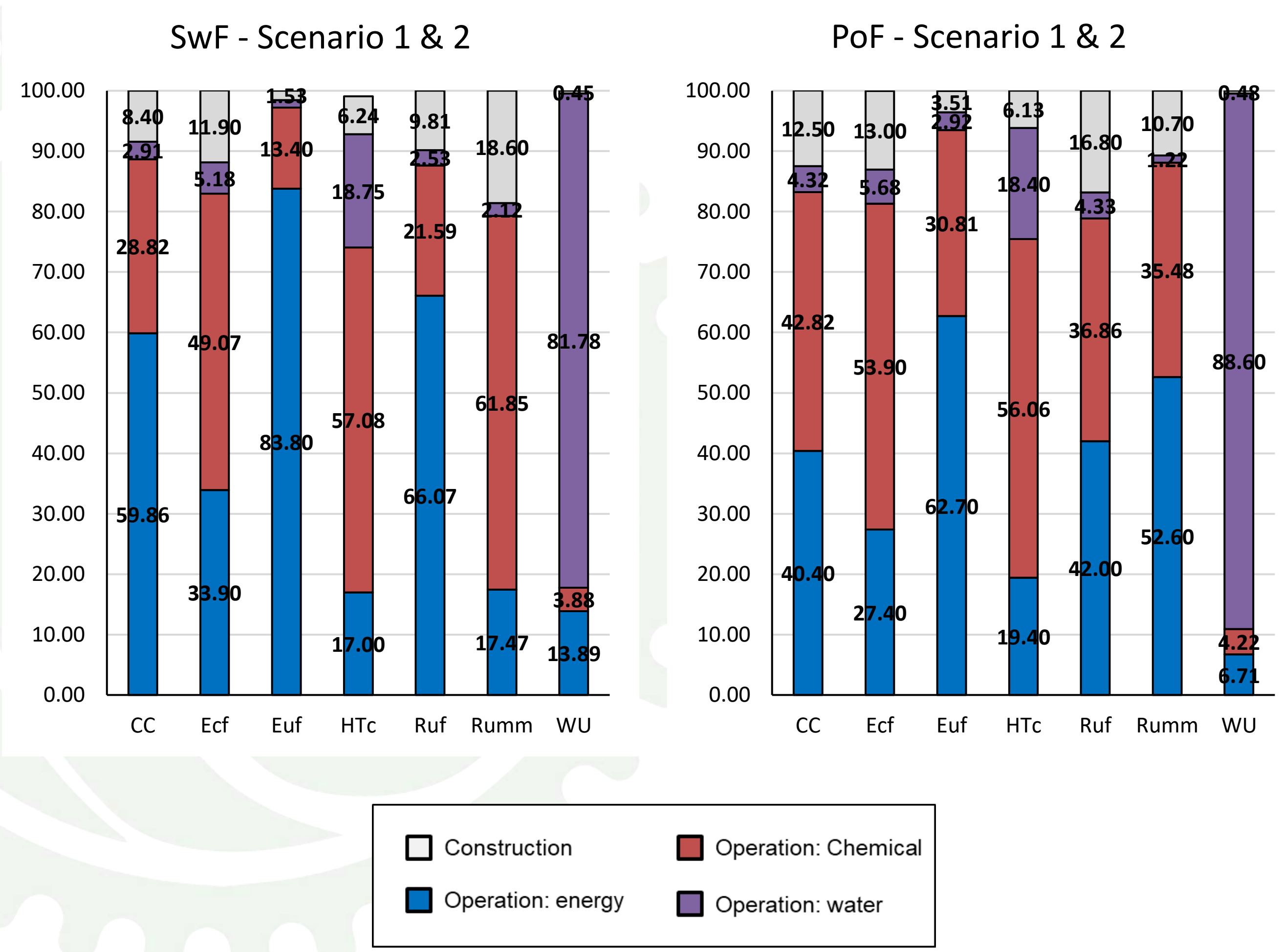

Figure 8: Contribution analysis - GVL

Figure 9 presents the parametric analysis for the Climate Change (CC) environmental indicator as a function of the capacity factor (CF) and the liquid flow rate of the biotrickling filter. Results are reported for both SwF-1 and PoF-1 scenarios. In addition, the dashed red lines represent the environmental impact associated with the production of sodium nitrate (RER and RoW). As shown in both graphs, the curves exhibit a relatively low slope, equal to 0.022, indicating a limited sensitivity of the CC indicator to variations in the analyzed parameters. Another relevant aspect is the width of the result range, represented by the area between CF = 0.6 and CF = 0.2, highlighted in green for SwF and in red for PoF. For the SwF scenario, this range is significantly wider than for PoF, since the use of grid electricity, compared with photovoltaic energy, leads to a stronger dependence on the capacity factor. A further important observation is that, for SwF at CF = 0.4, the CC impact falls within the range of conventional production processes. When CF = 0.2, the impacts are lower than the reference values for all liquid flow rates considered. Conversely, for the PoF scenario, the environmental impact remains below the benchmark level for all CF values and liquid flow rates analyzed.

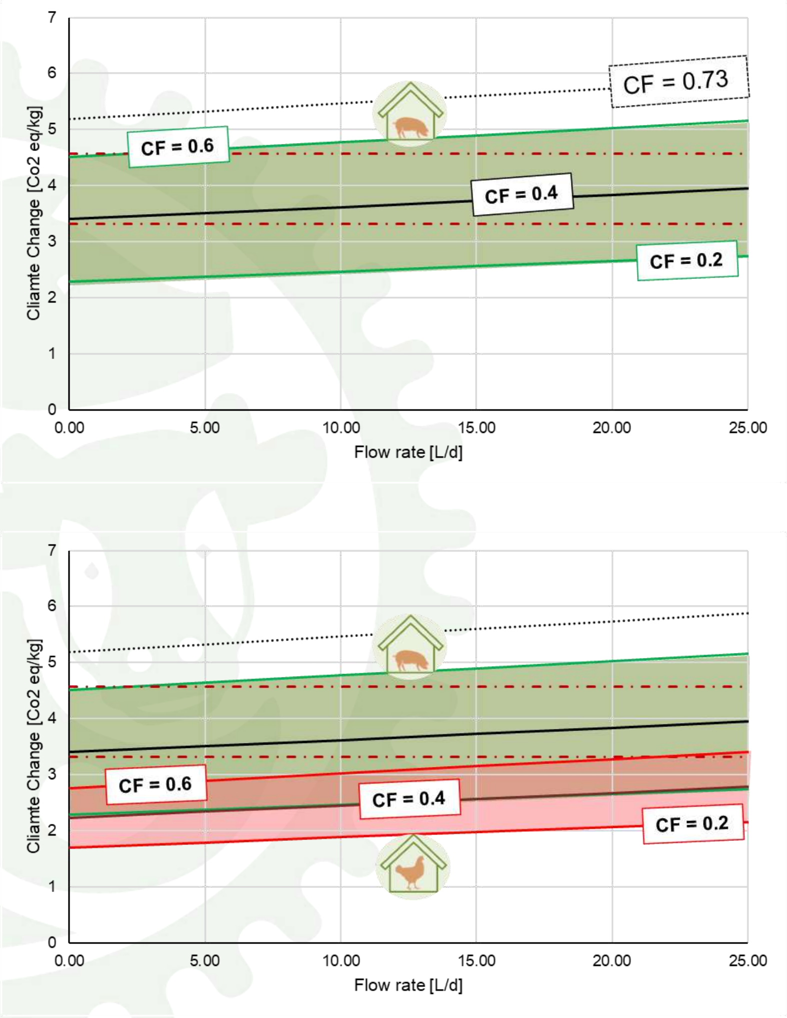

Figure 9: Parametric analysis for Climate Change indicator - GVL

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4.2. Liquid Valorisation Line

