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Comparative Assessment of a Decentralized Blackwater and Organic Household Waste Treatment System Using LCA

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Campus Ås Showcase

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Sustainable Water and Sanitation, Health and Development

“We can't solve problems by using the same

kind of thinking we used when we created them."

\- **Albert Einstein**”

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Ana Maria Santos Bouzada

ABSTRACT

This study evaluates the environmental performance of blackwater and organic household waste treatment in Campus Ås Showcase, located at the Norwegian University of Life Sciences, in Ås municipality, Norway. The Campus Ås Showcase is part of the SiEUGreen Project (www.sieugreen.eu) that aims to demonstrate that a combination of known and emerging technologies contributes to a more resilient and environmentally friendly urban development, with near zero emission, low water footprint and adoption of the circular economy concept.

In the Campus Ås Showcase, black water and organic household waste are collected from a dormitory, which is equipped with a vacuum toilet and a grinder system for organic waste. The treatment system comprises an anaerobic digestion reactor (AD), with recovery of biogas, and post-treatment methods that aim at plant nutrient recovery. The post-treatments are liquid fertilizer production (LF), struvite precipitation (SP) and microalgae cultivation (PBR). The systems demonstrated high efficiency of treatment and recovery of nutrients.

The analysis was carried out using the Life Cycle Assessment tool, described by ISO14040-44. The impact categories selected for analysis were the global warming potential (GWP), based on the 100-year potential, eutrophication potential (EP), water and energy consumption. The analysis was done for the construction and operational phase, and the fertilizer produced in the system was considered as an avoided burden of commercial fertilizer production. The results were compared to the conventional centralized treatment.

The results for the construction phase assessed the environmental impacts associated with the production of the materials used in the system under study. Only the main materials for each system were accounted for in this analysis. The production process of the stainless steel is responsible for the main impacts of the construction phase.

Two scenarios were evaluated. Scenario 1 comprises the AD, LF and PBR systems, and Scenario 2 includes struvite precipitation to the process. Scenario 1 presented better results in the GWP category than Scenario 2. The EP and the water consumption were similar for both scenarios. Scenario 2 consumed more energy due the addition of the struvite precipitation process. With the results, it is possible to infer that the addition of the struvite precipitation to the treatment process does not enhance the environmental performance of the system. However, it can be an interesting alternative in case the fertilizer should be transported from the production place.

The results of Scenario 1 were compared with the conventional treatment. The Nordre Follo Wastewater Treatment Plant was chosen for comparison and the operational data from the treatment plant was obtained. The anaerobic digestion treatment for organic waste is a theoretical set up. The comparative study has limitations as the technological representation of Campus Ås Showcase and the conventional system are not identical. Campus Ås Showcase demonstrated to have a better environmental performance with regards to GWP, EP and water consumption. On the other hand, the centralized system presented better results on energy consumption.

In the sensitivity analysis, the impact of the volume of flushing water used in the vacuum toilet on the performance of the system was investigated for Scenario 1. Volumes of 1 l, 0.75 l, 0.5 l and 0.25 were chosen. The results of the sensitivity analysis showed that the amount of biogas recovered can be increased significantly, as a result of a longer hydraulic retention time in the AD reactor. The liquid fertilizer produced had higher concentrations and lower volumes. There was not much difference from the results achieved in Scenario 1 in the categories GWP, EP and energy consumption. The water consumption decreased from 5.13 m^3 in Scenario 1 to 3.49 m^3, in the case of 0.25 l flushing volume.

Campus Ås Showcase demonstrated to be an environmentally friendly treatment process with low water consumption and of great potential for plant nutrient recovery and CO2 biofixation. To improve the system further, the biogas recovered can be used to supply heat to the AD reactor and it is also possible to complement the electricity source with solar power and decrease the tap water consumption with lower flush volume. To strengthen and validate the results of this study, it is recommended to conduct a LCA with the full-scale system once it is in full operation.

Key words: Life Cycle Assessment, DEWAT, wastewater, circular economy, nutrient recovery

ABSTRAKT

Denne studien evaluerer miljøytelsen til svartvann og organisk husholdningsavfall i Campus Ås Showcase, som ligger ved Norges miljø- og biovitenskapelige universitet, i Ås kommune. Campus Ås Showcase er en del av SiEUGreen -prosjektet (www.sieugreen.eu) som har som mål å demonstrere at en kombinasjon av kjente og nye teknologier bidrar til en mer spenstig og miljøvennlig byutvikling, med nært nullutslipp, lavt vannavtrykk og adopsjon av sirkulærøkonomikonseptet.

I Campus Ås Showcase samles svart vann og organisk husholdningsavfall fra en hybel, som er utstyrt med et vakuumtoalett og et kvernsystem for det organiske avfallet. Behandlingssystemet består av en anaerob fordøyelsesreaktor (AD), med utvinning av biogass og etterbehandlingsmetoder som tar sikte på utvinning av næringsstoffer fra plantene. Etterbehandlingene er flytende gjødselproduksjon (LF), struvitutfelling (SP) og dyrking av mikroalger (PBR). Systemene demonstrerte høy effektivitet ved behandling og gjenvinning av næringsstoffer.

Analysen ble utført ved hjelp av Life Cycle Assessment-verktøyet, beskrevet av ISO14040-44. Effektkategoriene som ble valgt for analyse var potensialet for global oppvarming (GWP), basert på 100-års potensial, eutrofieringspotensial (EP), vann og energiforbruk. Analysen ble utført for konstruksjons- og driftsfasen, og gjødsel som ble produsert i systemet ble sett på som en unngått byrde ved kommersiell gjødselproduksjon. Den funksjonelle enheten som er valgt for analyse av operasjonsfasen, er en populasjonsekvivalent som skal behandles i løpet av ett år. Resultatene ble sammenlignet med konvensjonell sentralisert behandling.

Resultatene for byggefasen vurderte miljøpåvirkningene knyttet til produksjonen av materialene som ble brukt i systemet som studeres. Bare hovedmaterialene for hvert system ble redegjort for i denne analysen. Produksjonsprosessen for rustfritt stål er ansvarlig for de viktigste konsekvensene av byggefasen.

To scenarier ble evaluert. Scenario 1 omfatter AD-, LF- og PBR -systemene, og scenario 2 inkluderer struvitutfelling til prosessen. I scenario 1 presenterte bedre resultater i GWP -kategorien enn scenario 1. EP og vannforbruket var like for begge scenariene. Scenario 2 brukte mer energi på grunn av tilførsel av struvitfellingprosessen. Med resultatene er det mulig å slutte at tilsetning av struvitfelling til behandlingsprosessen ikke forbedrer systemets miljøytelse. Imidlertid kan det være et interessant alternativ i tilfelle gjødsel skulle transporteres fra produksjonsstedet.

Resultatene fra Scenario 1 ble sammenlignet med konvensjonell behandling. Renseanlegget Nordre Follo ble valgt for sammenligning og driftsdata fra renseanlegget ble innhentet. Den anaerobe fordøyelsesbehandlingen for organisk avfall er et teoretisk oppsett. Den komparative studien har begrensninger ettersom den teknologiske representasjonen av Campus Ås Showcase og det konvensjonelle systemet ikke er identiske. Campus Ås Showcase viste seg å ha en bedre miljøytelse med hensyn til GWP, EP og vannforbruk. På den annen side presenterte det sentraliserte systemet bedre resultater på energiforbruk.

I sensitivitetsanalysen ble effekten av volumet av skyllevann som ble brukt i vakuumtoalettet på systemets ytelse undersøkt for scenario 1. Volum på 1 l, 0,75 l, 0,5 l og 0,25 ble valgt. Resultatene av sensitivitetsanalysen viste at mengden biogass som utvinnes kan øke betydelig, som følge av lengre hydraulisk oppbevaringstid i AD -reaktoren. Flytende gjødsel som ble produsert hadde høyere konsentrasjoner og lavere volumer. Det var ikke stor forskjell fra resultatene oppnådd i Scenario 1 i kategoriene GWP, EP og energiforbruk. Vannforbruket gikk ned fra 5,13 i Scenario 1 til 3,49 m3, ved 0,25 l skyllevolum.

Campus Ås Showcase viste seg å være en miljøvennlig behandlingsprosess med lavt vannforbruk og med stort potensial for utvinning av næringsstoffer og CO2 -biofiksering. For å forbedre systemet ytterligere kan biogassen som gjenvinnes brukes til å levere varme til AD -reaktoren, og det er også mulig å komplettere strømkilden med solenergi og redusere tappevannforbruket med lavere spylevolum. For å styrke og validere resultatene av denne studien, anbefales det å gjennomføre en LCA med fullskala systemet når det er i full drift.

Stikkord: Livssyklusvurdering, DEWAT, avløpsvann, sirkulær økonomi, utvinning av næringsstoffer

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ABBREVIATIONS AND ACRONYMS

ABR	:	Anaerobic Baffled Reactor
AD	:	Anaerobic Digestion
BOD	:	Biological Oxygen Demand
BW	:	Black Water
CE	:	Circular Economy
COD	:	Chemical Oxygen Demand
CSTR	:	Continuous Stirred Tank
EP	:	Eutrophication Potential
EPA	:	Environmental Protection Agency
FAO	:	Food and Agriculture Organization
GWP	:	Global Warming Potential
HRT	:	Hydraulic Retention Time
IPCC	:	Intergovernmental Panel on Climate Change
ISO	:	International Organization for Standardization
LCA	:	Life Cycle Assessment
LCFA	:	Long Chain Fatty Acids
LCI	:	Life Cycle Inventory Analysis
LCIA	:	Life Cycle Impact Assessment
LED	:	Light Emitting Diode
LF	:	Liquid Fertilizer
MCF	:	Methane Correction Factor
OHW	:	Organic Household Waste
PBR	:	Photobioreactor
SP	:	Struvite Precipitation
SRT	:	Solids Retention Time
SS	:	Suspended Solids
SSB	:	Statistics Norway
TN	:	Total Nitrogen
TOC	:	Total Organic Carbon
TP	:	Total Phosphorus
UASB	:	Upflow Anaerobic Sludge Blanket Reactor

UN : United Nations

UNEP : United Nations Environment Program

UNESCO : United Nations Educational, Scientific and Cultural Organization

UNICEF : United Nations International Children's Emergency Found

UV : Ultra Violet

VFA : Volatile Fatty Acids

VOLR : Volumetric Organic Loading Rate

WHO : World Health Organization

WWAP : World Water Assessment Project

WWTP : Wastewater Treatment Plant

1. Introduction

1.1. Background

There are several driving forces for the adoption of circular economy in wastewater treatment, such as continuous population growth, water scarcity and increasing demand for crop fertilization resources (UN WWAP, 2017). Sustainable sanitation concepts propose decentralized systems, with a focus on treatment and recycling resources present in the wastewater. The main resources are bio-energy, through biogas production, water and plant nutrients, mainly nitrogen and phosphorus (Zeeman et al., 2006).

In the light of the challenges for resilient and sustainable urban centers, the SiEUGreen project aims to study and develop resource-efficient systems to increase food security, minimize the environmental footprint and promote zero-waste solutions. For that, the Campus Ås Showcase was created '*to demonstrate that an innovative combination of known and emerging technologies, actions, and planning can contribute to achieve a more resilient, climate, environment and human friendly urban development with near zero emissions, circular economy, low climate and water footprint as well as economic and health benefits*' (www.sieugreen.eu). The showcase consists of a treatment system for blackwater and organic household waste, with an anaerobic digestion reactor and biogas recovery, and post-treatments aiming to recover plant nutrients, with liquid fertilizer production, struvite precipitation and microalgae biomass cultivation.

To evaluate the environmental performance of the system, the study was carried out with the Life Cycle Assessment (LCA) tool. The analysis was done using the SimaPro software, and it was evaluated in the impact categories of Global Warming Potential (GWP), Eutrophication Potential (EP) and the water consumption of the system.

1.2. Objectives of the study

The aim of the study is to perform a Life Cycle Assessment of the treatment of blackwater and organic household waste through anaerobic digestion and plant nutrient recovery processes, with the production of struvite, liquid fertilizer and microalgae biomass. The results will be compared to the impacts of centralized wastewater and organic waste treatment.

The specific objectives are:

- To perform a Life Cycle Impact Assessment of the construction and operational phase of anaerobic digestion of blackwater (BW) and organic household waste (OHW) and three distinct nutrient recovery processes.
- To identify the environmental hot spots of each treatment and recovery process and suggest measures for improvements.
- To compare the environmental impacts of the operational phase of the system with the local centralized wastewater treatment and organic waste treatment.

1.3. Overview of the content

This study comprises six main chapters, along with reference and annexes. A brief description follows:

Chapter 1 includes a brief background for the study, objectives and overview of contents.

Chapter 2 presents the literature review with background information on wastewater treatments and resource recovery processes, and the framework of the Life Cycle Assessment tool.

Chapter 3 gives a description of the systems under study and presents the methods used in the analysis.

Chapter 4 presents the results of the assessment.

Chapter 5 gives a discussion on the findings.

Chapter 6 presents the conclusion of the study and suggested recommendations.

2. Literature Review

2.1. Background Information on Wastewater Treatment and Resources Recovery Processes

In this chapter, a brief introduction to water and sanitation and conventional methods applied to wastewater treatment is presented. Moreover, a short discussion about how the circular economy strategy can be applied in the wastewater sector, the eco- sanitation concept and methods of resource recovery are described.

2.1.1 Water and Sanitation

It is projected that the world's population will reach 8.6 billion by 2030, and 60% of this population will live in urban areas. While cities are the core for economic development and innovation, it is also marked by inequities in economic opportunities, health, water and sanitation (UNESCO, 2020). Fresh water sources are scarce, representing only two and a half percent of the water on the planet and it is unevenly distributed, not matching the patterns of human settlements (Corcoran et al. 2010). A recent study has found that two-thirds of the world's population is currently living in areas affected by water scarcity at least one month per year (UN WWAP, 2017).

The Food and Agriculture Organization (FAO) (cited in UN WWAP, 2017) apprises the annual global freshwater withdrawal to be 3,928 km^3. An estimate of 44% of this share is consumed by agriculture, and the remaining 56% (2,212 km^3) is released to the environment as wastewater, from municipal and industrial effluent and agricultural drainage. Not to damage the water quality, ecosystem and human health, wastewater needs to be treated and safely disposed of. For that, UNEP (2015a) points out the need for regulations and legal frameworks effectively implemented.

The definition of wastewater most used in publications from the United Nations is adapted from Raschid-Sally and Jayakody, 2008: ‘ *Wastewater is regarded as a combination of one or more of: domestic effluent consisting of blackwater (excreta, urine and faecal sludge) and greywater (used water from washing and bathing); water from commercial establishments and institutions, including hospitals; industrial effluent, stormwater and other urban runoff; and agricultural, horticultural and aquaculture runoff.’* The composition and load of wastewater are very dependent on its origin. Table 1 presents the typical composition of wastewater from different sources:

Table 1: Typical composition of wastewater from different sources. Source: Adapted from WWAP, 2017 and Tilley et al., 2014.

Sources of wastewater	Typical components
Domestic wastewater	Human excreta (pathogenic microorganisms), nutrients and organic matter. May also contain emerging pollutants (e.g., pharmaceuticals, drugs and endocrine disruptors). It can be characterized in four types: - **Yellow water:** human urine. - **Blackwater:** mix of urine, faeces, flush water and toilet paper. - **Brownwater:** human faeces, flush water and toilet paper, it does not contain urine. - **Greywater:** is the total volume generated from washing clothes and dishes, and bathing. It does not contain human excreta.
Municipal wastewater	Very wide range of contaminants, such as pathogenic microorganisms, nutrients and organic matter, heavy metals and emerging pollutants
Urban runoff	Very wide range of contaminants, including incomplete products of combustion (e.g. polycyclic aromatic hydrocarbons and black carbon/soot from fossil fuel combustion), rubber, motor oil, heavy metals, non- degradable/ organic trash (especially plastics from roads and parking lots), suspended particulate and fertilizers and pesticides (from lawns)

UNEP (2015b) listed some impacts of discharged untreated wastewater on human health, environment and economy. Examples of impacts on health is the increased burden of diseases due to reduced water quality for drinking and bathing, and unsafe food. The environment is impacted through degradation of aquatic systems, decreased biodiversity, increased greenhouse gas emissions and water temperatures, bioaccumulation of toxins etc. Furthermore, the economic activities can be impacted due to reduced agricultural and industrial productivity, higher costs of water treatment and increased burden of the healthcare system, reduction in opportunities.

On the Synthesis Report of Sustainable Development Goal 6 on Water and Sanitation (UN, 2018), UNICEF estimated that in 2015, 12% of the world's population still practice open defecation, 12% have unimproved sanitation, 8% have it limited, 29% have basic sanitation and only 39% of the population have safely managed sanitation. There are two types of wastewater collection and treatment: off-site systems (centralized), in which the wastewater is transported through a sewage network to a treatment facility; and on-site systems (decentralized), which provide collection or treatment in the locality of the wastewater generation (UN WWAP, 2017). Table 2, summarizes the advantages and disadvantages of each system:

Table 2: Advantages and disadvantages of centralized and decentralized systems. Source: WWAP, 2019.

