Decentral Energy Recovery Potential of Black Water and Kitchen Refuse using Anaerobic Co-digestion in Eco-Districts

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Abstract

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On a local and global scale, wastewater collection and treatment plants are significant energy consumers and have a major impact on the environment and economy of many municipalities. Decentralization looks to be a promising option to address the sustainability issues of wastewater management systems since it focuses on on-site wastewater treatment as well as local recycling and reuse of domestic wastewater resources. In addition, Blackwater (BW) and Kitchen Refuse (KR) are household wastes with a high organic content that can be used as substrates for anaerobic co-digestion processes to recover biogas as a source of energy.

The research objective was to analyze a source separation decentralized BW and KR treatment system in which the energy is recovered from BW and KR co-digestion and digestate gasification. The coupling of biological and thermal technologies allows for the complete conversion of wastes into energy and biochar, eliminating sludge disposal.

A simplified anaerobic digestion model was developed and implemented to simulate the biogas production potential. The simulation is based on a mathematical model using biomass, organic substrate, and biogas mass balances. The model was implemented in the INSEL simulation environment, and experimental data from the literature was used for validation. The results of the simulation match the experimental data well. Using the model, the energy consumption and generation potential of anaerobic co-digestion of BW and KR were assessed.

Moreover, a greywater reuse system was investigated considering the same number of residents within an eco-district. It could be shown that conventional WWT systems require more energy and lead to more CO_2 emissions than the greywater reuse system.

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Moreover, I want to express my gratitude to all my friends and colleagues at the CERC team who have given me so much of their time, love, and energy.

In memory of Dr. Jürgen Schumacher, the creator and the spiritual father of INSEL, may this work help keep his memories alive.

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AD	Anaerobic Digestion	**LCA**	Life Cycle Assessment
AcoD	Anaerobic co-Digestion	**LHV**	Lower Heating Value
ADM1	Anaerobic digestion model No.1	**OLR**	organic loading rate
BW	Blackwater	**POPs**	Persistent organic pollutants are known as forever chemicals
CH4	Methane	**SRT**	sludge retention time
CHP	combined heat and power	**TEg**	Thermal Energy generation
COD	chemical oxygen demand	**Tw_d**	the hours that the digester is producing biogas
CSTR	continuous stirred tank reactor	**Tw_e**	the working hours per month of the CHP engine
CWWTS	Conventional wastewater treatment system	**U_w**	heat transfer coefficients of the walls
DGWRS	Decentralized greywater reuse system	**VS**	volatile solids
EEg	Electrical energy generation	**WWTPs**	wastewater treatment plants
GHG	Greenhouse gas	**η_T**	thermal efficiency of the CHP engine
HRT	hydraulic retention time	**η_E**	electric efficiency of the CHP engine
KR	Kitchen-refuse	**ρ**	sludge density

Chapter 1 Introduction

1.1 Background

Population growth and increasing consumption levels raise the question of the world's energy future and its environmental impacts. With the depletion of fossil energy (considering their mode of formation takes millions of years), various renewable energies are gaining importance. The exploitation of renewables is to a high extent characterized by being site-specific and focused on locally available renewable resources. Renewable energy sources can create electricity without relying on finite fossil fuel stocks. Bridging the energy gap and ensuring a sustainable future energy supply would necessitate a shift from fossil fuels toward renewable energy sources (Wei, 2015).

In the past decades, strong growth in the deployment of renewable energy technologies has been seen, such as the electrification master plan detailing the energy potential for hydroelectric, geothermal, solar, and wind resources (Arroyo & Miguel, 2020). Renewable resources include solar energy, wind, the heat of the earth (geothermal), biomass, water, and wastewater, commonly known as "resource water" because it contains water, nutrients, and energy. Examples of water as an energy carrier are falling water, waves, ocean currents, temperature differences in the oceans, Algae production in water, and tidal energy (Frijns et al., 2013). Table 1-1 presents some examples of available renewable technologies.

Table 1-1: The most common renewable technologies (Armstrong & Hamrin, 2000).

Type	Options
Solar	Photovoltaic. Active Thermal. Passive Thermal.
Wind	Horizontal and vertical axis wind turbines.
Hydro	Low to high head turbines and dams. Run of river
Geothermal	Cycles: Dry steam, Flash, and Binary
Bioenergy	Combustion. Fermentation. Digestion. Gasification.

Wastewater can be considered a renewable energy source, and it is a rich source of organic matter. On the other hand, wastewater from urban settlements and industries is a significant source of contamination for water reservoirs. As urbanization increases, the volume of wastewater produced increases; thus, wastewater management is a vital issue. (Mohammadi et al., 2021). On the other side, sanitation is a critical issue since poor sanitation causes serious health risks and directly impacts our quality of life.

Since the 1930s, centralized off-site sanitation concepts and aerobic wastewater treatment systems have been developed to discharge human excreta from residences as rapidly as possible, reducing sewage exposure of inhabitants. Centralized off-site aerobic processes are a typical wastewater treatment technology that many countries employ nowadays due to its ease of operation and proven concepts. This method has successfully reduced wastewater exposure to citizens. However, it consumes a significant quantity of potable water and energy for sewage transportation and aerobic treatment. Wastewater treatment plants (WWTP) in the United States consume around 1 to 4 percent of the country's total energy supply, with pumping and aeration accounting for 67 to 75 percent of this consumption (Gao et al., 2020). Centralized transport and treatment of wastewater is often not the most sustainable solution to wastewater management (Elmitwalli et al., 2006b; Gallagher, 2010). With growing concerns about the energy crisis and the paucity of clean water, more sustainable alternatives to centralized off-site sanitation and aerobic wastewater treatment facilities are needed. Figure 1-1 illustrates typical stages of conventional WWTP.

1.2 Source separation wastewater management toward sustainability

A long-standing good policy for environmental action is to "think globally and act locally." In wastewater management, sustainability means protecting human health and the environment, ensuring efficient and effective long-term water management, lowering energy consumption, and closing the loop on natural resource cycles (Fewless et al., 2015). Wastewater decentralization and district wastewater management systems provide collection, treatment, and dispersal or reuse and recovery of wastewater from individual buildings or clusters of buildings near the location where it is generated, and have been used in many applications so far; it is thus an interesting topic to analyse within the context of sustainable urban futures.

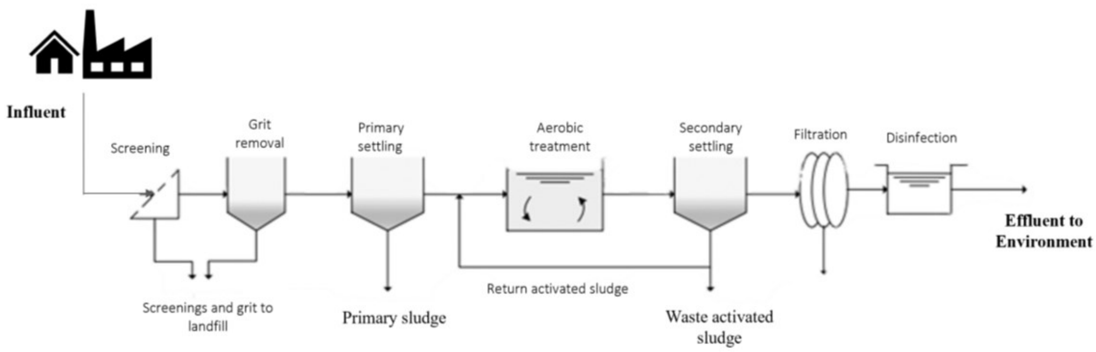

Figure 1-1: conventional biological WWTP process; adapted from (Snowden-Swan et al., 2017)

The traditional household sanitation concept heavily depends on centralized and aerobic wastewater treatment systems, which is not a long-term solution to the rising quantities of wastewater and increasingly diminishing fossil fuel and clean water supplies. Scientists and politicians have investigated decentralized systems in numerous European nations as a viable alternative to centralized and aerobic wastewater treatment systems (Wei, 2015). Figure 1-2 presents the Centralized vs. Decentralized WWTP.

