Animal Feed from Microalgae Grown on Biogas Digestate as Sustainable Alternative to Imported Soybean Meal

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Research Article

Keywords: Animal Feed, Microalgae Grown, Biogas Digestate, Imported Soybean Meal, environmental potential, United Kingdom, France, Belgium

Posted Date: November 15th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-1044765/v1

Version of Record: A version of this preprint was published at BioEnergy Research on February 4th, 2022. See the published version at https://doi.org/10.1007/s12155-022-10397-2.

Abstract

This work investigates the environmental potential to develop a circular economy solution to create benefit from agricultural waste by integrating microalgae technology into the nutrient-rich digestate (NRD) stream from anaerobic digestion plants. Different environmental benefits can be captured by algal uptake of nitrate and the scarce resource phosphorus from biogas digestate. First, unwanted excess nutrients polluting groundwater are reduced and second, the algal animal feed can substitute soybean meal (SM) imported to North-Western Europe (NWE). That allows a decentralised circular bio-economy and avoids deforestation of rainforests due to SM overseas import. Life cycle assessments were conducted based on novel data from engineers in academia and industry, acquired through pilot-scale research facilities in United Kingdom, France, and Belgium. The findings of this study highlight the environmental impacts of three different technologies with varying scales of production and offer recommendations based on sensitive analysis for more sustainable pathways. In this study, a pilot-scale bio-refinery is considered a promising solution to excess nutrients in fertilisers in the NWE and an alternative source for imported SM as an animal feed source, having a comparable environmental footprint.

1. Introduction

In quickly evolving and changing times, the environmental damage to planet earth has been unprecedented in the last century and has exceeded the Planetary Boundaries, which are considered as a safe operating space for humanity [1] [2] provided new insights regarding the thresholds that have been crossed beyond the Planetary Boundaries like the loss of biodiversity, changes in nutrient cycles (Phosphorus and Nitrogen) land use, and climate change.

Measures to limit or hinder this damage and allow the environment to naturally reconcile are promptly required across scales and sectors. Possible measures should be efficient and multidimensional, an example with these criteria is the use of microalgae to closing carbon and nutrient cycles as well as the transformation of the fossil-based economy to a bio-economy and providing beneficial commercial end-product. Microalgae have been an all-rounder in the field of the bio-economy for more than 50 years, in the sense of their capacity to produce high-value products including food, feed, cosmetics and medicine, and third-generation biofuels in fresh or seawater or to be used in wastewater and flue gas treatment. [3] [4] [5] Regulating growth conditions, microalgae can be grown to produce algal biomass, which is rich in lipids, proteins, carbohydrates, vitamins, mineral salts, or carotenoids. [3] [5] Their great potential has kept the research vigorously ongoing, especially in the field of fuel and feed.

In North-Western Europe (NWE), two environmental challenges could be addressed by microalgae cultivation. On the one hand, the NRD as effluent from anaerobic digestion plants, which is usually applied as fertilizers on agricultural lands is considered a critical issue for its groundwater quality due to the eutrophication impact as a result of high and access nitrogen content which is exceeding the nutrient demand of the plants grown on the fields. The other problem is depicted in the dependability of the NWE countries on importing animal feed such as SM to satisfy their needs, which leads to environmental impact through overseas transportation, deforestation of rain forest at the exporting land to satisfy the demand and is thwarting decentralization which is a goal of the energy transition. [6]

Microalgae's promise and potential to contribute to a natural-based biological solution to tackle these challenges is based on their ability to uptake nutrients from waste streams and thus to reduce the nutrient load by the application of digestate from biogas plants and reduce the eutrophication impacts respectively in vulnerable groundwater areas. Likewise, microalgae could grow on NRD, thus treating the digestate before it is used as a fertilizer. [7] Anaerobic digestion (AD) in NWE has become a crucial technology to produce biogas which is converted in a CHP plant to renewable electricity and heat or upgraded to methane and fed into the gas grid to substitute natural gas by green gas.

The main feedstock for anaerobic digestions (AD) in biogas plants is manure, crops such as maize, and organic waste.[8] A by-product of AD is digestate, which is mainly spread on the fields or exported as a fertilizer to countries with fertilizer demand and/or fewer regulations regarding the application of NRD. The other promising application of microalgae is their use as a substitute for animal feed. Some microalgae species like Spirulina, Chlorella vulgaris, Scenedesmus, *Laminaria digitate*, and *Porphyridium* sp are evaluated to be suitable, even preferred as the protein source for some animals, mainly fish, poultry, and pigs. [9]

In NWE, SM is one of the major sources of protein in the pig industries. [10] Due to weather conditions and the unavailability of agricultural lands, SM is mainly imported from Brazil in South America. [6] Soybean is one of the most important crops in the world to satisfy the growing demand for feed, food, and biofuel [11] [12], and its importance is still rising. This is evident by the soybean global harvested area which has been increased from 23.8 million hectares in 1961 to 120.5 million hectares in 2019. [13] South America is a key region in the world market for soybean, with Brazil, Argentina, Paraguay, and Uruguay being major producers and exporters worldwide. Since the products derived from soybean and maize are mainly destined for animal feeding, their production plays a fundamental role in the environmental sustainability of the growing world livestock activities [14], which are currently attributed to the greatest impact in agriculture. [15] Not only does soybean import afflict environmental damage through overseas transport processes, it also projects a risk factor on the stability of the European economy from a decentralization point of view. Besides, this disturbs the sustainability cycle where, pig manure as the waste product from SM, is not reutilized as a fertilizer for the original agricultural land.

Taelman et al. conducted a comparative LCA on algal and SM as a protein-rich animal feed ingredient. They concluded that the resource footprint of the large-scale soy meal production was a factor of 10^2 lower than small-scale microalgae production in ponds in the Netherlands. [6] The reason for the poor performance of the algae is mainly due to the energy-intensive algae cultivation stage. Taelman et al. (2015) pointed out that higher algae productivity and the use of renewable energy could significantly decrease the environmental impact of microalgae feed production. [6] Based on real data from three different pilot plants in the United Kingdom, France, and Belgium the objective of this work is to investigate if and how domestic small-scale microalgae with improved productivity and circularity by their integration in biogas plants and their material flows (e.g. energy and nutrients including CO_2) can be a potential substitute of SM from an environmental perspective.

For this purpose, we focused our research on the application of NRD from biogas plants fed with agricultural waste (e.g. manure) and carbon-rich biogenic waste (e.g. from the food industry) for the cultivation of microalgae. We aimed to close the knowledge gap on the possibilities of turning waste into raw materials and using them to create added value and establish a circular bio-economy at the local or regional scale and breaking the long global supply chains in animal feed production and the interlinked dependencies. This study with real experimental data to feed the life cycle assessment (LCA) model aims to help fill the gap identified in literature and take a step towards identifying the environmental chances and challenges of this novel approach. Beyond that our results and insights on the intended and unintended ecological impacts will be used to give scientific support to decision-maker. This novel combination of algae and biogas technologies with different technology readiness levels (TRL) can help to reach the political targets to reduce the nitrogen and phosphate loads from digestate spread on the fields as fertilizer. [7] This is a big challenge as this can lead to an increase in nitrate in the groundwater. Also, this technology could be an efficient way of using the scarce resource phosphate.

The method applied was LCA as this is a standardized analysis tool for compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle. In other words, it covers the environmental impact of every stage of a product or a system, from the utilized raw materials and their extraction, the production processes of the products, the operational impact “use phase” and the end of life “disposal”. [16]

2. Methods And Materials

2.1. LCA Methodology

This study follows the recommendations of the ISO 14040 and 14044 frameworks regarding goal and scope definition, inventory analysis, life cycle impact assessment (LCIA), and interpretation as shown in Figure 1. The tool used to carry out the LCA is openLCA version 1.10; an open-source software with a broad range of compatible databases and assessment methods that help to quantify the impact of different processes on the environment. The unit processes are selected from ecoinvent 3.5, which is used as the main database. Ecoinvent provides real-life data in the form of “flows” that are interconnected with the environmental data of these flows. [17]

2.1.1. Goal and Scope of the Study

The overall aim of the Interreg NWE funded interdisciplinary research project “ALG-AD - Creating value from waste nutrients by integrating algal and anaerobic digestion technology” bringing together a group of scientists and engineers from 11 different partners from academics and industry in four countries across the NWE was to develop a circular economy solution to create wealth from waste by the integration of the algae technology into the NRD stream produced by anaerobic digestion plants by extraction and reduction of excess nitrate and making use of the scarce phosphorus. The goal of this study is to assess the life cycle of the ALG-AD technologies for their environmental impacts and to have valuable insights concerning the combination of biogas production and microalgae cultivation.

The three pilot plants are located in the NWE region, specifically, United Kingdom (Langage-SU), Belgium (Innolab-UG), and France (CNRS-UBO). This region is characterized by rather wet and windy weather with intermediate temperature variations. The pilot plants are designed in combination with or as an extension of three different biogas plants where an AD is used to produce biogas from crops, agricultural, and food waste as a feedstock. The liquid fraction from the NRD produced by the AD is applied as a nutrient source to microalgae after dilution and treatment. The cultivated microalgae are harvested, partially dried, and post-treated to be used as animal feed. The LCA compares the combined algal AD technology with an existing animal feed production, considering that the traditional feed product will be substituted by the algal-based feed product. In this work, SM imported from Brazil is defined as the reference product, since it is commonly used as animal feed in the NWE region. Hence, overseas transportation and occupation of agricultural lands could be avoided by replacing SM with algae-based animal feed. Figure 2 shows the process outline of the ALG-AD.

2.1.2. Functional Unit and System Boundaries

The overall functional unit (reference product) of the ALG-AD technology is described as “1 kg dry mass of algae-based animal feed additive”. This functional unit shall consider and credit potential by-products and alternative functions (such as excess energy of the AD process, produced fertilizer, avoided emissions from NRD storage and spread) resulting from the overall system.