Centralized sewage system		Decentralized sewage system	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
Does not require the participation and information of the population, at least not to a degree that is necessary for the decentralized approach (Barnard et al., 2013).	Collection of wastewaters is expensive and can pose a serious threat to environment and public health (e.g. leaks, flooding or destruction of treatment sites) (Gikas and Tchobanoglous, 2009).	Collection of wastewaters from various sites is not necessary (Massoud et al., 2009).	Maintenance of treatment facilities is time-consuming and if faulty or broken can pose dangerous threats to the environment and population (Massoud et al., 2009).
Wastewater treatment is controllable and provides power to the local authorities and governments to effectively implement their goals and measures; processes can be monitored by trained personnel (Oakley et al., 2010).	The costs of wastewater collection are even greater for remote locations or densely populated areas, because sewer systems need to reach isolated places and cover greater distances.	Wastewater composition and variability in quantity and quality can be better estimated (Almeida et al., 1999; Anh et al., 2002). Predictability of composition allows for specialized treatment methods that can be optimized (Gillot et al., 1999).	Wastewater treatment is less controllable as more stakeholders can be involved. Insufficient oversight can cause serious problems and endanger the success of the project (Lienert and Larsen, 2006; Libralato et al., 2012).
Methods have been optimized for decades, providing a large amount of experience in maximizing the potential (and addressing the limitations) of centralized wastewater treatment (Anh et al. 2002).	Mixtures of different flows makes wastewater difficult to control (Anh et al. 2002). Municipal wastewater generation varies depending on the time of the day, holidays, population growth, in- or defluxes in the long term	New opportunities for optimized treatment effort; growing potential for reclaimed wastewater use. Specialized treatment methods can reduce treatment time and costs and raise the potential of reuse in the surrounding area (Asano and Levine, 1996).	
Limitations or benefits of centralized sewage systems		**Limitations or benefits of decentralized sewage systems**	
Requires sufficient funding (from government or other sources) to manage the systems in a sustainable manner.		Information about the area of implementation are very difficult to obtain (Tsagarakis et al., 2001), especially in regions that can profit the most (rural or isolated, poor, sparsely populated).	
Requires adequate technical and human capacity to manage, operate and monitor treatment of wastewater.		Can provide a multitude of benefits for certain regions under the right conditions (Massoud, et al., 2009).	
		Adaptability of such systems, as they are often built modularized and can be expanded or reduced to meet the current needs (Otterpohl et al., 2004), especially for refugee camps or other temporary shelters	

The conventional water-based sewage models, with flush-toilet, were built with the idea that human excreta is waste, only suitable for disposal, and that the natural environment is able to assimilate it. It has been successful in communities with access to water for flushing, but in communities where water is scarce, the conventional solution is on-site systems, e.g., pit latrine. It is important to recognize the success of the sanitation programs regarding the reduction of disease and improvement of living conditions. While the conventional centralized solutions have solved some problems, it has also contributed to other challenges we face today, i.e., water pollution, water scarcity, loss of soil fertility and lack of food security (Esrey et al. 2001).

2.1.2 Conventional wastewater treatment systems

With population growth and climate change intensifying extreme events, the consequent rise in wastewater generation, and the extension of impermeable surfaces, the pressure over the existing sewer systems and treatment facilities increased (UN WWAP, 2017). In conventional centralized wastewater treatment systems, the sewerage network can be separated or combined. In separate systems, there are different sets of pipes to transport wastewater and urban runoff, and in combined systems, both flows are transported together. When properly installed and operated, separate systems are supposed to reduce the volume of wastewater to be treated, which avoids overflows and contamination (WWAP, 2017). According to Massoud et al. (2009) (cited by WWAP, 2019), in centralized systems, the collection network accounts for over 60% of the budget for wastewater management.

There is a range of treatment methods for centralized systems, and it usually consists of a combination of physical, chemical and biological processes. The key function of mechanical treatment is to remove particles by gravity or by physical barriers. The chemical unit processes were developed to be combined with physical and biological treatment, and it is often used for disinfection, removal of heavy metals and nutrients. In biological unit processes, the treatment consists of the reproduction of natural degradation. It takes place in reactors under carefully controlled anaerobic or aerobic conditions. These unit processes are combined to achieve different levels of treatment and comply with effluent quality requirements (Tchobanoglous et al., 2003; WWAP, 2017).

The byproducts of wastewater treatment process are grit, scum, solids and biosolids (Metcalf and Eddy, 2003). The authors remark that the management of the solids and biosolids, also called sludge, is complex and costly because of the offensive nature of the material. With the improvement of regulations encouraging the reuse of the sludge after stabilization, significant effort has been directed to produce ‘clean sludge’ that meets the heavy metals and pathogens requirement (Tchobanoglous et al., 2003). Some of the processes to treat or stabilize the sludge are based on traditional methods, such as composting, incineration and digestion (Metcalf and Eddy, 2003).

Wastewater treatment in Norway

Water and wastewater services are usually controlled by authorities that operate at local, regional and national level, and the infrastructure can be public or with the private sector (Esrey et al. 2001). However, in the last decades, international initiatives are fostering agreements and policies on water and wastewater management (UNEP, 2015a), and their participation becomes even more relevant in cases that wastewater flows into international water bodies (UN WWAP, 2017). The regulation of water and wastewater services is the responsibility of the state, and may address treatment levels or processes used, regulate the quality of effluent by setting discharge standards, and provide economic regulations with investments and tariffs to ensure the quality of the services (UN WWAP, 2017).

In Norway, the wastewater discharges are regulated under the Pollution Control Regulations, part 4: Drainage, Act no.6, 1981 (Government.no, 1981). It gives the authority of discharge regulations to the local municipality, which can strengthen the requirements if discharge occurs in more sensitive areas. Besides differentiation on the requirements for discharge in sensitive areas, the regulation also accounts for population density and capacity of the treatment plant. The unit used to describe the capacity of treatment plants is person equivalent (pe). It is defined in § 11-3 as: *Person equivalent, pe: The amount of organic matter that is biodegradable with a biochemical oxygen consumption measured over five days, BOD_5, of 60g oxygen per day. The size of the sewage system in pe is calculated based on the largest weekly amount that goes to the overflow, treatment plant or discharge point during the year, with the exception of unusual condition, for example, are due to heavy rainfall.*

The applied regulation in Norway agrees with the European Commission Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment. The parameters for discharge are presented in Table 3. Table 4 presents the additional requirements for discharge in sensitive areas.

Table 3: Requirements for discharges from urban wastewater treatment plants subject to Articles 4 and 5 of the Directive. The values for concentration or for the percentage of reduction shall apply. Source: Directive 91/271/EEC. Annex I.

Parameters	**Concentration**	**Minimum percentage of reduction ***
Biochemical oxygen demand (BOD5) **	25 mg/l O_2	70-90
Chemical oxygen demand (COD)	125 mg/l O_2	75
Total suspended solids (TSS)	35 mg/l *** (more than 10 000 p.e.)	90 *** (more than 10 000 p.e.)
	60 mg/l (2 000 -10 000 p.e.)	70 (2 000 -10 000 p.e.)
* Reduction in relation to the load of the influent. ** The parameter can be replaced by another parameter: total organic carbon (TOC) or total oxygen demand (TOD) if a relationship can be established between BOD5 and the substitute parameter. *** This requirement is optional.		

The criteria established by the Directive 91/271/EEC *ANNEX II* for identification of sensitive areas are:' *freshwater bodies and coastal waters that are in eutrophic state or which may be in the near future; Surface freshwater used as a source of drinking water that has a concentration of nitrate at permitted limit and other areas that may request additional treatment'*.

Table 4: Requirements for discharges from urban wastewater treatment plants to sensitive areas which are subject to eutrophication. Adapted from Directive 91/271/EEC. Annex I.

Parameters	**Concentration**	**Minimum percentage of reduction ***
Total phosphorus	2 mg/l (10 000 — 100 000 p.e.)	80
	1 mg/l (more than 100 000 p.e.)	
Total nitrogen**	15 mg/l (10 000 -100 000 p.e.)***	70-80
	10 mg/l (more than 100 000 p.e.) ***	
* Reduction in relation to the load of the influent. ** Total nitrogen means the sum of total Kjeldahl nitrogen (organic and ammoniacal nitrogen) nitrate-nitrogen and nitrite-nitrogen. *** These values for concentration are annual means as referred to in Annex I, paragraph D.4(c).		

Traditionally, phosphorus is removed from wastewater by fixing P into the sludge chemically, by precipitation of soluble phosphorus with aluminum or iron salts into soluble phosphates compounds (Le Corre et al., 2009). Separation of precipitates is then achieved by sedimentation, filtration or flotation. Biological P removal processes are also used with the help of microorganisms that have the ability to accumulate phosphates as polyphosphates for their own metabolism. The authors (Le Corre et al., 2009) also highlight that these processes can be efficient (removal of P to less than 1 mg.L^{-1}) but also have disadvantages, such as accumulation of P in the final sludge and increased sludge volume, and resulting in spontaneous struvite precipitation in pipelines and other parts of the treatment line. For the nitrogen removal, Metcalf and Eddy (2003) explains that it can be integrated into the biological treatment step, or it can be an add-on process to the existing system. For biological nitrification and denitrification processes, some of the conventional techniques are activated sludge systems, sequencing batch reactors, fixed films and granules.

By 2019 in Norway, 64 % of the population was connected to advanced treatment, 21 % had mechanical treatment, 12 % of the population was connected to small wastewater facilities (normally with sludge separator and possibly additional filtration) and 2 % of the Norwegian population still discharged they wastewater directly, without treatment. From the plants with capacity for 50 p.e. or more, i.e., 2 710 treatment plants, only 35 % meet the discharge requirement, 58 % do not meet the requirements and the remaining 7% do not have available data (Berge and Sæther, 2020).

The produced sewage sludge (108 400 tons in 2019) from the treatment plants is used for different purposes; approximately 77 % was used in agriculture, delivered to soil producers, used in parks and other green areas (Berge and Sæther, 2020). It is estimated that in 2019 the Norwegian municipal wastewater sector discharged to water: 32 070 tons of BOD, 66 747 tons of COD, 1 490 tons of phosphorus, and 19 800 tons of nitrogen (Norwegian Environment Agency, 2019).

Organic household waste treatment in Norway

In Norway, household waste represents around 20 percent of the total share of municipal solid waste produced, and it is the duty of the municipality to manage it in an adequate way. The organic fraction of the solid waste is sorted at the source and collected separately. In 2019, 208 905 tons of food and wet organic waste were collected in the country, an average of 70 kg per person. Over 75% of the waste was treated by anaerobic digestion, with biogas production, 23 % was treated by composting, and the remaining was sent to incineration or other forms of treatment (Statistisk Sentralbyrå, 2019).

2.1.3 Circular economy and Ecological Sanitation

As stated by Esrey et al. (2001), the conventional wastewater treatment solutions have solved some problems, but it has also contributed to other challenges we face today, i.e., water pollution, water scarcity, loss of soil fertility and lack of food security. To address these challenges and support sustainable development, the Circular Economy strategy has now been directed to the wastewater sector and the Ecological Sanitation concept is getting the spotlight. Both concepts are discussed in the following.

Circular economy

Circular economy (CE) is defined by the European Commission (2015) as a system in which 'the value of the products, materials, and resources are maintained in the economy for as long as possible, and waste generation is minimized'. The circular economy (CE) strategy fosters innovation, supports sustainable and resource-efficient policies and practices, offering new relationships between natural resources and markets (Voulvoulis, 2018). The basic approaches of CE in wastewater management were communicated in 2014, by the European Commission, with the zero-waste strategy considering the interactions of waste, water, energy and raw material as sustainable source management, pointing out that wastewater can be an important source of energy and nutrients (European Commission, 2014). The Commission has not yet drawn the policy framework for wastewater management. However, in the latest publication in 2020, 'A new circular economy action plan for a cleaner and more competitive Europe', it is considered the review of the directives on wastewater treatment and sewage sludge and natural means of nutrient removal, with the development of an 'Integrated Nutrient Management Plan' (European Commission, 2020).

For effective resource management from wastewater, it is important to have supportive policies, adapted technologies and fit-for-purpose treatment to optimize resource recovery and to value the benefits of recovered resources utilization (UN WWAP, 2017). Figure 1 presents the frame of wastewater management from a resource perspective. In the World Water Development Report 2017, UN argues that such a perspective embraces the precautionary approach and the polluters-pay principle, promotes innovative financial mechanisms and strengthens police implementations.

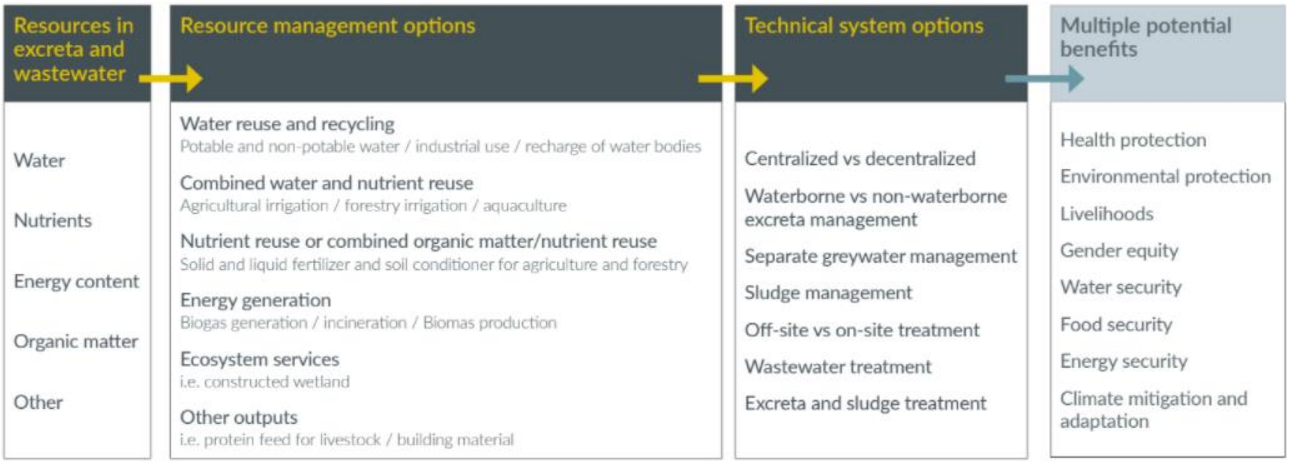

Figure 1: Framing wastewater management from a resource perspective. Source UN WWAP, 2017.

As stated by Smol et al. (2020), water management is critical in the transition from linear consumption towards circular economy and the reuse of wastewater is an important alternative. Wastewater reuse has been practiced for centuries as irrigation for agriculture (Salgot et al., 2018). Besides sparing freshwater, it provides nutrients to the soil. The wastewater can also be reused in industrial and urban contexts, e.g., for urban irrigation, toilet flushing, car wash, fire protection etc. (Neczaj et al., 2018). According to UN WWAP (2017), the biggest share of wastewater reuse after tertiary treatment is applied to agriculture irrigation (32%), followed by landscape irrigation (20%) and industrial purposes (19.3%), direct potable reuse is only 2,3%.

Even though households are the smaller consumers of water, just 10% of total water withdraw is for domestic purposes, they can have a bigger potential to implement on-site water-saving strategies and develop environmental awareness (Smol et al., 2020). One of the challenges faced by non-potable and potable water reuse is the increasing public opposition and many projects have been stopped. As highlighted by Voulvoulis (2018), the outcome principles of the failed projects are the importance of communication and public information, sound decision making and building and maintaining trust between institutions and population. The author also remarks on the findings of studies appointing that the biggest challenge is the authority's perception of the public acceptance. Another challenge is the great variation of wastewater reuse schemes and regulations on the level of treatment and removal requirements worldwide, which can pose a risk to water quality, health and environment (Voulvoulis, 2018).

Energy can be recovered as heat, biofuel and electricity, through heat pumps/exchangers, sludge incineration, biogas production etc. (Neczaj and Grosser, 2018). As stated by Kehrein et al. (2020), the total thermal energy in the wastewater exceeds by far the demand of the treatment plant, signifying the potential to supply other services. Central collection at sewer lines or treatment plants is more feasible (Frijns et al., 2013), and anaerobic digesters, for decentralized systems, need to be subsidized to become a more competitive option (Kehrein et al., 2020). There are several options to recover heat from the municipal wastewater, but most of the heat can be recovered decentral, within homes, which can be used for heating back the building. The main energy source in a treatment plant is biogas, via anaerobic digestion. Nowadays the existing self-sufficient processes adopt Combined Heat and Power, which can generate heat and electricity from biogas (Neczaj et al., 2018).

It is possible to recover nutrients from raw wastewater, semi-treated, from the sewage sludge and urine, reducing the demand for fossil-based fertilizers and, therefore, reducing the use of water and energy. Land application, as fertilizer, is the oldest method that uses by-products from wastewater treatment and it is widely practiced (Neczaj et al., 2018). Besides phosphorus, nitrogen and potassium, cellulose, volatile fatty acids, extracellular polymeric substances, single-cell protein and CO_2 can be recovered from wastewater and be used in different purposes (Kehrein et al., 2020). More about the resource recovery processes are discussed in the coming sections of this chapter.

Ecological Sanitation

Esrey et al. (2001) defines Ecological Sanitation as *'a system that prevents disease and promotes health; protects the environment and conserves water; recovers and recycles nutrients and organic matter*'. It is based on three fundamental principles: prevent pollution rather than control it after being polluted; sanitize urine and faeces; and use the safe products for agricultural purposes (Winblad et al. 2004). The ecological approach presented a new paradigm for wastewater treatment, considering urine and faeces as two components with distinct characteristics in terms of pathogens, nutrient content and benefits to soil and plants. Transforming the linear flows and disposal approach in sanitation to a circular flow, it is possible to avoid impacts to the environment and human health, while recovering important nutrients and organic matter, thus closing the nutrient loop (Esrey et al. 2001).

A sustainable sanitation system should meet the following criteria: *disease prevention*, it must be capable of destroying or isolating faecal pathogens*; environmental protection*, prevent pollution and conserve water resources*; nutrient recycling; affordability*, it must be accessible to all*; acceptability*, it must be aesthetically inoffensive and consistent with cultural and social values*; simplicity*, it must be robust enough to be easily maintained with the limitation of local technical capacity, institutional framework and economic resources (Winblad et al., 2004).

In the source-separated sanitation concept, there are mainly two streams of domestic wastewater, i.e., concentrated blackwater (BW), consisting of faeces, urine and optional organic kitchen waste, and low concentrated greywater (GW). With distinct characteristics and composition, both streams represent potential for reuse and resource recovery, and for that it requires a different treatment approach (Zeeman et al., 2008). Greywater represents up to 70 percent of the domestic wastewater volume, and its concentration and composition vary due to personal and cultural habits considering water use, and quantity and quality of hygiene and cleaning products used in the household. Greywater contains a major part of heavy metals and a minor part of pathogens and nutrients, which are mainly inorganic (Kujawa-Roeleveld and Zeeman, 2006).