Decentralized, sustainable sanitation concepts focus on treating and recycling resources present in domestic wastewater (Kujawa-Roeleveld and Zeeman, 2006). Source separation combined with decentralized wastewater treatment leads to more efficient nutrient recovery, reduction of micropollutant release to the environment, and water recycling than centralized wastewater treatment. Compared to the conventional sanitation systems with centralized sewage collection and treatment, more innovative sanitation systems allow separate collection and treatment of the heavily polluted blackwater (toilet wastewater) from the other less polluted wastewater or greywater streams at the household level. In the new sanitation design, bioenergy recovery from the source-diverted blackwater serves as one of the core components ensuring overall sustainability. The other benefits of decentralized source separation WWTP are separating greywater and blackwater, which can lead to reducing the consumption of water or recycled water, increasing the organic loading rate, retaining nutrients in digestate, and avoiding the dewatering of a considerable volume of digestate slurry (Peng et al., 2020).

A practical and straightforward approach to recover the bioenergy is through anaerobic digestion (AD), which can convert organic pollutants into biogas with the help of anaerobic microorganisms at a low operational cost. As the anaerobic treatment favors organic-rich substrates, it is economically beneficial to directly apply anaerobic digestion in the decentralized sanitation system where blackwater is the bioenergy resource (Gao et al., 2020).

In the field of wastewater management, anaerobic digestion (AD) is one of the robust technologies applied for wastewater treatment. It is a globally established technology applied to sustainable management of a wide range of organic waste, such as sewage sludge, municipal solid waste and/or different agro-industrial waste streams (Serrano et al., 2020). It can meet the global sustainable development goals, especially on the aspects of climate change, clean energy, and waste recycling (Alfa et al., 2014). Its main advantages are the gain of biogas and the smaller sludge production compared to aerobic treatment. Biogas is an interesting energy resource that can be recovered from wastewater, and it can be used internally in the WWTP for generating heat and electric power. Anaerobic digestion can considerably reduce the cost of wastewater treatment and help to decrease CO_2 emissions as it produces energy in biogas. Biogas has the potential to be used directly for various energy purposes. After purification, biogas can even reach the quality standard of natural gas and thus replace it. Biogas has a fuel lower heating value of about 20 to 26 MJ/m^3 is frequently utilized in digesters and gas engines for heating (Wendland, 2014).

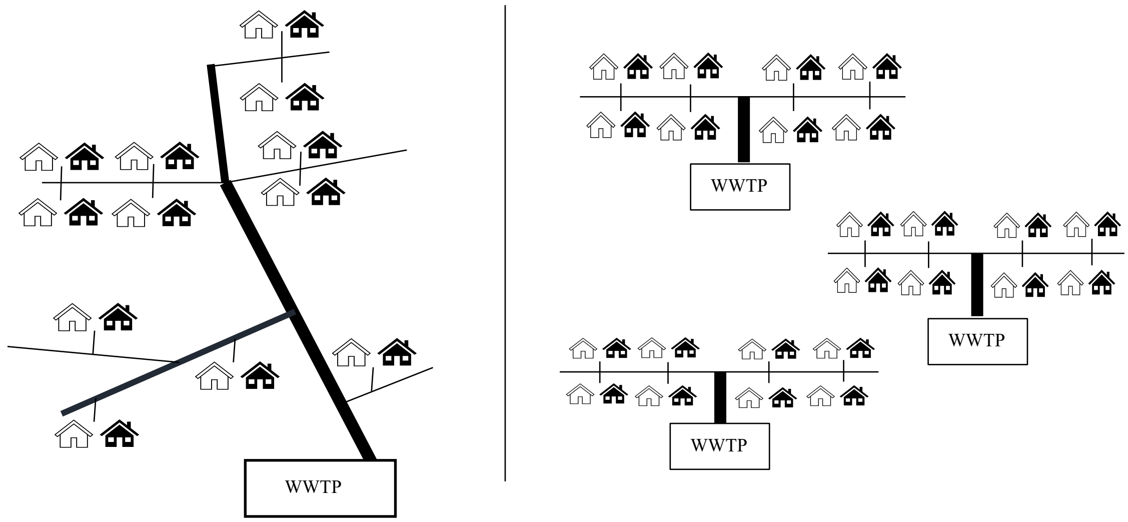

Figure 1-2: Centralized vs. Decentralized WWTP

Wastewater generated on the household level consists of blackwater (BW) and greywater (GW). Domestic wastewater is a mixture of wastewater from several sources – toilet, bath, kitchen, and wash. Table 1-2 illustrates the types of household wastewater.

Table 1-2: Domestic wastewater fractions; (J. Wei, 2015)

Type	**Content**
Conventional	Toilet, bath, kitchen, wash
Black	Toilet
Grey	Bath, kitchen, wash
Brown	Faeces
Yellow	Urine

a: in some studies, kitchen wastewater is considered blackwater (Claudia Wendland, 2008)

Blackwater (BW) is toilet-specific effluent that includes urine, faeces, toilet paper, and flushing water. The majority of nutrients, roughly half of the domestic chemical oxygen demand (COD) load, and most pathogens are found in blackwater.

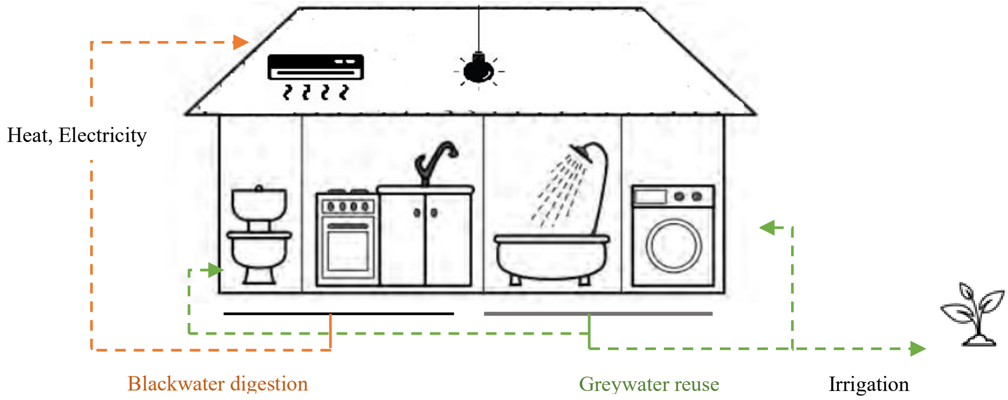

Figure 1-3 Diagram of the decentralized sanitation and re-use system

As a proven appropriate treatment option for concentrated wastewaters, anaerobic digestion is commonly used to treat organic wastewaters because of its high degree of waste stabilization and methane generation. Low flushing water usage in toilets aids in achieving low blackwater dilution and an efficient operation. As a result, low-flush or vacuum toilets are used for collecting blackwater before anaerobic digestion (Claudia Wendland et al., 2014). Greywater from handwashing, showers, and laundry that is less polluted can be cleaned for reuse. This design enables closing the water, nutrients, and energy cycle at the household level (Gao et al., 2020). For example, the bioenergy recovered can be used to heat the treatment facilities and the surrounding towns. The cleaned water can be used for toilet flushing, gardening, and floor cleaning, and the nutrients recovered can be used as agricultural fertilizers.

Nonetheless, in most studies on wastewater separation, the most attention was on the wastewater and water cycles and anaerobic digestion efficiency. Little research has been done on anaerobic digestion residue management.

1.3 Digestate management

Historically, the AD method has been used in sludge treatment to stabilize sludge and minimize odors and microorganisms. Currently, the focus is on maximizing and utilizing its present and potential energy-saving and recovery capabilities. However, the risks connected with hazardous compounds found in sludge (e.g., heavy metals and Persistent organic pollutants (POPs)) cannot be eliminated through anaerobic digestion. Therefore, the digested sludge would negatively affect the environment and public health if proper treatment were not applied. On the other hand, the digestion process has the limitation that it cannot fully extract the energy in sewage sludge. Hence, the digested sludge is still energy profitable in that it contains considerable organic matter but is poor in biodegradability (Cao & Pawłowski, 2012). Digested sludge has a complex mixture of major mineral grains and also biological and industrial fragments.

The conventional digested sludge disposal methods are landfill, incineration, ocean dumping, or disposal on agricultural land, which have become much less acceptable in recent years. Incineration has also become a cause for concern because of its emissions into the air, soil, and water. Within the last years, new thermal methodologies have been developed to get most of the by-products of the sludge treatment. One of the thermal technologies that have gained popularity is gasification (Valencia Arias et al., 2011). However, the integration of anaerobic digestion and gasification as thermal treatment of blackwater and kitchen refuse has not been investigated yet. This study proposes and investigates decentralized blackwater and kitchen refuse anaerobic digestion coupled with gasification as a valuable system for eco-districts.