The general approach of the LCA is gate-to-gate. It, therefore, does not include production, collection, and delivery of the biomass feedstock for anaerobic digestion and excludes the use of algae-based feed-additive in livestock production (end product). The system boundaries of the LCA are shown in Figure 3. The upstream processes include the production, pre-treatment of the digestate and microalgae cultivation. The downstream processes include the harvest and post-treatment to process the algal biomass to the feed product. The overall ALG-AD technology system (figure 3) consists of four subsystems (SS):

- SS1: Anaerobic digestion (including the combined heat and power plant);
- SS2: Digestate processing (separation of solids, nutrient separation, and preparation, i.e. dilution with water);
- SS3: Microalgae cultivation (inoculation, cultivation, and harvest);
- SS4: Algae biomass processing (drying, crushing, and milling, and oil extraction)

Within the system boundaries, the following inputs and outputs are considered:

- Material input and output flows and their production processes: biomass feedstock, freshwater, glucose feedstock, additional nutrients, chemicals for cleaning, ammonia emissions during biogas production and NRD storage;
- Energy inputs, outputs, and internal usage: for digestate processing, pumping the NRD fertilizer and carbon source supply to the algae culture as nutrient and for pH control, heating and cooling the photo-bioreactor (PBR), harvesting and processing the algal biomass;
- Construction and infrastructure: buildings, greenhouse, filters, storage tanks for NRD fertilizer, pipelines, pumps, microalgae cultivation reactors, centrifuge, and incubation tank.

The temporal boundary reflects a one-year baseline period of the technology. All data (by considering lifespan and useful life of construction, appliances, or tools) is, therefore, annualized accordingly.

2.2. ALG-AD Pilot Plants and Case Studies Outline and Description

This section describes three different ALG-AD pilot plants with combined algae and biogas technology and their specific settings and configurations: Langage-SU, CNRS-UBO, and Innolab-UG. The description is based exactly on how the real experiments were conducted without any improvement or literature-based protocols. More details about the subsystems are discussed in the section 'Life cycle inventory (LCI)'.

2.2.1. Langage-SU

The company Langage is active along the entire value chain, from the herding of cows to the sale of the dairy product. They have designed a closed-loop system consisting of the Langage Dairy Farm with 250 cows, the Langage AD plant, and the dairy production unit. The company is using bio-fertilizer (digestate) from the AD plant to grow lush grass to feed its Jersey herd, which then produces the rich Jersey milk which is turned into dairy products such as clotted cream, ice-cream and yogurt. Wastes from both the product outlets and the dairy products factory are brought back to the AD plant to produce electrical power, heat, and fertilizers which are required to run the Langage closed-loop system.

In this section, the base scenario of the ALG-AD pilot facility Langage-SU is described reflecting that of the actual pilot plant which is located within the AD plant Langage-SU in Plymouth and operated in association with Swansea University (SU), both located in the United Kingdom (figure 4). Being located within the AD plant complex, the digestate treatment, microalgae cultivation and harvesting take place in a specially built greenhouse. The AD consists of three digesters, which are fed with food waste and waste from dairy products. A combined heat and power plant (CHP) is affiliated to the plant, where the biogas is used to produce electricity and heat, for internal and external use. The digestate is treated on-site to separate the solid part from the liquid part. The solid part is then sun-dried and transported for use as a fertilizer. Whereas, the liquid part is further filtered and stored in a digestate storage tank to be used in the microalgae cultivation phase. Concerning the cultivation of microalgae, *Chlorella vulgaris* is the specie of choice. The culture is first cultivated under phototrophic conditions and then under mixotrophic conditions before the algal biomass is harvested. Through hydrolyzation, the biomass can be treated to increase the bioavailability of the ingredients, respectively the protein content, then dried to be eligible for use with the animal feed.

2.2.2. CNRS-UBO

is part entails the base scenario of the ALG-AD CNRS-UBO's case study, where the processes to be mentioned, reflect those of the actual pilot plant located in Brest (France) within the University of Western Brittany (UBO) and being investigated in close cooperation with the French National Centre for Scientific Research (CNRS), both located in France (figure 5). UBO is closely interlinked with the company Cooperl which is an agricultural and agri-food cooperative of the Grand-Ouest region of France. Over the years, it has become the French leader in pork with a very strong capacity for innovation and a perfect mastery of all the links in the chain from breeding, genetics, animal nutrition, building equipment, slaughtering and processing, and salting to a network of butcher's shops and delicatessens, and even on-farm shops. Beyond that Cooperl operates a center based on the circular economy which is dedicated to the recycling of effluents into organic fertilizers, energy (steam, biogas, and biofuels), and recycled water.

The pilot plant for the cultivation of microalgae is located within the AD plant complex, however, in an uninsulated industrial building. The biomass feedstock is solid manure from local farms. Biogas is produced and sold to the national grid, while the energy required for running the plants is bought from the grid. The digestate is centrifuged, and the solid part is then dried and the liquid part delivered to the evapo-concentrator, to be filtered and purified. A heterotrophic-based reactor is used for microalgae cultivation. The species of microalgae used in this pilot is *Aurantiochytrium m.*, which is a genus of eukaryotes. The algal biomass is harvested and treated to be used as animal feed.

2.2.3. Innolab-UG

In this section the base scenario of the Innolab-UG pilot facility at Innolab, located in Oostkamp, Belgium and affiliated to the Ghent University is described (Figure 6). Innolab is a laboratory offering a wide range of services in connection with biogas production, purification of waste water and analysis of biomass. They are a research and service laboratory with more than 10 years of experience in the entire analytical follow up and technical guidance of biological purification and processing. The AD plant, which is located in Pittem, 20 km away from the pilot plant at Innolab, is using food waste as the main feedstock. A CHP converts the biogas into electricity and thermal energy for internal use and to be fed to the grid. The digestate is treated first at the AD plant through centrifugation. The solid part of the digestate is dried and used as a fertilizer, whereas, part of the liquid part is taken to the microalgae pilot plant Innolab-UG and further filtered before added to the PBR. Microalgae species mixture of *Chlorella* and *Scenedesmus* is used. After inoculation in the lab, the culture grows in a multi-layer horizontal PBR, the microalgae are continuously circulated in the PBR under the sun and flow through a dark tank triggering a mixotrophic phase.

2.3. General assumptions for the three ALG-AD pilot plants

The pilot facilities of the ALG-AD are assumed to operate in the same location without any renovation and under the same settings and policies for eleven months of the year. For one month the plants are not in operation to allow for maintenance work and major cleaning. This period of inactivity is divided into 4 weeks and it is assumed that this production stop will happen during one week every three months. However, regarding the ALG-AD pilot plant CNRS-UBO in France, the facility is assumed to be running for 12 months a year due to the simplicity of cleaning and maintaining the reactors.

Energy consumption during the inoculum preparation at the ALG-AD pilot plants Langage-SU and Innolab-UG was not considered, as it is done only at the beginning of the pilot plant operation and due to the negligible impact of this process in comparison to the whole system (Onorato and Rösch 2020). The embodied energy during the production and transport of equipment was not considered due to the complexity of acquiring such information. This complexity is based on the lack of reliable communication with the manufacturers and/or confidentiality. Considering a lifetime of only one year, constructions and equipment used within this pilot facility are assumed to have a maintenance-free one-year operation. Since the pilot facility Langage-SU in Plymouth is located on-site of the AD plant, no transportation impact is included. The microalgae cultivation is assumed to be stable with continuous production throughout one year and with no contamination or crush of cultures. All the processes are done on-site with no transportation requirements to subcontractors. There was no monitoring of emissions within the pilot facilities and hence data for gaseous emissions were not included.

2.4. Life Cycle Inventory (LCI)

Data acquisition is a very challenging yet sensitive step in LCA. It depends on the reliability of the source, from a feasibility point of view and a veracity point of view. It also depends on the compatibility of these data with the database that is being used in the assessment, because in most cases, it is very hard to obtain and create LCA elements without having the background data at hand. Be it personal communication or literature review, there are challenges with the ease and willingness of providing the data in a profound manner and challenges with the accuracy, punctuality, and availability of the data, especially for new technologies and processes. In this study, primary data from the project partners working in the pilot facilities are used, however, some literature-based data was essential to create elements that were not provided or found on the database. Information about the equipment was gathered from the manufacturers' websites and/or by interviewing colleagues from the relevant technical departments. Background data was based on ecoinvent database v3.5. [18]

Table S1 shows the inputs and outputs of the three ALG-AD pilot plant base scenarios presenting two different cultivation technologies, which are compared during this assessment. Inputs and outputs of the LCA model including equipment, materials, and consumables data are found in Table 1. The negative numbers for the nutrients nitrogen, potassium, and phosphates displayed in Table 1 are given to acknowledge and model the reduced environmental impacts by the avoided nutrient excess from the digestate, which is up taken by microalgae instead of being wasted as shown in the cultivation section of Table 1. All equipment used at the microalgae facility is modelled according to available data, either from the partners, manufacture websites or contacts in the industry. The details for the equipment mentioned as items in Table 1 will be found in Table S2 in the supplementary information.