Kujawa-Roeleveld and Zeeman (2006) compiled data on the volume and concentration of separated domestic wastewater, mainly using European data, presented in Table 5. As the authors argue, the composition of the different streams of domestic wastewater will vary to a certain extent according to the geographical location and culture, the determination approach selected, the test used and calculation procedures.

Table 5: Volume and concentration of separated domestic wastewater. Source: Kujawa-Roeleveld and Zeeman, 2006.

Parameter	**Unit**	**Urine**	**Faeces**	**Greywater**	**Kitchen refuse**
Volume	g or L $p^{-1}d^{-1}$	**1.25–1.5**	**0.07–0.17**	**91.3**	**0.2**
Nitrogen	gN $p^{-1}d^{-1}$	**7–11**	**1.5–2**	**1.0–1.4**	**1.5–1.9**
Phosphorus	gP $p^{-1}d^{-1}$	**0.6–1.0**	**0.3–0.7**	**0.3–0.5**	**0.13–0.28**
Potassium	gK $p^{-1}d^{-1}$	**2.2–3.3**	**0.8–1.0**	**0.5–1**	**0.22**
Calcium	gCa $p^{-1}d^{-1}$	**0.2**	**0.53**		
Magnesium	gMg $p^{-1}d^{-1}$	**0.2**	**0.18**		
BOD	gBOD $p^{-1}d^{-1}$	**5–6**	**14–33.5**	**26–28**	
COD	gCOD $p^{-1}d^{-1}$	**10–12**	**45.7–54.5**	**52**	**59**
Dry matter	g $p^{-1}d^{-1}$	**20–60**	**30**	**54.8**	**75**

Besides the chemical parameters, blackwater may contain a display of pathogenic viruses, bacteria, protozoa and helminths. In general, urine is sterile and does not contain pathogens. However, in cases when the host is infected, pathogens can be excreted in the urine (Feachem et al., 1983). There are five groups of viruses of particular importance present in feces: adenoviruses, enteroviruses, hepatitis A virus and diarrhea-causing viruses, especially rotavirus. The concentration and species of bacteria found in feces vary among communities and their habits. Bacteria is present and numerous in feces of healthy people, and for that, it has been used as an indicator of fecal pollution, e.g., fecal coliform Escherichia coli, the most widely used indicator. On the protozoa present in the human intestines, three species are considered to be pathogenic: giardia lamblia, Balantidum coli and Entamoeba histolytica. Regarding helminths, only concerns those whose eggs and larval forms are present in the excreta (Feachem et al., 1983).

Time and the environmental conditions are the overall features affecting the viability of pathogens, whereas physicochemical and biological factors impact differently each microorganism. The concentration of pathogens in the blackwater declines with time by death or loss of infectivity. The number of viruses and protozoa will always decline, once they are unable to grow outside a host. Bacteria can multiply under favorable conditions, and helminths need a dormant period before being infective (Schonning and Stenstrom, 2004).

The removal potential of a treatment system should be related to the incoming concentrations of pathogens, the disposal form or the intended reuse of treated wastewater, and the associated health risks (Feachem et al., 1983). The choice of the treatment technology depends on local variables, such as climate, population density and settlement pattern, social/ cultural behavior, agriculture, economy, technical capacity and institutional support (Winblad et al. 2004).

The design of the toilet is a critical component of ecological sanitation. There are various ecological toilets that can be separated into mainly two groups: the most used type is the urine-diverting toilet, and the other type is non- urine-diverting toilets (Esrey et al. 2001). Besides diversion of urine, toilets can have different categories of flushing, which aims for water saving and efficiency of management with less dilution. Kujawa-Roeleveld and Zeeman (2006) presented a comparison of the different categories of toilet flushing (Table 6), considering individual use of 5 times for urine and one time for feces a day.

Table 6: Different categories of flushing toilet. Source: Kujawa-Roeleveld and Zeeman, 2006.

Toilet type	**One flush (L per flush)**	**Large flush (L per flush)**	**Small flush (L per flush)**	**Total Volume (L per person a day)**
Very low flush with gravity sewers	0.6 - 1	2	0.2	3- 6
Vacuum	0.8 - 2			
Urine diverting		4 - 6	0.2	5 -7
Conventional low flush (two buttons)		4	2	14
Conventional toilet	6 - 12			36 - 72

As highlighted by Tilley et al. (2014), the choice of toilet depends on factors such as availability of water for flushing, habits and preferences of users, local availability of materials and compatibility with the subsequent storage and collection, conveyance and treatment technology. The storage and collection methods depend on the availability of space, soil and groundwater characteristics, type and quantity of wastewater, desired output product, financial resources, compatibility with treatment and management considerations. Some of the storage and collection technologies are pit latrine and ventilated improved pit, dehydration vaults, composting chamber, septic tank, etc. (Tilley et al., 2014). In eco-san systems, the primary processing of excreta is through dehydration or decomposition, or a combination of both, and are mostly intended to be applied at household level. Systems based on dehydration decrease the humidity content to less than 25% through evaporation and additions of dry materials; it also requires urine diversion. Decomposition systems are based on biological processes in which organic substances are mineralized and turned into humus (Esrey et al., 1998).

Some of the treatment technologies that can be applied at household or neighborhood level are, for example, anaerobic ponds, septic tank, anaerobic baffled reactor (ABR), anaerobic filter, constructed wetland, upflow anaerobic sludge blanket reactor (UASB). For all these technologies, the effluent and sludge produced require further treatment and appropriate discharge. For sludge treatment, some of the options are the sedimentation/ thickening ponds, drying bed, co-composting, biogas reactor. These treatment technologies presented by Tilley et al. (2014) are intended to be applied at neighborhood level, for they are designed to treat increased volumes and provide removal of nutrients, organic matter and pathogens. On the other hand, the operation, maintenance, and energy demand are generally higher when compared to household-level treatment systems.

2.1.4 Resource recovery processes

Adopting the circular economy and fostering sustainability, the application of resource recovery processes in wastewater treatment and the development of new methods are increasing. This section will explore one popular energy recovery process, anaerobic digestion, and three different methods of nutrient recovery from the effluent of the anaerobic reactor. The first method is liquid fertilizer production, through a new technique combining filtration and ultraviolet (UV) light. The second method is microalgae cultivation, and the last method discussed is the struvite precipitation, a well-known and applied method.

2.1.4.1 Energy recovery process

As mentioned in the previous section, the main energy source in a wastewater treatment system is biogas, via anaerobic digestion (Neczaj et al., 2018). Furthermore, when compared to other sludge treatment methods, the AD appears to be more advantageous due to its small land acquisition and low sludge production. As stated by Wendland (2008), other main drivers for adopting source separation systems and anaerobic treatment of blackwater are the safe sanitation it provides, water-saving through low flushing, production of a reliable source of renewable energy, and production of organic fertilizer for agriculture. Table 7 displays the advantages and disadvantages of the anaerobic process:

Table 7: Advantages and disadvantages of anaerobic digestion. Source: Chong et al., 2012, p.3436 (citing Seghezzo et al., 1998).

Advantages	**Disadvantages**
High efficiency: Good removal efficiency can be achieved in the system, even at high loading rates and low temperatures. Simplicity: The construction and operation of these reactors is relatively simple. Flexibility: Anaerobic treatment can easily be applied on either a very large or a very small scale. Low space requirements: When high loading rates are accommodated, the area needed for the reactor is small. Low energy consumption: As far as no heating of the influent is needed to reach the working temperature and all plant operations can be done by gravity, the energy consumption of the reactor is almost negligible. Moreover, energy is produced during the process in the form of methane. Low sludge production: The sludge production is low, when compared to aerobic methods, due to the slow growth rate of anaerobic bacteria. The sludge is well stabilized for final disposal and has good dewatering characteristics. It can be preserved for long periods of time without a significant reduction of activity, allowing its use as inoculum for the start-up of new reactors. Low nutrients and chemicals requirement: Especially in the case of sewage, an adequate and stable pH can be maintained without the addition of chemicals. Macronutrients (nitrogen and phosphorus) and micronutrients are also available in sewage, while toxic compounds are absent.	Low pathogen and nutrient removal: Pathogens are only partially removed, except helminth eggs, which are effectively captured in the sludge bed. Nutrients removal is not complete and therefore a post-treatment is required. Long start-up: Due to the low growth rate of methanogenic organisms, the start-up takes longer as compared to aerobic processes, when no good inoculum is available. Possible bad odors: Hydrogen sulphide is produced during the anaerobic process, especially when there are high concentrations of sulphate in the influent. A proper handling of the biogas is required to avoid bad smell. Necessity of post-treatment: post-treatment of the anaerobic effluent is generally required to reach the discharge standards for organic matter, nutrients and pathogens.

Anaerobic digestion is a biological process in which the organic matter is decomposed in the absence of oxygen, producing a mixture of methane, carbon dioxide and traces of other gases. AD of black water is a multistep process of series and parallel reactions (Figure 2). These processes are classified in four stages, summarized by Wendland (2008) as:

- *Disintegration and hydrolysis:* complex organic matter is broken down into smaller particles. Particulate organic matter is converted to components such as amino acids, single sugar and long chain fatty acids (LCFA). Such compounds can pass through the cell membrane (hydrolysis).
- *Acidogenesis:* Hydrolysis products are fermented or anaerobically oxidized to volatile fatty acids (VFA), alcohol and ammonia.
- *Acetogenesis:* Alcohol and VFA are converted to acetic or hydrogen and carbon dioxide.
- *Methanogenesis:* Acetic acids, carbon dioxide and hydrogen are converted to methane and carbon dioxide.

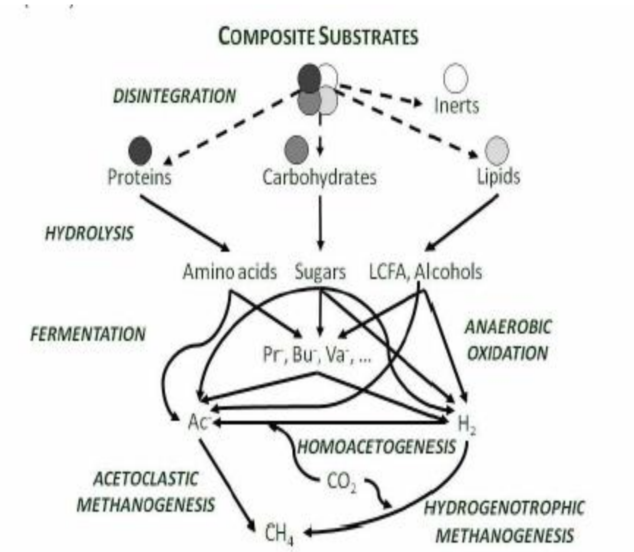

Figure 2: Process of anaerobic degradation. Source: Labatut et al., 2014.

The AD is susceptible to environmental conditions, and it requires meticulous control of the factors influencing the microorganisms in the process. As pointed out by Labatut et al. (2014), the stability and efficiency of the AD will be determined by the balance between the reactants and products. Methanogenesis is a rate-limiting step in the AD, and the effect of environmental factors on the AD efficiency is usually assessed by the methane yield (Khanal, 2018). The important environmental conditions affecting the AD are primarily the temperature and pH, as well as the oxidation reduction potential, nutrients and trace metals, toxicity and inhibition. Table 8 summarizes the main features of anaerobic digestion phases:

Table 8: Environmental requirements for AD phases. Source: Deublein and Steinhauser, 2008.

Parameter	Hydrolysis/ Acidogenesis	Methane formation
Temperature	25 -30℃	Mesophilic: 32-42℃ Thermophilic: 50-58℃
pH	5.2-6.3	6.7-7.5
C:N ratio	10-45	20-30
Dry Matter content	<40% DM	<30%DM
Redox potential	+400 to -300 mV	<- 250 mV
Required C:N:P:S ratio	500:15:5:3	600:15:5:3
Trace elements	No special requirements	Essential: Ni, Co, Mo, Se

Temperature

AD processes can be classified according to their temperature range, i.e., psychrophilic (10 to 20℃), mesophilic (20 to 40℃) and thermophilic (50 to 60℃). The conversion of organic matter is most efficient at 35 to 40℃ in mesophilic conditions and for thermophilic conditions it is about 55℃ (Khanal, 2008, p.13). Mesophilic conditions are normally applied because of more stable treatment, and the variety of robust mesophilic bacteria available (Metcalf and Eddy, 2003).

pH, alkalinity and volatile fatty acids (VFA)

As explained by Wendland (2008), the pH of the AD is dependent on the substrate composition and operational conditions. In terms of optimal pH, there are two groups of bacteria: acid-producing bacteria (acidogens), which prefer a pH range of 5.5 to 6.5, and methane-producing bacteria (methanogens), with pH range of 7.8 - 8.2. Once the rate-limiting step is methanogenesis, in which both bacterial cultures coexist, it is important to maintain the process close to neutral pH (Khanal, 2008). In case of imbalance in the process, caused by changes in operating conditions or introduction of toxic substances, it may result in accumulation of VFA if the system does not present enough buffer capacity, i.e., alkalinity (Labatut and Gooch, 2014).

Labatut and Gooch (2014) explained that the main source of buffer capacity in the system is the bicarbonate ion (HCO_3^-) and its concentration in solution is related to the percent of carbon dioxide in the gaseous phase. As remarked by Wendland (2008), another important parameter that has a direct effect on the stability of the process is the ammonia content. Wendland (2008) explains that the formation of VFA decreases the buffer capacity, but at the same time, the NH_4^+ produced increases the bicarbonate buffer concentration. In addition, reduction in the sulphate concentration leads to COD decrease, thus increasing pH and buffer capacity. The author summarized that in case of pH increase due to high ammonia or sulphate concentration, subsequent inhibition of methanogenic bacteria and the decline of microorganism activity leads to VFA accumulation, and a new steady state will take place. However, an irreversible breakdown can occur if pH drops drastically.

Ammonia concentrations

In blackwater, most of the nitrogen is in the form of urea ($CO(NH_2)_2$), which is a product of protein degradation. Urea is decomposed by bacteria via enzymatic catalyzed reaction (1); thus, ammonia and carbonate are present in high concentration in blackwater, giving the system a high buffer capacity.

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{2-} \qquad (1)$$

Ammonia is important as a nitrogen source for the bacterial cell mass synthesis, which they obtain from NH_4 (Wendland, 2008), but free ammonia (NH_3) at high concentration can be toxic to methanogenic bacteria (Metcalf and Eddy, 2003). The amount of free ammonia is a function of the temperature and pH (Metcalf and Eddy, 2003), according to equation (2):

$$NH_3 + H_2O \leftrightarrow NH_4^+ + OH^- \qquad (2)$$

Wendland (2008) explains that there are two mechanisms in which the process is inhibited by free ammonia: (1) methane synthesizing enzymes are directly inhibited, and (2) bacteria cell walls are more permeable, intracellular pH conditions are affected. The author mentions that higher pH and temperature lead to higher free ammonia concentrations, thus start inhibiting the methanogenic bacteria and increasing VFA concentrations. With that, pH decreases and so free ammonia concentrations, leading to a self-stabilization of the process.

Nutrients and trace elements

As explained by Deublein and Steinhauser (2008), there is no need for nutrients in the AD, once not much biomass is developing in the process. The C/N ratio in the substrate should be in the range of 16:1 to 25:1, and for methane formation, it is sufficient the ratio C:N:P:S of 500-100:15-20:5:3 or the organic matter ratio of COD:N:P:S as 800:5:1:0.5. Too high C/N ratio means lack of nitrogen, and too low can lead to high ammonia production and inhibition of methane production (Deublein and Steinhauser, 2008). The authors complement that for the microorganism’s survival, a minimum concentration of trace elements, such as Fe, Co, Ni, Se, W and Mg, is needed.

Volumetric organic loading, hydraulic retention time and solids retention time

As highlighted by Khanal (2008), AD processes are characterized by high volumetric organic loading rates (VOLRs), meaning that more wastewater can be treated per unit of reactor volume. The author explains that VOLR is dependent on several factors such as reactor type, the kinetics of the degradation and biomass level. VOLR is given by equation (3), where Ci is the COD concentration (mg/L), Q is the flow rate (m^3/day) and V is the reactors volume (m^3):

VOLR= (Ci . Q) / V (3)

Two other parameters are discussed by the author: the biomass yield (equation 4), represented by the yield coefficient (Y), and the specific substrate utilization rate (equation 5). The first indicates cell growth in the system, where ΔX is the increase in biomass concentration (mg VSS/L) and ΔS is the decrease in substrate concentration (mg COD/L). Metcalf and Eddy (2003) argue that the main advantage of the AD processes is the lower biomass yield, resulting in less sludge produced, and thus the sludge processing and disposal costs are reduced significantly. Furthermore, the specific substrate utilization rate indicates the ability of the biomass to utilize the substrate.

Biomass yield: $Y= \Delta X / \Delta S$ (4)

Specific substrate utilization rate = kg COD removed / (kg VSS.day) (5)

For the design of biological treatments, there are two important parameters, hydraulic retention time (HRT) and solids retention time (SRT). Khanal (2008) explains that 'SRT is a measure of the biological systems capability to achieve specific effluent standards and /or to maintain a satisfactory biodegradation rate of pollutants'. Zeeman and Lettinga (1999) complement that the SRT is determined by the amount of sludge retained in the reactor and the excess produced daily and can be calculated according to equation (6), where X is the sludge concentration in the reactor (g COD/ L), and Xp is the sludge production (g COD/L.day)

SRT = X /Xp (6)

As discussed by Khanal (2008), the rate of microbial metabolism is the key to find the time required to achieve the desired degree of treatment. The author defines HRT as the time the waste remains in the reactor, in contact with the biomass. Zeeman and Lettinga (1999) proposed the following equation (7) to calculate HRT:

$$\text{HRT} = C \cdot \frac{SS}{X} \cdot R \cdot (1-H) \cdot \text{SRT} \quad (7)$$

where C is the COD concentration in the influent (COD total, in g COD/L), SS is the fraction of suspended solids in the influent (COD SS/COD total), X is the sludge concentration in the reactor (in g COD/L), R is the fraction of COD SS removed and H is the level of hydrolysis of the removed solids. The HRT will be different for each anaerobic system.

