

Life Cycle Assessment and Circularity Analysis of Bioproduct and Syngas Production from Agro-Industrial Waste

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Abstract:

Livestock farming is a major pillar of the European rural economy but also a key source of environmental pollution, particularly contributing to ammonia and methane emissions and nutrient losses. Despite long-standing mitigation efforts, conventional manure management still leads to soil degradation and water eutrophication. Current EU strategies promote bio-based and digital innovations, highlighting small-scale biorefineries as promising solutions, although significant technical and economic challenges remain in achieving efficient, circular, and competitive manure valorisation. Within this framework, the ManuREfinery project aims to implement a smart, modular, mobile, and sustainable small-scale decentralized biorefinery to convert livestock manure into value-added bio-based feed products, fertilizers and syngas or biogas. The proposed innovative system consists of three distinct treatment lines targeting the valorisation of gaseous, liquid, and solid effluents. Each treatment line is applied to a real case study: a poultry and swine farm in Romania, a swine farm in Spain, and a cattle farm in Slovenia. In this study, a Life Cycle Assessment is conducted to evaluate the environmental performance of the three valorisation pathways, with the aim of identifying their main strengths and weaknesses

Keywords:

Manurerefinery; Life Cycle Assessment, Biogas production, Circular Economy

1. Introduction

The livestock sector supports the livelihoods of millions of people, but entails significant environmental challenges, including greenhouse gas emissions, eutrophication, acidification and biodiversity loss (Mottet et al., 2017).

One of the main critical issues in the agro-industrial sector is concerned to nutrient management. In fact, between 55 and 95% of the nitrogen (N) and approximately 70% of the phosphorus (P) ingested by livestock are excreted through urine or faeces (Menzi et al., 2010). The imbalances between imported and exported nutrients in livestock systems can cause significant losses to the environment (Waldrip et al., 2015). In this context, manure represents one of the most problematic residues: of little commercial value, it is responsible for multiple environmental impacts (Battini et al., 2014). However, owing to its high content of organic matter and nutrients such as nitrogen, phosphorus and potassium (Zubair et al., 2020), it can become a valuable resource if managed properly. Advanced management strategies have indeed been developed, such as anaerobic digestion and reuse waste material as fertilizers. The latter approach offer great potential for nutrient recovery, bioenergy production and pollution reduction (Flores-Orozco et al., 2020; Pelaez-Samaniego et al., 2017). In particular, anaerobic digestion represents the most effective solution for mitigating the impacts of manure, as it generates energy in the form of biogas and produces digestate that can be used as a biofertilizer (Whiting and Azapagic, 2014; Fantin et al., 2015). The biogas thus obtained is considered a potential substitute for fossil natural gas (Morero et al., 2015) and can be used in several ways: converted into heat and energy (Boulamanti et al., 2013), purified into biomethane for injection into gas distribution networks (Agostini et al., 2015), or used for domestic purposes (Russo and von Blottnitz, 2017).

From a circular economy perspective, these strategies aim to replace the current linear system with closed-loop waste management (Montemayor et al., 2019; Tomić and Schneider, 2018), contributing to a partial reduction in dependence on chemical fertilizer production and fossil fuels (Istrate et al., 2020). A pathway thus emerges towards a more sustainable livestock sector, in which manure is no longer a waste to be disposed of, but a resource to be valorised within circular production chains.

In this context, the Manurefinery project is situated, which aims to create an innovative modular value chain to treat all waste streams from livestock farming, including the gaseous, liquid and solid phases, in order to produce bioproducts and increase the level of circularity. Specifically, the project targets the production of

biofertilizers, microbial protein as animal feed, and biogas/syngas for on-site energy self-production from the treatment of these waste streams.

In this work, an LCA analysis is presented, highlighting the advantages and disadvantages of this system compared to conventional technologies from an environmental perspective.

2. Material and Method

2.1. General description of Manurefinery Concept

As mentioned in the introduction, the Manurefinery project proposes a valorisation chain based on three lines, which are described in detail below.

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 m³ 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. **Liquid Valorisation Line (LVL)** treat raw animal manure through a thermophilic anaerobic digester, which produces biogas and mineralises organic nitrogen into ammonia. Part of the biogas is converted into microbial protein via a pressurised bioreactor, while the digestate is centrifuged to recover phosphorus. The liquid fraction is treated through an innovative ammonia stripping process that fixes CO_2 as ammonium bicarbonate (NH_4HCO_3) for fertiliser production, and the residual water is reused for on-farm fertigation. In parallel, harvested grass is processed to extract proteins and a sugar-rich liquid, the latter being biologically converted into caproic acid for use as a prebiotic in pig nutrition. The demonstration plant, installed at a pig farm in Spain, annually produces approximately 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, thus circularly valorising both livestock waste and plant biomass. **The Solid Valorisation Line (SVL)** processes the solid fraction of digestate obtained after centrifugation, which is continuously dried using residual on-site heat. This phosphorus- and potassium-rich material is then gasified into syngas, which is biologically converted into acetate using an acetogenic microbial consortium in a U-loop fermenter. The resulting acetic acid is subsequently fermented aerobically by *Cupriavidus necator* to produce microbial protein for feed applications, while the ash from gasification is recovered as a phosphorus- and potassium-rich raw material for fertiliser production. The system consists of a fixed drying unit and mobile units for gasification, syngas fermentation, and protein production, deployed on-farm when sufficient dried digestate is available. At demonstration scale, the plant produces annually 1,588 kg of microbial protein and 4,285 kg of ash, corresponding to 3.5–6.2 kg of protein and 10–17 kg of ash per tonne of manure treated. Additionally, the physicochemical properties of the gaseous streams are used to define suitable CHP configurations to meet farm-specific energy demands. In Figure 1 there is the diagram of the three lines. However, due to a lack of data, the LVL is not addressed in this work; only the two lines GVL and SVL are covered.