Table 1
Inputs and outputs of the LCA model of the three ALG-AD pilot plants

	ALG-AD pilot plants			
	Langage-SU	CNRS-UBO	Innolab-UG	Unit
Greenhouse	140	-	52	m^2
Subsystem 2: Digestate treatment				
Inputs				
Untreated digestate	5	1.56E+05	1.6	ton/yr
Filter membrane	1	-	-	items
Electricity	77	36500	-	kWh/yr
Mobile pump	1	-	-	items
Polyethylene	12.7	-	-	kg/yr
Paper filter	-	-	1	items
Centrifuge	-	1	-	items
Polyacrylamide	-	5.00E+04	-	ton/yr
Output				
Treated digestate	4	1.70E+05	1.5	ton/yr
Subsystem 3: Microalgae cultivation and harvesting				
Inoculation				
Inputs				
Glass tube	0.01	2	0.01	kg/yr
Polyethylene	0.0005	1	0.0005	kg/yr
F/2 media	2.5	-	-	g/yr
Glucose	-	46	-	kg/yr
Yeast	-	0.2	-	kg/yr
sea salt	-	34.5	-	kg/yr
Water	1	6.8	0.5	m^3
Electricity	-	2	-	MWh/yr
Output				
Inoculum	1	6.9	0.5	ton/yr
Photo-bioreactors				
Inputs				
Polyethylene	500	-	9	kg
Polymethyl methacrýlate	505	-	-	kg
Polyvinylchloride	590	40	40	kg
Galvanized steel	5.7	-	0.4	ton/yr
Borosilicate glass	-	-	133	kg
Stainless steel	-	-	20	kg
Polyethylene terephthalate	-	67	-	kg
Cultivation				
Inputs				

	ALG-AD pilot plants			
Electricity	51	26.3	0.74	MWh/yr
Treated digestate	4	4.3	1.6	ton/yr
Inoculum	1	6.9	0.5	ton/yr
CO_2	450	-	35	kg/yr
Glucose	132	2,590	-	kg/yr
Fluorescent lamp	40	-	-	Items
Heat pump	1	-	-	Items
Water	66	144	10	m^3/yr
Nitrogen	-147	-100	-35	kg/yr
Phosphates	-2.5	-3	-0.08	kg/yr
Potassium	-29	-27	-21	kg/yr
Pumps	3	2	1	items
Yeast	-	3.8	-	kg/yr
Seawater	-	1.44	-	ton/yr
Blower	-	1	-	items
Outputs				
Cultivar	11.26	144.5	8.8	ton/yr
Harvesting				
Inputs				
Electricity	0.96	9	0.12	MWh/yr
Cultivar	11.26	144.5	8.8	ton/yr
Filter membrane	1	1	1	items
Centrifuge	1	-	-	items
Pumps	2	1	2	items
Output				
Biomass paste	0.82	7.2	0.44	ton/yr
Wastewater	11	130	9	m^3/yr
Cleaning				
Inputs				
Water	348	713	84	m^3/yr
Bleach	150	-	-	kg/yr
Sodium hydroxide	-	240	-	kg/yr
Sulfuric acid	-	176	-	kg/yr
Sodium metasilicate	54	-	-	kg/yr
Output				
Wastewater	346	670	84	m^3/yr
Subsystem 4: Algal biomass treatment				
Incubation				
Inputs				

ALG-AD pilot plants				
Electricity	1.2	2.4	0.6	MWh/yr
Biomass paste	0.82	7.2	0.44	ton/yr
Enzyme	16.32	144.6	8.8	kg/yr
Polyethylene	12.7	12.7	12.7	kg/yr
Incubator	1	1	1	items
Water	0.82	7.23	0.44	m^3/yr
Output				
Hydrolysate	1.63	14.6	0.89	ton/yr
Spray drying				
Inputs				
Electricity	1.27	2.5	0.63	MWh/yr
Hydrolysate	1.63	14.6	0.89	ton/yr
Antioxidant	44	87	3.4	kg/yr
Drying agent	220	433	17.6	kg/yr
Spray dryer	1	1	1	items
Output				
Dried powder	0.48	0.95	0.039	ton/yr
Wastewater	1.15	13.6	0.85	m^3/yr

2.4.1. Anaerobic digestion and biogas plant (Subsystem 1)

In this section, details about the AD plant at each of the three ALG-AD pilot facilities are communicated. Since the AD plants at the three locations are not entirely part of the project, not enough data could have been provided by the operators for a detailed description of subsystem 1. Therefore, for this study, readily available AD plants, as well as CHP units taken from the ecoinvent database v3.5, were scaled accordingly to conform to a more realistic and consistent estimate.

Langage-SU

The Langage-SU AD plant comprises three mesophilic digesters each of 1,000 m^3 in volume. The digester is fed with around 20,000 tons/yr of feedstock from food waste and dairy. The AD plant produces 80,000 tons/yr of digestate and 1.8E6 m^3/yr biogas. The total produced energy by the CHP unit is around 500 kWh/yr from which the pilot facility is powered. The data used in this study however is based on a readily available process on ecoinvent v3.5 [19] and is scaled up to the size of that of the AD plant in Langage. For the CHP, also a readily available process from ecoinvent is used representing the one in Langage-SU.

CNRS-UBO

The AD plant located in Lamballe, France, has a mesophilic digester volume of 15,000 m^3 and is fed with wastewater from the slaughterhouse, pig manure, and recycled water. The plant produces around 156,000 tons of raw digestate per year and 530 m^3/h of bio-methane, which is purified and fed to the gas grid. For this study, the data used for the AD plant is based on the readily available AD process which was also used for Langage, however, employing a higher scaling factor. As Systemic does not have a CHP unit on-site, subsystem 1 for CNRS-UBO comprises only the AD plant.

Innolab-UG

The AD plant belonging to the ALG-AD system of Innolab-UG is not located at the PBR-site but in Pittem. With a capacity of 180,000 tons of feedstock per year, the four digesters and a post-digester with a total volume of 20,000 m^3 are fed with organic bio-waste, manure, and other waste sources. Through the CHP unit, the plant can produce around 32,500 MWh and 29,100 MWh of heat and electricity per year, respectively. The readily available AD process [20] is scaled up to model the one in Pittem. For the CHP unit, two readily available CHP processes are selected with the same load.

2.4.2. Digestate treatment (Subsystem 2)

After disclosing the data used for the AD plant and the CHP unit, Subsystem 2 (see figure 4, 5, 6) considers the treatment of the digestate before adding it to the cultivar. In addition to the onsite treatment of the digestate at the AD plant, where separation of the solid digestate is essential for fertilizing applications, the digestate is further treated at the pilot facility for sterilization and further separation of the concentrate. The technology used at each location and its details are described in the following subsections.

Langage-SU

At Langage-SU, the digestate is treated at the microalgae facility through filter membranes. A 0.2 μm mesh size filter membrane is used along with a dirty pump for two hours for every 150 L digestate treated. The solid part is separated and dried and added to the solid fertilizer. The liquid part is stored in a 1,000 L intermediate bulk container (IBC) tank at the facility, to be ready for use during the cultivation process.

CNRS-UBO

At Lambelle, France, the digestate is treated in two stages, the first is through a decanting centrifuge with the addition of polymer, and the second is, through an evapo-concentrator. The treated digestate is then stored in a 1,000 L IBC tank.

Innolab-UG

After treating the digestate at the AD plant in Pittem, some 80 L per week are transported to the microalgae facility in Oostkamp. The digestate is further filtered using the paper filtration technique to get rid of more solid chunks.

2.4.3. Microalgae inoculation, cultivation, and harvesting (Subsystem 3)

This is considered to be the main subsystem of the ALG-AD technology. It includes inoculation, cultivation of the algal species and finally the harvesting of the algal biomass. For the three facilities, the inoculation process differs mainly in the algal species inoculated as well as the frequency of inoculation. For the cultivation, there are many differences between the facilities as will be discussed in the following subsections. This is also true for the different harvesting processes and frequencies.

Langage-SU

The inoculation process starts in three lab-scale glass flasks of 1 L each, then moved to carboy bottles of 5 L each before they are added to three 80 L polyethylene bags filled with water for final inoculation. The nutrients used during inoculation are in the form of F/2 media. The growth medium is then moved to the 7,000 L vertical tubular PBR (V-PBR) and diluted with fresh tap water after treatment. The tap water is chemically treated with bleach and sodium thyosulphate and is set in continuous motion using pumps until use to prevent bacterial contamination. The cylinders of the V-PBR are made of polymethyl methacrylate sheets (PMME) whereas the pipework and valves are made of polyvinylchloride (PVC). Stainless steel frames are used to support the PBR structure.

During cultivation, filtered digestate from Subsystem 2 is added at an average amount of 90 L/batch. Liquid CO_2 (31 L/hr), which comes in pressurized bottle-packs, is continuously added to adjust the pH of the culture. A heat pump and a lighting system consisting of fluorescent lamps of annual energy consumption of 34 MWh and 1.8 MWh are employed, respectively. For the circulation of the culture, a pump is used with an annual energy demand of 2 MWh. After five days of cultivation, around 15 % of the cultivar are filtered in a 0.2 μm mesh size filter membrane to concentrate the culture as a preparation for the mixotrophic phase. The mixotrophic bioreactor (MBR) is a downsized version of the PBR, where only around 250 L of the cultivar can be grown before centrifugation. The algal biomass production increases from a concentration of 0.4 g/L in the PBR to 6 g/L after membrane filtration and finally to 12 g/L after 48 hours growth period in the MBR. The mixotrophic phase requires an additional carbon input which is provided in the form of 3 kg dextrose per batch of 250 L. For the harvesting process, a suspended centrifuge runs for 6 hours every batch yielding 270 g/L algal biomass paste.

CNRS-UBO

This ALG-AD pilot CNRS-UBO differs from the other two ALG-AD facilities as here no prokaryotic microalgae but a unicellular eukaryotic heterotrophic fungus-like clade of *Stramenopiles* is applied. [21] Since they are considered as an increasingly important source of polyunsaturated fatty acids (PUFAs) for biotechnological industries these organisms are subsequently referred to in some literature and marketing sources as being derived from 'algae', despite their non-photosynthetic source organism. [22] The species *Aurantiochytrium m.* applied in CNRS-UBO belongs to the family of *Thraustochytrids* which are associated with two main features responsible for the increasing interest in this family of microorganisms. They display high growth performance, reaching very high cell concentrations in a few days, and exhibit the striking ability to produce and accumulate docosahexaenoic acid (DHA). [23] In contrast with the majority of microorganisms that produce saturated fatty acids as energy storage lipids, *Thraustochytrids* synthesize long chain-polyunsaturated fatty acids (LC-PUFAs), like DHA, as energy storage.

Aurantiochytrium m. is cultivated under heterotrophic conditions in a batch system production. This entails that the inoculation is freshly prepared for every batch. The inoculum is prepared in 1 mL cryovials stored at -80°C then left for six days with the addition of 20 g glucose, 2 g yeast, 2 g peptone, and 15 g sea salt for every litre. The inoculum is then moved into 24 L carboy bottles filled with water. The bioreactor used at CNRS-UBO comprises three PET columns of 800 L full volume and 500 L active volume each. As the cultivation type is heterotrophic, this eliminates the application of lighting systems and carbon dioxide. However, to ensure optimal growth conditions, the aforementioned additives are added with the following quantities; 2.5 tons/yr of 900 g/L corn syrup as a source of glucose, tap water, and sea salt for digestate dilution and a mixture of yeast and peptides of around 4 kg/yr each, diluted in tap water. Three IBC tanks of 1 m^3 each are used to store those three additives. Circulation pumps are used at the beginning of each batch during the addition and starting of the culture, whereas an air-blower running at one-fourth of its power rating is operating continuously. The reactors are cleaned after every batch with water. The cultivar is harvested twice a week through a tangential flow filtration system that concentrates the diluted algal biomass to an average of 90 g/L biomass paste to be further processed in Subsystem 4.