1.4 Proposed decentralized source separation

Figure 1-4 shows the concept of the proposed decentralized source separation plant for sustainable wastewater management. As previously discussed, the decentralized sanitation system focuses on separating wastewater flows (black and grey water) and organic waste at the home level, then treating each stream appropriately in decentralized or semi-centralized systems and reusing water and nutrients as a result. Blackwater (BW) is the main cause of water contamination in terms of organic matter and pathogens among the various wastewaters. Food waste is another source of waste with a high organic content (FW). Because BW and FW are high in organic matter, they are suitable substrates for anaerobic digestion, converting the biodegradable biomass component into high calorific gases, hence recovery energy from biomass. Although decentralized source separation of wastewater for energy recovery is not a new concept, digestate management is another approach towards sustainability that helps avoid unnecessary transportation and landfilling.

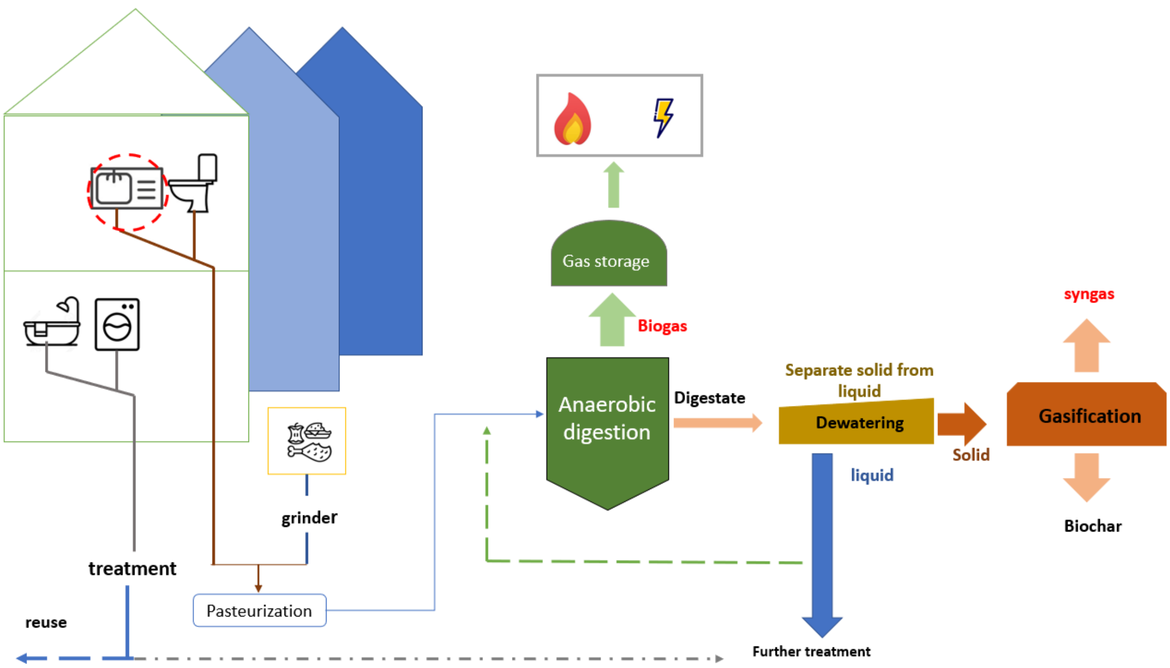

Figure 1-4: proposed system for sustainable energy recovery from blackwater and kitchen refuse by coupling anaerobic digestion and gasification process

1.5 Objectives

One of the main objectives of this thesis is to investigate source-separated, decentralized wastewater treatment systems for eco-districts that include a gasification process for digestate treatment. By developing simplified simulation models, the aim is to predict biogas generation from the digestion of blackwater and kitchen refuse to supply energy to highly efficient eco-districts.

The specific objectives of this work are:

- Determining the wastewater generation and decentralized source-separation system operation potential in a given urban area.

- Simulation model development and implementation of anaerobic digestion of BW and KR in the integrated simulation environment language INSEL to allow the combination with other urban models.
- Determination of the potential of generating biogas from co-digestion of Blackwater and Kitchen refuse.
- Propose new approaches for digestate management (integration of AD and gasification).
- Evaluate the energy generation potential and energy consumption of AD on a district scale to support eco-district planning.
- Evaluate the energy consumption and carbon footprint of conventional and decentralized greywater reuse systems.

Chapter 2 provides a literature review of previous works. Chapter 3 describes the methodology. Chapter 4 provides modeling equations and model validation. Chapter 5 shows case-study results, including AD energy balance calculation, digestate management, and the performance of the greywater reuse system.

Chapter 2 Literature Review

This chapter begins with an overall classification of the different types of wastewater, followed by a more detailed description of domestic wastewater and decentralized wastewater treatment plant needs in urban districts. Additionally, the most important concepts are discussed to provide some background information required for understanding the anaerobic digestion processes investigated in the thesis. The literature review aims to provide a background of novel decentralized source separation wastewater technologies and management approaches to aid in planning and designing optimal wastewater treatment for an eco-district.

2.1 Wastewater classification

Wastewaters can be categorized into the following groups (Council Directive 91/271/EEC):

• Domestic wastewater,

• Municipal (urban) wastewater (domestic wastewater mixed with stormwater and effluents from commercial and industrial sectors, pre-treated or not), and

• Industrial wastewater.

Domestic wastewater is commonly recognized to be separated into two major streams: concentrated blackwater (faeces and urine, occasionally mixed with kitchen waste) and less concentrated greywater (washing activities). Urine (yellow water) and faeces (brown-water) can be separated from blackwater using urine-diverting toilets or urinals.

The amount, intensity, and quality of greywater and blackwater are different. Greywater makes up most domestic wastewater, although it is relatively uncontaminated and hence suitable for reuse. After minor on-site processing, less concentrated greywater streams could serve as alternative water sources. While containing a minor proportion of nutrients, greywater contains a significant fraction of household-originated heavy metals, from dust and chemicals (detergents and personal care products) to fats/grease from kitchen wastewater (Capodaglio, 2017).

Table 2-1: Constituents and volumes of domestic wastewater and its fractions (Beler-Baykal 2012)

	Conventional	Greywater	Blackwater
Volume	100%	75%	25%
Organic matter	100%	41%	59%
Nitrogen	100%	3%	97%
Potassium	100%	34%	66%
Phosphorus	100%	10%	90%
Pathogens	100%	Very low	Very high

Table 2-1 summarizes the quantity and quality of blackwater and greywater and reveals that greywater makes up three-fourths of conventional domestic wastewater volume. Greywater is a good source of reused water, particularly for water that does not need drinking water quality. It can be used for various applications in the water cycle after organics have been removed and pathogens are controlled.

There appears to be much variation between countries when it comes to greywater legislation. While some countries encourage the use of greywater, others have prohibited it. Germany appears to be the European leader, followed by Australia. Domestic greywater reuse is permitted in Germany, but it must be registered. Greywater separation is required in Tokyo, Japan, for buildings having an area of more than 30 000 m^2 or a potential reuse capacity of more than 100 m^3 per day (Beler-Baykal, 2015). Currently, there are no national guidelines or regulations for water reclamation and reuse in Canada, except for the "Canadian Guidelines for Domestic Reclaimed Water for Use in Toilet and Urinal Flushing" (Health Canada, 2010).

2.2 Decentral new sanitation systems towards sustainable development

As a concept, sustainability aims to maintain economic well-being, protection of the environment, prudent use of natural resources, and equitable social progress. Due to rapid city expansion and industrialization, pollution and resource scarcity have become the critical barriers to a sustainable future. Recovery and reuse of water, energy, and nutrient resources have become an important necessity for today's society to address these difficulties. Traditional centralized sanitation systems were designed to suit the needs of human hygiene, but due to high energy and water consumption and a large footprint required, they are not sustainable.

To achieve sustainability goals, the notion of "decentralized sanitation and reuse" has been proposed. Compared to the conventional sewage system, this innovative sanitation method provides benefits in economics, energy, ecology, social-cultural impact, and human health (Gao, 2020). Decentralized sanitation that is sustainable relies on on-site wastewater treatment and local recycling and reuse of domestic wastewater resources. Decentralized treatment systems are said to favor water recycling and reuse close to their location. Decentralized wastewater treatment could be implemented at various scales; single household, multi-resident (cluster), or city-wide, and it is most likely to occur in new developments or new commercial/institutional buildings (Fewless et al., 2015).