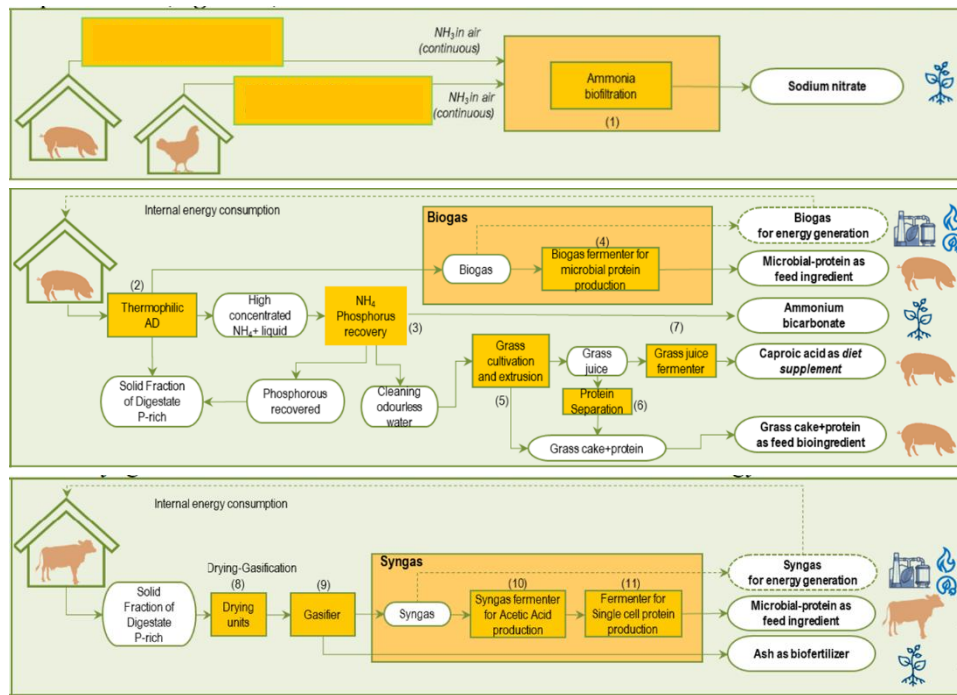


Figure 1: Manurefinery concept

2.2. Main assumptions for GVL

The functional unit (FU) of the GVL is defined as 1 kg of sodium nitrate (NaNO_3) produced, with two reference production rates considered, 0.4 kg/day and 1.1 kg/day, defining Scenario 1 and Scenario 2 respectively. Since the GVL is a single-product process, no allocation approach is applied. The two farm configurations differ only in the presence of an existing 200 kW photovoltaic system at one farm, which is assumed to exclusively cover the electricity demand of the ventilation system feeding the GVL, meeting approximately 73% of its total electrical energy needs. Two additional key parameters, the capacity factor (CF, ranging between 0.4 and 0.6) and the liquid flow rate within the biotrickling filter, significantly influence the results and were therefore included in a combined parametric analysis, with all relevant scenario parameters summarised in Table 1.

Table 1. Main Parameter for GVL model.

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	NaNO_3 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:

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

2.3. Main assumption for SVL

The SVL is a multi-product process yielding three bioproducts: microbial protein, biofertilizer, and syngas. A combined allocation approach was adopted. Mass-based allocation was applied to the two primary bioproducts, distributing environmental burdens proportionally to their mass flows, resulting in allocation

factors of 72.96% for biofertilizer and 27.04% for microbial protein, based on annual productions of 4,285 kg/year and 1,588 kg/year respectively. Syngas, on the other hand, was handled via system expansion, treating it as an avoided conventional energy source and crediting the system with the corresponding environmental offsets. The functional unit is defined as 1 kg of either microbial protein or biofertilizer. Five scenarios were investigated, each reflecting a progressively higher share of renewable energy through incremental 25% steps of PV integration. A parametric analysis was conducted on three syngas-related variables, production rate (0–40 m³/h), lower heating value (10–20 MJ/m³), and conversion efficiency to electrical energy (20–30%), given their significant influence on the overall environmental results.

Table 2. Main Parameter for SVL model.