Figure 10 presents the comparison of all midpoint indicators for the LVL solution against the conventional production processes of ammonium bicarbonate (AM) and protein feed. The initial comparison highlights environmental benefits for five indicators, namely CC, Ecf, Eum and WU. For all remaining impact categories, the LVL supply chain shows higher impacts than the corresponding industrial processes modelled using ecoinvent data. In this graph, the Ruf indicator is not reported because it assumes negative values and is therefore excluded for graphical clarity; it is instead analysed in detail in the subsequent figures. The negative value reflects an environmental benefit associated with the system, which arises from the high level of energy recovery from biogas, leading to a net reduction in overall impacts.

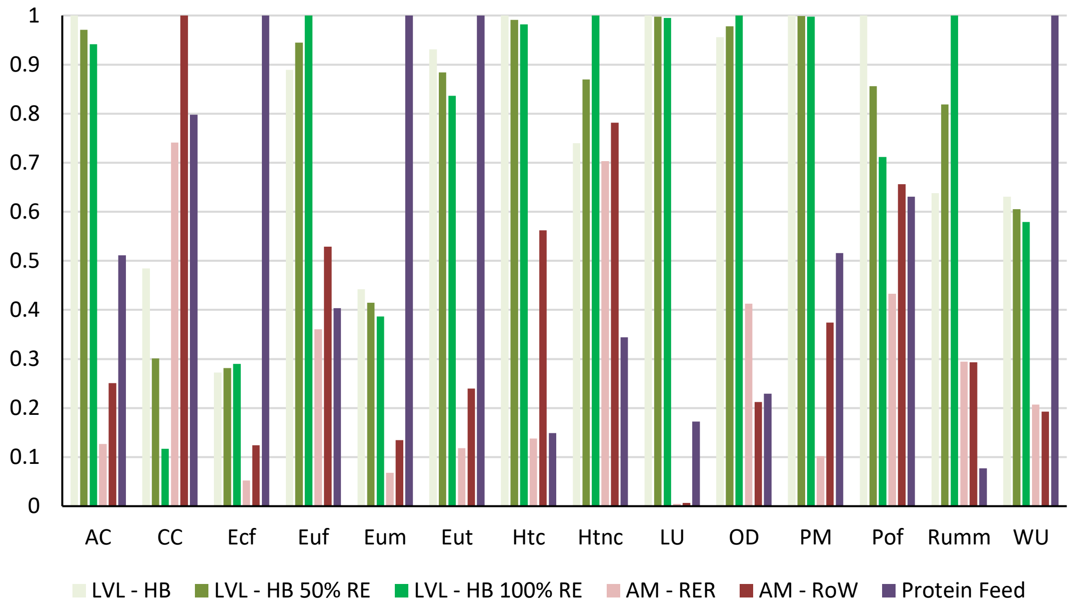

Figure 10: Impact analysis percentage comparison LVL

The normalisation of the environmental indicators shows that, overall, CC is not a dominant category, accounting for approximately 5% of the total impact. A slightly higher contribution is observed for both AC and Rumm, each representing around 7%. Higher contributions are associated with Ruf and LU, which account for 9.3% and 10.3%, respectively.

The largest contribution is related to Htc, which represents about 23% of the total impact, while the remaining 38% is attributable to all other indicators, each contributing less than 5% individually.

These results indicate that, with the exception of Htc, the environmental impacts are relatively well distributed across categories, without the presence of a single clearly dominant indicator.

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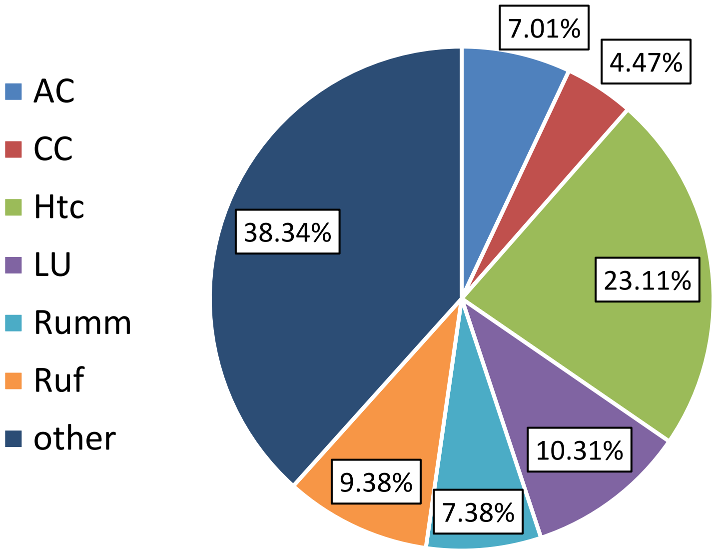
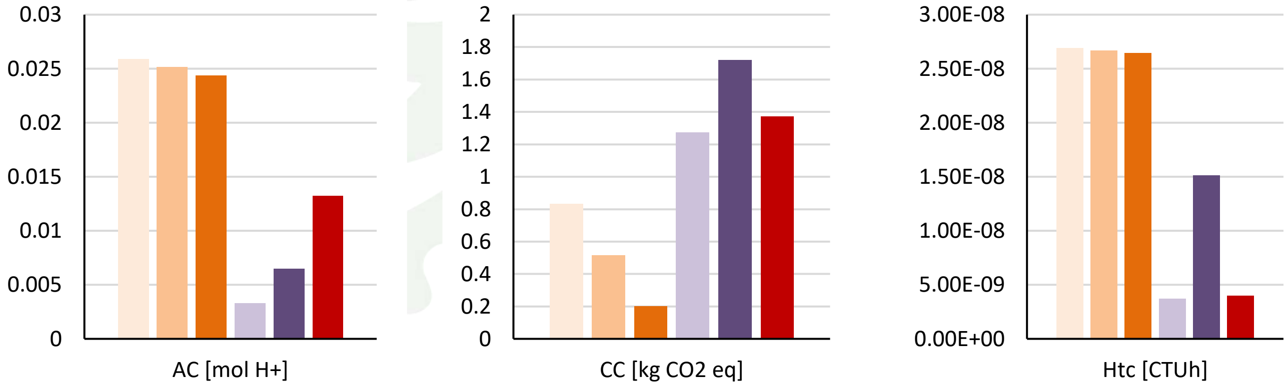


Figure 11: Normalization results LVL

As shown by the midpoint indicators in Figure 12, only two impact categories exhibit an environmental benefit, namely CC and Ruf. CC remains lower even in the worst-case scenario (LVL – baseline), where it is substantially below the reference standard processes, with a reduction in the range of 30–50%. This improvement becomes even more pronounced under the scenario with the highest level of PV integration, reaching an impact value of approximately 0.2 kg CO_2 eq.