Types of anaerobic reactors

Among the anaerobic reactors, the high-rate reactors are more popular for it allows improved sludge stabilization and higher loading capacity. The different high-rate reactors commonly used are upflow anaerobic sludge blanket (UASB), anaerobic filter, anaerobic baffled, sequencing batch, hybrid upflow anaerobic sludge blanket, continuous- stirred tank digester etc. These are designed to operate at long solids retention time and short hydraulic retention time (Chong et al., 2012). Tiwari et al. (2006) state that among the reactors installed worldwide, the UASB is the most robust. Table 9 shows the classification of anaerobic reactors:

Table 9: Classification of anaerobic reactors. Source: Khanal, 2008.

Low-rate anaerobic reactors	**High-rate anaerobic reactors**
• Anaerobic pond • Septic tank • Imhoff tank • Standard-rate anaerobic digester	Suspended growth • High-rate anaerobic digester • Upflow anaerobic sludge blanket (UASB) • Anaerobic sequencing batch reactor (ASBR) Attached growth • Anaerobic filter • Fluidized bed reactor Others • Static granular bed reactor • Anaerobic membrane reactor • Hybrid reactor

Biogas production

Biogas production is one of the most important features of the AD; it can be used as a parameter to measure the process performance (Labatut and Gooch, 2014). Biogas is composed of methane and carbon dioxide, but as Khanal (2008) remarks, the quantity and quality of the biogas produced are dependent on the characteristics of the substrate. The addition of organic kitchen waste to the AD of blackwater can double the biogas production (Zeeman et al., 2008). The gas production is usually estimated by the percentage of volatile solids reduced in the process; it can be considered that it is produced from 0.75 to 1.12 m^3 of biogas per kg of volatile solids digested (Metcalf and Eddy, 2013).

Khanal (2008) explains that the methane production can also be estimated by the COD and BOD stabilization, i.e., 1 kg of COD destroyed produces 0.35 m^3 of CH_4, at standard temperature and pressure.

Hygienic aspects

In the AD process, complete degradation of organic matter does not occur. Thus, remaining fractions of COD, nutrients and pathogens demand a post-treatment to meet the requirements for discharge (Kujawa-Roeleveld and Zeeman, 2006). As discussed previously, in Europe the standard set by the Council Directive 91/271/EEC is less than 125 mg of COD per liter of effluent and for reuse of wastewater in irrigation, the World Health Organization (WHO, 2006) set the standard for less than 1000 fecal coliform per 100 mL and less than one helminth egg per liter.

As explained by Logan and Visvanathan (2018), there are two approaches for digestate processing. The first can be considered the treatment, and it is applied to remove nutrients and organic matter from the effluent. The second approach can be described as digestate conditioning, which produces biofertilizer. Some common post processing methods for AD digestate are stabilization ponds, rotating biological contactors, trickling filters, activated sludge, pasteurization, liming, composting and others (Kujawa-Roeleveld and Zeeman, 2006; Wendland, 2018).

With the increasing application of AD technology, effluent disposal is a challenge for biogas plants (Fuchs and Drosg, 2013). As Moges et al. (2018) addressed, the AD does not meet the requirements for nutrient recovery. Thus, it is necessary to apply a mechanism to remove residual contaminants while keeping plant nutrients in the liquid -phase. Adopting the circular economy concepts, the processes described in the next section promote the recycling of nutrients present in the AD digestate.

2.1.4.2 Nutrient recovery processes

It is estimated that in 2019, the Norwegian municipal wastewater sector discharged 1 490 tons of phosphorus (P) and 19 800 tons of nitrogen (N) (Berge and Sæther, 2020). Phosphorus is an essential element for all life forms. The development of human settlement, global food production and consumption system changed the phosphorus cycle, leading to environmental epidemics of freshwater eutrophication and marine dead zones, and resulting in great uncertainty on the future availability of the world's main sources of phosphorus (Ashley et al., 2011). As remarked by WWAP (2017), it is estimated that 22% of the global P demand could be satisfied by recycling human urine and faeces. Nitrogen is also an essential element in water resources, in the atmosphere and for all life forms. As

Sawyer et al. (2003) explain, the chemistry of nitrogen is complex and excessive concentrations of certain nitrogen species can lead to significant environmental problems.

Liquid fertilizer production

There are different approaches to post-treat the liquid fraction of the digestate aiming for nutrient recovery. Some of these methods are membrane technology, evaporation, ammonia stripping and biological treatment (Logan and Visvanathan, 2018). Moges et al. (2018) investigated another method to produce liquid fertilizer from the digestate. The author's method consists of a filter set and UV light chamber (Figure 3). The filter is composed of six columns operating in upflow and six operating in downflow mode. The filter media used is coarse polonite, granulated activated carbon and cocos char, with particle size of 2.8–4.0 mm, 0.5–1.4 mm and 0.35–1.18 mm, respectively. Furthermore, to guarantee the required disinfection, the filtered effluent passes through a UV light chamber with a retention time of 3 hours.

Samples were taken from the upflow and downflow to analyze the effect of the different filter media. The results showed that the carbon-based filters removed 80% of the residual organic matter, more than 90% of residual TSS and 93% of the turbidity. The authors concluded that the filtration and UV as post-treatment is a cost-effective method to recover nutrients in two ways: nutrient solution in the liquid phase and also preserving the nutrients absorbed in the filter media, which can be used as a slow-release fertilizer.

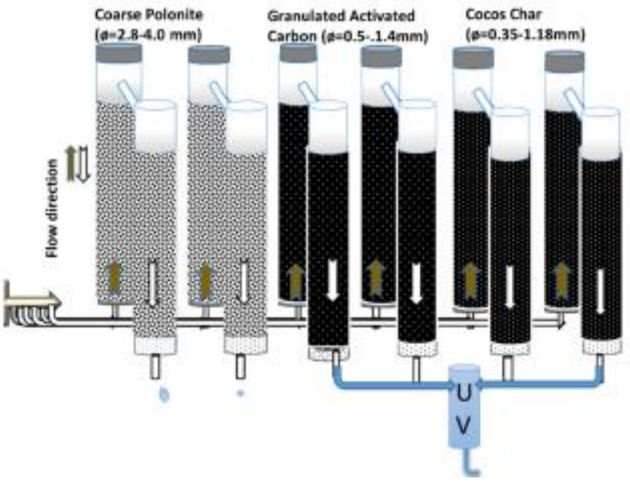

Figure 3: Flow scheme of sequential upflow and downflow filtration system: coarse polonite (ø = 2.8–4.0 mm), granulated activated carbon (ø = 0.5–1.4 mm) and Cocos char (ø = 0.35–1.18 mm). Source: Moges et al. (2018).

Struvite precipitation

Struvite precipitation can occur naturally in the pipelines and other parts of the treatment in a conventional process, and it was considered a problem until it became an interesting method of phosphorus recovery (Siciliano et al., 2020; Le Corre et al., 2009). As described by Le Corre et al. (2009), struvite ($MgNH_4PO_4·6H_2O$) is an orthophosphate containing magnesium, ammonium and phosphate in equal molar concentration (Mg:N:P). Siciliano et al. (2020) remarks that despite the equal molar amounts required for struvite precipitation, the optimal ratios must be assessed individually, for it is dependent on the chemical-physical characteristics of the wastewater. Struvite precipitation follows the general equation (8), in which n=0, 1, or 2:

$$Mg^{2+} + NH_4^{+} + H_nPO_4^{3-n} + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O + nH^{+} \qquad (8)$$

There are two main chemical stages involved in the struvite formation process: nucleation (crystal birth) and crystal growth. Siciliano et al. (2020) explains that the nucleation process is controlled by diffusive mechanisms and the degree of saturation in the solution. The process can be homogeneous, occurring spontaneously, or heterogeneous, if foreign particles or impurities occur. Mass transfer mechanisms control the crystal growth process, from the solute to the crystal's surface, and by surface integration mechanism, i.e., material is incorporated into the crystal. These processes depend on parameters such as pH, supersaturation ratio, temperature and the presence of competitive ions (Siciliano et al., 2020). However, as highlighted by Le Corre et al. (2009), the supersaturation ratio and pH on the crystallization were found to be the most influential parameters.

As cited in Le Corre et al. (2009), Bouropoulos and Koutsoukos (2009) confirmed that the specific pH range for optimum precipitation rate is about 8.5 to 9.5. Moreover, both authors agree that pH can be used as an indicator for struvite nucleation once the rate at pH decreases reflects the speed of the process. The pH affects the struvite crystallization growth and the crystal characteristics and can reduce nitrogen concentration, through gaseous ammonia formation, thus affecting the molar ratio Mg:N:P (Le Corre et al., 2009). At a fixed pH, the rate of the crystallization process and its induction time are affected by the supersaturation level of the solution (Le Corre et al., 2009). Temperature can affect the solubility, morphology and crystal formation, and the range of 25°C to 35°C is considered to be optimal for the process (Siciliano et al., 2020). Figure 4 presents a schematic illustration of struvite formation at constant pH:

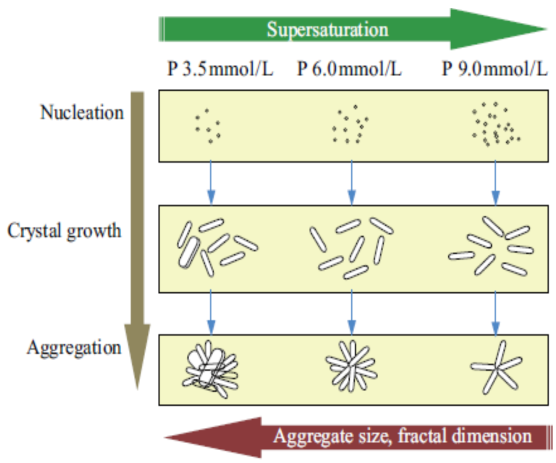

Figure 4: Schematic illustration of struvite formation at constant pH. Source: Ye et al., 2014.

For struvite precipitation, addition of magnesium and phosphorus is required, if ammonia must be removed, and supplementation of alkaline compounds to correct the pH. As Siciliano et al. (2020) explains, the efficiency of the process is dependent on the reagent types, which should be effective, simple to use and free of inhibiting elements. The demand for these reagents can represent a large share of the cost of the process. The authors cited some low-cost magnesium sources that have been tested: mineral rock Magnesite ($MgCO_3$), seawater, wood ash and bittern (bio product from sea salt manufacturing). For low-cost sources of phosphorus, the authors remark on the use of meat waste, specifically ashes from bones, mixed with low-cost magnesium as an effective reagent with high removal percentages. One low-cost reactant for pH mentioned by the authors is plant ashes that have been tested and achieved high efficiency.

Siciliano et al. (2020) investigated the different types of reactors used for the process. The authors concluded that stirred tank reactors (STR) and fluidized bed reactors (FBR) are the most applied reactors. However, other reactors, such as bio electrochemical systems, ion exchange and membrane were found to have constraints in field conditions and need further improvements.

Microalgae biomass cultivation

Wang et al. (2010) remark that the research on algae cultivation as a tertiary wastewater treatment process started in the 1970s, due to the energy crisis that the concept of wastewater as a source for algae production, thus biofuel, got the spotlight. The authors argue that compared to conventional processes, the algae can achieve pollutant reduction in a more sustainable way. Schenk et al. (2008) highlight the main advantages of the microalgal systems: higher photon conversion efficiency; reliable and continuous source, as it can be harvested nearly all year-around; reuse of wastewater, thus reduction of freshwater use; it is a CO_2 neutral due to CO_2 sequestration and produces nontoxic and biodegradable biofuels.

The driving process for microalgae biomass production is photosynthesis. However, as Schenk et al. (2008) explain, the optimization of the cultivation is complex. Some of the limiting factors are the temperature, water quality, pH, salinity, mineral and carbon bioavailability, mixing and fluid dynamics, gas exchange, gas bubbles size and distribution, mass transfer, light cycle and intensity, and other specific characteristics of the algae strain cultivated, such as cell density and growth inhibition. The authors comment that there are two approaches to increasing biomass production: increasing the photosynthetic efficiency, and the selecting and improving of algal strains for optimal growth and survivability.

From the wide range of microalgae, the *Chlorella* species is widely applied in wastewater treatment for its high potential to remove nitrogen, phosphorus, COD and metals, with different retention times ranging from 10h to 42 days (Wang et al., 2010). The authors concluded in their study that *Chlorella* sp. is very adaptive for cultivation in wastewaters with different characteristics. The absolute abundance of N and P is important for algal growth, irrespective of an optimal N:P ratio in the cultivation media.

There are two common methods of microalgae cultivation: open cultivation systems, e.g., ponds and open tanks, and controlled closed cultivation systems, using different types of bioreactors, commonly called photobioreactors (PBRs) (Narala et al., 2016). The design of most closed systems are tubular reactors, plate reactors or bubble column reactors, explains Shenk et al. (2008). Narala et al. (2016) mentions that the major advantages of the open system are the low capital and operating costs and lower energy requirement for mixing. On the other side, the system requires large areas and is susceptible to contamination and adverse weather conditions. As the authors highlight, the closed cultivation systems are operated in highly controlled conditions, hence it is more efficient. It requires less space, increases light availability and reduces contamination issues. On the other hand, some disadvantages of the PBRs are the high cost for design and operation, overheating, cleaning issues, biofouling and others. As remarked by Shenk et al. (2008), the higher costs are compensated by the high productivity and small footprint of the system, with less consumption of energy, water and chemicals.

2.2 Life Cycle Assessment (LCA) as a Holistic Environmental Tool

Agenda 21 defined environmental sound technologies as a total system that protects the environment, are less polluting, uses resources sustainably, promotes recycling of their wastes and products, and handles residual waste in a more acceptable manner than the other options (UNCED, 1992, chapter 34). One of the objectives proposed by Agenda 21 is to ensure access to information and to the environmental sound technologies to all. For that, it is important to build up technology assessment capacity. In order to determine the performance of specific technologies in different conditions and recommend the best option, it is essential to perform an environmental impact assessment (UNCED, 1992). Among the methods to assess the environmental impact of these technologies is the Life Cycle Assessment. An LCA addresses the environmental aspects and potential impacts throughout a product or a process's life cycle, from raw materials production, processing, use, end-of-life treatment, recycling and final disposal. The LCA can assist in the selection of relevant indicators of environmental performance and identification of possible improvements of products and processes, can support decision making at various levels, and be a helpful tool for marketing (ISO, 2006).

The LCA methodology has been used in the wastewater field for more than two decades. It has been applied to the planning phase in order to evaluate the different management strategies, to compare centralized and decentralized options, etc. It has been applied in the design phase and for optimization, for example to compare different treatment technologies, operating strategies, for technology development, to evaluate the sludge treatment and disposal, identification of the environmental hotspots of a WWTP etc. LCA can provide information for the decision-makers and be a great tool to support the paradigm transition from the pollutant removal process to include resource recovery and the pursuit of a circular economy (Corominas et al., 2020).

2.2.1 LCA framework

The requirements for conducting an LCA are presented by the ISO 14040 family, and it was prepared by Technical Committee ISO/TC 207, Environmental management, Subcommittee SC 5, Life Cycle Assessment. There are four phases in an LCA study: goal and scope definition, inventory analysis (LCI), impact assessment (LCIA) and interpretation (ISO, 2006). The LCA framework is presented in Figure 5:

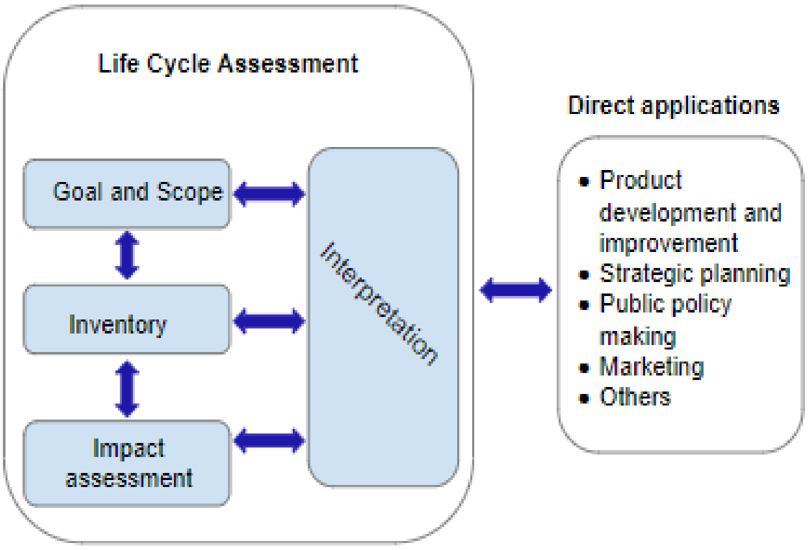

Figure 5: LCA framework. Source ISO 14040:2006(E).

Goal and scope definition

The goal definition is the first phase of the LCA and has great influence on the following phases. For the iterative nature of the LCA, further unforeseen limitations may require revision of the goal definition (Hauschild et al., 2018). ISO 14044 series presents the requirements and guidelines to conduct an LCA. It specifies that the goal of an LCA must state:

- The intended application,
- The reasons for carrying out the study,
- The intended audience of the results,
- Whether the results are intended to be used in comparative assertions to be disclosed to the public.

In the general requirements in ISO 14040:2006(E), it is stated that the scope should be well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal. It highlights that the LCA is an iterative method and as data and information are collected, various aspects of the scope may require alteration in order to meet the original goal of the study. From the twelve elements listed by ISO 14040:2006(E) to be included in the scope, we will focus on five key elements:

- The production system and its boundary,
- Functional unit,
- Data and data quality requirements and
- Impact categories selected and methodology of impact assessment.