2.2.1 Decentralized wastewater treatment plants vs. centralized

Initially, most centralized sewerage systems accept wastewater from homes, businesses, and other wastewater producers then discharge it into receiving waterways without treatment. Upon implementation, this solved a lot of public health issues. In 1843, Hamburg, Germany, built the first modern centralized wastewater management system, and in the 1850s, Chicago and Brooklyn followed suit, creating centralized wastewater infrastructure (Burian et al., 2000). Decentralized wastewater treatment was considered a viable management strategy in the 1980s due to a drop in federal financing for centralized wastewater systems and the development and innovation of technologies for smaller-scale wastewater treatment (Gallagher, 2010).

The US Environmental Protection Agency (EPA) has recognized that "decentralized wastewater systems may provide a cost-effective and long-term option for meeting public health and water quality goals, particularly in less densely populated areas." (Capodaglio et al., 2017). Furthermore, decentralized solutions can be deployed on an as-needed basis, avoiding the high costs of centralized treatment systems. Suriyachan et al. investigated three examples in Bangkok using case study research methodologies to assess the potential of centralized and decentralized wastewater management approaches for urban growth. According to the findings, decentralized management proved to be economically and technically efficient and conducive to long-term urban development in the application region. Decentralization revealed a competitive cost structure (because of shorter sewer lines), simpler technology, and limited additional expenditures, yet high efficiency could be reached with proper operation and maintenance. Locally reclaimed water was mainly used for landscape irrigation of green areas (30–100%), but less than 5% of the wastewater from centralized systems was recycled. Aside from the financial component, the social benefit of the public facilities provided by such systems was demonstrated, as was the implication that they could be an additional motivator for smart growth. Even in the most densely inhabited metropolitan regions, no issues with sustainable urban growth were found in the study (Capodaglio et al., 2017).

Traditional systems combine household discharge streams and transmit them to a centralized WWTP via an extensive sewer system. As a result, centralized wastewater treatment requires more pumps, longer pipes, more energy than decentralized wastewater treatment, raising the system's infrastructure costs. The collection system accounts for 80–90% of capital expenses in such systems, with some economies of scale in densely populated areas. By reducing the volume of liquid waste, not only does the amount of energy required to operate the sewerage collection system (lower pumped volumes) decrease, but it also allows for a shift to more sustainable energy (e.g., anaerobic vs. aerobic with biogas or biohydrogen production) and resource recovery (primarily N and P) final processing technologies. This will also necessitate lower primary energy inputs (for example, by foregoing aeration) and a reduction in the amount of by-products (extra sludge) that must be treated at a cost. A further paradigm shift in the technology commonly employed for wastewater collection systems could increase the overall sustainability of these systems.

(Tervahauta et al., 2013) assessed primary energy consumption of standardized, centralized, and decentralized collection systems based on Dutch conditions; their findings suggest that centralized sanitation systems consume the most primary energy (914 MJ/cap/year). Direct energy usage can be reduced to 687 MJ/cap/year by adopting urine source separation. By separating blackwater, kitchen waste, and greywater at the source, primary energy consumption would be decreased from 767 MJ/cap/year to 522 MJ/cap/year, including indirect energy gains from water conservation and reuse, as well as nutrient recovery. Urine-diverting toilets using vacuum-based systems would reduce usage to 555 MJ/cap/year. The lowest calculated energy consumptions were 208 MJ/cap/year (gravity-based systems) and 190 MJ/cap/year (nutrient recovery and lowered energy usage) when all indirect energy gains from water-saving and reuse, nutrient recovery, and decreased energy consumption were taken into account (vacuum-based systems). Heat recovery from sewer hookups was not factored into the calculations (Capodaglio et al., 2017).

If alternative technologies and techniques are required, they are more likely to be implemented in small, decentralized systems, as a capital investment in decentralized systems is typically lower than in centralized systems. While ostensibly having a positive impact on the administration of urban water systems, decentralized systems entail significant changes in the way planning and decisions about water resource management and infrastructure, operations, and maintenance are made (Capodaglio et al., 2017).

2.2.2 Source-separation systems examples

Netherlands, *Sneek*

The most notable pilot project is called Decentralized Sanitation and Reuse project in Sneek, the Netherlands, which connects 32 houses to an anaerobic digester with vacuum sewers. The research scopes were vacuum collection and transport to condense blackwater, energy recovery from anaerobic digestion at the local scale, and the utilization of the leftover product as fertilizer. The system included a collection, transport, and anaerobic treatment of blackwater from vacuum toilets. Residents created an average of 7 liters per person per day of concentrated black water and, using vacuum toilets, saved 30 to 42 liters per person per day of flushing water. Two UASB septic tanks treated blackwater, food waste at 25◦C, and gas production was approximately 11 m^3 CH_4/cap.year. In this demonstration, Blackwater digestion covers around 12% of the district's gas consumption for home and tap water heating (Alp, 2010; Wei, 2015).

Germany, *Lübeck-Flintenbreite*

Sustainable wastewater management was successfully incorporated into the initial design of the Flintenbreite housing development in Lübeck, Germany. The settlement had no connection to the central sewerage system, which demonstrates a working example of the concept of sustainable sanitation (energy production, water-saving with additional fertilizer). The wastewater is collected and treated in an internal cycle. The vacuum toilet generates 5 L/cap.day of BW on average and is combined with kitchen refuse for digestion in a semi-centralized biogas plant, and recycling the digestate from anaerobic digestion is used for agricultural applications. For combined heat and power generation, biogas produced in the digester is used to supplement natural gas. Greywater, along with rainwater collected from rooftops and sealed areas, is processed in vertical flow built wetlands and locally infused into the soil (Alp, 2010; Beler-Baykal, 2015; Gallagher, 2010; Wei, 2015).

China

Due to a shortage of power stations or coal pits in some locations, China built a large number of biogas plants, making it one of the leading countries in Asia in biogas technology. A Chinese initiative in 1975 called "biogas for every household" resulted in the building of roughly 1.6 million domestic biogas plants every year (Wei, 2015). Today, in China, more than 5 million anaerobic digesters with capacities ranging from 6 to 10 m^3 serve individual houses and are fed with organic wastes such as animal and human excreta and organic kitchen waste (Gallagher, 2010). In the framework of rising energy demand in China, the Ministry of Agriculture emphasizes the relevance of biogas and further encourages residential connections to biogas plants. There is also an increasing interest in sustainable features such as water conservation, and sanitation programs incorporating vacuum toilets with black water digestion have been implemented progressively (Wei, 2015).

2.3 Introduction to Anaerobic Digestion and benefits

Anaerobic digestion is one of the oldest processes applied to treat domestic wastewater (McCarty 1985). Reynolds and Richards (1996) represent microbial interactions and biological oxidation of degradable organic sludge under anaerobic conditions. It has been widely used to treat industrial, agricultural, and municipal waters and sludge; Hobson et al. (1981) define it as a method of stabilizing and thus reducing pollution from the sewage sludge produced in several treatments works (Igoni, 2016). Traditional anaerobic digestion applications focus on the stabilization and volume reduction of sewage sludge generated in municipal wastewater primary and secondary treatment. However, changing societal norms and economic concerns have necessitated broadening the target area. This expanded scope includes the beneficial use of biogas, a by-product of the anaerobic digestion process (Wickham, 2019).

For the industry, biogas is a renewable energy source (Esposito et al., 2012). It comprises around 60% CH_4, 40% CO_2, and a few trace gases, including H_2S and water vapor (Chynoweth et al., 2001; Tchobanoglous et al., 1991). Tchobanoglous et al., 1991 found that biogas can be easily converted to electrical and thermal energy via a co-generator for on-site use (Wickham, 2019). In terms of reducing GHG emissions, anaerobic digestion is the clear leader among industrial wastewater treatment methods (Greenfield & Batstone, 2005).