A significant environmental benefit is also observed for Ruf. This result is attributable to the biogas produced and reused within the LVL supply chain, which generates substantial environmental credits and leads to a net beneficial performance in this category. In contrast, the remaining indicators (AC, Htc, LU and Rumm) show unfavourable results. Although the impacts are of the same order of magnitude for most categories, with the exception of Htc and LU, they nevertheless remain relatively high. These findings highlight the need for a more detailed and in-depth analysis in order to identify the dominant contributing processes within these impact categories and to define potential improvement strategies.



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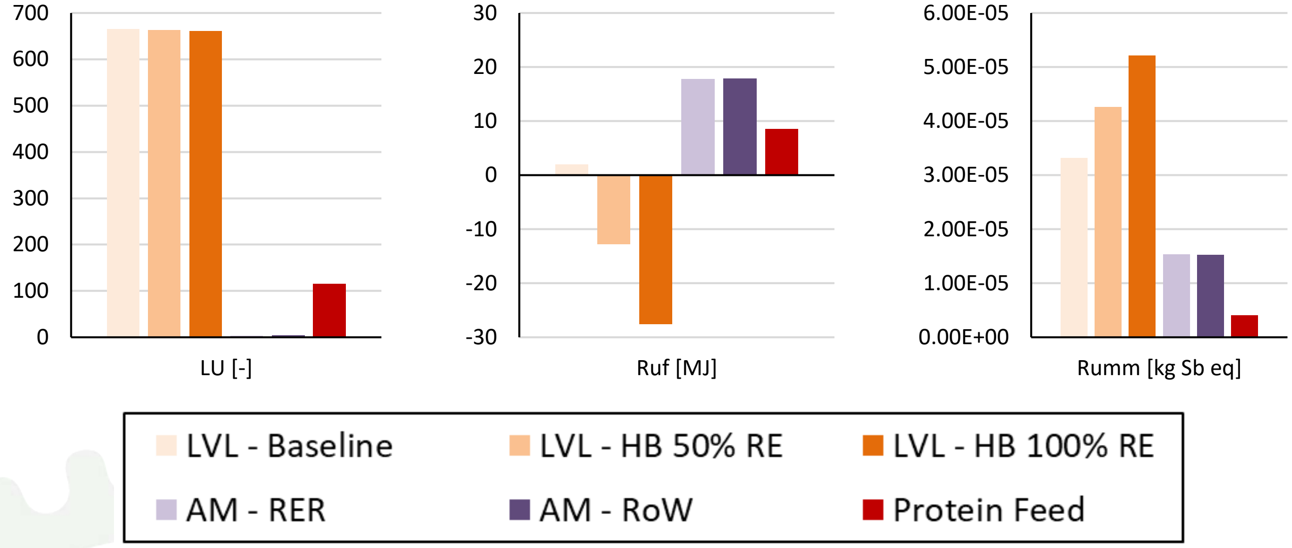

Figure 12: Impact assessment analysis, main indicator and comparison - LVL

The contribution analysis presented in Figure 13 provides several relevant insights. First, the results are disaggregated into the commissioning phase (Co) and the operational phase (Op). In addition, the contributions of each LVL subsystem are reported, namely the anaerobic digester (AD), the biogas fermenter (BF), the nitrogen and phosphorus recovery section (NPR), and the caproic acid production section (CA). Environmental credits associated with electricity and heat generation from biogas are also included.

As can be observed, each indicator exhibits a different contribution pattern, with the common feature that the construction phases of NPR and CA contribute only marginally. It should be noted that the CA section is currently characterised by a very limited inventory due to data gaps; therefore, its low impact is expected and justified.

For AC, a major contribution (31.2%) originates from the operational phase of NPR, mainly due to the use of chemical substances such as sulphuric acid. This is followed by the operational phase of AD (29.7%), which is driven by energy consumption (37%) and by the use of molasses (63%). Environmental credits account for approximately 16% of the total, while the construction phase does not play a significant role.

With respect to CC, the largest contributions arise from Op-BF (15.7%), entirely due to the consumption of chemicals such as sodium hydroxide and sodium nitrate, and from Op-AD (23.2%), which is mainly driven by energy use (81%) and, to a lesser extent, by molasses (19%). In this case, environmental credits offset approximately 41% of the total impacts.

For Htc, about 21% of the impact is attributable to Co-BF, due to the extensive use of metallic materials, in particular stainless steel. Nevertheless, the operational phase also contributes substantially, with 14.9% from AD, 17% from BF, and slightly more than 10% from NPR and CA.

LU shows a distinctive behaviour: in addition to exhibiting high absolute values, as highlighted in the previous figures, it is almost entirely driven by a single process, namely Op-CA. This is due to the extensive use of grass as feedstock, which results in a high land requirement and accounts for approximately 95% of this impact category.

For Ruf, environmental credits represent about 51% of the total contribution, while the most impactful process is Op-AD, mainly as a result of energy consumption. Finally, Rumm is strongly influenced by Co-BF due to the use of metallic materials for machinery, while the operational phase contributes 11% from AD, 12% from NPR and 20.5% from BF.

Overall, this contribution analysis highlights the key processes and life cycle stages driving the environmental performance of the LVL system and provides a basis for identifying targeted improvement strategies.

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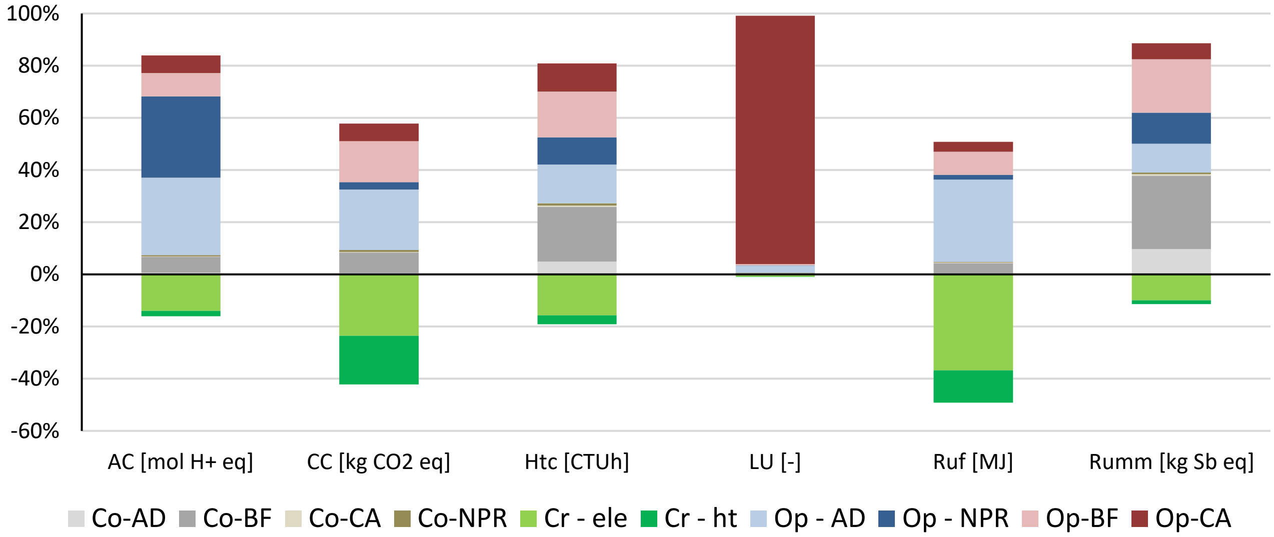