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 include the construction, maintenance, and operation of all mechanical devices within the SVL, as well as direct emissions, grid electricity, and chemical and water consumption. Transportation of machinery and control devices are excluded. For the comparative assessment, multiple reference products were considered from the ecoinvent database for both bioproducts. For the biofertilizer, four reference products were selected, covering nitrogen- and phosphorus-based fertilisers in both inorganic and organic forms; inorganic fertilisers are based on a European market average, while organic ones are assessed at a global level. The specific ecoinvent dataset providers are reported below.

- Inorganic Fertilizer N: market for inorganic nitrogen fertiliser, as N (Germany, Spain, France, Italy, Romania, Slovenia)
- Inorganic Fertilizer 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

Regarding microbial protein, all protein-based substances available in the ecoinvent database that are applicable to animal feed were selected as reference products, on the grounds that they can fulfill the same functional role as the Manurefinery bioproduct. The specific ecoinvent dataset providers are reported in the table 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

3. Life Cycle Impact Assessment

3.1. GVL

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 2, 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 NaNO₃ production amounts to 401 g/d, these categories show unfavourable environmental performance. In contrast, Scenario 2, corresponding to maximum NaNO₃ 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.

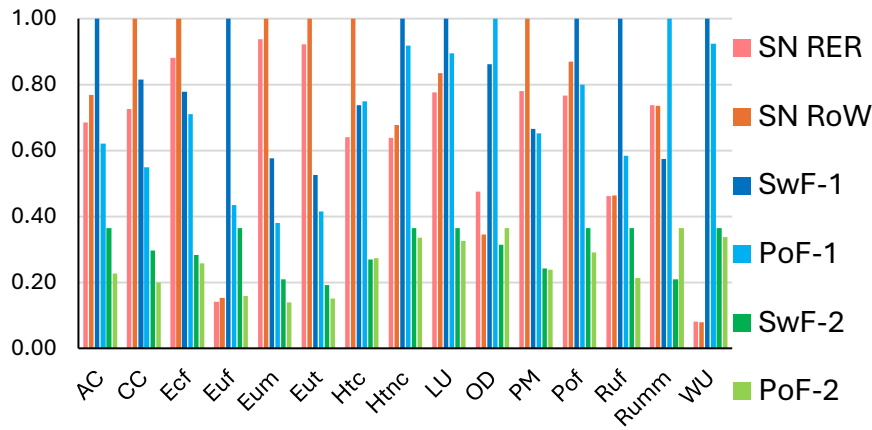


Figure 2: Impact analysis percentage comparison GVL

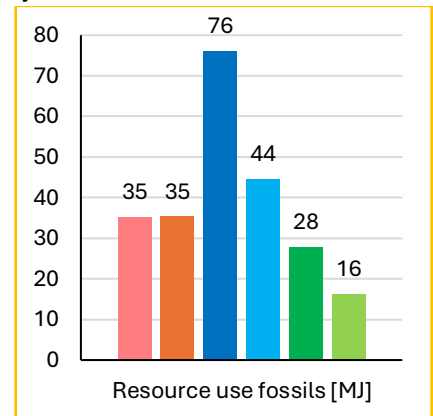
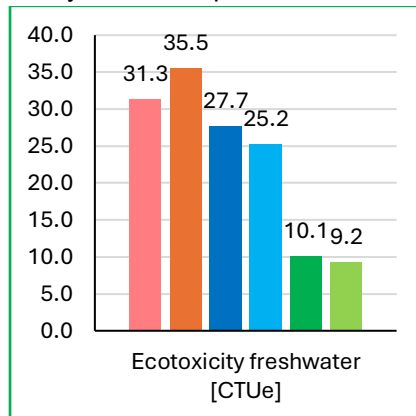
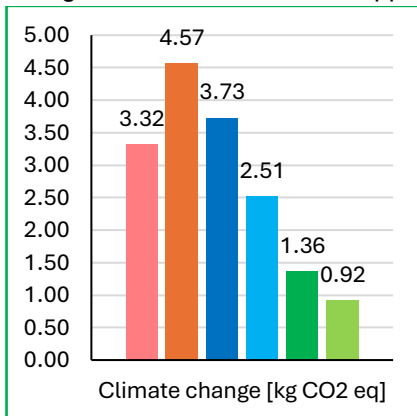
Figure 3 presents the most relevant indicator, evaluated by normalization. The reported indicators are expressed at the midpoint level and refer to their specific units of measurement. Graphs highlighted with a green box identify indicators that are favorable for the GVL system. As shown for CC, the worst-performing scenario (SwF-1) exhibits an impact of 3.73 kg CO₂ 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. 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.