Innolab-UG

At Innolab-UG, the inoculation is like that at Langage-SU, done only at the beginning of the cultivation period. Lab-scale inoculum preparation follows almost similar procedures like the one at Langage-SU with the only difference regarding the source of nutrients, where at Innolab-UG treated digestate in place of F/2 media is applied. A horizontal tubular PBR (H-PBR) with a volume of 800 L is used for the cultivation process. The lifetime of the H-PBR at Innolab-UG is estimated at around 10 years as it is made of glass, whereas that made of plastic would attain scratches from scrubbing and cleaning that would impact on the light penetration through the tube walls, hence estimated to have around only 5 years lifetime. After filling the H-PBR with the inoculum and adding UV-treated tap water, the cultivation process runs for almost three weeks before being harvested. During this period, liquid carbon dioxide (12 L/hr) is supplied through pressurized bottles to adjust the pH of the cultivar. The cultivar grows on sunlight during the daytime, however, at dark hours few fluorescent lamps are utilized to keep the culture from crashing. The treated digestate is supplied at a rate of 30 L/month. After reaching a biomass concentration of around 2.7 g/L, around 500 L of the cultivar are filtered in a 0.2 µm mesh size filter membrane reaching a concentration of 150 g/L.

2.4.4. Biomass treatment (Subsystem 4)

Subsystem 4 covers the post-treatment of the algal biomass. The hydrogenation of the harvested algal biomass is carried out once for all three facilities and at the same time. The data used for the LCA model is therefore identical for all ALG-AD pilot facilities. However, each facility would be modelled to have the hydrolyzation equipment on-site. These are: incubation tank with temperature and pH control, settling tank and spray dryer. During the hydrogenation process, water for dilution is added depending on the amount of the harvested biomass with a 1:1 ratio and protease as the enzyme for hydrolyzation. Then, the hydrolysate is heated to 90°C to stop the enzyme activity. After hydrolyzation the hydrolysate is left to settle in an IBC tank as a conditioning step before going through the spray dryer. Modified starch is added to the biomass being dried as a protective agent to the algal biomass as well as ascorbyl palmitate which acts as an antioxidant.

2.4.5. Soybean meal production (Reference scenario)

Data used to model the Soybean meal (SM) scenario is based on “Life cycle inventories of bioenergy”. [24] Considering material and energy consumption, Land transformation and emissions. While data for overseas transportation is acquired from, [25] from the scenario of the Central West (CW) in Brazil, where more deforestation and transportation take place.

3. Life Cycle Impact Assessment (Lcia)

One of the limitations of environmental impact assessment (LCIA) is that it can never account for all impacts, especially not in one analysis. However, there is a significant number of methods that provide a reliable and in most cases, sufficient overview of the product’s impact on the environment. In this study, ReCiPe 2016 midpoint (H) is the chosen assessment methodology. The authors of this method chose human health, ecosystem, and resource scarcity as the areas of focus. For the NWE region, some of the most relevant and essential impact categories are addressed through this method which are: global warming potential (GWP), eutrophication, eco-toxicity, water depletion and land use.

4. Mass Balance

The mass balances for the three ALG-AD pilot facilities are shown in figures S1, S2, and S3 in the supplementary information. The mass balances depict the amounts of inputs and outputs to the main processes of the systems. A unit reference of one week was chosen as the average harvesting frequency between the three facilities. The difference between the diagrams in mass and volume units of the harvested biomass is due to the different measurements conducted by the technical partners and was left as it is to avoid inaccurate calculations. The facility CNRS-UBO does not have an integrated CHP plant and so it was not included in the Figure. In subsystem 2, the mass balance shows the amounts of raw digestate being treated either at the biogas plant or on site at the pilot facility, where most of the digestate are depicted as an out of boundary value with a dashed line.

5. Results And Discussion

5.1. Base scenario (LCA)

In this study, the environmental impacts of three ALG-AD pilot facilities in different locations in the NWE region were analysed. The study comprises the LCA of microalgae cultivation while utilizing the NRD digestate from AD plants. The digestate composition, as well as the efficiency of nutrient removal by the microalgae, are shown in Table 3. Moreover, the study incorporates the end product of the ALG-AD technology, which is 1 kg of animal feed. A sensitivity analysis is also carried out to demonstrate and endorse possible technological improvements. Table 4 displays the different values of environmental impact categories based on the ReCiPe 2016 Midpoint (H) for the three base scenarios in the United Kingdom, France and Belgium as well as the soybean meal imported from Brazil (reference scenario).

Table 2
Digestate composition of the three regions and the efficiency of nutrient removal through microalgae cultivation

Element	Langage-SU (mg/L)	CNRS-UBO (mg/L)	Innolab-UG (mg/L)	Assumed efficiency of nutrient removal (%)*
Nitrogen	4,474	2,480	2,370	92.5
Phosphorus	135	138	9.6	51.9
Potassium	1,360	1,054	2,130	62.9
* Data from Scherer, Marisa Daniele, et al 2017 [26]				

Table 3
Impact results of the base scenarios of the ALG-AD pilot facilities and the reference scenario SM of 1 kg FU

Impact category	Unit	Langage-SU	CNRS-UBO	Innolab-UG	SM
Freshwater ecotoxicity (FET)	kg 1,4-DCB	0.32382	0.58425	1.26337	0.02855
Freshwater eutrophication (FE)	kg P eq	0.00297	0.00667	0.01287	0.00056
Human carcinogenic toxicity (HT)	kg 1,4-DCB	0.78197	0.93444	2.98562	0.0577
Marine ecotoxicity (MET)	kg 1,4-DCB	0.47109	0.84049	1.82017	0.04421
Ionizing radiation (IR)	kBq Co-60 eq	0.66336	82.47724	69.34049	0.02635
Stratospheric ozone depletion (SOD)	kg CFC11 eq	8.9645E-06	5.40E-05	7.22E-05	6.26E-06
Ozone formation, Terrestrial ecosystems(OF-TET)	kg NOx eq	0.01608	0.05068	0.09577	0.00981
Terrestrial ecotoxicity (TET)	kg 1,4-DCB	57.68807	79.6957	180.26584	2.70577
Mineral resource scarcity (MRS)	kg Cu eq	0.06621	0.13714	0.39741	0.00689
Fine particulate matter formation (FPM)	kg PM2.5 eq	0.0138	0.04745	0.13067	0.00932
Human non-carcinogenic toxicity (HNT)	kg 1,4-DCB	11.02283	19.51126	33.29799	0.84371
Ozone formation, Human health (OF-HH)	kg NOx eq	0.01525	0.0496	0.09238	0.00899
Terrestrial acidification (TA)	kg SO2 eq	0.03625	0.20585	0.68174	0.00873
Water consumption (WC)	m3	1.17977	1.80172	3.69232	0.00532
Marine eutrophication (ME)	kg N eq	0.00227	0.0156	0.02194	0.00248
Land use (LU)	m2a crop eq	0.02525	0.09626	0.15355	6.60511
Global warming (GW)	kg CO_2 eq	7.61395	24.61413	66.87257	1.46029
Fossil resource scarcity (FRS)	kg oil eq	2.45168	8.37444	24.83046	0.27643

Following the endpoint area of protection approach, where the impact indicators are referred to three fundamental categories: Human health, Ecosystems and Resources through damage pathways [27], the values in Table 4 could be collated and plotted as shown in Figure 9a. The vertical axis is the relative impact of each of the three ALG-AD facilities on the three areas of protection (AoP). The Innolab-UG facility is having the highest impact in each of the three AoP: Human health, Ecosystems and Resources. This is due to the relatively low biomass powder production of only 38.5 kg annually, in addition to the energy source coming from the electricity grid of Belgium. Although the Langage-SU facility has a more complex system comprising two-step cultivation and extra filtration cycle with relatively larger capacities and high-energy consumption from continuous heating and illumination, its contribution to all AoP is minimal compared to the other two facilities. This is mainly due to the internal usage of energy from the AD plant, in addition to the relatively high biomass powder production of 484 kg annually.

Figure 9a also presents the impact of SM import from Brazil to Europe. It is obvious that the difference in environmental impacts compared to all three ALG-AD pilot plants is immense in the category of resources. However, an established industry like soybean production would in general have an edge over all other immature technologies, not to mention the difference in scale. What is abundant through assessing the three systems is that the potential of the ALG-AD pilot facilities to produce at least twice their current capacity is easily attainable with only a small increase in energy and material consumption. This would narrow the gap between the two industries even at pilot scale. Langage-SU is already close to having the same footprint as SM even though, only 300 L is harvested weekly from the mixotrophic reactor. As per S.E. Taelman et al., in the upscaling scenario, a decrease by a factor of 23 could be achieved in the consumption of natural resources. [28] This goes back to nutrients and other consumables recycling, like water and flue gas recovery, PBR design optimization and more energy-efficient equipment.

The other sub-Figures of Figure 9 depict the impact of the main processes of each facility following the usual Midpoint approach. Figure 9b assesses the Innolab-UG facility's base scenario. The Figure displays a noteworthy result which is contradicting many literature findings [29] [30] [31] claiming that the microalgae cultivation process and especially in tubular PBRs, is usually responsible for more than 80 % of the total impact. As shown in Figures 9c and 9d referring to the facilities Langage-SU and CNRS-UBO, respectively, that claim holds true. However, Innolab-UG facility shows otherwise, since the productivity was averaged over a one-year period with only few weeks of poorly functioning cultivation, which is why the facility engineers applied neither heating nor artificial lights at the reactor. This results in a significant decrease in consumables and equipment for the cultivation process. The biomass treatment is manifested in the case of Innolab-UG, due to the employment of the same post-treatment equipment as the ones in the other two facilities, however, with a significantly lower production rate.