Figure 13: Contribution analysis - LVL

4.3. Solid Valorisation Line

Figure 14 reports all the environmental indicators of the EF 3.1 methodology, comparing the SVL system with two reference processes, namely the production of 1 kg of fertilizer and 1 kg of protein feed. The results are expressed as relative percentages, where the process showing the highest impact among the four compared systems is set to 100%, and the remaining values are reported as a percentage relative to this reference. The figure includes two SVL scenarios, corresponding to 0% and 100% integration of renewable energy sources, while the remaining energy demand is supplied by the Slovenian national electricity grid. As shown in the graph, eight indicators are environmentally favorable for SVL, specifically AC, CC, Ecf, Eum, Eut, LU, OD, and PM. Only two indicators (Pof and Ruf) are favorable when compared with fertilizer production, but unfavorable when compared with protein feed production. By contrast, five indicators are identified as critical for SVL in both comparisons, namely Euf, Htc, Htnc, Rumm, and WU.

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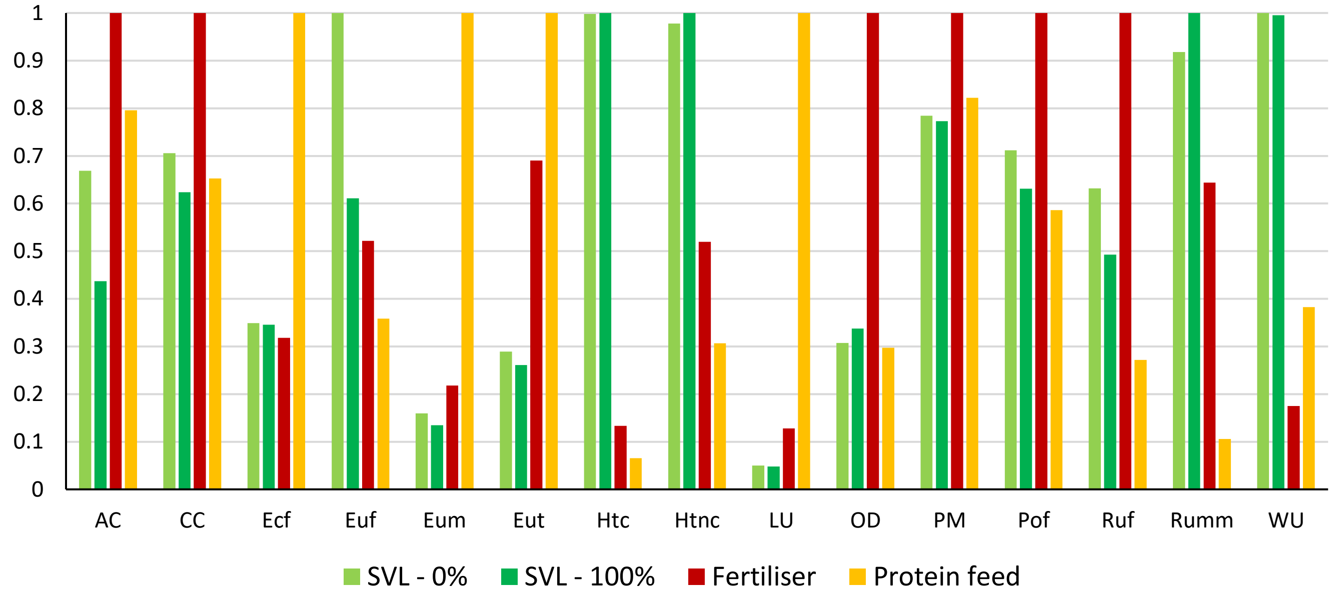

Figure 14: Impact analysis percentage comparison SVL

The normalization of the indicators identifies the six most relevant environmental categories, as shown in Figure 15. This analysis indicates that CC contributes only 2.6% to the total impact, whereas Htc represents the dominant contribution with 47%. WU accounts for approximately 12.1%, while Euf and Rumm each contribute slightly more than 7%, and Ecf accounts for about 6%. Based on these results, a priority scale can be defined for the indicators requiring further investigation, with greater emphasis placed on understanding the origin and drivers of impacts associated with the most influential categories. For the sake of simplicity, only four indicators are considered for the comparison with protein feed and fertilizer production, namely **Htc, WU, Euf, and CC**.

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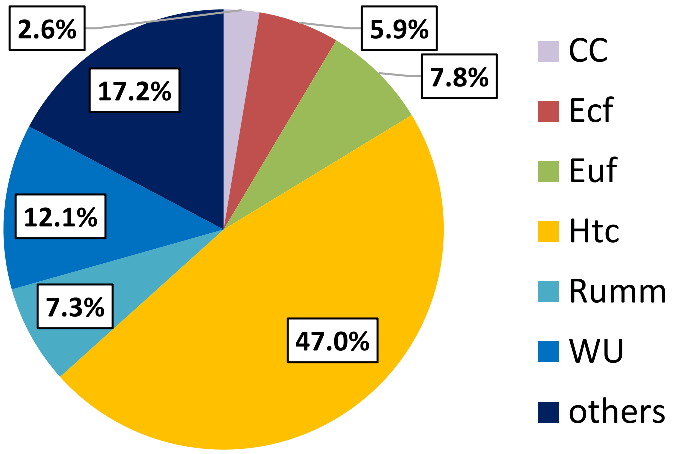

Figure 15: Normalization results SVL

In the following Figure 16, four environmental impact indicators are analysed in detail by comparing five SVL scenarios under different levels of renewable energy integration and benchmarked against the production of inorganic and organic fertilisers.
With respect to CC, the manurefinery-based solution clearly yields a fertiliser whose overall impacts lie approximately midway between those associated with conventional inorganic and organic fertiliser production. This indicates that the proposed system represents a viable option from a climate mitigation perspective.
Regarding Euf, the results are strongly dependent on the level of renewable energy integration. When 25–50% of the energy demand is supplied by PV sources, eutrophication impacts are slightly lower than those of inorganic fertiliser production, with a reduction of approximately 3–6%. Conversely, at higher PV integration levels (75–100%), impacts decrease by more than 30% compared to the inorganic reference scenario.
For both Htc and WU, impacts are substantially higher. In particular, WU shows markedly increased values, highlighting the necessity of implementing water recycling strategies within the system. In the case of Htc, a significant contribution arises from metallic materials, suggesting that alternative plant design solutions employing less impactful materials should be considered.
Overall, the comparison confirms that fertiliser production from organic sources is environmentally more favourable than conventional inorganic production. However, it should be emphasised that this assessment does not account for the agronomic effectiveness of the fertiliser. As is well known, many organic fertilisers do not necessarily achieve the same performance levels as those obtainable from manurefinery-based products, and this aspect is not captured within the present analysis.