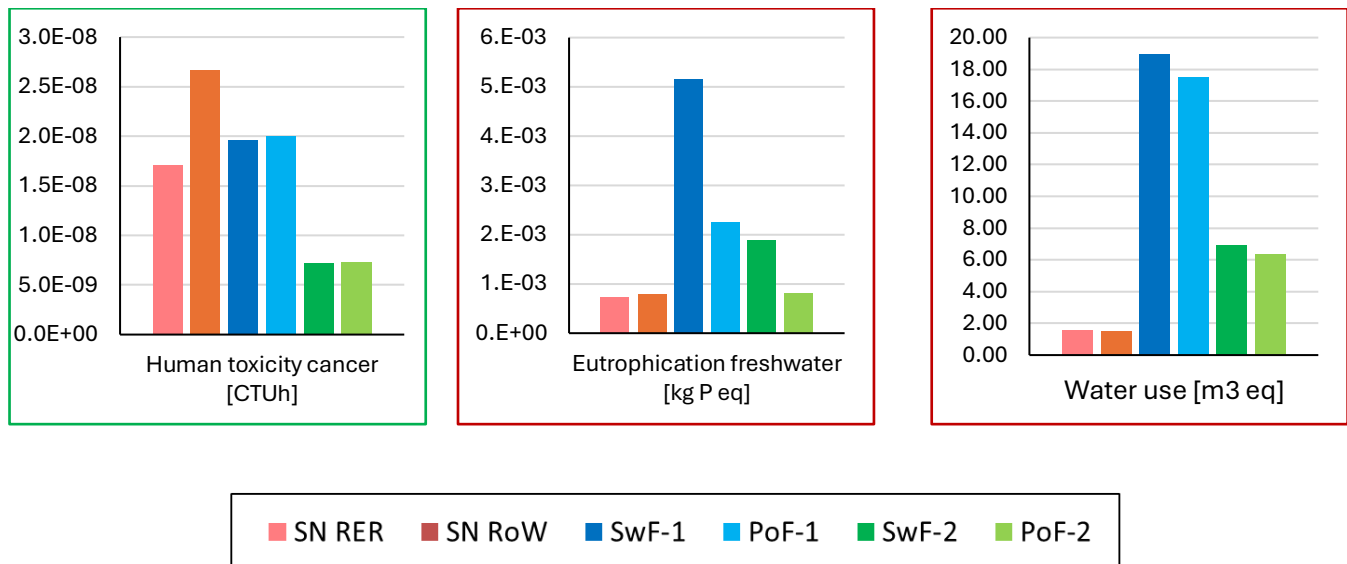


Figure 3: Impact assessment analysis, main indicator and comparison - GVL

Figure 4 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.

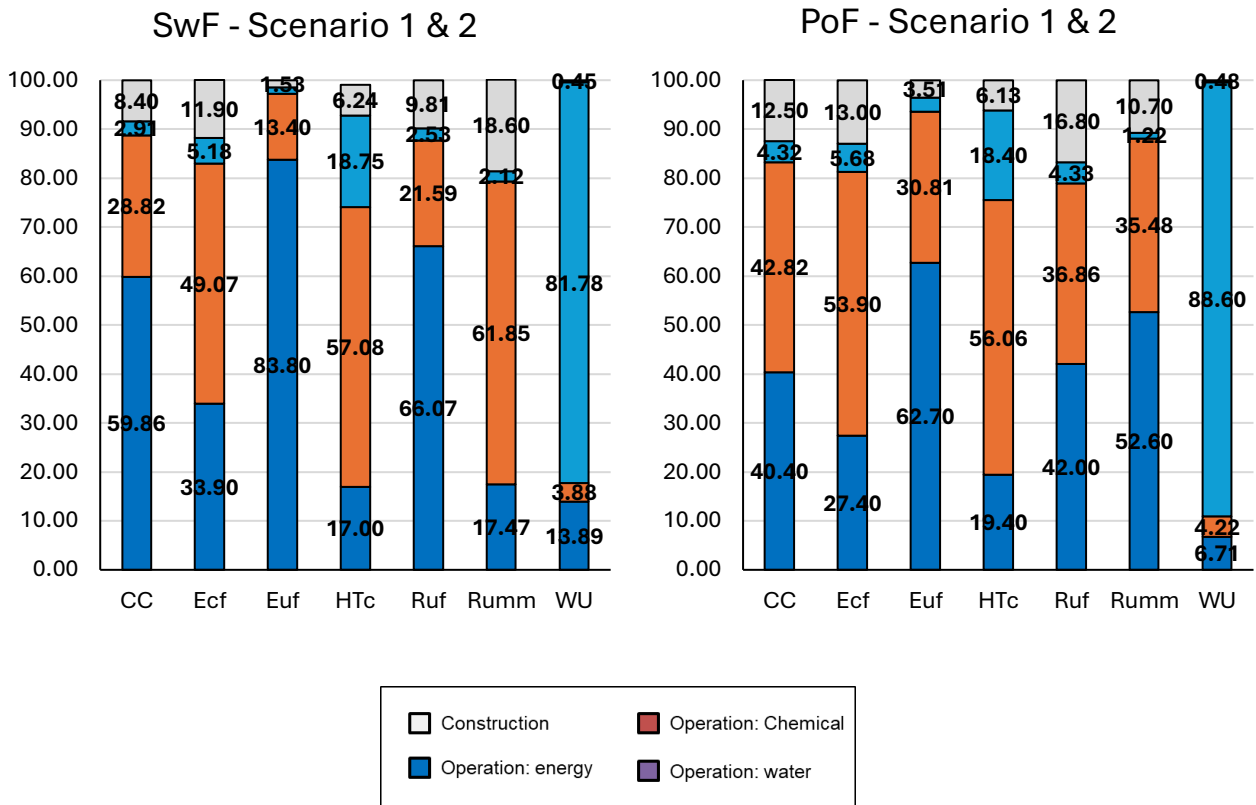
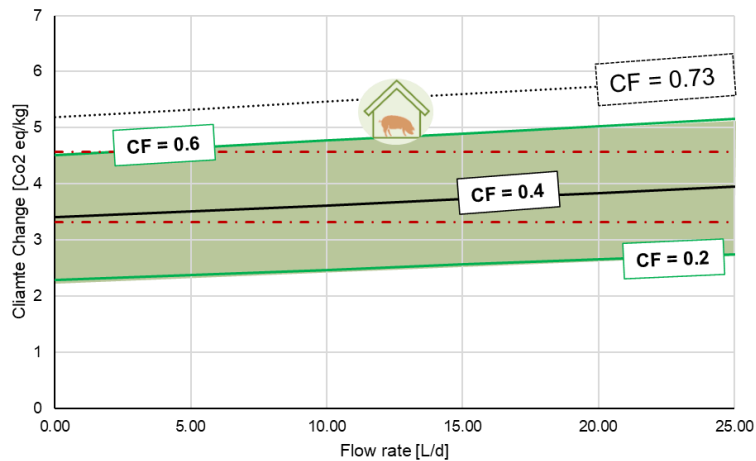