In the case of Innolab-UG and CNRS-UBO, the digestate treatment process is prominent, this goes back to the intensive polymer use as a flocculant during the decanting centrifuge process as shown in the Figures 10b and 10c. The cultivation process at the CNRS-UBO facility is dominant compared to the other three main processes, however, when looking at the overall impact, it contributes to around 60 % in each of the impact categories which is less than the 80 - 90 % from literature and as evident from Langage-SU in Figure 9b. One of the reasons for that different behaviour is the intensive use of flocculants as just mentioned above, the other reason is the highly frequent operation of the harvesting membrane, demanding high-energy consumption from filtration and cleaning processes.

Figure 10 presents a more in-depth look into the different processes at each facility. The major hotspot which is common between CNRS-UBO and Innolab-UG pilot facilities and also in literature is the electricity demand. [31] [28] For Innolab-UG and CNRS-UBO, the electricity is provided through the national grid, the data used are from the electricity share in 2019, as listed in Table 5. It is obvious that the nuclear power share is the dominant one and hence the unfavourable environmental impact, along with natural gas. It is, however, predicted to decrease significantly in the coming years if the energy transition continues and will reach significantly higher shares of renewable energy supply at the national scale. Dissimilarly, the electricity consumption at the Langage-SU facility is relatively low due to the dependence of the pilot facility on the internally produced energy from the biogas plant. However, it should be mentioned that with a scale of 3,000 m^3 for Langage AD with annual electricity production of around 4,200 MWh, it is a lot smaller than those associated with the pilot plants in Innolab-UG and CNRS-UBO and yet only contributes an average of 20 % to the environmental impact categories (Figure 10a). The second hotspot of the Langage-SU facility is the PBR. The relatively large volumetric capacity coupled with a short lifetime and a low production capacity lead to the dominance of the bioreactors in the Langage-SU hotspot assessment.

The use of cleaning detergents is frequent at the Langage-SU facility especially in tap water treatment which is done on-site to prevent contamination while maintaining the water at a warm temperature. The impact of bleach, neutralizing agent, and sulphuric acid is rarely highlighted in the literature, it is usually either ignored or manifested in water consumption. The need for intensive cleaning of the harvesting membrane at the CNRS-UBO facility together with the high harvesting frequency also made the impact of cleaning for CNRS-UBO noteworthy. For CNRS-UBO and Innolab-UG facilities, the high ratio of flocculant use in the decanting centrifugation process for initial digestate treatment, has significantly influenced the overall environmental impact of the two facilities. The drying additives are also considered hotspots in the case of the three facilities due to the high environmental impact of maize starch which acts as the raw material of those additives. Although used at a small ratio, enzymes produced from potato starch and bacterial strain and utilizing heat and electricity are also evident in the hotspot analysis, especially in the case of CNRS-UBO due to the relatively large biomass-paste quantities. Finally, since carbon dioxide is essential for phototrophic cultivation, pressurized carbon dioxide bottles were used regularly for pH regulation. The high processing and material demand in the production of these bottles are reflected in the hotspot analysis of Innolab-UG and Langage-SU.

The difference in production capacity of Langage-SU to that of Innolab-UG, although cultivating the same species, is due to the application of a mixotrophic process at Langage-SU. Even though the harvested capacity of Langage-SU is only 300 L, whereas the capacity at Innolab-UG is 400 L, the final algal biomass production of Langage-SU is more than 10 times that of Innolab-UG. However, the mixotrophic phase is more prone to crashing due to contamination, so the need for a sterile medium is crucial. [32] The heterotrophic cultivation at CNRS-UBO on the other hand has an edge over the other facilities due to the frequency and the amount of harvest, twice per batch and 1,500 L per batch, respectively. These factors have overcome the advantage of the mixotrophic phase at Langage-SU, having the highest biomass productivity. Heterotrophic seems to be advantageous as a cultivation type especially in regions with shorter and weaker daylight, as it avoids the need to supply carbon dioxide and for lighting. The benefits can be captured in particular in regions like NWE, with low average temperatures and less sunlight during wintertime, as here mixotrophic algae cultivation is a balanced compromise between good insulation for lower heating load, thus impeding light penetration and open-air or greenhouse while consuming more heat energy. [33]

Without any technological improvement, the facilities within the ALG-AD could increase their production capacity within the same available space, PBRs can be larger in volume while occupying the same surface area due to the possibility of having multi-layer H-PBR and taller V-PBR. This upgrade would however, require more material and energy consumption, like more inputs to the culture, more reactor construction materials and more operating hours of equipment. The yield of such a simple upgrade would lead to a drastic change in the environmental impact, although staying at a pilot scale. According to Smetana, Sergiy, et al, studies showed that a 2.5 m^3 heterotrophic reactor, 25 m^3 PBR and an open raceway pond of 300 m^3 could yield (1.4 – 1.8 tons/year) dry algal biomass. [34] In comparison to the ALG-AD facilities where the 1.5 m^3 heterotrophic reactor at the CNRS-UBO facility, yields around 1 ton/year of dried biomass, bearing in mind the change in growth rates between species and at Langage-SU, a 0.3 m^3 mixotrophic bioreactor being harvested weekly, which yields around 0.5 ton/year of dried biomass. From these values, it is feasible to conclude that it is feasible to maximize the production capacity of the facilities with at least a factor of 2 without requiring new resource-intensive equipment nor facility expansion.

5.2. Comparison between base and reference scenarios

Soybean meal is modelled and assessed at 1 kg, matching the functional unit of 1 kg algal dried biomass. Comparing the impact of the SM from Brazil in this study with the one from [25], shows that from this model, the impact of SM is twice as much as the one from them. Having only used their transportation data implies that the differences are due to the plantation, processing and local transportation of SM. As seen from Table 4, the impact on acidification is around 8.7 kg SO_2 eq whereas in their study the acidification impact in case of the CW scenario is 4.6 kg SO_2 eq for 1 ton of SM, also, climate change impact was 960 kg CO_2 eq in their case while in this study, 1460. In da Silva, Vamilson Prudêncio, et al, they fed their model with data from a Spanish report and due to the language barrier, it was hard to pinpoint the key differences. [25]

Microalgae as a feed source have been mentioned many times in literature to be a good substitute of SM and to even have health benefits which SM lacks, regarding protein content, carotenoid contents and omega 3 fatty acids. [35] [36] [37] Moreover, the decentralization and local economic goals can be empowered through improving and encouraging local production. However, comparing an immature technology as microalgae cultivation to a mature one, SM, is made not to declare a winner but rather show the potential and hotspots for improvement, so that the developing technology could replace or be an alternative for diversity. Taelman et al. pointed out that as a result of a sensitivity analysis, they found out that microalgae cultivation could have an impact in the same scale as SM if the energy sources are dependent on renewable energies and by using more efficient equipment [6]. Our results are supporting this conclusion.

5.3. Sensitivity analysis

The sensitivity analysis aims to assess the significance of potential improvements to the system and to present scientific recommendations for a sustainable development of the technology. Three different hypothetical scenarios were conducted regarding the source of electricity, recovery of CO_2 and heat.

Source of electricity

This scenario differs from the base scenario, in that, the energy source for the pilot plant Langage-SU comes from the electricity grid of the UK. The electricity mix of the UK is shown in Table 5 along with the one of France and Belgium. On the other hand, in case of Innolab-UG and CNRS-UBO, the electricity source is modelled to be coming from the biogas plant through a CHP unit.

CO_2 recovery from biogas plant

This scenario differs from the base scenario, in that the CO_2 needed during the autotrophic phase comes from the AD plant, instead of using industrial CO_2 bottles. There are three main types of CO_2 separation, either pre-combustion, post-combustion or oxyfuel combustion. [39] For the hypothetical scenario purpose, a commonly applied CO_2 separation method is used, pre-combustion with absorption process. [38] [39] Data used for the model could largely deviate in real life as it is mainly based on assumptions and approximations due to the lack of data in literature regarding the CO_2 recovery technologies.

Waste heat recovery

In case of Langage-SU and CNRS-UBO, heat from the CHP unit at the biogas plant is transported to the microalgae facility. This hypothetical scenario aims to show the impact of making use of the heat already produced at the biogas plant. Since this is not considered as waste heat, the CHP unit thermal parts were considered alongside the heat exchanger, vents and ducts to transfer the heat. All data are acquired from ecoinvent database v3.5 and scaled down/up in line with approximations based on area and load. [40]

Table 4
Present electricity mix of each country where the three ALG-AD pilot facilities are located (2019)

*Data from 2019 (Data & Statistics – IEA)	Electricity production mix (%)		
	United Kingdom	France	Belgium
Natural gas	40.92	6.69	27.52
Hard coal	2.38	1.13	2.71
Oil & other fossil fuels	0.32	1.25	0.5
Hydro power	2.38	10.89	1.26
Wind power	19.81	6.07	10.21
Solar power	3.92	1.99	4.22
Nuclear power	17.36	69.90	46.55
Bioenergy	12.91	1.96	7.03
Tide energy	0.004	0.08	-
Geothermal energy	-	0.02	-

5.3.1. Sensitivity analysis results

A sensitivity analysis was carried out using four hypothetical scenarios, the results are shown in Figure 11. The plot depicts the deviation of the scenarios from the base scenario, a value of more than 1, meaning bigger impact and vice versa.

Langage-SU

In the case of Langage-SU, changing the energy source to the electricity grid instead of the biogas plant resulted in a significant increase in the environmental impact from 9 indicators as shown in Figure 11a. The IR increase of a factor of 26 is due to the nuclear share in the electricity mix of UK Table 5. Whereas the increase from the SOD, FPMF and TA indicators comes from the share of bioenergy in the grid. The increase in the GW, FRS, FF-HH and OF-TE impacts, results from the share of natural gas as well as hard coal In the UK grid, which is also having the most contribution to the land use indicator. The other two scenarios, heat from the CHP unit and CO_2 recovery from flue gases, do not depict any significant increase nor decrease in the environmental impact.

In the case of internal usage of heat, the increase in the impact from some indicators originates from the extra instalments necessary to transfer the heat. Finally, the recovery of CO_2 from the biogas plant is almost only dominant from an impact point of view compared to the base scenario in the FRS indicator, which is due to the handling processes of pure CO_2. The fluctuation of the Langage-SU_IC scenario compared to the base scenario is small and thus should be neglected due to the inaccuracy of the IC scenario model.