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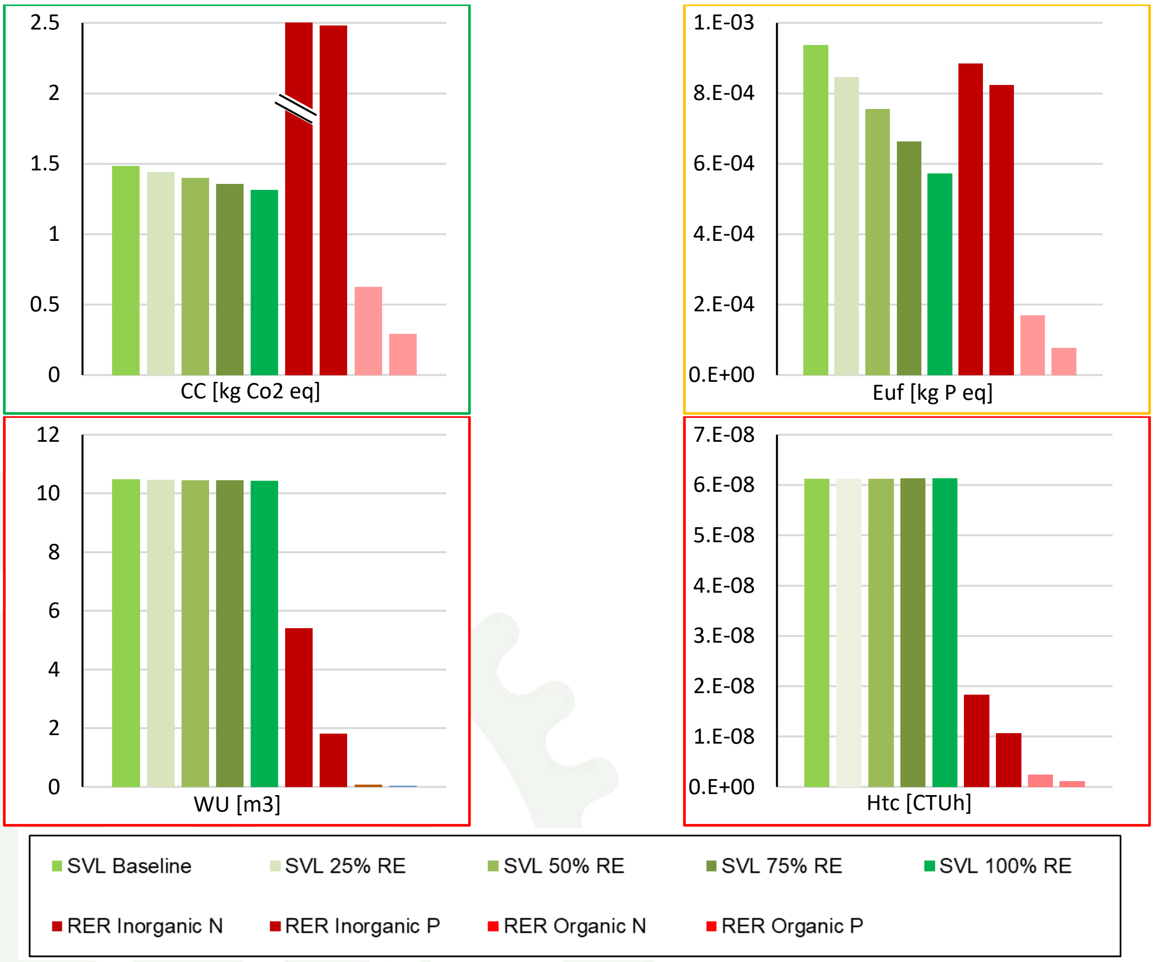

Figure 16: Impact assessment analysis, main indicator and comparison – LVL Fertiliser comparison

The comparison with protein feed is presented in Figure 17. Also in this case, the results vary considerably depending on the indicator considered and on the reference product. Overall, the integration of renewable energy sources shows a relatively limited influence on the environmental indicators.

For CC, impacts decrease from 1.48 kg CO_2 eq to 1.31 kg CO_2 eq and are clearly lower than those associated with conventional protein feed production, indicating a favourable performance of the proposed system. A different pattern is observed for Euf, WU and Htc, for which no environmental advantage emerges.

With respect to WU, the results further highlight the need for water recycling strategies. A reduction in water consumption of at least 30% would likely allow a significant decrease in impacts, making them comparable to those of protein feed with the highest water requirements, given that the current difference is relatively limited (approximately +19%). For Htc and Euf, the critical issues are mainly related to the construction phase in the former case and to the energy demand in the latter.

It is also important to clarify that the comparison is carried out with protein feed such as soybean meal, maize chop, tofu, barley grain, rapeseed meal and protein compounds. The final product obtained from the manurefinery process is characterised by a high protein content and by a higher quality standard compared to these reference products. However, this potential benefit for animal nutrition is not captured within the present assessment.

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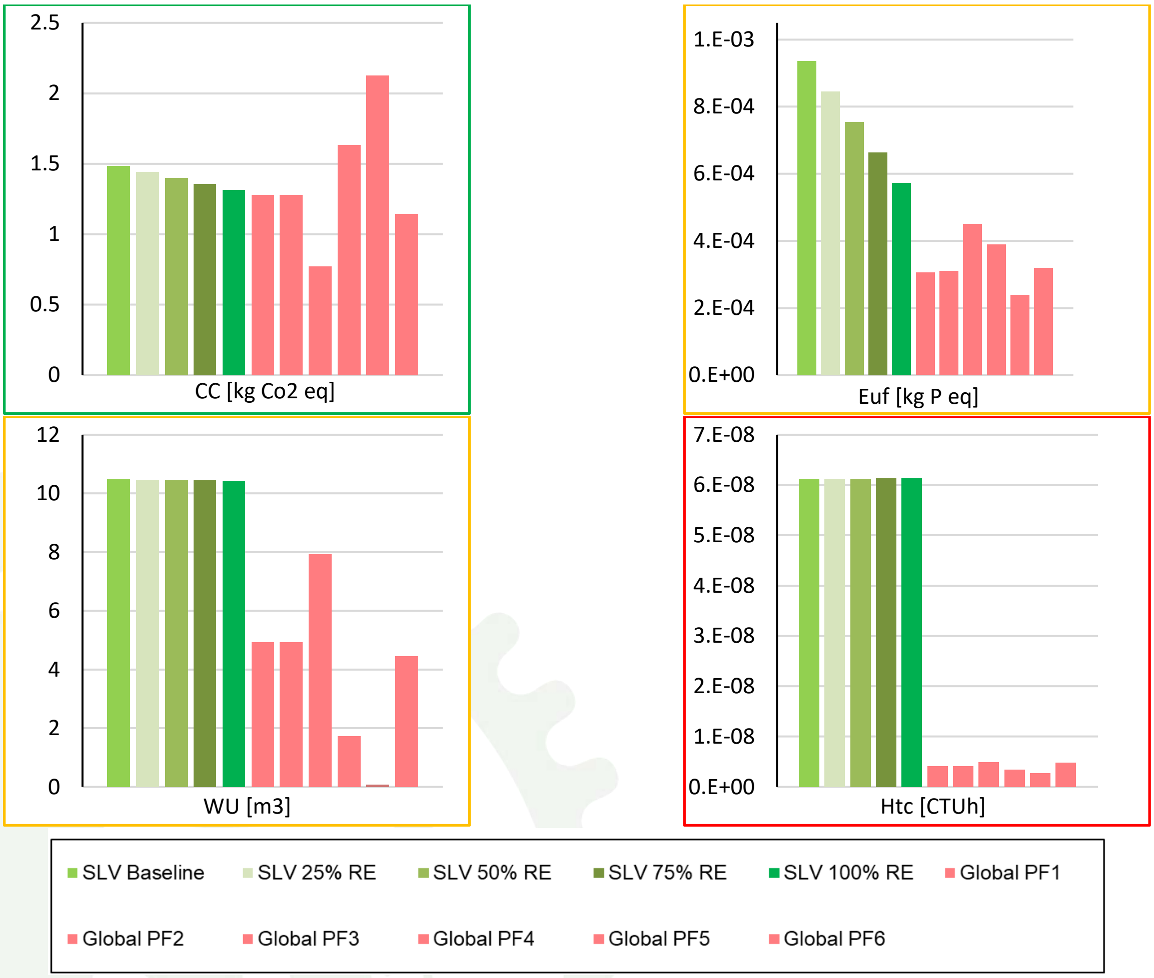