Figure 4: Contribution analysis - GVL

Figure 5 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.



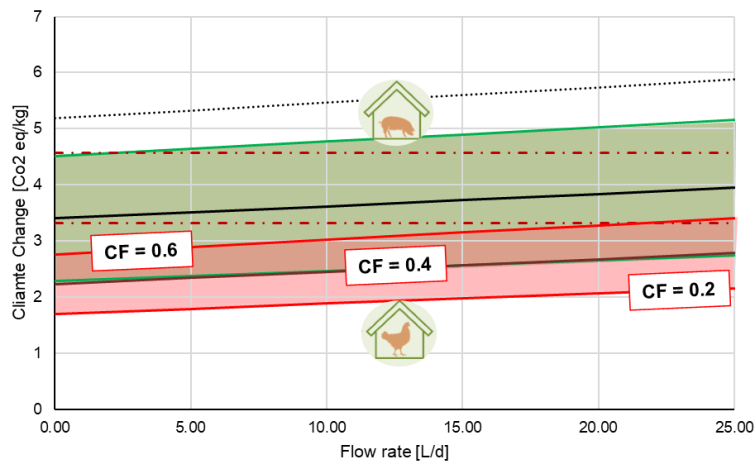


Figure 5: Parametric analysis for Climate Change indicator - GVL

3.2. SVL

Figure 6 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.

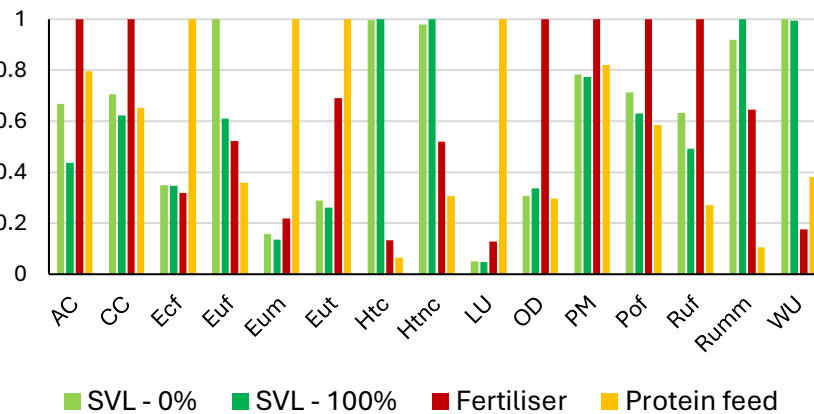


Figure 6: Impact analysis percentage comparison SVL

Figure 7 compares five SVL scenarios under different levels of renewable energy integration against conventional inorganic and organic fertiliser production across four environmental impact indicators. For CC, the Manurefinery-based fertiliser performs approximately midway between inorganic and organic references, confirming its viability from a climate mitigation perspective. For Euf, results are strongly dependent on PV integration: at 25–50%, impacts are only slightly lower than inorganic production, while at 75–100%, reductions exceed 30%. WU and Htc show substantially higher impacts, highlighting the need for water recycling strategies and the adoption of less impactful materials in plant design, respectively. Overall, organic-based fertiliser production proves environmentally more favourable than conventional inorganic production, though it should be noted that the agronomic effectiveness of the fertiliser, which may differ from conventional products, is not captured within this analysis.