The scope is more extensive than the goal description and a clear understanding of the terminology and concepts is essential to carry out an LCA. The following terms are defined in ISO 14040:2006(E) as:

- ***Function:*** *a system may have several possible functions and the one(s) selected for a study depend(s) on the goal and scope of the LCA.*
- ***System boundary:*** *establishes the unit processes to be included in the system under analysis, and the inputs and outputs at its boundary are elementary flows.*
- ***Functional unit:*** *it defines the quantification of the identified function of the product.*
- ***Reference flow:*** *measures of outputs from processes in a given system required to fulfill the function expressed by the functional unit.*

The guidelines highlight that the criteria used to define the system boundary and cut-off criteria are important for the degree of confidence in the LCA results. ISO 14040:2006(E) also remarks that to understand the results' reliability and make a correct interpretation, the description of the data quality is very important. It provides general characteristics of the data needed for the study. As specified in the Standard, it should include the expectations with respect to the source of data, age and geospatial reach, completeness, etc. The goal and scope should also include the level of detail, choice of impact categories, methodologies of impact assessment, and the interpretation to be used in the LCIA phase.

Life Cycle Inventory Analysis (LCI)

This phase includes data collection and the calculation procedures when quantifying relevant inputs and outputs of a product system (ISO 14040:2006(E)). The result from the LCI is a list quantifying the elementary flows crossing the systems boundary, e.g., energy, water, raw materials, products, air/ soil/ water emission and solid waste and others. Therefore, it must be consistent with the goal definition and the requirements set in the scope (Hauschild et al., 2018). Four steps to perform this phase are suggested by EPA (2006): (1) develop a flow diagram of the process, (2) develop a data collection plan, (3) collect data and (4) evaluate and report the results.

Steps 1 and 2 are a preparation for the LCI, and the flow diagram can work as a map of inputs and outputs of the system. It is important to include as many flows as possible in the LCI because the more elaborated the diagram is, the more reliable the results are (EPA, 2006; Hauschild et al., 2018). EPA (2006) also remarks that key elements of the data collection plan are the definition of data quality goals, identification of data sources and types and data quality indicators. ISO 14040:2006(E) mentions that data collection procedures can be a resource-intensive process and that practical constraints should be considered in the scope of the LCA. Therefore, the complexity of the analysis can be a balance between the resources for data acquisition and the accuracy and utility of the results intended.

There are two types of data involved in the LCI, foreground and background data. EPA (2006) defines it as: (1) *Foreground Data: data from the foreground system that is the system of primary concern to the analyst*, and (2) *Background Data: include energy and materials that are delivered to the foreground system as aggregated data sets in which individual plants and operations are not identified.*

Matthews et al. (2014) remark that the gold standard of LCI is to collect primary data, i.e., direct measuring of inputs and outputs (foreground data). Alternatively, data from secondary sources and LCA databases can be used. To assemble the inventory, it is needed to include the calculation procedure, the validation of the data collected, the relation of data to the unit process, and to the reference flow of the functional unit, as recommended in ISO 14040:2006(E). When collected and evaluated, the data can be organized by specific processes, life cycle stage, media of emission or other combinations that suits better the goal and scope (EPA, 2006).

2.2.2 Life Cycle Impact Assessment (LCIA)

The LCIA is composed of three mandatory elements: (1) selection of impact categories, indicator and characterization models, (2) assignment of LCI results (classification) and (3) calculation of category indicator results (characterization); and optional elements, such as normalization, grouping, and weighing of impacts (Figure 6). As remarked in ISO 14040:2006(E), the LCIA phase only addresses the environmental issues specified in the goal and scope, and thus, it is not a complete assessment of the environmental impacts of the system. EPA (2006) summarizes the steps of the LCIA as:

1. *Selection and Definition of Impact Categories* - identifying relevant environmental impact categories (e.g., global warming, acidification, terrestrial toxicity).

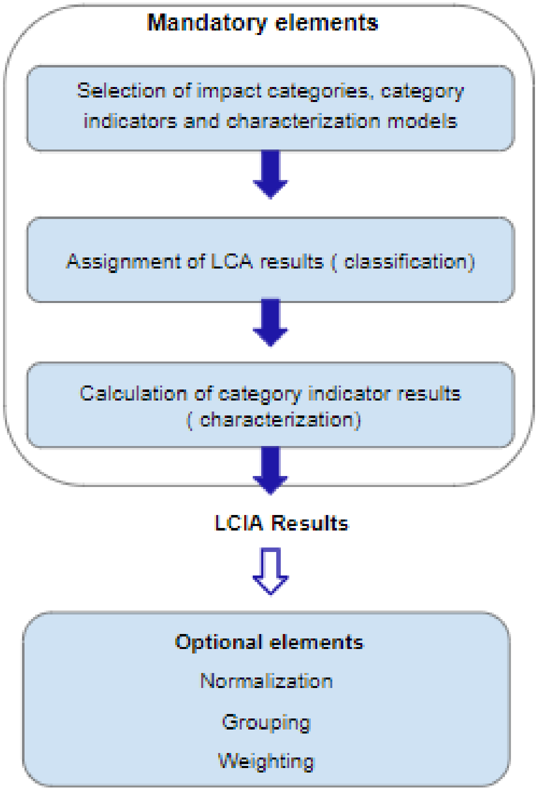

Figure 6: Elements of the LCIA phase. Source: ISO 14040:2006(E).

2. *Classification* - assigning LCI results to the impact categories (e.g., classifying carbon dioxide emissions to global warming).

3. *Characterization* - modeling LCI impacts within impact categories using science-based conversion factors (e.g., modeling the potential impact of carbon dioxide and methane on global warming).

4. *Normalization* - expressing potential impacts in ways that can be compared (e.g., comparing the global warming impact of carbon dioxide and methane).

5. *Grouping* - sorting or ranking the indicators (e.g., sorting the indicators by location: local, regional, and global).

6. *Weighting* - emphasizing the most important potential impacts.

7. *Evaluating and Reporting LCIA Results* - gaining a better understanding of the reliability of the LCIA results.

Impact category is defined in ISO 14040:2006 (E) as a *class representing environmental issues of concern to which life cycle analysis results may be assigned*, category indicator as a *quantifiable representation of an impact category* and the characterization model *is applied to convert assigned life cycle inventory analysis result to a common unit of the category indicator*. The first step, selection and definition of the impact categories relevant for the analysis, should be stated in the goal and scope of the LCA. Some of the commonly used Life Cycle Impact Categories and according to characterization factors listed by EPA (2006) are presented in Table 10:

Table 10: Commonly used Life Cycle Impact Categories. Source: adapted from EPA (2006).

Impact category	**Scale**	**Examples of LCI Data (i.e. classification)**	**Possible Characterization Factor**	**Description of Characterization Factor**
Global Warming	Global	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons Hydrochlorofluorocarbon Methyl Bromide (CH_3Br)	Global Warming Potential	Converts LCI data to carbon dioxide (CO_2) equivalents Note: global warming potentials can be 50, 100, or 500 year potentials.
Acidification	Regional Local	Sulfur Oxides (SOx) Nitrogen Oxides (NOx) Hydrochloric Acid (HCL) Hydroflouric Acid (HF) Ammonia (NH_4)	Acidification Potential	Converts LCI data to hydrogen (H^+) ion equivalents.
Eutrophication	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Ammonia (NH_4)	Eutrophication Potential	Converts LCI data to phosphate (PO_4) equivalents.
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents	LC50	Converts LC50 data to equivalents; uses multi-media modeling, exposure pathways.
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish	LC50	Converts LC50 data to equivalents; uses multi-media modeling, exposure pathways.
Water Use	Global Regional Local	Water used or consumed	Water Shortage Potential	Converts LCI data to a ratio of quantity of water used versus quantity of resource left in reserve.

As explained by Hauschild et al. (2018), 'characterization factor (CF) represents the contribution per quantity of an elementary flow to a specific environmental impact (category). It is calculated using (scientifically valid and quantitative) models of the environmental mechanism representing as realistically as possible the cause–effect chain of events leading to effects impacts on the environment for all elementary flows which contribute to this impact'.

EPA (2006) gives an example of the calculation of characterization factor used to estimate the global warming potential (GWP), using factor values proposed by the Intergovernmental Panel on Climate Change (IPCC) Model:

Chloroform GWP Factor Value = 9 Quantity = 20 pounds

Methane GWP Factor Value = 21 Quantity = 10 pounds

Chloroform GWP Impact = 20 pounds x 9 = 180

Methane GWP Impact = 10 pounds x 21 = 210

2.2.3 Life Cycle Interpretation

As stated in ISO 14040:2006(E), the objectives of the life cycle interpretation are to a*nalyze results, reach conclusions, explain limitations, and provide recommendations based on the findings of the preceding phases of the LCA, and report the results of the life cycle interpretation in a transparent manner*. Furthermore, *provide a readily understandable, complete, and consistent presentation of the results of an LCA study in accordance with the goal and scope of the study.*

Three steps are proposed for the LCA interpretation:

- Identification of the significant issues based on the results of the LCI and LCIA phases,
- Evaluation of completeness, sensitivity and consistency checks,
- Conclusion, recommendations and reporting.
-

2.2.4 Limitations and Uncertainties of LCA

As remarked in ISO 14040:2006 (E), the LCIA phase concerns only the environmental specified in the goal and scope; thus, it does not present a complete assessment of all the environmental impacts of the system. Uncertainties and variabilities throughout the LCA phases can also limit the liability of the results.

2.2.5 LCA software

To simplify the execution of LCA, different software has been developed as a tool, e.g., EcoPro, Gabi 5, Umberto, SimaPro and others. In this study, the software chosen is SimaPro. This software was developed in 1990 by PRé Consultants, based in the Netherlands.

SimaPro

According to the SimaPro manual (PRé Sustainability 2020), the impact assessment methods in the software follow the basic structure: (1) Characterization, (2) Damage assessment, (3) Normalization,

(4) Weighting and (5) Addition. Once the last four steps are optional, according to ISO standards, and it can be switched on or off when editing the model at SimaPro.

As explained by Goedkoop et al. (2010), there are three sections to define the goal and scope of SimaPro:

- Text field: the description of different aspects of goal and scope definition is made.
- Libraries section: it is possible to pre-define the library with standard databases relevant for the project to be studied.
- Data quality section: in which the characteristics of data can be pre-defined.

For the inventory phase, SimaPro comes with the EcoInvent database (background data), covering a broad range of data from thousands of processes and products (Goedkoop et al., 2010). It is possible to select which libraries, i.e., data set, are more suitable to the goal and scope of the analysis.

SimaPro includes various methods to perform the classification and characterization, which are mandatory in the LCIA. The chosen methodology can be selected when doing the calculations, e.g., ReCiPe 2016 Midpoint and Endpoint, IPCC 2013 GWP, etc. The optional elements of LCIA, i.e., normalization, grouping and weighing, can be defined in the model according to the impact assessment method selected (Goedkoop et al., 2010).

The interpretation of the results in SimaPro was designed as a checklist of relevant issues mentioned in the ISO standard. It aims to ensure that the conclusions you want to draw are adequately supported by the data and procedures used (Goedkoop et al., 2010).

3. Materials and Methods

3.1 Study cases

3.1.1 Campus Ås Showcase

Campus Ås, at the Norwegian University of Life Sciences, is one of the Showcase in SiEUGreen project. In the showcase, the waste from 24 student flats will be used for testing and demonstration. The 24 student flats are already equipped with vacuum toilets. The experimental set up considered in the study treats BW and OHW from the student dormitory. The wastewater is treated by anaerobic digestion and the digestate is post-treated with three different methods for nutrient recovery: liquid fertilizer, struvite precipitation and microalgae production.

Anaerobic digestion

The AD set-up consists of a vacuum toilet with 1.2 l flushing volume and a grinder for food waste, a storage tank of 1800L volume, and an anaerobic reactor (type UASB with 700 L daily capacity, that operates at mesophilic condition). The pilot scale is still under construction, so the anaerobic digestion process under analysis is a theoretical system.

The values for the substrate's characteristics and the treatment efficiency were taken from Wendland (2008). The author's study investigated an anaerobic process of blackwater and organic waste for one p.e. with similar amounts, i.e., around 550 l BW and 70 kg OHW, vacuum toilet flush, and 5.5 kg of toilet paper. The reactor used in the experiment was a mesophilic continuous stirred tank (CSTR) with 20 hrs. HRT. It achieved a removal efficiency of 71% for COD, 65% for VS and 72% for TOC. Table 11 presents the concentration of the raw substrate and the liquid AD effluent:

Table 11: Concentration of substrate for anaerobic digestion of BW and OHW and AD effluent. Adapted from: Wendland, 2008.

Parameter	Unit	Raw BW+ OHW	AD effluent
total COD	mg/L	15,690	4,550
TS	mg/L	10,080	3,878
VS	mg/L	7,920	2,772
Total N	mg/L	1,531	1,531
Total P	mg/L	171	171

It is assumed that a theoretical biogas production of $0.35m^3$ CH_4 per kg of COD extracted in the reactor (Kujawa-Roeleveld et al., 2003). Considering the short HRT of the process at mesophilic conditions, no losses on the volume of the liquid digestate were determined. Therefore 2800 L of digestate was directed for the post-treatments. Figure 7 presents a scheme of the AD system:

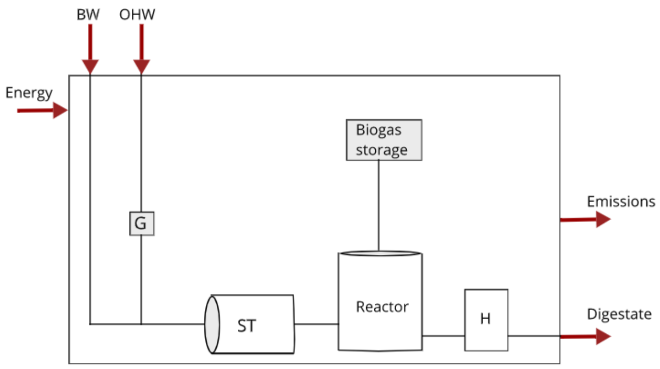

Figure 7: Scheme of anaerobic digestion system. ST: storage tank, H: holding tank.

Water consumption

The AD process does not require water. The water consumption is 2190 L per person/ year for flushing.

Energy consumption

To maintain the system, it is assumed consumption of 33 kWh/pe/ year for the vacuum toilet systems (Wendland, 2008) and an estimated 51 kWh for the pumps. The electricity requirement for the AD reactor was estimated based on the values presented by Banks et al. (2011), which estimates a requirement for heating and electricity of 172 kWh per ton of substrate.

Emissions

The air emissions considered in the process are leakage of biogas, assuming 2,5% of the total produced, and the emissions from the other 97.5% of the biogas that is flared (Gourdet et al., 2017). The effluent from the anaerobic digestion is further treated for nutrient recovery. Therefore, there are no emissions to the water in this process.

Liquid fertilizer production

The setup for the liquid fertilizer production consists of a filter set of eight columns, with cocos char and granular activated carbon as filter media, and an UV light chamber. The columns were made of plexiglass, with a height of 50 cm. Each column was filled with 200 gr of filter media, with a bed height of 39 cm and an extra 2 cm of glass beads (with 3mm diameter) on the top and bottom. The filtered effluent passes through a UV light chamber 29 cm long and diameter of 5.5 cm, with an 11 Watt UV lamp. The chamber has a working load of 21 hrs. daily, with a volume of 0.9 L and a retention time of 3 hrs. The removal efficiency of the filters achieved an average of 80% for COD and 90% for suspended solids, meeting the requirements for discharge for both parameters. Sample analysis and other details about the set up are discussed in Moges et al., 2018.

When saturated, the filter media can also be used as a slow-release fertilizer. Therefore, it is not considered as a waste of the process in this analysis. The application of the liquid fertilizer is not included in the boundary. The scheme of the system is presented in Figure 8:

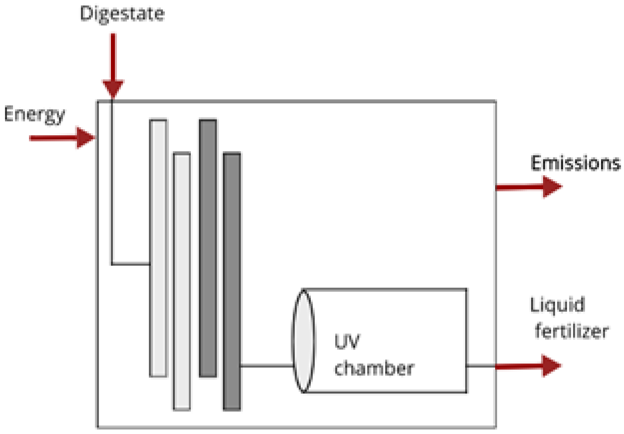

Figure 8: Scheme of liquid fertilizer production system.

Energy consumption

The energy consumption was estimated to be around 484 kWh, according to the equipment requirements.

Emissions

The system is hermetic, and therefore no emissions from this process are accounted for.

Avoided burden of commercial fertilizer

The avoided burden of commercial fertilizer was estimated according to the molecular weight of the nutrients recovered in the liquid phase. A total of 3.5 kg of N and 0.16 kg of P were recovered in the process.