Figure 17: Impact assessment analysis, main indicator and comparison - LVL protein feed comparison

Figure 18 presents the contribution analysis of the SVL system under the two scenarios with 0% and 100% renewable energy integration. The trend observed for each indicator is generally similar in both scenarios, with the main difference being a reduction in the relative contribution associated with energy consumption in the fully renewable scenario.

In particular, a marked decrease is observed for CC, which drops from 46.5% to 15.9%, and for Ecf, which decreases from 33.9% to 24.6%. A comparable effect is found for Euf, whose contribution is reduced from 49.0% to 6.7%. By contrast, an opposite trend is observed for Rumm, which is highly sensitive to indirect impacts related to energy production and therefore increases from 20.0% to 67.1%.

For SVL, the contribution associated with chemical inputs is consistently negligible and never exceeds 3% of the total impact for any indicator. This is due to the limited number of chemical substances involved compared with other material and energy flows. Conversely, the construction phase represents a major source of impact, mainly attributable to the extensive use of metals for mechanical components. This contribution is particularly relevant for Htc, for which it exceeds 71%, indicating that materials used during the construction phase generate substantial indirect impacts on human toxicity.

A further relevant contribution arises from syngas, which affects several indicators in a substantial manner, accounting for more than 45% of CC, 33% of Ecf, and 48% of Euf. Although less pronounced, its contribution remains significant for Rumm, WU, and Htc, with shares of 19.0%, 19.6%, and 11.0%, respectively.

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Finally, a major contribution is associated with WU, which accounts for 57% and 63% of the total impacts due to water consumption in the two scenarios. This result further highlights the importance of implementing water recirculation strategies within the SVL system, especially when considering the absolute magnitude of this indicator at the midpoint level.

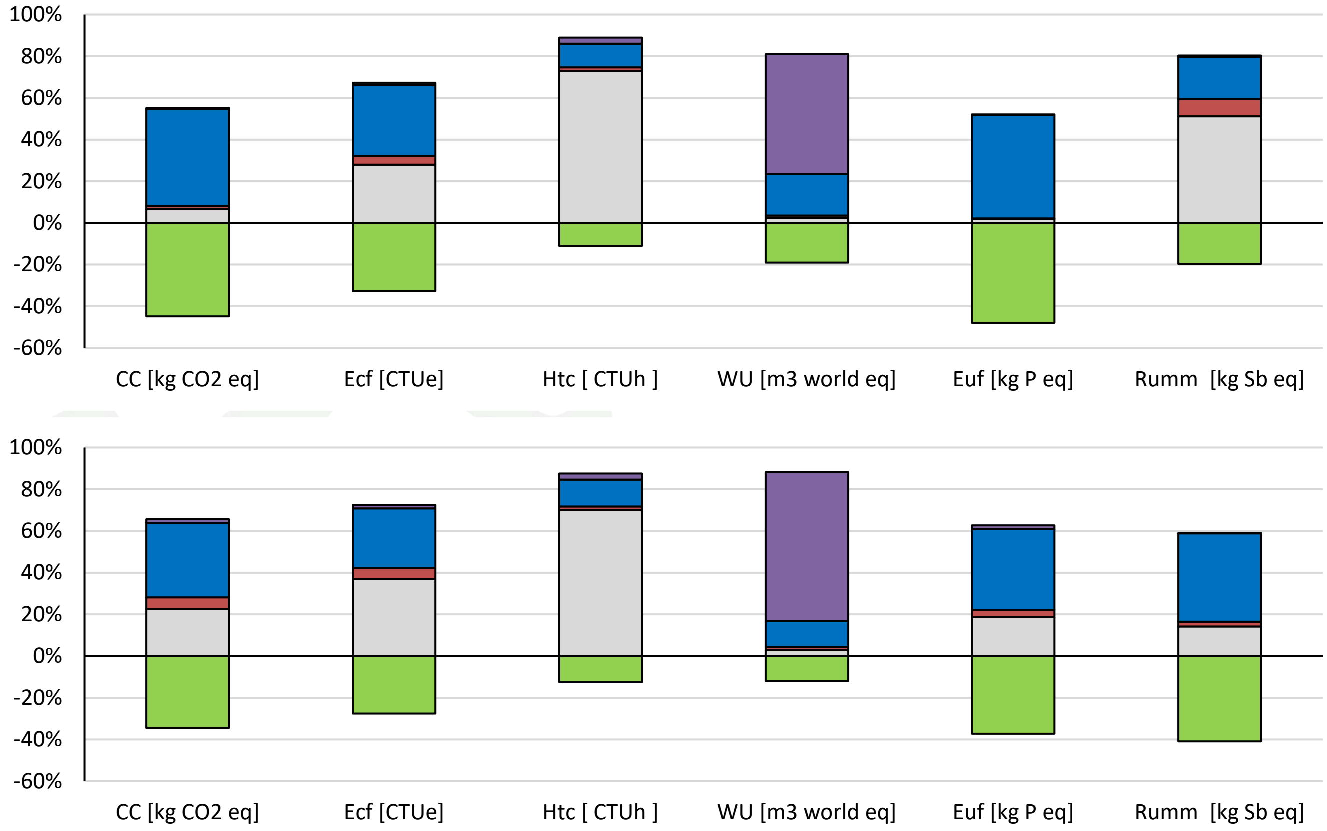

Figure 18: Contribution analysis - SVL

Figure 19 shows the parametric analysis performed for the CC indicator as a function of syngas productivity, under different conditions of lower heating value (LHV) and efficiency (Eff). The figure also reports four reference impact levels corresponding to organic fertilizers, inorganic fertilizers, and protein feed production.

As shown in the graph, the impact trend decreases with increasing syngas productivity, as expected. However, each scenario covers a different response range. The green area represents the trend obtained for the highest LHV value (20 MJ/m^3), for which the lowest impact values are achieved compared to the reference systems. In this case, at a productivity of 20 m^3/h, the impacts reach the minimum level and even result in an environmental credit (i.e., a negative net impact).

The blue area, corresponding to an LHV of 15 MJ/m^3, reaches a level comparable to the reference systems at a productivity of 30 m^3/h, which represents approximately 30% higher syngas production compared to the previous scenario. A different behavior is observed for LHV = 10 MJ/m^3, for which a similar impact level is only achieved at a productivity of about 38 m^3/h.