The reduction of fossil fuel usage is a major goal of the biogas business, with the ultimate goal of reducing global warming. On the other hand, anaerobic digestion is linked to the production of greenhouse gases such as carbon dioxide, methane, and nitrous oxide. According to (Paolini et al., 2018), The following are the main measures that biogas plants can take to improve their global warming reduction potential: use a flare to avoid methane discharge, cover tanks, improve the efficiency of combined heat and power (CHP) units, improve the electric power utilization strategy, exploit as much thermal energy as possible, and avoid leaks. Moreover. They reported that biogas use results in a negative CO_2 balance because CO_2 caption is always higher in absolute quantities than positive emissions from feedstock supply and biogas plant operation.

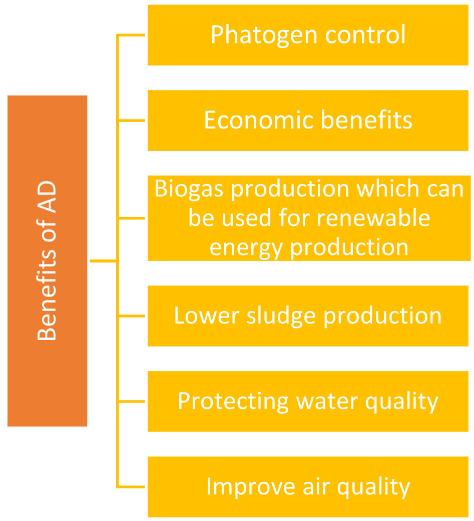

Figure -2-1: Advantages of the AD system

There are some advantages related to the aeration process, such as keeping solids suspended that can be cleaned easily. The presence of oxygen can help avoid odors caused by anaerobic microorganisms and leads to better nutrient removal efficacy, facilitating direct discharge into surface waters or disinfection. Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD_5) performance can be enhanced. Anaerobic digestion (AD) of sludge is an effective technology for destroying pathogenic microorganisms. The biogas and the residual organic solids and liquids can be used in many ways, providing economic and environmental benefits. by comparing the energy consumption and carbon balance in aerobic and anaerobic wastewater treatment, aerobic treatments require significant energy for aeration due to the large volume of sludge produced by the COD conversion; they have high operating expenses. In contrast, anaerobic digestion produces a lower amount of surplus sludge that is well stabilized. Furthermore, instead of using energy, renewable energy is created in the form of biogas. Aerobic treatment is typically applied to efficiently treat low-strength wastewater (COD <1000 mg/L), whereas anaerobic treatment, is typically applied to treat wastewater with higher organic loading (COD >4000 mg/L).

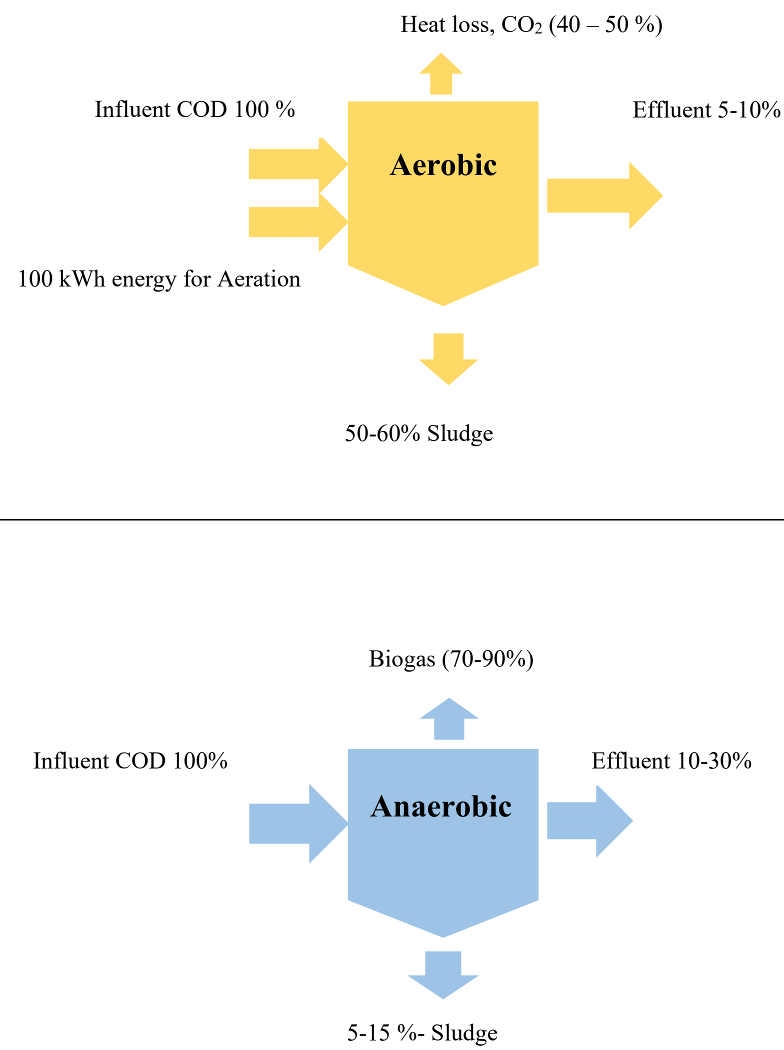

Figure 2-2: Energy consumption and COD balance Anaerobic VS. Aerobic sewage treatment, adapted from (Ni & Nyns, 1993; Wei, 2015)

2.3.1 Basics of Anaerobic digestion process

Anaerobic digestion (AD) is a technique that has been around for decades. AD has been widely used to handle organic wastes such as municipal wastewater sludge, biomass, and agroindustry manure throughout the last century. Through its capacity to create renewable energy in the form of biogas, AD provides a particularly enticing route for progress towards environmental sustainability. The overall Anaerobic digestion (AD) process is a biological degradation of organic matter by a group of microorganisms that convert organics into biogas in the absence of oxygen (Claudia Wendland, 2008; Wickham, 2019).

Anaerobic decomposition is a complex process, occurring in three main stages because of the actions of a range of microorganisms. Reynolds and Richards (1996) list the three phases of anaerobic digestion as follows:

i. liquefaction of solids
ii. digestion of soluble solids, and
iii. gas production

Kiely (1998) explains the three stages thus:

Hydrolysis: The breakdown of complex organic matter by hydrolytic and fermentative bacteria to more minor molecular compounds. Particulate organic matter is converted by extracellular enzymes to monomeric or dimeric components as in lipids to fatty acids, polysaccharides to monosaccharides, proteins to amino acids, etc.

Acidogenesis and Acetogenesis: hydrolysis products are fermented to volatile fatty acids, alcohol, and ammonia. Then, volatile fatty acids and alcohol are converted to acetate, H_2, and CO_2.

Methanogenesis: the final stage of CH4 production by methanogenic bacteria utilizing acetic acid or H2 and CO2.

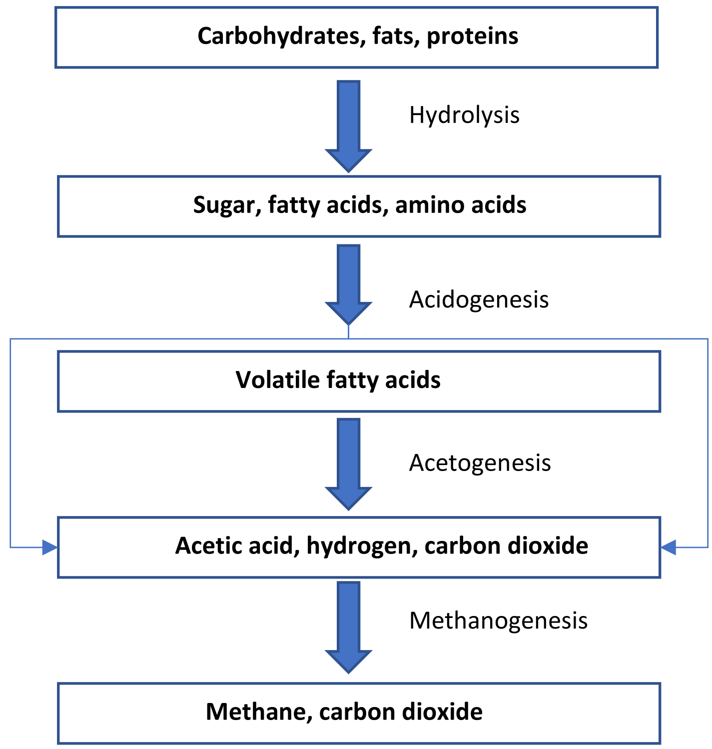

Figure 2-3: Anaerobic digestion process

The following chemical formula can be used to indicate the breakdown of carbohydrates, nitrogenous substances, and fats:

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2C_2H_4O_2 + 2CO_2 + 4H_2 \quad 2.1$$

Methane would be created from the acetic acid and hydrogen products of the aforementioned process.

$$2C_2H_4O_2 \rightarrow 2CH_4 + 2CO_2 \quad 2.2$$

$$4H_2 + CO_2\ CH_4 + 2H_2O \quad 2.3$$

The generalized equation for the anaerobic digestion process is generated by combining these formulas as follows:

$$\text{Organic matter} + \text{combined water} \xrightarrow[\text{anaerobic microbs}]{} \text{New cells} + \text{energy for cells} + CH_4 + CO_2 + \text{other products} \quad 2.4$$

2.3.2 Models of AD

Anaerobic digestion modeling is complex since it involves a variety of physicochemical and biological parameters for an unsteady-state process (Rafey, 2020). The International Water Association (IWA) Task Group created the ADM1 model (Anaerobic Digestion Model No 1) for mathematical modeling of the anaerobic digestion process. It describes physical-chemical reactions with a large number of constants and coefficients. Other models, such as mass balance models, black-box models for complex processes, and heuristic models, are also available and utilized (Damien J Batstone, 2006; Dimitrova & Krastanov, 2012; Gerber & Span, 2008; C. Hu et al., 2018; Lübken et al., 2007).

During the last three decades, the mathematical anaerobic digestion model (ADM) has been widely explored and developed (Gavala et al., 2003). The most basic ADM has only one biological process, whereas the most complicated ADM has over 20 biological and physicochemical processes. The Task Group for Mathematical Modelling of Anaerobic Digestion Processes of the International Water Association (IWA) issued one ADM in 2002, titled IWA, Anaerobic Digestion Model No. 1. (ADM1) (D J Batstone et al., 2002). ADM1 is a generic platform that includes 19 biochemical processes involving seven species, eight intermediates, and three different types of physicochemical processes. ADM1 was chosen as the foundation of our work because it is one of the most advanced models (Ralf et al., 2004).

2.3.3 Important physical parameters and limiting factors

Each anaerobic reaction steps need to work in a balanced state to maintain a stable anaerobic digestion process. The substrate properties determine the rate-limiting step. Generally, hydrolysis is in high particle matter concentration, such as organic waste (Velsen, 1981). Other elements, such as sulphur and trace elements, are also necessary for bacterial development (Ni, Co, Mo, Fe, Se, Wo, Zn, Cu, Mn). Such compounds are commonly found in household wastewater, as they are generated in significant amounts from urine and faeces (Claudia Wendland, 2008).

The anaerobic digestion process is a complex one exhibiting close syntrophic relations between different microbial groups with different physiological and environmental conditions. The primary factors are pH and temperature (Wickham, 2019).

PH and Alkalinity

pH is a measure of the acidity or basicity of an aqueous solution. As a result, this parameter represents the anaerobic system's ambient conditions and influences the process in two ways: directly, by altering the structure of enzymes, or indirectly, by altering the toxicity of specific chemicals present in the anaerobic system environment (de Lemos Chernicharo, 2015). In this setting, acidogenic enzymatic activity is disrupted at pH values over 5.0, but the enzymatic activity of the methanogenic population is significantly harmed at pH levels below 6.2. The pH range for acidogenic microbial population development is 5.0 to 6.0, while the pH range for methanogenic microbial population growth is 6.6 to 7.4 (Gerardy,2003). Some authors found the optimal pH of acetoclastic bacteria between 6 and 7 (Claudia Wendland, 2008). The methane generation rate can be significantly reduced if the pH of an anaerobic reactor is continuously below 6.5 or above 8.0) (de Lemos Chernicharo, 2015).

The capacity of water to neutralize acid is defined as alkalinity (Rittmann & McCarty, 2001). The usual percentage of carbon dioxide in the gas phase of anaerobic digestion is 25–45 percent.

Temperature

Depending on the operating temperature, three temperature ranges are related to microbial development (Batstone et al., 2002): Psychrophilic (4 to 20 °C), mesophilic (20 to 45 °C), and thermophilic (45 to 70 °C) with each specific microflora. Therefore, bacteria may produce methane at temperatures ranging from (0 to 97 °C) (de Lemos Chernicharo, 2015).

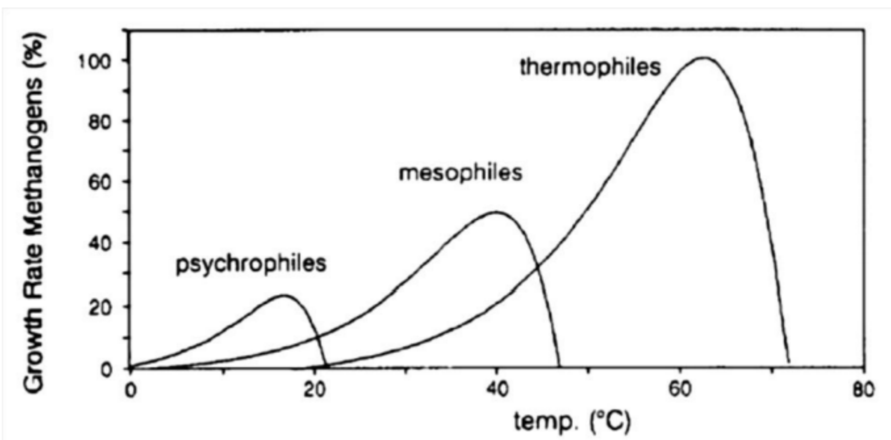

Figure 2-4: The effect of temperature on the rate of biomass growth. Psychrophilic, mesophilic, and thermophilic methanogens' relative growth rates (Gavala et al., 2003).

Most AD systems are run in mesophilic settings because mesophilic bacteria are reasonably hardy and have a broad range of species, ensuring a steady and straightforward process. Thermophilic digestion can achieve faster growth rates, but it is more susceptible to operational issues. It was chosen primarily to meet more outstanding pathogen elimination standards.

Retention time

The average period that liquid and sludge remain in the reactor is referred to as hydraulic retention time (HRT) and the solid retention time (SRT). The hydraulic retention time is critical for reactor operation and design because it determines how long the substrate and specific constituents intended for removal will be in contact with the biomass inside the reactor. "The mass of organisms in the reactor divided by the mass of organisms removed from the system each day" is how solids retention time, also known as mean cell residence time, is calculated. Solid retention time (SRT) is critical because organism washout occurs if SRT is too low. The system becomes nutrient-limited if SRT is too long (Erika Rowse, 2011). When there is no sludge recycling or supernatant withdrawal in the digesting system, HRT equals SRT (J. Hu, 2013).

Organic Loading Rate (ORL)

The organic loading rate is the amount (mass) of substrate applied to the reactor's volume on a daily basis (Ravn & Simonsen, 2020). Because an OLR exceeding loading capacity would result in a low biogas yield due to the accumulation of inhibitory fatty acids in the reactor, OLR is a critical control parameter in digestion systems (J. Hu, 2013).

2.4 Types of Anaerobic Reactor

Digesters for anaerobic processes have evolved into various configurations over time. There are many different types of digesters, such as traditional or low-rate digesters, high-rate digesters, batch digesters, continuous digesters, fixed-cover digesters, floating cover digesters, and high solids digesters and two-stage digesters. Every type or variant of digester could trap methane and reduce feed coliform bacteria, but they range in price and the type of manure solids they can digest (Igoni, 2016).

Kiely (1998) divided reactors into two categories: first-generation and second-generation reactors:

a. In the first-generation type, which includes batch digesters, plug-flow digesters, continuously stirred tank reactors (CSTR), and anaerobic contact reactors, the hydraulic retention time equals the solid retention time.

   while:

b. The second-generation type comprises an up-flow-downflow anaerobic filter, downflow stationary fixed film reactor, fluidized bed reactor, up-flow anaerobic sludge blanket reactor, and the hybrid anaerobic sludge reactor; the solids retention time is greater than the hydraulic retention time.

In follow, the two most common reactors will be explained in detail, which is the focus of the modeling section; These systems were mostly applied for sewage sludge, and manure digestion at mesophilic conditions. more explanation about other types could be found in Anaerobic Reactors (de Lemos Chernicharo, 2015).