CNRS-UBO

As a heterotrophic cultivation facility, glucose from a waste source like cellulose or factory waste (wastewater) would have projected less environmental impact than the highly concentrated corn syrup which is used at CNRS-UBO. [42] However, there is no experimental data that suggests the same productivity and if at all, growth of *Aurantiochytrium m.*, so only two scenarios were chosen for the sensitivity analysis of this facility. As shown in Figure 11b, the use of internal heat generated in the AD plant has led to a decrease in the environmental impact in all impact categories. This is due to lowering the electricity consumption from the grid and relying instead on a heat pump from the CHP unit. The lower impact of internal utilization of energy is even more redundant for the other scenario CNRS-UBO_IE, where all electricity used at the pilot facility, comes from the biogas plant. The maximal impact reduction in IR indicator is a result of nuclear power evasion which is having a share of 70 % of the electricity grid mix (see Table 5). A significant reduction in MRS is also due to avoiding nuclear-based energy production. Other footprints reduction results from avoiding power generation from conventional power plants like in GW and FRS. The major hotspots of the French electricity grid are nuclear, conventional power plants and gas engine energy sources.

Innolab-UG

For the scenario Innolab-UG_IE in Figure 11c, where the facility is depending on energy generated at the AD plant, the environmental footprint has also significantly improved similarly to the CNRS-UBO case. The differences in the magnitudes of improvement like in GW and other indicators are due to the bigger share of natural gas and bioenergy and the smaller share of nuclear in the Belgian electricity grid when compared to the French one. For the other scenario where CO_2 is recovered from flue gases instead of being supplied in bottles, the potential of improvement exists but not on that small scale.

6. Conclusions And Outlook

Three microalgae pilot facilities with different systems and settings at different locations in North-Western Europe were environmentally assessed using LCA. The study investigates the integration of microalgae technology in existing biogas technology, which seems to be a win-win-constellation by reducing the negative environmental impacts of biogas plants mainly due to the excess of nutrients in their waste and the algae technology to produce animal feed by making use of these nutrients and the electricity, heat and CO_2 provided by biogas plants for added value creation in rural areas. The three investigated facilities Langage-SU, CNRS-UBO and Innolab-UG were all performing as bio-refineries in correspondence to existing AD plants. The established method of LCA was applied to compare the environmental footprint of the three facilities as well as identifying the potential of this immature technology by comparing its impact to the matured well-established soybean meal industry. However, applying the LCA was no easy task and full of challenges due to difficulties to develop a consistent and comparable data inventory with real data from pilot plants. This would not have been possible without a profound biological and technical understanding of the ALG-AD technology, an iterative and multi-layered literature search and close cooperation with the technicians. This is also true for performing sensitivity analysis as an important means of measuring the potential improvements to the technology. The hypothetical scenarios used for the sensitive analysis were based on sustainable means of improving the technology, in particular: the internal usage of electricity and/or heat and CO_2 recovery. The results indicate that the environmental benefits of electricity use from biogas plants is much more significant than those of internal heat or CO_2 use. It has to be noted that the uptake of nutrients for AD digestate has environmental advantages, but large algae cultivation units operating at a continuous mode are needed to uptake significant amounts of the liquid and pre-treated NRD from AD as the nutritional source for growing microalgae. The second main advantage of the ALG-AD technology is the use of the harvested and post-treated algal biomass as a source for animal feed, thus replacing imported soybean meal and closing in the regional nutrients cycle.

There is a wide scope of scenarios to investigate potential technological improvement from the environmental footprint perspective. The sensitivity analysis for this study was however, limited to only a few studies for each facility due to time and data availability limitations. Hypothetical scenarios to investigate the maximum production capacity according to space limitation would conclude an evidential assessment of the sustainability of this technology and thus its applicability at an industrial scale. Another scenario could be recycling of wastewater, which for other than cleaning purposes would have to be well treated to prevent the culture from contamination. Electricity supply from other renewable energy sources would also be a very promising analysis when compared to electricity from the AD plant. Depending on the region and the feedstock of the AD plant, more efficient digestate treatment methods should be applied which are less energy and material intensive, like paper filtration. Given these many and different proposals for improvement of the ALG-AD technology that have been identified, further research in this area is considered as highly promising and, because of the existing environmental challenges at the regional, national and global scale and the ongoing overstretching of the Planetary Boundaries, also urgently needed.

Declarations

Acknowedgement

We want to thank our colleagues from Swansea University, Ghent University, and the University of Brest for their efforts to complete the ALG-AD project and provide the technical data required for the analysis. As well as The Birmingham City University for their collaboration on data acquisition and leading the work package. This work was funded by the ALG-AD project funded under the INTERREG North-West Europe program (project number: NWE 520).

Supplementary Information

The online version contains supplementary material available at

Funding

This work was supported by the Interreg NWE funded project ALG-AD

Data Availability All data generated or analysed during this study are included in this published article [and its supplementary information files].

Conflict of interest The authors declare no competing interests

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Figures

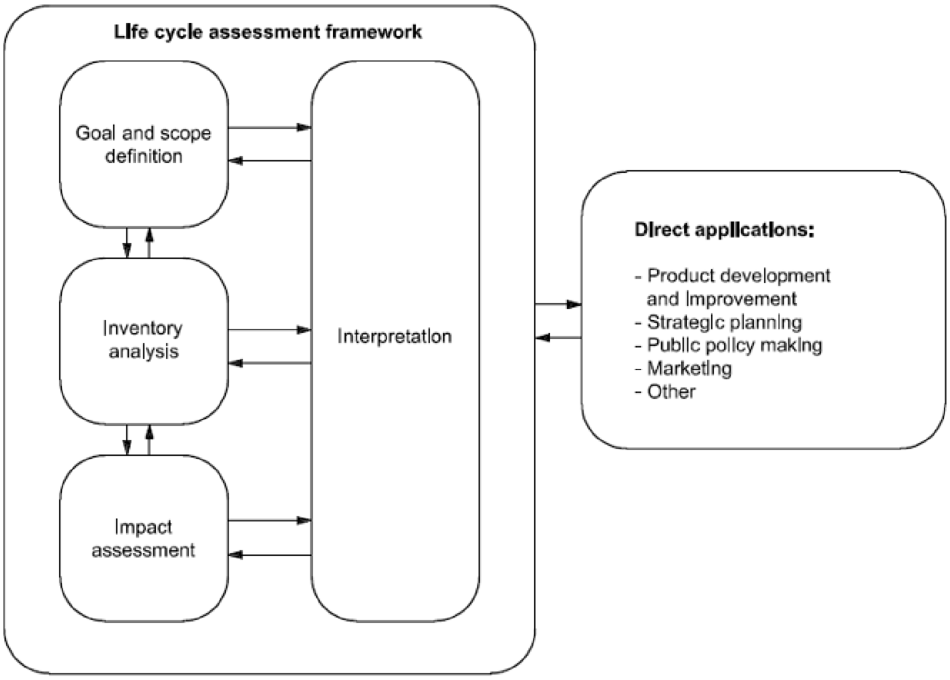

Figure 1

Stages of an LCA

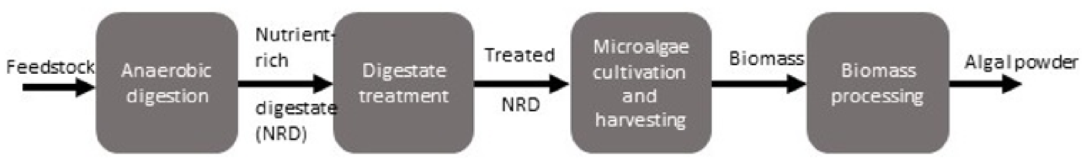

Figure 2

LCA system boundaries of the combined algae and biogas process and single steps included in the LCA

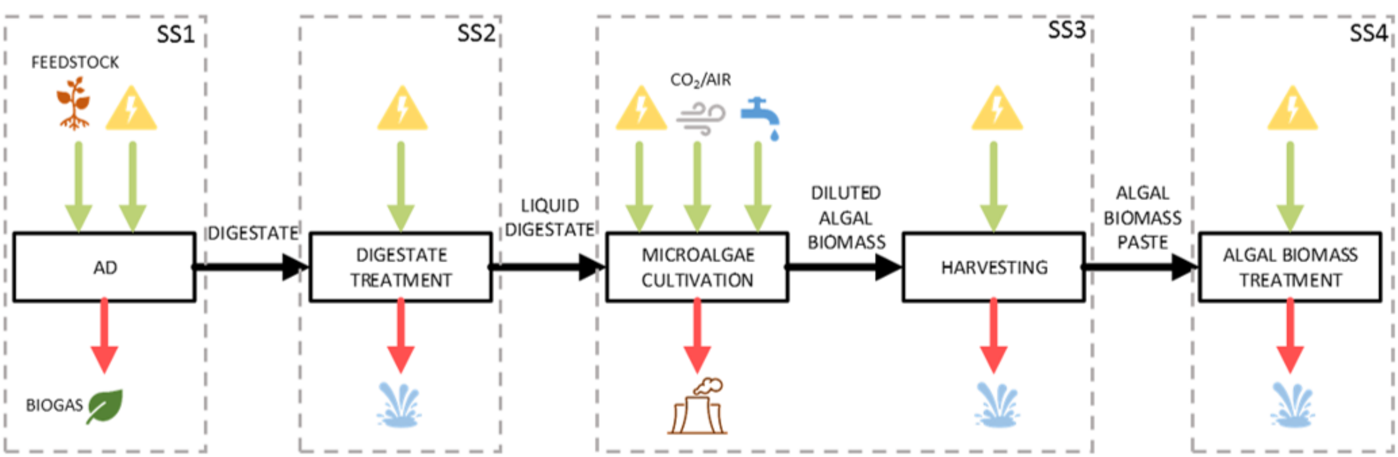

Figure 3

Generic LCA model of combined algae and anaerobic digestion (ALG-AD) technology with four subsystems and their major inputs and outputs