Microalgae cultivation

The system comprises two flat-panel photobioreactors (PBR) continuously illuminated by light-emitting diode (LED) panels. The algae strain cultivated is Chlorella sorokiniana NIVA CHAL176, and the culture volumes were kept at 2.5 L each. The culture was mixed by aeration with compressed air and was operated with the temperature controlled at 37°C and the pH at 7.0± 0.5, by intermittent addition of 0.1 L CO_2 per minute. The HRT in the reactor is 17 hrs, and the total capacity of the reactor is around 7 liters per day. Before feeding the PBR, the liquid fertilizer was diluted to a 10% solution. With a N:P ratio of 14, the nutrient uptake by the algae was 99.8% for N and 99.2% for P. The volumetric biomass productivity was 1.5 grams $L^{-1}d^{-1}$, which corresponds to 0.29 g of dried weight. The effluent from the PBR presented concentration under the discharge limit. More details about the system are discussed in Moges et al. (2020). In Figure 9 is a scheme of the microalgae cultivation system:

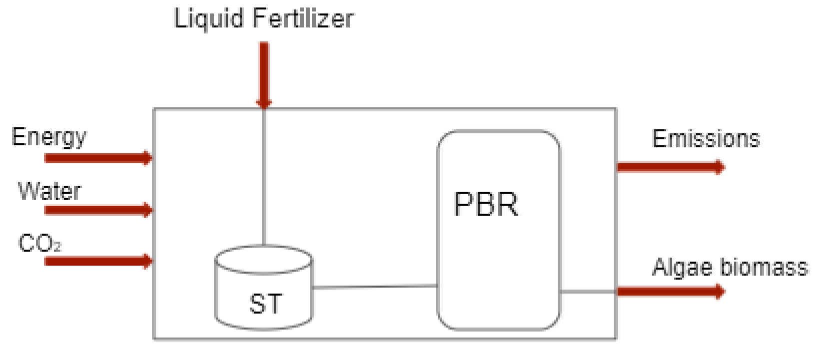

Figure 9: Scheme of the microalgae cultivation system. ST: storage tank, PBR: photobioreactor.

Water consumption

It is necessary 2660 L of water to dilute the liquid fertilizer.

Energy consumption

The energy consumption was estimated to be 1311 kWh, according to the equipment requirements.

Emissions

The system is considered hermetic, therefore, no emissions to the air are accounted for. Nearly total removal of NH_4-N and PO_4-P was achieved in the PBR, and the effluent meets the discharge limits.

Avoided burden of commercial fertilizer

The avoided burden was estimated by the molar weight of the recovered nutrients in the algae biomass. A total of 0.175 kg of N and 0.008 kg of P were recovered.

Struvite precipitation

The reactor for struvite precipitation was a bench-scale setup, constructed with stainless steel and plexiglass, coupled with a mixer. The initial tests were done with magnesium plates as Mg source and a rate of 1 gr of struvite was produced per liter of liquid digestate, considering precipitation of 90% of the P. The effluent from the process can be used as liquid fertilizer with concentration of 1470 mg/L and 17 mg/L of N and P, respectively. The avoided burden of commercial fertilizer production was estimated by the molar weight of the recovered nutrient in the struvite and the effluent from the process. Figure 10 presents a scheme of the reactor:

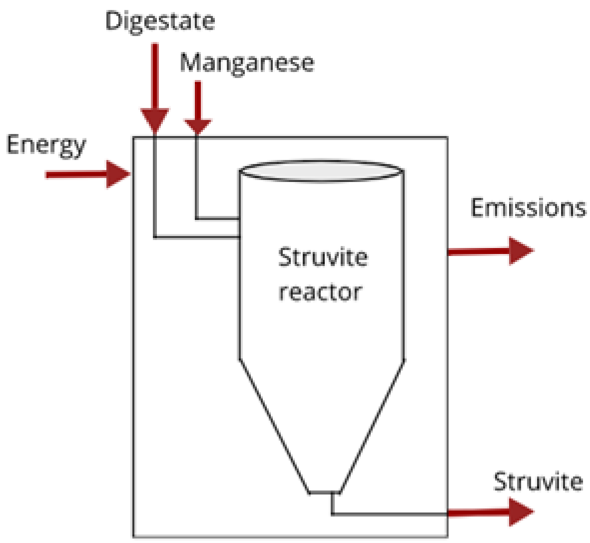

Figure 10: Scheme of the struvite precipitation system.

Energy consumption

The energy consumption was estimated with the values presented by Rodriguez - Garcia et al. (2014), 2.57 kWh per m^3 of digestate, and an estimated 400 kWh for the pumps.

Emissions

It was considered that 0.075g N_2O and 5.77 g NH_3 is emitted per m^3 of digestate treated in the reactor (Rodriguez - Garcia et al., 2014). The effluent from struvite precipitation will be directed to the PBR and the remaining part can be used as liquid fertilizer. Therefore, no emissions to the water will be accounted for in this process.

Avoided burden of commercial fertilizer

The avoided burden was estimated by the molar weight of the recovered nutrients in the struvite. It was estimated that a production 0.08 kg of N based fertilizer and 0.42 kg of P2O5 based fertilizer can be avoided.

3.1.2 Conventional treatment system considered for comparative study

Nordre Follo Wastewater Treatment Plant

For the comparison, the treatment facility selected was the Nordre Follo Wastewater Treatment Plant, located in Vinterbro. The facility receives sewage from three neighboring cities, Ås, Oppegård and Ski, serving a total population of 45,447 people. The treatment process is mechanical, biological and chemical. It consists of a sand filter followed by a sedimentation tank, a nitrogen removal reactor and a flocculation tank. The method applied for nitrogen removal is a biological process that occurs in two stages, aerobic nitrification and anaerobic denitrification. For the treatment process, the consumables used are polymer Zetag, methanol, water and polyaluminum chloride. The biofilm carriers used in the biological stage was not considered consumable. Therefore, it was not accounted for in the analysis of the operational phase.

The sludge is treated in the facility by anaerobic digestion, with the recovery of biogas, and in 2020, 730 816 m^3 was recovered. The biogas is used to produce electricity and heat to supply the facility through boilers for heating water, gas turbines and flares, producing 44 667 kWh in 2020. The concentrations of the influent treated in the plant is presented in Table 12:

Table 12: Concentration of influent of Nordre Follo WWTP in 2021.

Parameter	Total (tonn/year)	Removal efficiency (%)	Discharge (tonn/year)
P	29.68	93.3	1.9
N	188.66	72.9	50.94
BOD	352	95	17.6
COD	1192.30	87	155

Water consumption

With a conventional toilet that uses 6 L of water per flush, considering 5 uses per person a day, 11 m^3 of water is used for flushing per year per person. For the treatment process, it uses an average of 90.4 m^3 water per year per p.e. treated in the plant.

Energy consumption

In 2020, the treatment plant demanded 4 316 507 kWh of electricity from the grid to operate, an average of 95 kWh per p.e.

Emissions

The air emissions from the process are calculated according to the IPCC (2006) guidelines for greenhouse gas inventories. The following equation is used to calculate the CH_4 emissions:

CH4 emissions (kg CH_4/yr) = [BOD removed * B0 *MCF]

Where: BOD removed = BOD removed by the treatment process (kg BOD/yr);

Bo= maximum CH_4 producing capacity (kg CH_4/kg BOD)

MCF = methane correction factor

IPCC suggested a default value for Bo of 0.6 kg CH_4/kg BOD removed and MCF = 0.09 for centralized aerobic treatment plants.

For the calculation of N_2O emissions of the treatment process, the following equation is used:

N_2O emissions (kg N_2O /yr) = (U* Ti* Ef)* TN* 44/28

Where: U = fraction of population in income group,

Ti= degree of utilization of treatment/discharge pathway or system,

Ef = emission factor for treatment system,

TN =total nitrogen in domestic wastewater (kg N/yr)

44/28 is the conversion factor of kg N_2O -N into kg N_2O.

IPCC presents the values for each variable according to the global region and degree of urbanization. In this study, it was adopted the variables presented for Germany, U= 0.94, Ti= 0.95, and suggested default value for Ef= 0.016 for centralized aerobic treatment plants.

The IPCC calculation disregards the emissions caused by biogas utilization. In this study it will be considered leakage of 2,5 % of the total biogas produced (Gourdet et al., 2017) and the direct emissions from biogas combustion were calculated with the conversion factors for biogas combustion presented by Nielsen et al. (2014).

It is also required in the IPCC methodology to estimate N_2O emissions from the discharge of treated wastewater to the aquatic environment. For that IPCC proposes the following equation:

N2O emissions (kg N_2O /yr) = Neff * EFeff* 44/28

Where: N eff = nitrogen in the effluent discharged into water bodies (kg/N/yr);

Ef = emission factor for N_2O emissions from wastewater discharged into water bodies (kg N2O-N/kg N), 44/28 is the conversion factor of kg N_2O -N into kg N_2O.

IPCC suggested a default value for EF eff= 0.016 for centralised aerobic treatment plants.

Other emissions to water bodies due to effluent discharge: 3.40 kg COD,0.39 kg BOD, 1.1 kg N and 0.04 kg P per person treated in the facility. This analysis did not consider emissions from the sludge during storage, transport and utilization as soil conditioning will not be considered in this analysis.

Organic household waste treatment

The predominant treatment for organic household waste in Norway is anaerobic digestion with biogas production and to better improve the process, many treatment plants are practicing co-digestion with various wastes as substrate (SSB, 2020). For that, the conventional treatment of the OHW in this analysis was a theoretical anaerobic digestion system, with energy production through biogas combustion.

Energy consumption and production

For 70 kg of OHW, the energy demand for electricity and heat is estimated to be 13 kWh and the potential recoverable energy to be 16 kWh, from the possible reclaim of 8.25m^3 of biogas (Banks et al., 2018).

Emissions

The emissions to the air are from the biogas leakage (2,5%) and combustion of the remaining for energy production. Emissions to the water bodies were estimated considering the requirement for discharge of treated wastewater, Directive 91/271/EEC.

3.2 Methodology

3.2.1 Goal and Scope definition

Objectives

The study aims to assess the environmental performance of the treatment of blackwater and organic household waste through anaerobic digestion and three nutrient recovery processes. The goal of the treatment is to produce liquid fertilizer, struvite and microalgae. The evaluation of the environmental performance of the process is carried out with the LCA tool. ISO14040-44 describes the procedural framework used to conduct the LCA. The LCA software tool SimaPro was used to model the process and to conduct the impact analysis. The database available in SimaPro was also used for inventory analysis, whenever applicable. The case considered is the Campus Ås Showcase. The results will be compared to the conventional wastewater treatment and organic waste treatment.

Functional Unit

It is considered that a person utilizes the toilet around five times a day, producing an average of 550 l of blackwater per year (Kujawa-Roeleveld and Zeeman, 2006), and uses around 5.5 kg of toilet paper annually (Wendland, 2008). The system under analysis is equipped with vacuum toilets of 1.2 l flushing volume, which consumes approximately 2190 l water per person per year. Furthermore, according to the Norwegian statistics, a person produces an average of 70 kg of organic household waste per year (SSB, 2019). Therefore, the system's primary function is blackwater and organic household waste treatment, and the secondary function is plant nutrient recovery. The secondary function will be considered as an avoided burden of commercial fertilizer production.

The functional unit for this study is **one person equivalent in the period of one year** to be treated in the systems.

The functional most used in the reviewed studies was the volume of wastewater to treat. On the other hand, this unit does not reflect the influent quality and removal efficiency of the treatment process. The unit used in this analysis is population equivalent, p.e., defined as the organic biodegradable load of 60 g BOD_5 per day.

System's boundaries

Campus Ås Showcase

In this analysis, two scenarios were studied. Figure 11 presents the system's boundary of Scenario 1. In this scenario, 5% of the liquid fertilizer (LF) produced is sent to the microalgae cultivation. The avoided burden of commercial fertilizer production was estimated by the molar weight of the recovered nutrients in each process. The boundary of the systems does not include the impacts related to the storage, transport and utilization of the fertilizers produced.

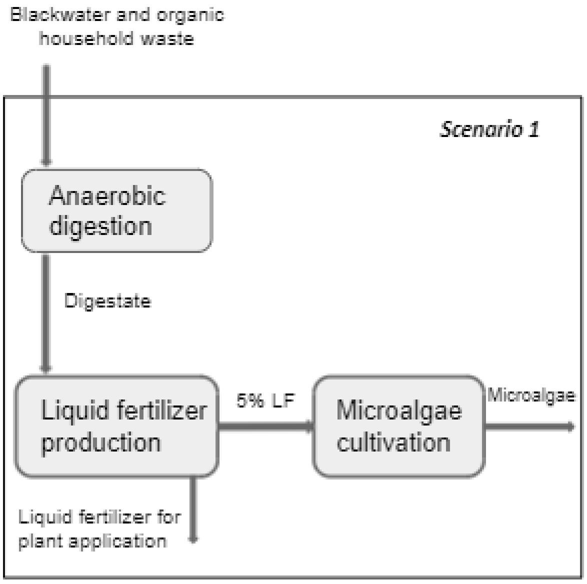

Figure 11: System's boundary Scenario 1.

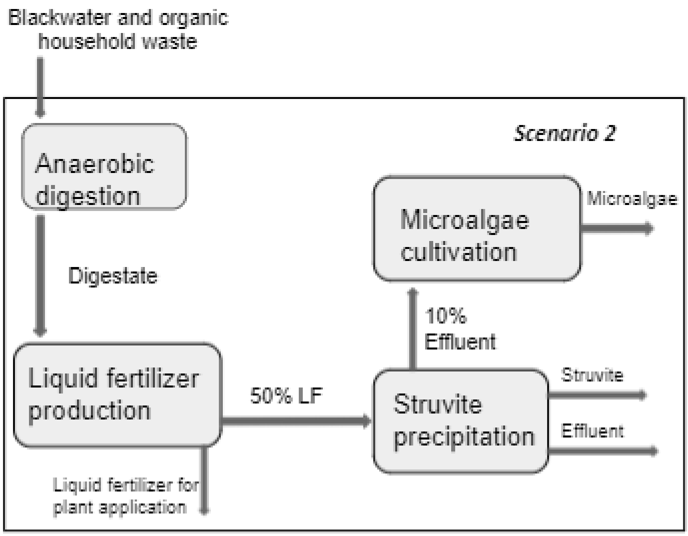

Figure 12: System's boundary Scenario 2.

In the second scenario, presented in Figure 12, struvite precipitation was included previous to the microalgae cultivation. In Scenario 2, half of the liquid fertilizer produced is sent to the struvite reactor and 10% of the effluent from this process is sent to the microalgae cultivation.

Conventional Systems

Figure 13 illustrates the system's boundary of the centralized treatment of wastewater and organic household waste. The analysis does not include the transport of wastewater or organic waste to the treatment facility, as well as the management of the sludge produced in the processes.

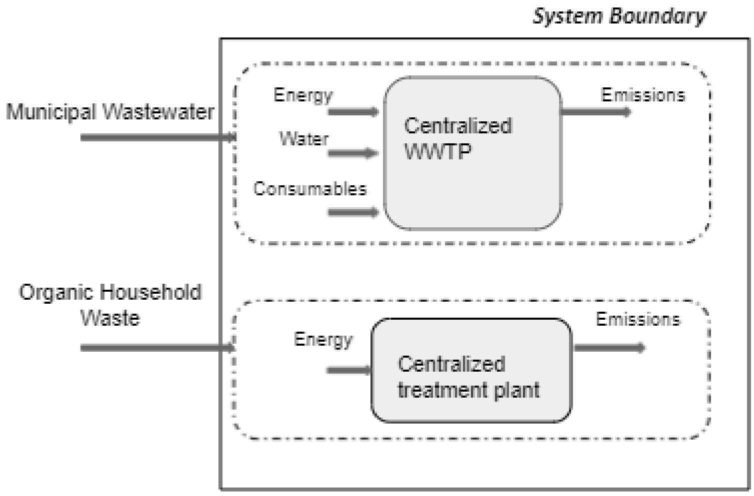

Figure 13: System's boundary centralized treatment.

Impact Assessment Methods

The impact assessment method used in this analysis is the ReCiPe 2016, in the midpoint impact categories: Global warming potential (GWP), based on the 100-year potential and represented in Kg of CO2 equivalent; eutrophication potential (EP), represented in Kg phosphate equivalent, and water consumption (m^3).

General assumptions and limitations of the study

The lack of primary data for the full representation of the system is a limitation of this study. However, the general assumptions made, theoretical values and literature review data adopted for each setup are explained in the system's description. Another limitation of the study is the technological representation of the systems to be compared. The decentralized system is a bench-scale laboratory model, the centralized wastewater treatment is a full-scale plant, and the organic waste treatment is a theoretical system.

3.2.2 Life Cycle Inventory

The requirement for foreground data is primary data and literature review. For background data, i.e., production of material for construction and electricity production, the EcoInvent database was used. The criteria to select the construction materials to be included in the study is based on the mass. In order to simplify the analysis, the inventory includes only the main materials that are needed to construct each system, i.e., small pieces and materials in lower quantity were disregarded, as well as the energy, water and working hours for the assembling of the system. Table 13 presents the inventory of the construction phase:

Table 13: Inventory of materials for construction phase.

Inputs	Unit	Quantity
Storage tank and AD reactor		
Toilet	piece	1
Stainless steel (storage tank)	kg	2340.8
Stainless steel (AD reactor)	kg	334.4
Plexiglass	kg	10
Polystyrene foam	kg	2.26
Struvite precipitation reactor		
Stainless steel	kg	7.28
Stainless steel tube	Kg	1.23
Plexiglass	kg	0.714
Liquid fertilizer filtering system		
Plexiglass	kg	2.85
Cocos char	kg	0.8
Granular activated carbon	kg	0.8
UV lamp	piece	1
polyethylene	kg	1
Photobioreactor		
Stainless steel	kg	20
Plexiglass	kg	0.9
Polyethylene	kg	1.7
Light panel	kg	2

A combination of primary and secondary data was used to complete the inventory of the operational phase. The data is explained in the description of the system, and in Annex 3 the references from the data used is presented. Table 14 presents the inventory of inputs and Table 15 presents the outputs of the operational phase:

Table 14: Inventory of inputs.

Inputs	Unit	Quantity
Anaerobic Digestion		
Water (flushing)	L	2190
BW	L	550
OHW	Kg	70
Electricity	kWh	569
Toilet paper	kg	5.5
Liquid fertilizer		
AD digestate	L	2800
Electricity	kWh	484
PBR		
Liquid fertilizer	L	140
Electricity	kWh	1311
CO_2	Kg	104
water	L	2520
P addition (Scenario2)	Kg	0.0123
Struvite		
Liquid fertilizer	L	1400
Electricity	kWh	404
Manganese plates	kg	0.168

Table 12: Inventory of outputs.