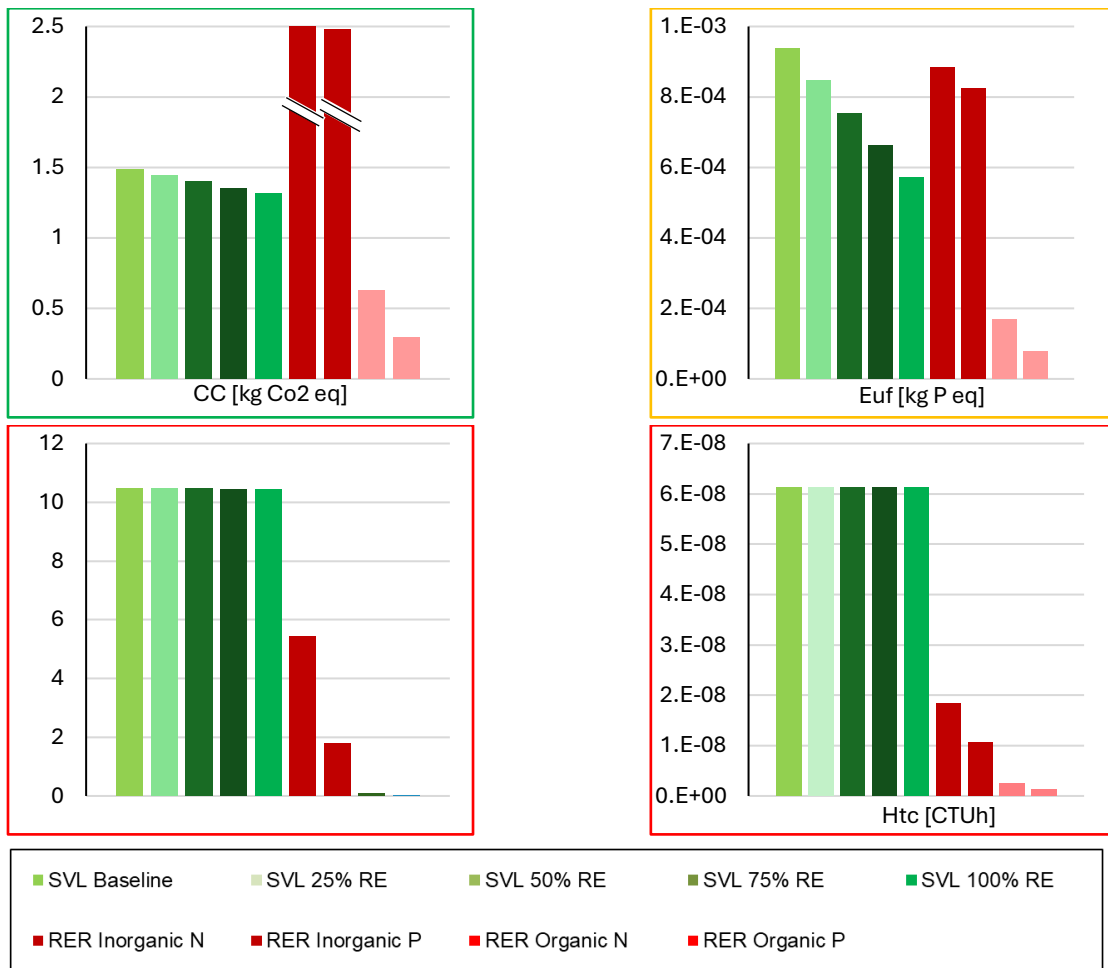
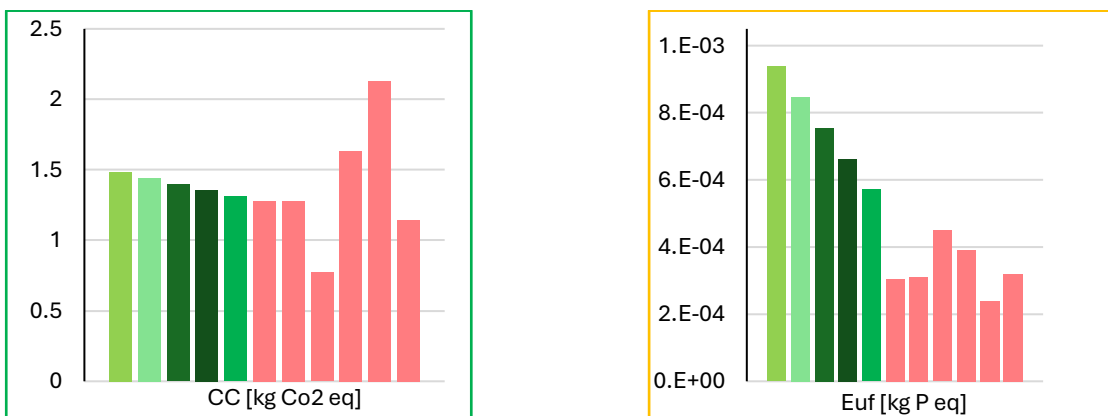


Figure 7: Impact assessment analysis, main indicator and comparison – LVL Fertiliser comparison

Figure 8 compares the SVL microbial protein against conventional protein feed products, showing that renewable energy integration has a relatively limited influence on the results. For CC, the Manurefinery-based protein performs favourably, with impacts ranging from 1.48 to 1.31 kg CO₂ eq, clearly below those of conventional protein feed. However, no environmental advantage emerges for Euf, WU, and Htc. Water use remains a critical issue, though a reduction of at least 30% in water consumption would likely bring impacts close to those of the most water-intensive reference products, given the current difference is relatively modest (~19%). Htc is mainly driven by the construction phase, while Euf is primarily influenced by energy demand. It should also be noted that the reference products include soybean meal, maize, tofu, barley, rapeseed meal, and protein compounds, and that the Manurefinery product is characterised by a higher protein content and quality standard, an aspect that, however, is not captured within the present assessment.