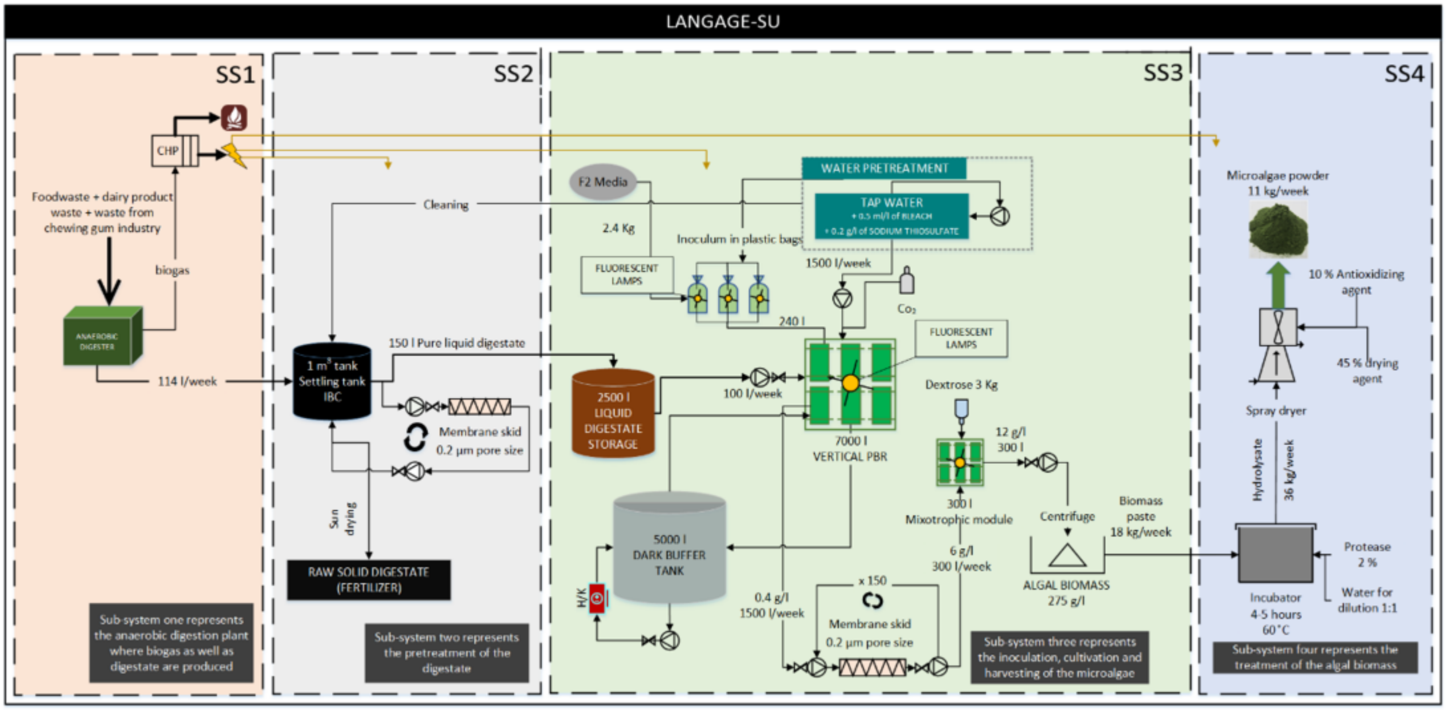

Figure 4

LCA model with four subsystems of the ALG-AD pilot plant Langage-SU in Plymouth, UK

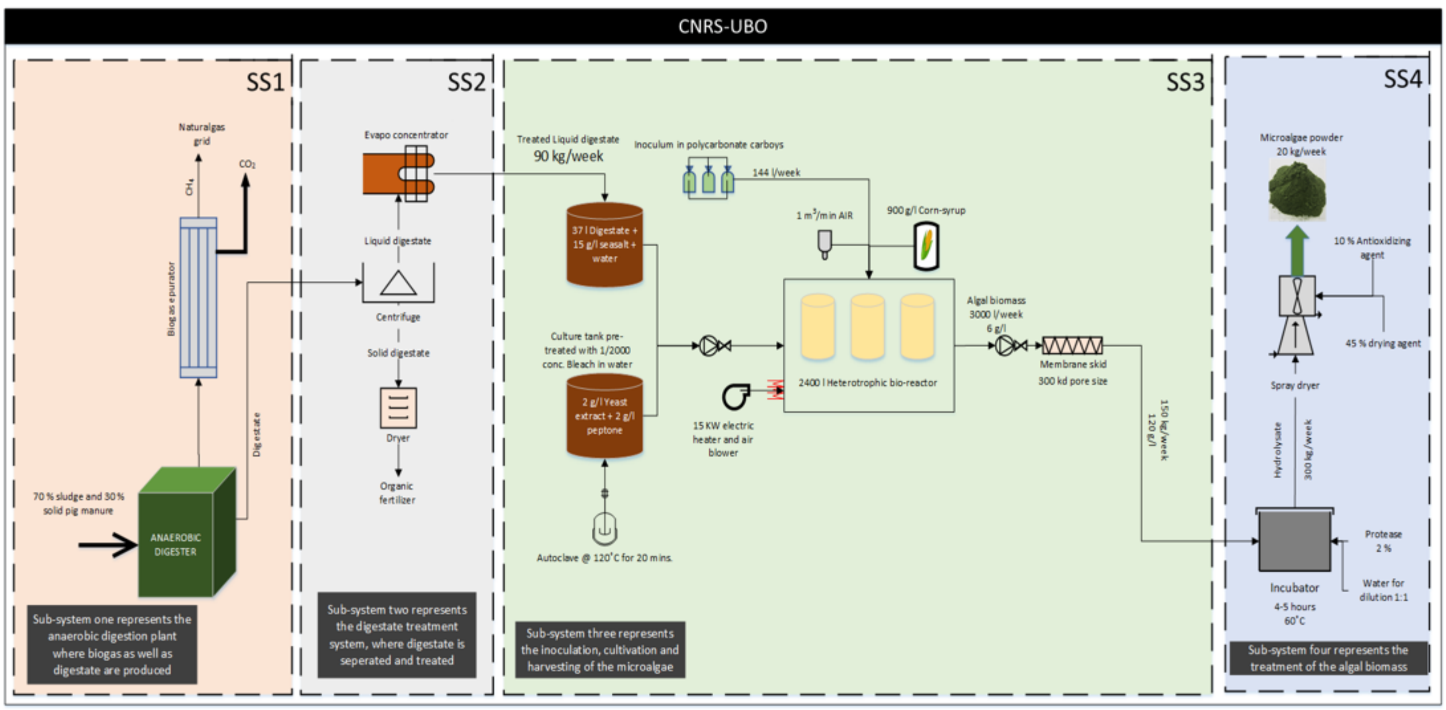

Figure 5

LCA model with four subsystems of the ALG-AD pilot plant CNRS-UBO in Lamballe and Brest, France

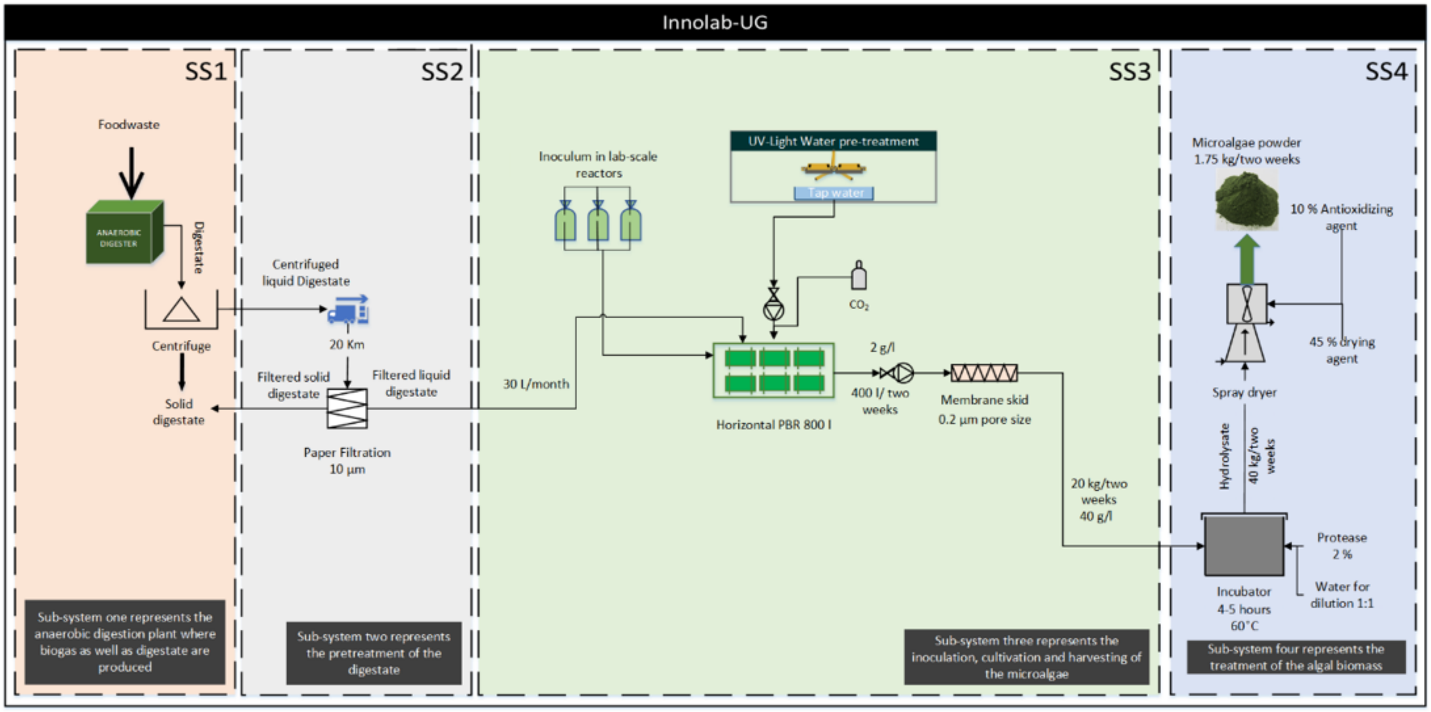

Figure 6

LCA model with four subsystems of the ALG-AD pilot plant Innolab-UG in Pittem and Oostkamp, Belgium