Outputs	Unit	Quantity
Anaerobic Digestion		
Liquid Digestate	L	2800
Biogas	L	11680
Emissions to the air		
CO_2	Kg	0.099
CH_4	Kg	0.190
N_2	Kg	0.002
H_2S	Kg	0.001
CO	Kg	0.07
SO_2	Kg	0.01
NO_x	Kg	0.05
NMVOC	Kg	0.0024
CH_2O	Kg	0.0021
Liquid fertilizer		
Liquid fertilizer	L	2800
Avoided products		
N based fertilizer	kg	3.33
P based fertilizer	kg	0.152
PBR		
Microalgae	kg	3.83
Avoided products		
N based fertilizer	kg	0.175
P based fertilizer	kg	0.008
Struvite		
Struvite	kg	1.4
Emissions to the air		
N_2O	kg	0.0001
NH_3	kg	0.008
Avoided products		
N based fertilizer	kg	1.93
P_2O_5 based fertilizer	kg	0.471

For the comparison case, data was given by the Nordre Follo Wastewater Treatment Plant and the EcoInvent database was used for these background data as well. Table 16 presents the inventory of the Nordre Follo WWTP, for one p.e.. Table 17 presents the inventory of the theoretical set up treatment of organic household waste:

Table 16: Inventory for Nordre Follo WWTP, for one p.e.

Flow	Unit	Quantity
INPUTS		
Water (flushing)	m^3	11
Water	m^3	90.4
Electricity consumption	kWh	94.98
Polymer Zetag	kg	0.1
Methanol	L	4.95
Polyaluminium chloride	Kg	9.6
Toilet paper	kg	5.5
OUTPUT		
Biogas	m^3	16.08
Electricity	kWh	0.98
Sludge	m^3	0.09
Emissions to the air		
CH_4	kg	0.397
N_2O	kg	0.036
CO	kg	0.108
SO_2	kg	0.009
NOx	kg	0.070
NMVOC	kg	0.003
CH_2O	kg	0.003
CO_2	kg	0.00014
CH_4	kg	0.00026
Emissions to the water		
P	Kg	0.041
N	Kg	1.102
BOD	Kg	0.387
COD	Kg	3.410
N2O	kg	0.028

Table 17: Inventory of theoretical organic waste treatment.

Flow	Unit	Quantity
INPUTS		
OHW	kg	70
Energy (electricity + heat)	kWh	13.33
OUTPUTS		
Recoverable energy	kWh	16.5
Biogas produced	m^3	8.24
Emissions to air from biogas		
CO_2	Kg	0.000070
CH_4	Kg	0.000134
CO	Kg	3.1000
SO_2	Kg	0.0025
NOx	Kg	0.0202
NMVOC	Kg	0.0010
CH_2O	Kg	0.0009
Emissions to water		
BOD	Kg	0.175
COD	Kg	0.875
P	Kg	0.014
N	Kg	0.105

4. Results

4.1 Construction phase

The LCIA of the construction phase assesses the environmental impacts related to the production of the materials needed. Figure 14 shows the results for the global warming potential. The most impact in the construction phase is contributed by the AD system, with 1087 kg CO_2 eq. The material that contributed the most for CO_2 emissions is stainless steel, with 922 kg CO_2 eq. With 530 kg CO_2 eq., the PBR reactor had the most impact contribution from the production of the LED lights, which accounted for 496.5 kg CO_2 eq. The construction of the filter set for liquid fertilizer production had low results for global warming potential. The material that contributed the most was the plexiglass (20.9 kg CO_2 eq.). The least contribution is from the construction of the struvite reactor, as the material requirement is low for this system.

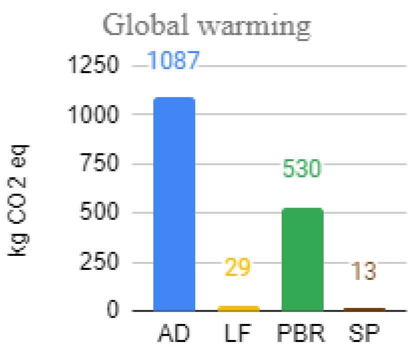

Figure 14: Results of GWP of the construction phase.

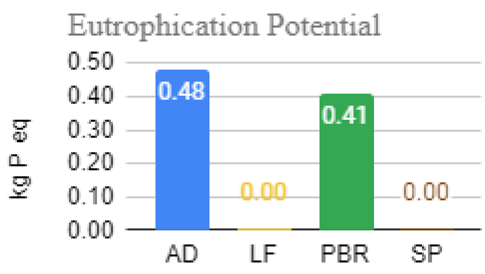

Figure 15: Results of EP of the construction phase.

For the eutrophication potential presented in Figure 15, the results followed the same order. The AD system has the higher potential for P emission, with 0.48 kg P eq, and the stainless steel used in the system contributed the most (0.45 kg P eq.). For the PBR, the LED light have higher contribution to the impacts, with 0.40 kg P eq. The liquid fertilizer production system (0.004 kg P eq.) and struvite reactor (0.0039 kg P eq.) had very low impacts.

Figure 16 presents the results for the estimation of water consumption in the production of the materials. The AD system has the highest water consumption, and again, mostly for stainless steel production (20 m^3 water). In the PBR, the LED light was also the most contributing material, with 5.65 m^3 water consumed. For the liquid fertilizer system, the plexiglass is also the one requiring most of the water (0.09 m^3). The stainless steel is the material that most contributes to the impacts of the struvite reactor construction too, accounting for 0.054 m^3.

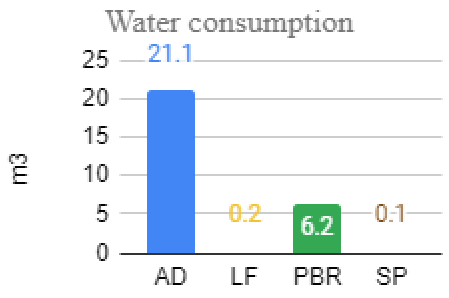

Figure 16: Results of water consumption of construction phase.

4.2 Operational phase

Scenario 1:

Figure 17 shows the GWP contribution for Scenario 1. The AD process, represented in blue, resulted in 40 kg CO_2 eq., and what contributed most to the GWP was the production of toilet paper (25.5 kg CO_2 eq), followed by the energy requirement (12.75 kg CO_2 eq.). In the LF system, represented in yellow, the avoided burden of commercial fertilizer (- 20.2 kg CO_2 eq.) surpassed the emission from the energy requirement (10.82 kg CO_2 eq.), culminating in a negative result of -9.38 kg CO_2 eq. The PBR system, represented in green, shows negative GWP of -75 kg CO_2 eq, as a result of carbon sequestration during the cultivation of microalgae (-104 kg CO_2 eq.). For Scenario 1, the total contribution for GWP is equal to -44 kg CO_2 eq.

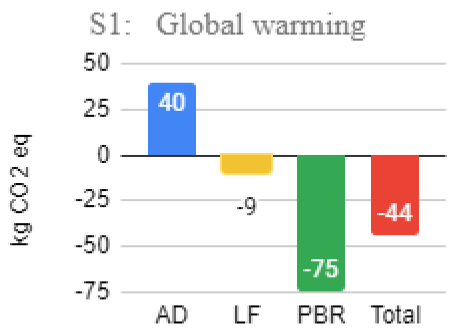

Figure 17: Results of GWP of Scenario 1.

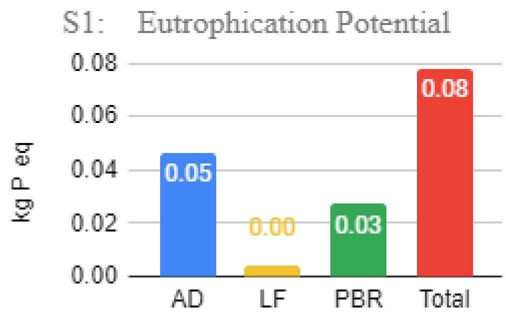

Figure 18: Results of EP of Scenario 1.

In the EP category, the total emission from the system is equal to 0.08 kg P eq (Figure 18). The AD system had an emission of 0.05 kg P eq. The most contributing factor was the toilet paper (0.034 kg P eq.), followed by the energy requirement (0.011 kg P eq.). The emission of phosphorus in the LF (0.004 kg P eq.) and PBR (0.03 kg P eq.) was very low.

The water consumed in the AD system is the water used for flushing, which resulted in a volume of 3.04 m^3 (Figure 19). The negative results (-0.33 m^3) for the LF system are due to the avoided burden of commercial fertilizer production. And the PBR consumes 2.41 m^3 of water to dilute the digestate feeding the reactor. The total water consumption is estimated to be 5.13 m^3.

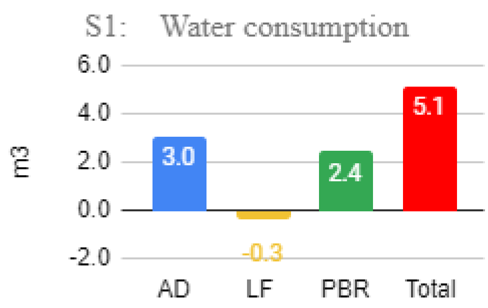

Figure 19: Results of water consumption of Scenario 1.

Scenario 2:

In Scenario 2, the results for the AD system were the same in all categories. The LF had increased the GWP to 0.19 kg CO_2 eq., due to lower production of liquid fertilizer and consequently the avoided burden was lower, and it could not surpass the emission from the energy requirement. In the struvite precipitation, represented in brown in Figure 20, the main contribution for GWP was the energy requirement (9.74 kg CO_2 eq.), followed by the production of magnesium (4 kg CO_2 eq.). The avoided burden from the production of struvite (- 12.35 kg CO_2 eq.) was not enough to counterbalance the emissions. The PBR results had a slight increase (0.1 kg CO_2 eq.) due to the addition of phosphorus. The result for Scenario 2 is -33 kg CO_2 eq, which is 25% higher than the previous scenario.

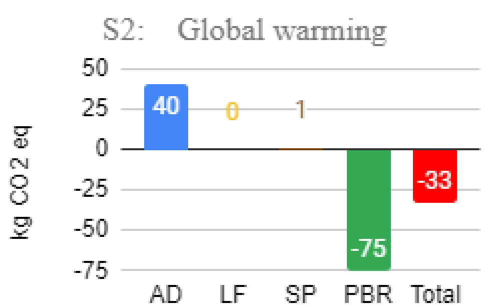

Figure 20: Results of GWP of Scenario 2.

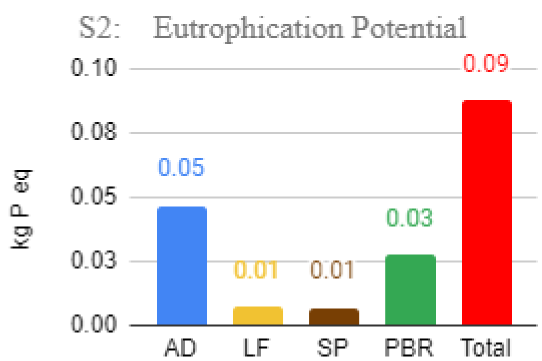

Figure 21: Results of EP of Scenario 2.

In EP results (Figure 21) there was an increase in the total emission of 0.01 kg P eq., because of the additional contribution coming from the struvite precipitation. However, the SP contributed to the decrease in the total water consumption by 0.05 m^3 (Figure 22). Figure

The energy consumption of each system and the total for both scenarios are presented in Figure 23. Scenarios 1 and 2 differ only by the addition of the SP system. The PBR is the most energy-intensive process, contributing 55% to the total consumption of the system.

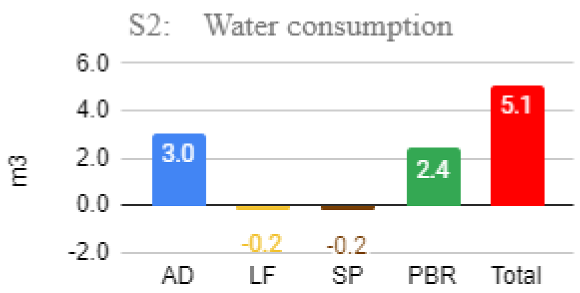

Figure 22: Results of water consumption of Scenario 2.

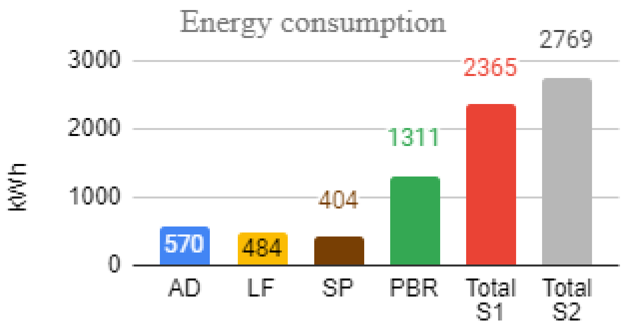

Figure 23: Results of energy consumption of Scenarios 1 and 2.

4.3 Centralized treatment

Figure 24 presents the comparison of the results for the centralized treatment and Scenario 1. The contribution of CO_2 eq. from the centralized system is 71.13 kg. The most contribution comes from tap water (32.15 kg CO_2 eq.) and the coagulant (15.75kg CO_2 eq.) consumed during the wastewater treatment process. In the EP category, the systems presented similar results (Figure 24). In the conventional system, the tap water consumed in the WWTP contributed the most to the P emissions (0.026 kg P eq.), followed by the emission to water due to the effluent discharge (0.042 kg CO_2 eq.).

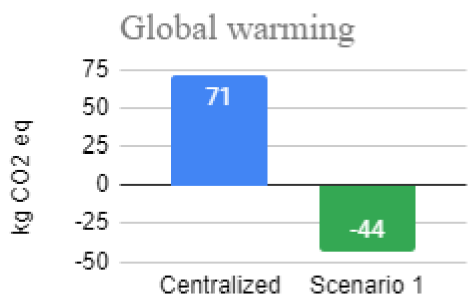

Figure 24: Results of GWP of centralized treatment and Scenario 1.

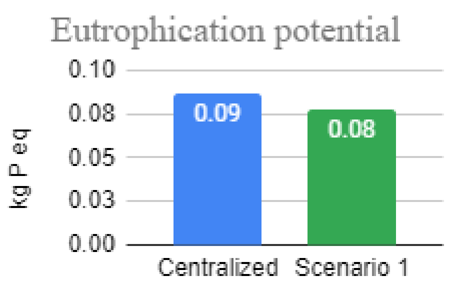

Figure 25: Results of GWP of centralized treatment and Scenario 1.

Figure 26 shows a significant difference in the amount of water consumed in the centralized system and Scenario 1. The centralized system used around 102 m^3 in the process, while in Scenario it is 1, 5 m^3. On the other hand, a significant difference also appears in the comparative consumption of electricity of the two systems (Figure 27).

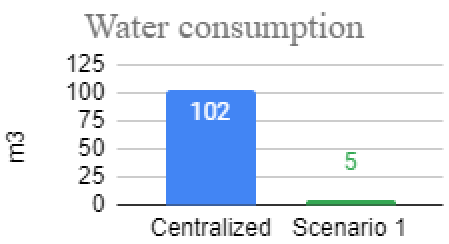

Figure 266: Results of water consumption of centralized treatment and Scenario 1.

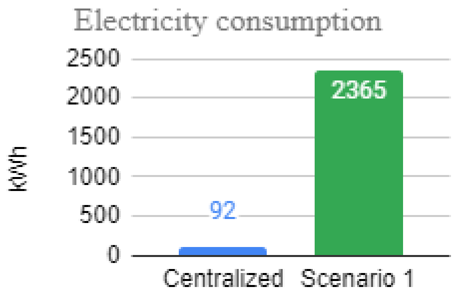

Figure 27: Results of electricity consumption of centralized treatment and Scenario1.

4.4 Sensitivity analysis

The impact of the volume of flushing water in the performance of the system was investigated for Scenario 1. The current flushing volume is 1.2 l and in the sensitivity analysis it was considered the volumes of 1, 0.75, 0.5 and 0.25 liters. The total volume and concentration of the substrate with the different flushing volumes is presented in Table 18:

Table 18: Estimation of concentration of substrate with different flushing volume.

Parameter	**Unit**	**1,2 l**	**1 l**	**0.75 l**	**0.5 l**	**0.25 l**
Total volume	L	2800	2445	1988.75	1532.5	1076.25
Total COD	mg/L	15,690	17,968	22,090	28,667	40,820
TS	mg/L	11,080	12,689	15,600	20,244	28,826
VS	mg/L	7,920	9,070	11,151	14,470	20,605
Total N	mg/L	1,503	1,721	2,116	2,746	3,910
Total P	mg/L	171	196	241	312	445

Having less volume to treat, it is possible to rescale the reactor and decrease its space requirement and electricity demand. Another option is to increase the HTR and consequently improve the treatment efficiency and increase the biogas production. With increased HRT, the microorganisms have a longer time to degrade the organic matter (Baati et al., 2018). To simplify the analysis, it will be considered higher HRT, according to the volume of substrate, and increased COD removal efficiency and biogas production potential according to the HRT. Therefore, the energy requirement for the AD reactor was the same, with less volume but higher HRT. The biogas production increased and so did the emission due flaring. The HRT and biogas yield for each scenario of the sensitivity analysis is presented in Table 20.

The LF system now requires less electricity once the UV chamber works less hours daily. It was not considered changes in the energy demand of the pumps. The volume of fertilizer produced declines, but with higher concentration of nutrients. The estimation of the concentration of nutrients in the liquid fertilizer according to the flushing volume is presented in Table 19:

Table 19: Estimation of nutrient concentration in liquid fertilizer with different flushing volume.

	Unit	**1,2 l**	**1 l**	**0.75 l**	**0.5 l**	**0.25 l**
Total N	mg/L	1,488	1,704	2,095	2,719	3,871
Total P	mg/L	169	194	239	309	441

With a more concentrated liquid fertilizer, more dilution prior to the PBR is needed. There is no expected decrease in electricity consumption or increase in microalgae biomass production once the total volume treated in the PBR remains the same and at similar concentration. Table 20 shows the parameters that have changed in the sensitivity analysis.

Table 20: Adapted inventory for sensitivity analysis.