2.4.1 Batch Reactor

Batch reactors are easy to operate. These reactors are characteristically operated in which a given quantity of material is fed at specified intervals and withdrawn after a given time. It is described as a non-flow system, as a batch digester's composition is not uniform, and it is well suited to high solids digesting operations.

A schematic of a batch digester is shown in Figure 2-5

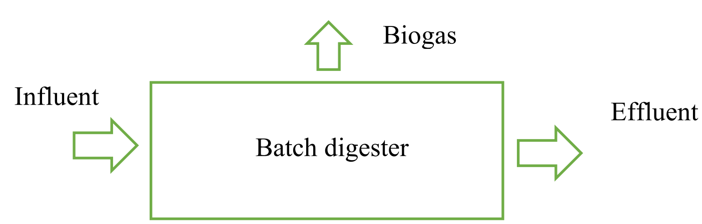

Figure 2-5: Batch reactor scheme

2.4.2 Continuous stirred tank reactor (CSTR)

CSTR reactors were among the earliest anaerobic bioreactors to be used in municipal sewage treatment. This reactor is known for continuous and constant rates of both feeding and discharging, which has a complete mixing of substrate and bacteria. Because of its simplicity and convenience of operation and its ability to handle feedstocks with TS ranges of 2–12 percent, the continuously Stirred Tank Reactor (CSTR) is the most frequently used reactor type for liquid or low solids content AD.

The CSTR is generally operated at a steady-state and in a well-mixed condition. Both bacteria and wastewater have the same retention time, so hydraulic retention time (HRT) equals solid/sludge retention time (SRT). The CSTR system usually operates well at HRT above 15 or 20 days at mesophilic conditions. Complete mix reactors are ideal for treating wastewater containing a high solids content and have more excellent resistance to biological upsets because mixing helps spread harmful substances (Fannin & Biljetina 1987).

A schematic of a CSTR digester is shown in Figure 2-6

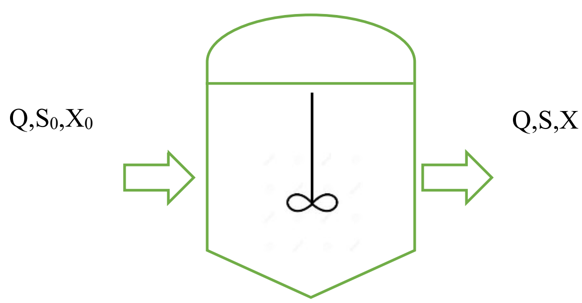

Figure 2-6: CSTR reactor scheme

Q: flows of the liquid, S_0, and S: substrate concentrations at the inlet and the outlet (g/L). X_0 and X: biomass concentration at the inlet and the outlet (g/L).

2.5 Substrates

2.5.1 Blackwater

To date, only limited studies are available on the use of anaerobic digestion methods for blackwater treatment. It is worth noting that the effects of different blackwater characteristics (due to different blackwater collection systems, such as conventional toilets, dual-flush toilets, vacuum toilets, and kitchen refuse addition) on blackwater digestibility can also contribute to the wide range of reported methane production in the literature. The conventional toilet flush systems use 9 L water per flush, dual flush systems use 3-6 L per flush, and vacuum flush toilets use 0.5- 1.2 L water per flush (Gao et al., 2019; Alp, 2010; Wendland et al., 2007). Blackwater collected from vacuum toilets contains rich organics and nutrients, with chemical oxygen demand (COD) concentrations ranging from 5,500 mg/L to 15,500 mg/L, owing to its lower dilution. On the other hand, COD readings in conventional toilets ranged from 932 mg/L to 2,887 mg/L.

Saving water and concentrating organic matter to increase blackwater energy recovery efficiency are two advantages of vacuum toilet collected blackwater. The feasibility of anaerobic blackwater treatment has been evaluated in the above literature.

2.5.2 Blackwater and kitchen refuse

Decentralized wastewater treatment can be studied and developed based on source diversion of residential wastewater discharges such as blackwater and kitchen waste, which can then be treated locally to maximize energy and water recovery (Xu et al., 2019). Daily residential waste streams mainly consist of blackwater (BW) and kitchen refuse (KR) (K. Kujawa-Roeleveld et al., 2003). Kujawa-Roeleveld and Zeeman (2006) found that the most efficient systems include anaerobic digestion of brown or blackwater and the solid fraction of kitchen waste. The feasibility of their co-digestion has been proven in many research studies (Elmitwalli et al., 2006a; Minale &

Worku, 2014; Wang et al., 2020). Solid kitchen waste biodegrades quickly and has a comparable organic load as blackwater. Vacuum systems may be connected to kitchen sinks to reduce the amount of water used in standard waste disposal operations. Blackwater enriched with kitchen refuse has a considerable potential to be treated in an anaerobic digestion system (Wang et al., 2020). The amount of blackwater generated in the urban environment is significant, as it is the primary source of domestic liquid waste. BW is high in organic nutrients, and it, along with KR, is a promising candidate for bioenergy recovery by anaerobic digestion due to its high water content and biodegradability. (Xu et al., 2019). Blackwater and kitchen refuse chemical oxygen demand concentration ranges from 13,300 mg/L to 25,750 mg/L (Gallagher, 2010; Wendland et al., 2007). Data are scarce on mixing blackwater with kitchen wastewater and compost. To grasp this subject better, laboratory research would be required. Variability in faecal sludge and kitchen wastewater content is a major design concern (related to nutrition, processes that occur during transport and storage, environmental conditions). Transport to and from the reactor and nutrient reuse is also an issue (Hertel et al., 2015; Prado et al., 2020; Zhang et al., 2019).

2.6 Digestate from biogas plant

Digestate management involving integrated solutions has received much attention in the previous decade. Digestate management strategies are designed not only for proper disposal but also to increase value and marketability.

After anaerobic digestion of a biodegradable feedstock, digestate is a nutrient-rich residue made up of indigestible elements and dead bacteria after anaerobic digestion of a biodegradable feedstock. Biogas production by wet anaerobic digestion of the organic waste is a sustainable way to produce bioenergy and converts the biomass resources to the nutrient-rich end product, namely biogas digestate. Environmental authorities strongly encourage the use of anaerobic digestion (AD) for all forms of organic waste. However, this strategy only partially fixes the problem. Although AD reduces the volume and mass of sludge, the water content of digested sludge known as digestate remains high (Lacroix, Nicolas, 2014). Digested sewage sludge is typically dewatered before being disposed of. Dewatered sludge still includes a significant amount of water, often as much as 70%, but it no longer behaves like a liquid and may be treated as a solid. The land is usually the end destination of treated sewage sludge. Meanwhile, because sludge may contain toxic chemicals, it is not put on the ground where crops are grown for human consumption. Moreover, the nature and quality of digestate are determined by the feedstock characteristics, type of conversion technology, and the efficiency of the digestion process to produce biogas. As a result, circular economy-based integrated systems have become a hot topic. The environmental impact of these integrated digestate management technologies has been explored in several studies. (Y. Li et al., 2018; Rehl & Müller, 2011).

For biogas digestate management, a specific digestate treatment option should be developed to reduce transportation costs, improve revenues due to increased product value, and expand the market with novel fertilizers. Therefore, this study recommended coupling anaerobic digestion with the gasification process to choose a profitable treatment option.

Gasification is the thermochemical conversion of organic content into high-value gases known as synthesis gas and ash. The resulting gas can be used to heat or generate power using a heat engine. This reaction occurs at a high temperature (800–1000 ˚C) in a partially oxidized reaction environment. Gasification can be done using air, carbon dioxide, oxygen, steam, or mixtures of such gases. As previously explained, the main products from the reactor are gases and ash, and depending on the chemical characteristics of input, the ash produced by this process can be disposed of in a landfill or recycled for agricultural or building use (Oladejo et al., 2019).

In the study of (Lacroix et al., 2014), the goal of the experiment was to see if the combination of anaerobic digestion and gasification may be beneficial in terms of energy efficiency for wastewater sludge treatment. According to theoretical calculations and experimental evaluations, the results illustrate that more than 90% of the energy content from sludge was extracted; this shows that combining two processes exposes a significant improvement in energy recovery and reuse. Mentioned research implies that anaerobic digestion, followed by dehydration, drying, and gasification, could be a feasible and practical alternative to municipal sludge's traditional energy and nutrient recovery methods. Additionally, from an environmental point of view, sludge AD and digestate gasification led to the most significant reduction in carbon emissions. In this regard, gasification of sludge digestate has been experimentally tested by

(Gnanendra et al., 2012), results showing a significant reduction of flue gas emissions compared to emissions from direct combustion of digester pellets.