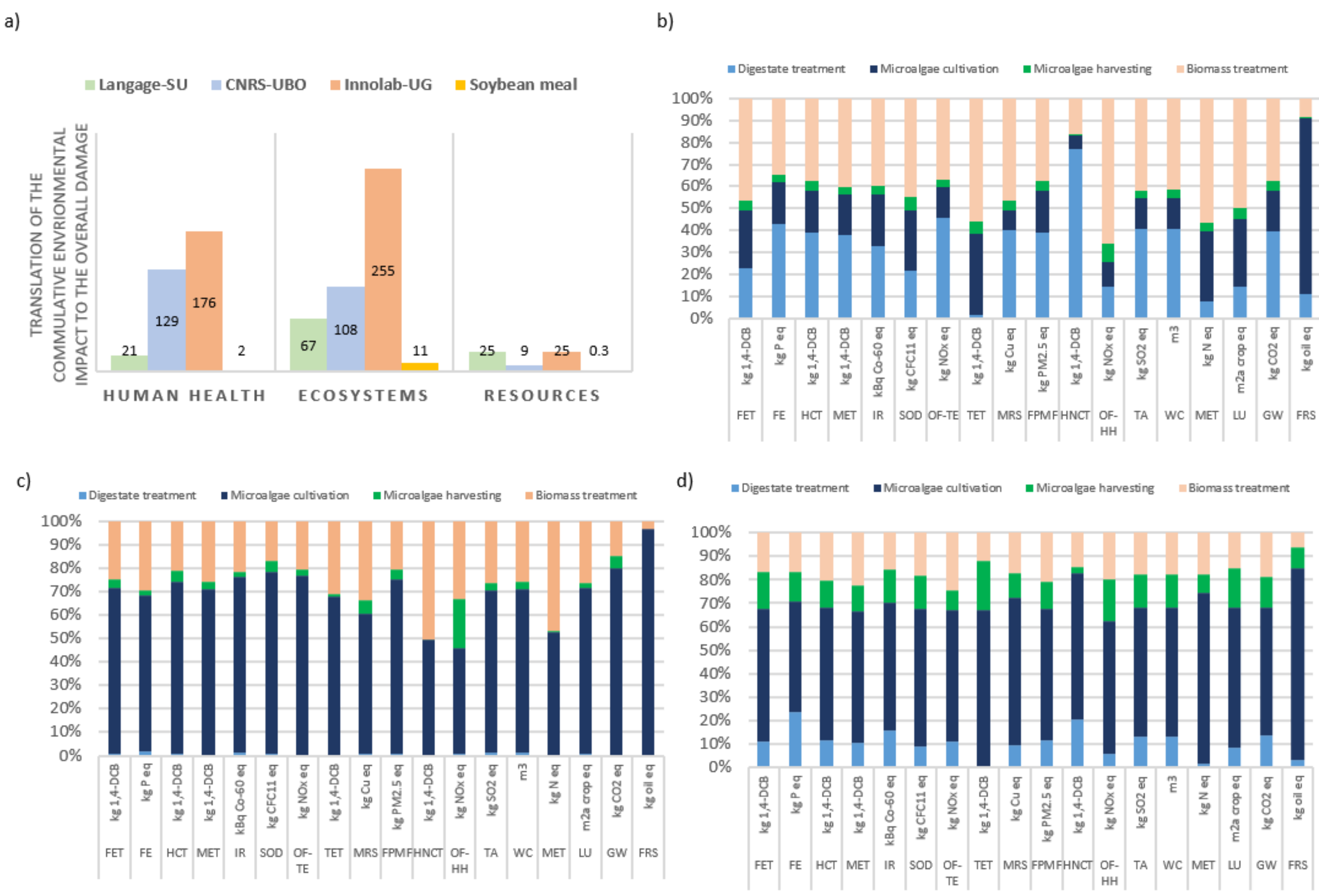

Figure 7

a) Overall contribution of the three ALG-AD pilot plants to the three main indicators of environmental impact, Human health, Ecosystems and Resources b) Main process impact assessment of the Innolab-UG facility c) Main process impact assessment of the Langage-SU facility d) Main process impact assessment of the CNRS-UBO facility

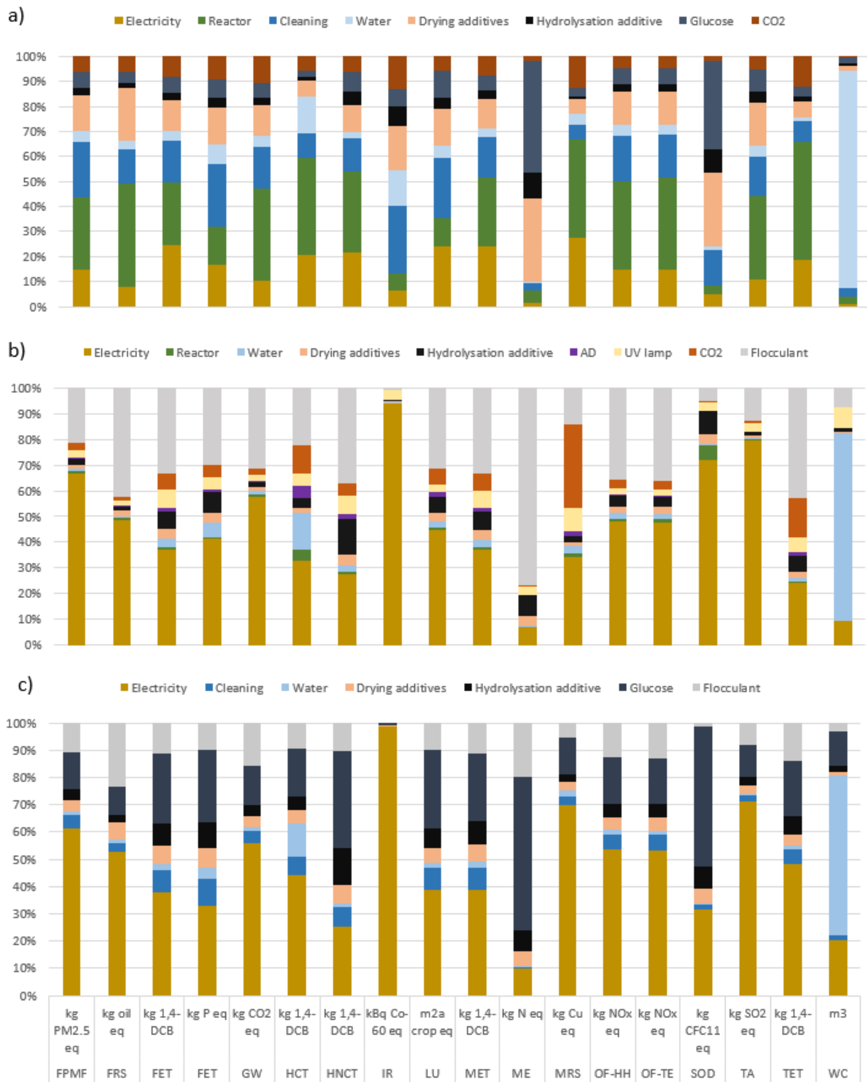

Figure 8

Hotspot analysis of the three ALG-AD pilot plants showing system processes with the highest contribution to the overall impact a) Langage-SU b) Innolab-UG c) CNRS-UB

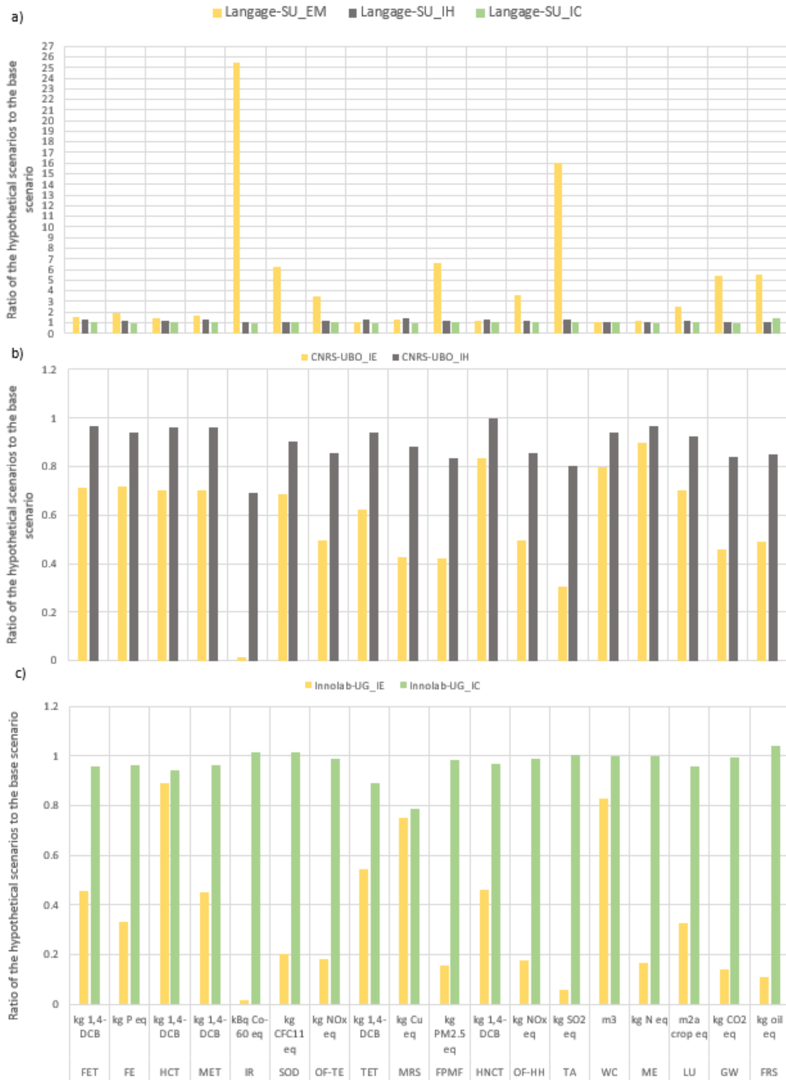

Figure 9

Sensitivity analysis of three hypothetical scenarios for the three ALG-AD pilot plants, with electricity from the grid (EM), Heat from the biogas plant (IH), Carbon dioxide recovery from the biogas plant (IC) and electricity from the biogas plant (IE). a) Langage-SU b) CNRS-UBO c) Innolab-UG

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Figure 10

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Image not available with this version

Figure 11

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