Parameter	Unit		Quantity			
Anaerobic Digestion						
Flushing volume	**L**	**1.2**	**1**	**0.75**	**0.5**	**0.25**
HRT	**days**	**20**	**24**	**28**	**32**	**36**
INPUTS						
Water (flushing)	L	2190	1825	1368.75	912.5	456.25
OUTPUTS						
Liquid Digestate	L	2800	2445	1988.75	1532.5	1076.25
Biogas	L	11680	13432	16352	18688	21024
Emissions to the air						
CO2	Kg	0.099	0.114	0.139	0.159	0.179
CH4	Kg	0.190	0.218	0.266	0.304	0.342
N2	Kg	0.002	0.002	0.002	0.003	0.003
H2S	Kg	0.001	0.001	0.002	0.002	0.002
CO	Kg	0.074	0.086	0.104	0.119	0.134
SO2	Kg	0.006	0.007	0.008	0.010	0.011
NOx	Kg	0.048	0.056	0.068	0.078	0.087
NMVOC	Kg	0.002	0.003	0.003	0.004	0.004
CH2O	Kg	0.002	0.002	0.003	0.003	0.004
Liquid fertilizer						
INPUTS						
AD digestate	L	2800	2445.00	1988.75	1532.50	1076.25
Electricity (UV light)	kWh	84.00	69.72	52.92	35.2800	17.64
OUTPUTS						
Liquid fertilizer	L		2445.00	1988.75	1532.50	1076.25
PBR						
INPUTS						
Liquid fertilizer	L	140	116.2	88.2	58.8	29.4
water	L	2415	2438.8	2466.8	2496.2	2525.6

The results of the sensitivity analysis indicate no changes in the EP, and marginal changes in the GWP of the systems. The LF system had the highest change in the contribution to GWP, from -9.38 kg CO2 eq., in Scenario 1 with 1.2 l flushing, to -10.9 kg CO2 eq., with 0.25 l flushing. The results on GWP for Scenario 1 and each case in the sensitivity analysis are presented in Figure 28:

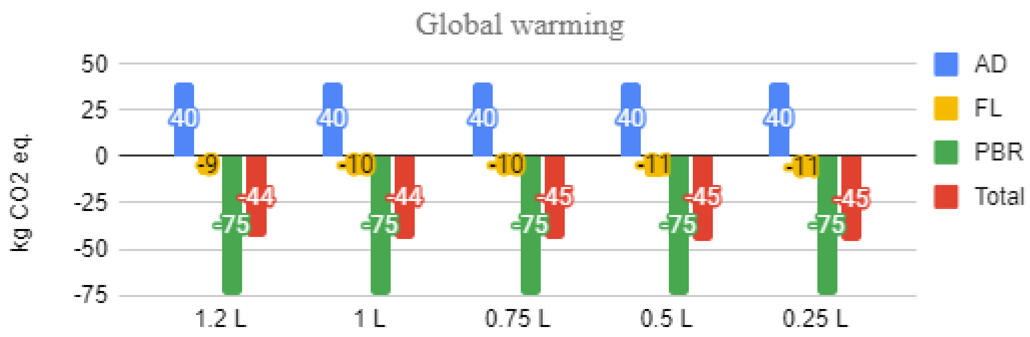

Figure 28: Results for GWP in the sensitivity analysis.

The total water consumption decreased from 5.13 m^3, with 1,2 l flushing to 3.82 m^3, with 0.25 l flushing. The results are presented in Figure 29:

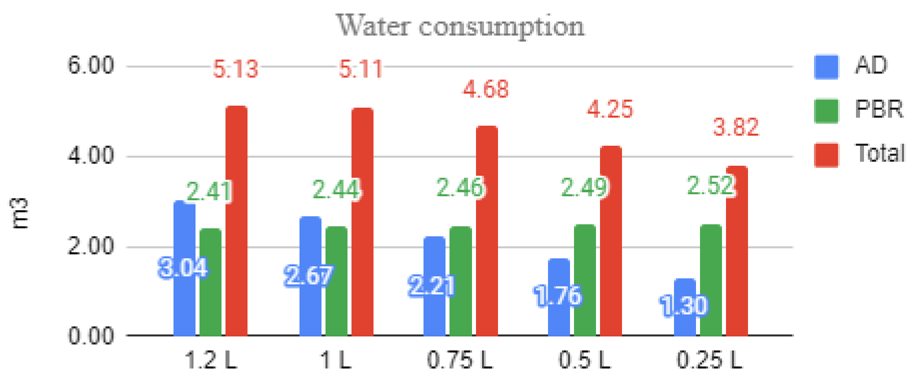

Figure 29: Results for water consumption in the sensitivity analysis.

In terms of energy consumption, the results are also like Scenario 1, once the only change considered was the electricity demand of the UV light of FL system. The biogas recovery potential increased, and with 21 m^3 of biogas (0.25 L flushing scenario) it is possible to recover around 126 kWh of heat, which can be used to heat the AD reactor. And moreover, avoid burden to the municipal grid and decrease further the environmental impacts related to the energy consumption.

5. Discussion

This chapter discusses the findings of the results of the life cycle assessment.

5.1 Construction phase

From the results of the construction phase, it is possible to observe the impact of the choice of materials. The main material used was stainless steel, which is estimated to be 344,65 Kg CO_2 eq per ton produced. In the studied system, the storage tank used the most stainless steel. To better understand possible improvements in the construction of the system, it is necessary to do a LCA of the design of the type of equipment, with a complete inventory of material and flows needed in the assembly of the system, testing alternative materials.

5.2 Comparative assessment between Scenarios 1 and 2

In the results for the AD system, the toilet paper contributed the most with the GWP and EP. The impacts due to toilet paper use are not directly linked to the performance of the system, but consumers' behavior and preference for products.

The AD system can be upgraded by using the biogas to supply heat for the reactor. With the recovery of 12 $m^3$of biogas, it is possible to generate 70 kWh of heat energy (Metcalf and Eddy, 2003).

As the results show, the PBR is the best system in the GWP category once it biofixes CO_2. To improve the general performance of the system, it would be interesting to investigate an enlargement of the PBR capacity and treat higher volume. This will also represent an increase in energy and water consumption. To enhance the system even further, it is possible to complement the electricity source with solar power and decrease the tap water consumption with rain harvesting. Microalgae have also been used as biofuel and it would be interesting to investigate the possibility of adapting the cultivation method for the recovery of energy.

When comparing Scenarios 1 and 2, we can argue that Scenario 1 performs better results, and that the introduction of struvite precipitation seems unnecessary. On the other hand, when considering the transportation of the fertilizer produced, Scenario 1 accounts for 2660 kg of fertilizer, which can contribute to 0.908 kg CO_2 eq per km transported. In Scenario 2, a total of 1402 kg was produced, and the estimated emission is 0.48 kg CO_2 per km transported. Furthermore, with an enlarged PBR and more algae production, the impacts due to transportation can decrease considerably, for one liter of liquid fertilizer can produce 15 grams of algae biomass, equivalent to 2.9 grams of dried weight.

5.3 Comparison to centralized treatment

The main drawback of the results of the comparison between the centralized treatment and Campus Ås is regarding the limitation of the technological representation of the systems. On one side, we have a full-scale operating system, and on the other side, a lab-scale system.

The results for the centralized system may have been underestimated because the boundary excluded the transport of sewage and OHW to the treatment facility, not accounting for the impacts of this part of the process. However, the centralized system also treats grey water.

Considering the limitations of the study, Campus Ås Showcase demonstrated a better environmental performance regarding the categories GWP, EP and water consumption. On the other hand, the centralized system presented better results on energy consumption.

As discussed previously, the PBR system shows promising results regarding treatment efficiency and CO_2 biofixation. It would be interesting to perform a feasibility study of the integration of microalgae cultivation in the centralized treatment system.

5.4 Sensitivity analysis

The results of the sensitivity analysis did not differ much from Scenario 1 in the categories GWP and EP. On the other hand, it was demonstrated that with lower flushing volume the water footprint of the system can decline and that it is possible to recover more biogas from the same substrate if the HRT is extended, which can improve the energy efficiency of the system. The liquid fertilizer produced had a higher concentration and lower volume, and for that, the transport of the fertilizers produced can have reduced environmental impacts as well.

6. Conclusion and recommendation

6.1 Conclusion

Campus Ås Showcase demonstrated to be an environmentally friendly treatment process with low water consumption, great potential for plant nutrient recovery and CO_2 biofixation. The inclusion of struvite precipitation in the treatment systems can be attractive if there is a need to transport the fertilizer produced offsite. The results for the PBR system are promising, especially in the GWP category. When comparing to the centralized treatment, Campus Ås Showcase presents better performance in the categories GWP, EP and water consumption, on the other hand, the electricity consumption is higher.

6.2 Recommendations

From this analysis, some recommendations were drawn:

- To improve the environmental performance of the construction phase, it can be interesting to carry out a LCA of the design of the types of equipment, testing other possible materials, with a complete inventory of material and flows necessary for the assembly of the system.
- To have reliable results, it is recommended to carry out another LCA when the Campus Ås Showcase is fully operating, and measurements can be taken.
- To understand the environmental impacts related to the use of the fertilizers produced, it is recommended to include the storage, transportation and use of the fertilizers in the systems' boundaries.
- It is possible to improve the energy efficiency of the system with the generation of energy from the biogas recovered and the inclusion of solar power.
- It would be interesting to investigate an enlargement of the PBR capacity and treat higher volume, consequently improving the GWP of the system. The energy efficiency of the PBR can be enhanced, and for that the recovery of biofuel from the microalgae can be considered.
- To reduce the limitations of the comparative assessment between Campus Ås and the centralized system, it is recommended to carry a LCA when the Campus Ås Showcase is fully operating, including in the analysis the grey water treatment system. And include the transport of flows in the centralized system's boundary.
- It can be interesting to carry a feasibility study regarding the implementation of microalgae cultivation to the centralized treatment system. It could enhance the environmental performance of the treatment.

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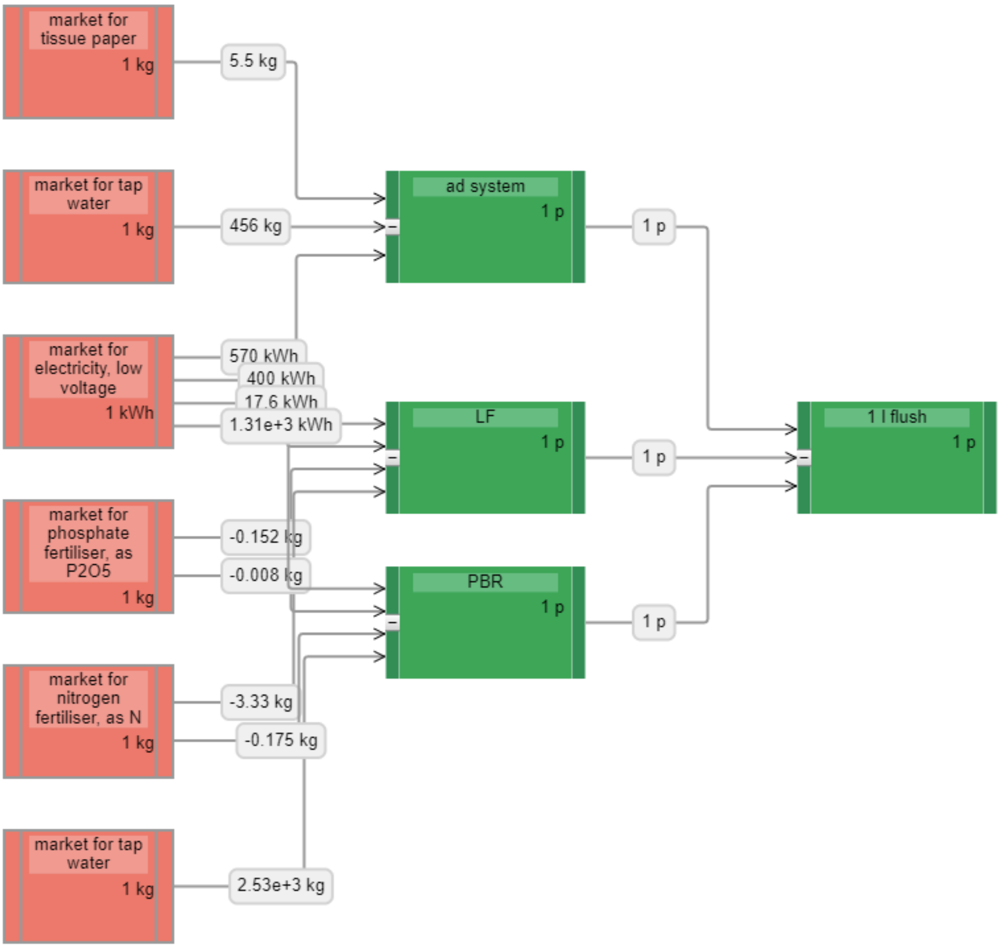
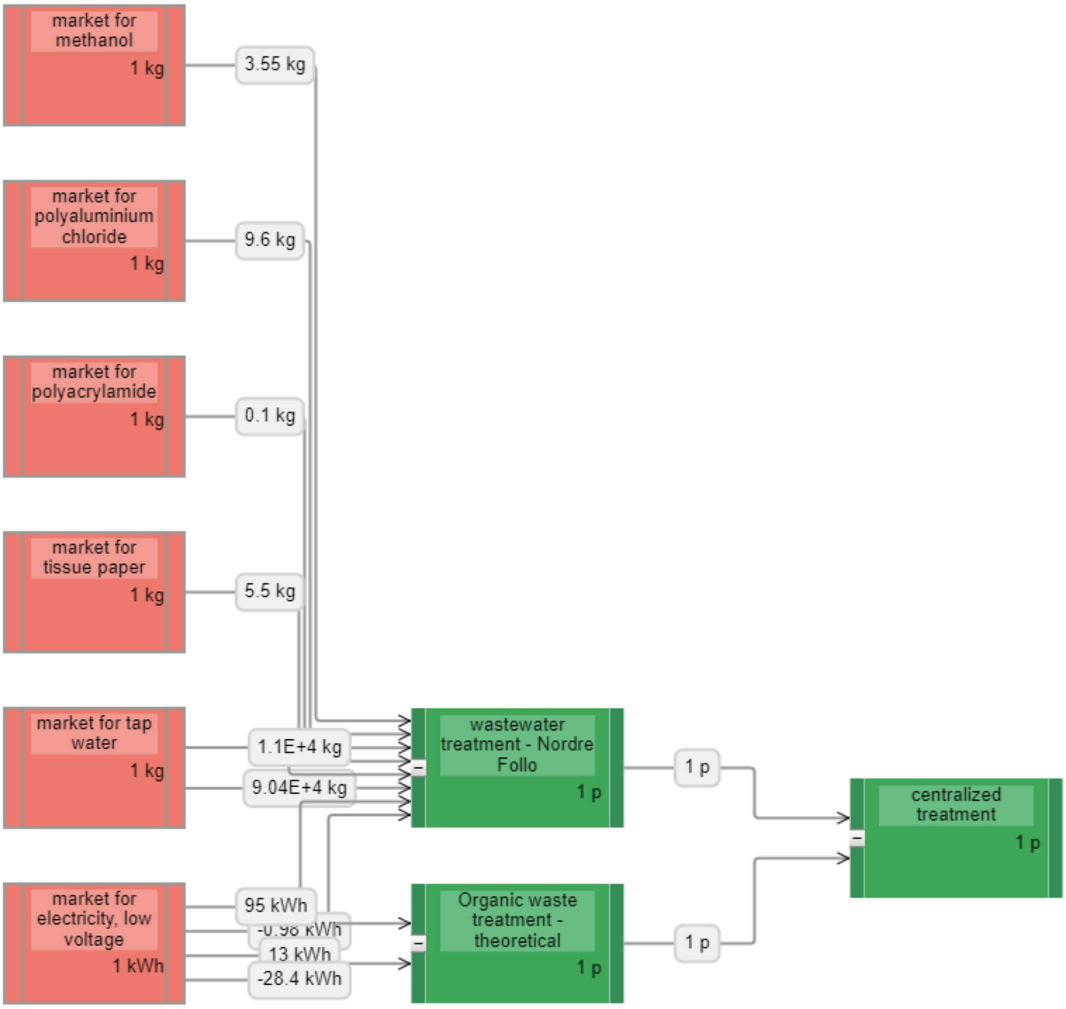
Annexes

Annex 1: Layout of SimaPro set up for Scenario 1.



Annex 2: Layout of SimaPro set up for the centralized treatment.



Annex 3: Source of inventory data

Parameter	source	comments
	AD system	
Water consumption (flushing)	primary data	Vacuum toilets with 1.2 L flushing volume
BW volume	Kujawa-Roeleveld, K. and Zeeman, G. (2006)	1.42 L per day
OHW volume	SSB (2020)	https://www.ssb.no/en/avfkomm
Substrate concentration	Wendland (2008)	
Electricity requirement	Wendland (2008)	Energy consumption of vacuum toilet systems.
	Banks et al. (2011)	Requirements for heating and electricity for AD reactor
Toilet paper	Wendland (2008)	
Biogas yield	Kujawa-Roeleveld et al. (2003)	
Fraction of biogas leakage	Gourdet et al. (2017)	Considered 2.5% leakage
Conversion factors	Nielsen et al. (2014)	Air emissions from biogas flaring
	Liquid fertilizer	
Electricity requirement	primary data	From the equipments description
Avoided products	primary data	Calculated according to the molecular weight
Efficiency of the system	Moges et al. (2018)	
	PBR	
Electricity requirement	primary data	From the equipments description
CO_2 consumption	Moges et al. (2018)	
Water consumption	Moges et al. (2018)	
Avoided products	primary data	Calculated according to the molecular weight
Efficiency of the system	Moges et al. (2018)	
	Struvite Precipitation	
Electricity requirement	Rodriguez - Garcia et al. (2014)	
Manganese plates consumption	primary data	From the experiments carried by Moges
Emissions from the process	Rodriguez - Garcia et al. (2014)	
Avoided products	primary data	Calculated according to the molecular weight

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