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These results indicate that, depending on the LHV of the syngas, a substantial environmental benefit can be obtained even at lower productivity levels, highlighting the strong influence of syngas quality on the environmental performance of the system.

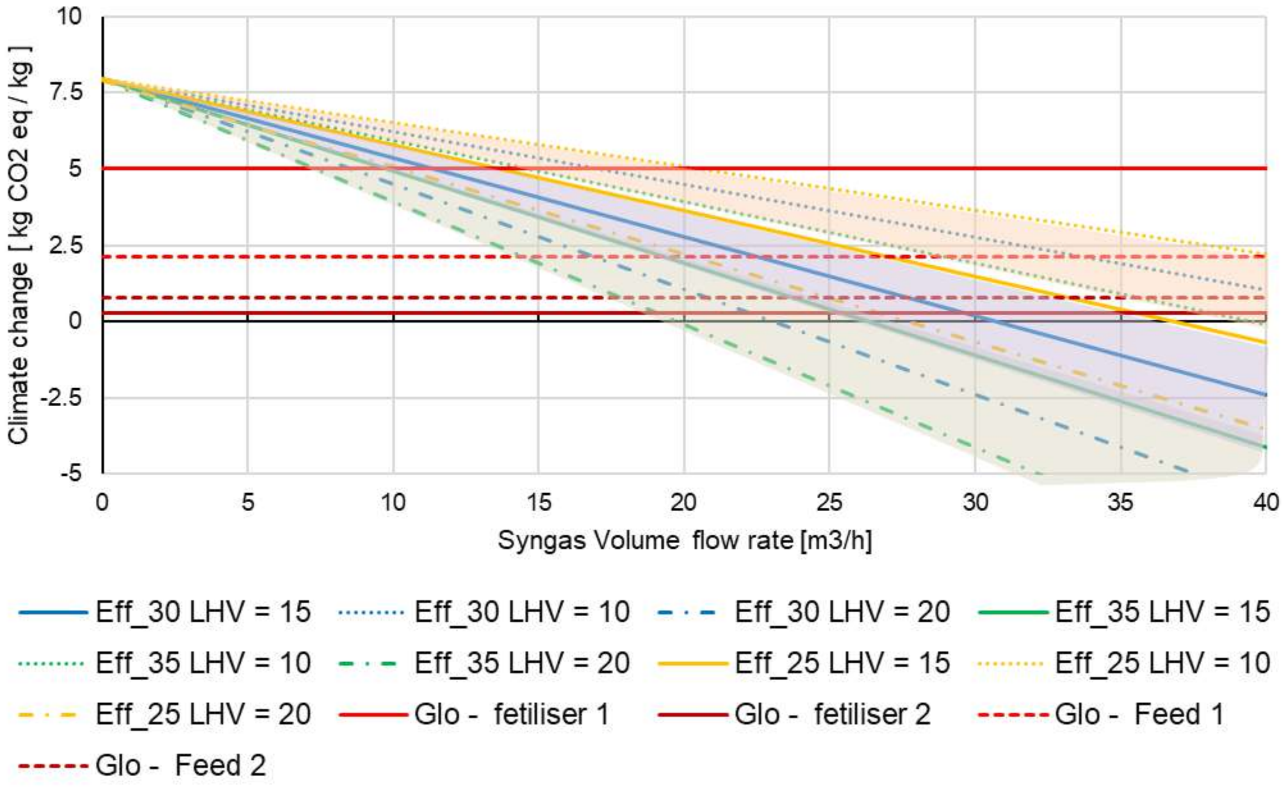

Figure 19: Parametric analysis for Climate Change indicator – LVL

4.1. Whole environmental evaluation: GVL, LVL & SVL

To provide an integrated comparison of the environmental performance across all processing lines, a single score analysis was conducted, normalizing and weighting all midpoint impact categories into a single aggregated metric expressed per tonne of manure (or equivalent input flow) treated. This approach allows for a direct, cross-category comparison of environmental burdens and benefits associated with each line within the ManuREfinery system.

The assessment was performed adopting a system expansion approach. All bio-based products generated along the various processing lines, including those described in the preceding sections, were credited by substituting their conventional counterparts, i.e., the reference processes identified and discussed throughout this report. This methodological choice allows the avoided environmental burdens associated with conventional production to be explicitly accounted for within the system boundary, thereby enabling a holistic evaluation of whether the ManureRnery system, on balance, generates net environmental benefits or net environmental burdens.

Under this framework, a negative single score value (below zero) indicates that the cumulative avoided impacts, attributable to the substitution of conventional products, outweigh the direct environmental burdens of the ManuREfinery process itself, resulting in a net environmental credit. Conversely, a positive single score value denotes a net environmental burden, meaning the system's direct impacts exceed the credits generated through product substitution.

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The results of this analysis are presented in Figure 20, where the contributions are distinguished visually between the green area, representing net environmental credits, and the red area, representing net environmental impacts. This representation provides a transparent and intuitive overview of the overall environmental sustainability of each processing line, supporting evidence-based decision-making for the optimisation and scale-up of the ManuREfinery concept.

As illustrated in Figure 20, the single score analysis reveals that at least six impact categories yield net environmental credits under the system expansion approach, namely CC, ECf, EUm, POF, RUf, and WU. These results demonstrate that, for these categories, the substitution of conventional products by the bio-based outputs of the ManuREfinery system generates avoided burdens sufficient to offset, and indeed surpass, the direct environmental impacts associated with the treatment process. This outcome underscores the potential of the ManuREfinery concept to deliver meaningful environmental co-benefits, particularly in terms of climate change mitigation, fossil resource depletion, and freshwater quality preservation.

However, three impact categories remain critically burdened and warrant particular attention: LU, AC, and EUt. For these categories, the ManuREfinery system generates net positive impacts, i.e. environmental burdens, that are not offset by the credits accrued through product substitution. The analysis indicates that these impacts are predominantly driven by the LVL processing line, which emerges as the most critical contributor across all three problematic categories. This finding highlights the need for targeted optimisation efforts focused on the LVL line, particularly with regard to emission management strategies and land-related pressures, in order to improve the overall environmental profile of the ManuREfinery system.