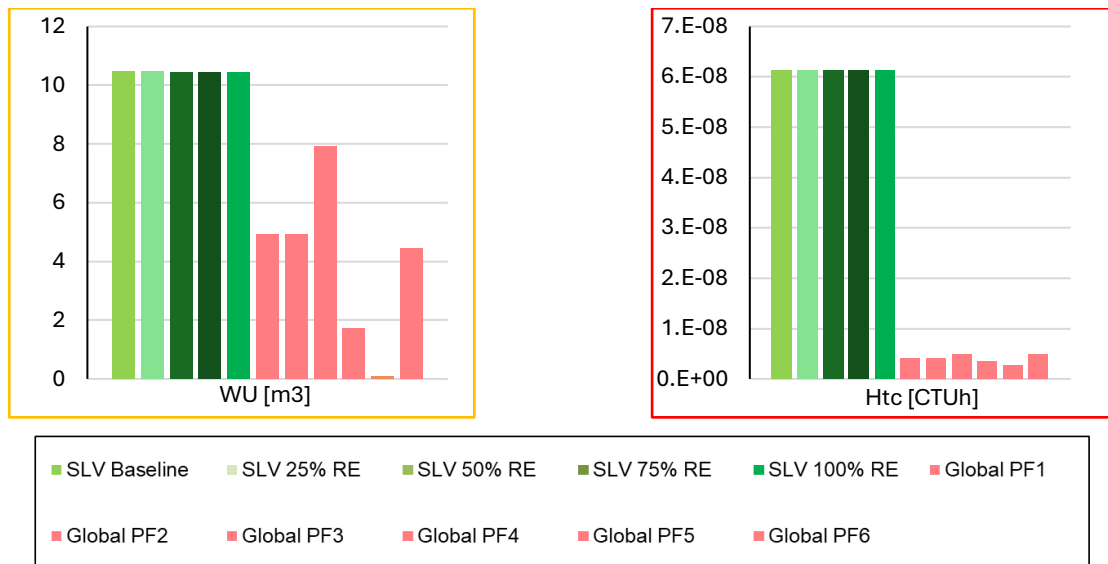


Figure 8: Impact assessment analysis, main indicator and comparison - LVL protein feed comparison

Figure 9 presents the contribution analysis for the SVL system under 0% and 100% renewable energy scenarios. The overall trend is similar across both, with the main difference being a reduction in the relative contribution of energy consumption in the fully renewable scenario: CC drops from 46.5% to 15.9%, Euf from 49.0% to 6.7%, and Ecf from 33.9% to 24.6%, while Rumm increases from 20.0% to 67.1% due to its sensitivity to indirect energy-related impacts. Chemical inputs contribute negligibly across all indicators (never exceeding 3%), whereas the construction phase represents a major source of impact, particularly for Htc, where it exceeds 71%, driven by the extensive use of metals. Syngas also plays a significant role, accounting for more than 45% of CC, 33% of Ecf, and 48% of Euf. Finally, water consumption is the dominant contributor to WU, reaching 57–63% of total impacts across the two scenarios, further underlining the need for water recirculation strategies within the SVL system.

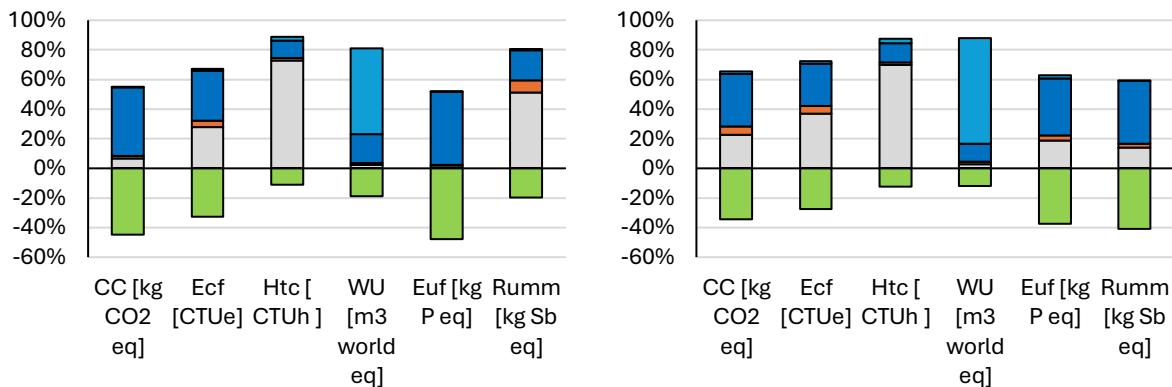


Figure 9: Contribution analysis - SVL

Figure 10 illustrates the parametric analysis of the CC indicator as a function of syngas productivity, under varying conditions of lower heating value (LHV) and conversion efficiency. As expected, environmental impacts decrease with increasing syngas productivity, though the response range differs across scenarios. At LHV = 20 MJ/m³, the lowest impacts are achieved, reaching a minimum at 20 m³/h and even resulting in a net environmental credit. At LHV = 15 MJ/m³, comparable impact levels to the reference systems are reached at approximately 30 m³/h, while at LHV = 10 MJ/m³, a similar performance is only achieved at around 38 m³/h. These results highlight the strong influence of syngas quality on the overall environmental performance of the SVL system, showing that substantial environmental benefits can be obtained even at lower productivity levels when syngas quality is high.