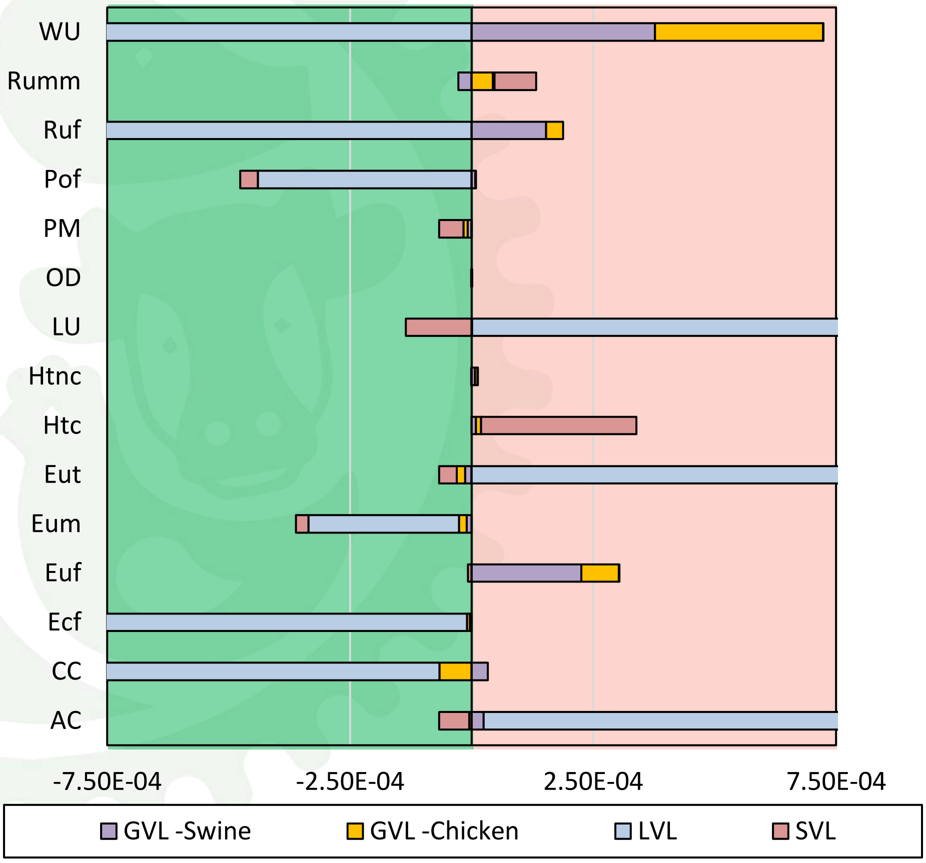

Figure 20: Whole environmental Burder or Credit in ManuREfinery

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5. CONCLUSION

The detailed Life Cycle Assessment (LCA) conducted at the design level for the MANUREFINERY project provides a comprehensive evaluation of the environmental performance of modular biorefining technologies for manure valorization. The assessment, based on the Environmental Footprint (EF) 3.1 methodology, highlights that the transition from conventional manure management to integrated biorefining pathways (GVL, LVL, and SVL) offers significant opportunities for decarbonization and nutrient recovery, although specific environmental hotspots must be addressed during the project's scale-up phase.

Gas Valorisation Line (GVL): The biological recovery of ammonia into sodium nitrate ($NaNO_3$) proves environmentally beneficial for Climate Change (CC) and Freshwater Ecotoxicity (ECf), particularly under optimized production scenarios. However, the process is characterized by a high Water Use (WU) impact, which is approximately 320% higher than conventional benchmarks even in the best-performing conditions.

Liquid Valorisation Line (LVL): This multi-product line demonstrates a net environmental advantage in Climate Change and Resource Use (Fossils), primarily due to the internal recovery of energy from biogas, which offsets a substantial portion of operational impacts (up to 41% for CC). Conversely, Land Use (LU) remains a critical category, driven by the requirement of grass as a primary feedstock.

Solid Valorisation Line (SVL): The thermochemical conversion of solid digestate into microbial protein and biofertilizers is competitive with organic and inorganic fertilizers regarding Climate Change. The environmental viability of this line is highly sensitive to syngas productivity and quality (LHV); achieving high productivity (e.g., 20 m^3/h at 20 MJ/m^3) can even result in net environmental credits.

The design-level analysis confirms the potential of the MANUREFINERY project to support a sustainable bioeconomy. To further enhance the environmental sustainability of the proposed systems, the following strategies are recommended:

Implementation of advanced water recirculation and treatment strategies is mandatory to reduce the direct impact on water resources. For the manufacturing of mobile units, consideration should be given to alternative materials with lower toxicity footprints to replace or minimize the use of heavy metallic structures where technically feasible. The environmental benefit of the modular units is strongly correlated with their operational efficiency (Capacity Factor); hence, ensuring continuous operation and high yields of bioproducts is essential to justify the environmental investment of the construction phase.

In conclusion, while the modular biorefinery concept yields clear benefits in terms of circularity and climate mitigation, future design iterations must focus on minimizing the resource-intensity (water and materials) of the infrastructure and operational processes

The future steps of this analysis are as follows:

- Final structuring of the LCI inventory with respect to the installed mechanical components
- Integration of Digital Twin data for the operational phase
- Integration of the End-of-Life phase
- Integration of economic data for the Life Cycle Costing (LCC) assessment

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ANNEX NO 1.

Material / Energy flows	Amount	Unit	Note
Input			
aluminium, wrought alloy	0.5	kg	
cast iron	30	kg	
copper, cathode	6.25	kg	
hot water tank factory	0.000005	Item(s)	
polyvinylchloride, emulsion polymerised	0.095745	kg	
polyvinylchloride, suspension polymerised	0.654255	kg	
steel, chromium steel 18/8, hot rolled	23	kg	
synthetic rubber	0.175	kg	
Output			
Pump	1	kW	

Tabel A1: Input of materials for the construction phase of a 1 kW capacity pump

Material / Energy flows	Amount	Unit	Note
Input			
aluminium, cast alloy	0.23	kg	
aluminium, wrought alloy	0.50	kg	
cast iron	5.67	kg	
copper, cathode	1.00	kg	
injection moulding	0.07	kg	
polystyrene, high impact	0.07	kg	
printed wiring board, surface mounted, unspecified, Pb containing	0.00	kg	
printed wiring board, surface mounted, unspecified, Pb free	0.00	kg	
sheet rolling, aluminium	0.73	kg	
sheet rolling, chromium steel	0.83	kg	
sheet rolling, steel	7.00	kg	
steel, chromium steel 18/8, hot rolled	0.83	kg	
steel, low-alloyed, hot rolled	7.00	kg	
synthetic rubber	0.03	kg	
wire drawing, copper	1.00	kg	
Output			
Compressor	1	kW	

Tabel A2: Input of materials for the construction phase of a 1 kW capacity compressor

Material / Energy flows	Amount	Unit	Note
Input			
section bar rolling, steel	500	kg	
steel, low-alloyed, hot rolled	530	kg	
synthetic rubber	13.6	kg	
wire drawing, steel	29.6	kg	
Output			
Conveyor Belt	1	m	

Tabel A3: Input of materials for the construction phase of a 1 m of conveyor belt

Material / Energy flows	Amount	Unit	Note
Input			
plastic processing factory	2.96E-10	kg	
polar fleece, energy use only	5.25E-02	kg	
polyethylene terephthalate, granulate, amorphous	5.25E-02	kg	
sheet rolling, steel	3.85E-01	kg	
steel, low-alloyed	1.42E-01	kg	
steel, unalloyed	2.43E-01	kg	
zinc coat, coils	1.00E-01	kg	
Output			
Air filter	600	m3/h	

Tabel A4: Input of materials for the construction phase of air filter

Material / Energy flows	Amount	Unit	Note
Input			
electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted - RO	1*RO*RE	kWh	GVL: RO=1;ES=0;SI=0 LVL: RO=0;ES=1;SI=0 SVL: RO=0;ES=0;SI=1 RE depends on the % of renewable integration in the system
electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted - ES	1*ES*RE	kWh	
electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted - SI	1*SI*RE	kWh	

market for electricity, medium voltage - RO	1.0*RO*(1-RE)	kWh	
market for electricity, medium voltage - SI	1.0*SI*(1-RE)	kWh	
market for electricity, medium voltage - ES	1.0*ES*(1-RE)	kWh	
Output			
Electricity	1	kWh	

Tabel A5: Electricity different mix for manurefinery case studies

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