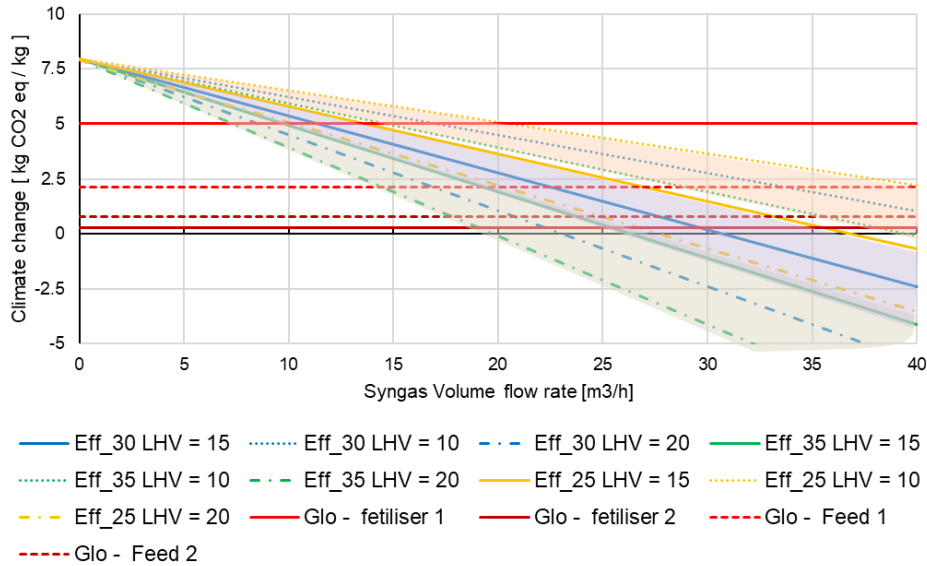


Figure 10: Parametric analysis for Climate Change indicator – LVL

4. Conclusion

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.

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., $20 \text{ m}^3/\text{h}$ at $20 \text{ MJ}/\text{m}^3$) can even result in net environmental credits, as showed in Figure 11

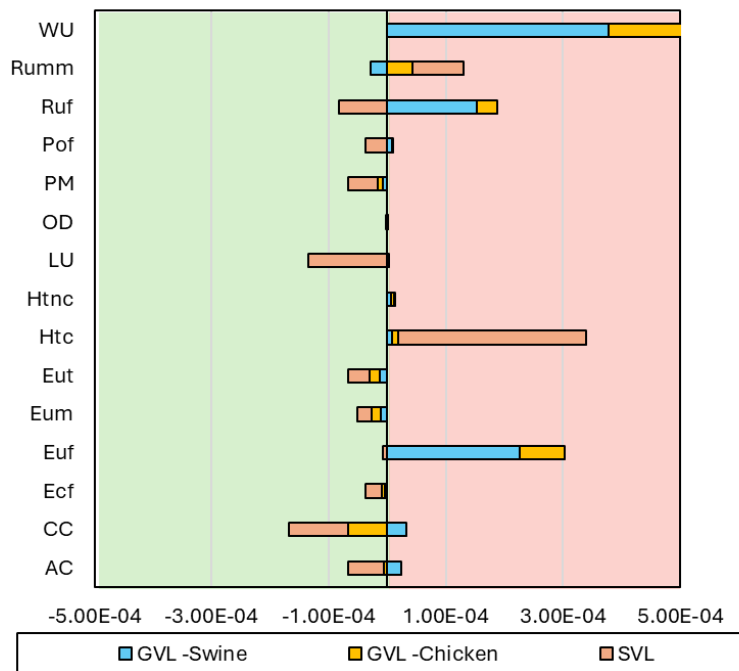


Figure 11: Whole environmental Burden or Credit in ManuREFinery

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.

Nomenclature

FU	Functional Unit	Euf	Eutrophication freshwater
LCI	Life Cycle Inventory	Eum	Eutrophication marine
LCIA	Life Cycle Impact Assessment	Eut	Eutrophication terrestrial
LCA	Life Cycle Assessment	Htc	Human toxicity cancer
EF	Environmental Footprint	Htnc	Human toxicity non-cancer
GVL	Gas Valorisation Line	LU	Land Use
SVL	Solid Valorisation Line	PM	Particulate Matter
LVL	Liquid Valorisation Line	Pof	Photochemical ozone formation
AC	Acidification	Ruf	Resource use fossil
CC	Climate Change	Rum	Resource use mineral and metal
Ecf	Ecotoxicity freshwater	WU	Water Use

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