In another work (Ramachandran et al., 2017), a comparison was made between the life cycle assessment of a new system that gasifies sewage sludge after AD and an existing AD plant. According to these estimations, energy recovered from the initial feedstock improved by 2.8 to 24 percent. (Kengne et al., 2014) reported calorific values from syngas from the gasification of wastewater sludge are similar to that produced from coal (7-9.5 MJ/m^3).

There is sparse information in the public domain on the properties of human faeces. Apart from the abundance of published literature in the medical sciences, with limited evidence for energy recovery analysis, there is little information on how faeces composition influences product and energy recovery. However, gasification technology is widely applied for converting biomass feedstocks. The majority of investigations on faecal-related materials typically use feedstocks, including animal manure, poultry waste, and, at most, sewage sludge as feedstocks (Onabanjo et al., 2016). Unfortunately, up to now, there is quite a lack of information in the literature regarding the detailed gasification of domestic sewage sludge digestate. To date, the limited quantitative research on faecal sludge fuel has concentrated on heating value, moisture, ash fraction, and heavy metals. Other parameters influencing fuel utility, such as ash speciation, haven't been fully quantified for faecal sludge (Hafford et al., 2018). Furthermore, there is no study of BW and KR factors to the best of the author's knowledge.

2.7 Greywater

Domestic wastewater is one of the "wastes" that can be profited from if domestic wastewater fractions are separated at their generation sources, as recommended by the current sanitation strategy based on stream segregation called ECOlogical SANitation (ECOSAN). Two important components that can be retrieved from this approach are water and plant nutrients (Beler-Baykal, 2015). Greywater (shower, basins, and laundry) is one of the wastewater streams with a large volume that can be treated individually in a low-cost and straightforward manner can significantly reduce conveyance and treatment system loading. It is a part of the water cycle because of its features, and it is penetrated locally, discharged to the receiving water, or reused for irrigation. Graywater is the greatest contributor to total wastewater volume but is the minimum contaminated of the three streams (low in nutrients and pathogens but includes detergents and personal care products). It also has a low organic content due to the absence of kitchen wastes (Fewless et al., 2015).

2.7.1 Greywater treatment

In the conventional system, primary treatment, biological treatment, and ultraviolet disinfection are all part of the treatment system at the centralized WWTP. Constructed wetland systems (CW) are a natural treatment process that can be characterized as a method that uses ecological processes found in natural wetland ecosystems to remove contaminants from wastewater by employing wetland plants, soils, and associated microorganisms. CW is a cost-effective and environmentally beneficial technology. In terms of GW treatment, it can be utilized on a small size in domestic level to a larger scale (Sijimol & Joseph, 2021). Moreover, Membrane bioreactor (MBR) systems are made up of screens and ultrafiltration modules, which combine biodegradation with membrane filtration for solid-liquid separation with electricity usage calculated based on the energy demands of various MBR scales. The MBR has been regarded as an innovative technology for greywater treatment due to its process stability and ability to remove pathogens (F. Li et al., 2009). Anaerobic digestion is not very suitable for greywater treatment; in general, greywater contains fewer particles and nutrients than urine and blackwater/kitchen wastewater. According to (Larsen et al., 2019), BOD ranges between 5 and 900 mg/L and COD ranges between 23 and 1600 mg/L. Biodegradability is low, and there can be a high presence of micropollutants (cleaning products, shampoo/soap, perfumes, cosmetics, etc.) (Fewless et al., 2015). One drawback of greywater AD is the relatively high amount of dissolved methane that escapes in the effluent. If dilution is high and/or temperature low, dissolved methane rises to 21% for greywater at 15 °C. This fact causes an undesirable impact on global warming and should be prevented. As diffusion is high, methane can be stripped easily (Claudia Wendland et al., 2014).

Greywater reuse is usually done on-site, where it is treated and used in the exact location, which is usually the manufacturing site. Water reuse applications include agricultural and landscape irrigation, cooling water for industrial operations and power generation, groundwater recharging, snowmaking, fire protection, and toilet flushing. Greywater can be utilized for landscape irrigation without being treated. Greywater treatment improves quality and expands reuse options, such as toilet flushing (Gallagher, 2010).

During the wastewater treatment, a lot of energy is used with fossil fuel sources, resulting in high CO_2 emissions. Municipal wastewater is typically treated to fulfill primary, secondary, and sometimes tertiary treatment levels then disinfected. Due to the fact that the wastewater in a centralized reuse system requires further treatment, it uses more energy and emits more CO_2 into the atmosphere than the DGWRS (decentralized greywater reuse system), which used between 11.8 and 37.5 percent of the energy used in the WWCRS for the same number of people served (Matos et al., 2014).

Chapter 3 Methodology

Wastewater source separation is an approach for wastewater water management in order to improve effluent quality, more energy-efficient treatment (by treating smaller, more contaminated volumes), maximizing water reuse while minimizing reclaimed water transport, and opportunities to recover nutrients and generate energy from high organic wastewater streams are all possibilities.

This work is divided into four sections. The first and the main part of this thesis is creating a simulation model of an anaerobic digestion system based on mass balance equations. Because of anaerobic digestion's unsteady-state behavior and the interaction of several components, detailed modeling such as the model AMD1, which is more complex and widely used for simulating biogas plants, exists in most studies. It requires many parameters that are usually not available when modeling wastewater streams in urban areas. The model used in this study was designed to work with only few parameters and is accurate and straightforward enough to be integrated with other models in an urban energy system modeling platform. The AD model developed in this study is based on mass balance equations and is a simple one-stage mathematical model for anaerobic digestion kinetics. It can be used for designing ADs and estimating digester volume, methane, and biogas production. This study uses the INSEL modeling environment to create a simulation model for anaerobic co-digestion of BW and KR. The model is then used to quantify and predict the methane and biogas production potential of a case study eco-district. The AD model was validated with data from the literature as input, and the model's results indicate similar trends and outcomes as the experimental data. More testing and validating the model were done based on various data sets from the scientific literature. Finally, simulation results were obtained for an urban case study to analyze energy recovery potential for black water anaerobic digestion with and without kitchen refuse. The inventory for this study is based on a collection of data gathered from literature research, mainly from (Claudia Wendland, 2008), which presents data for the case study district Flintenbreite in Lübeck, Germany.

The second part aims to evaluate the energy balance (production and consumption) of anaerobic digestion in two different scenarios considering insulation and non-insulation of the reactor to investigate, whether the produced energy can compensate for the own energy usage of the biogas plant.

In the third section, when digested sludge is treated successively through AD and dewatered, a gasification model is used to estimate the energy potential of generated syngas, calculate surplus energy produced from gasification, and compare with the biogas energy generation potential.

The energy consumption and CO_2 emissions in conventional and decentralized greywater and reuse systems were investigated in the last part. The energy consumption calculation uses a range of data obtained from a literature review. Reference values from the literature research were also used to calculate CO_2 emissions and CO_2 reduction for decentralized source separation concepts.

3.1 INSEL Simulation Environment

A model for designing an energy system is prepared using INSEL 8.2. INSEL is an acronym for INtegrated Simulation Environment Language, which provides an integrated environment and a graphical programming language to create simulation applications. INSEL is a general dynamic simulation tool developed at the University of Concordia, which allows one to model any energy system using built-in components libraries or employing user-developed models (Calise, Eicker, et al., 2020). It is a block-based graphical programming language focusing on renewable energy systems. User-defined blocks can be written in various languages, including Fortran, C++, and Python, giving the INSEL block concept more versatility (Eicker et al., 2020; Weiler et al., 2019). In the current study, the block is programmed with a custom FORTRAN code to calculate the output variables.

Chapter 4 Model description and validation

4.1 Anaerobic digestion model

Anaerobic digesters are principally described as "microbiological production plants," which necessitates a thorough understanding of bacteria, their reactions, growth constraints, and factors affecting growth in the design and operation of digesters (Hobson et al., 1981).

The biochemical models used in anaerobic systems are steady-state models from the least to the most complex (Damien J Batstone, 2006). Scientific models have been created for nearly 40 years, motivated by increasing efficiency due to the importance of anaerobic digestion as a treatment procedure (Liu & Smith, 2020). Anaerobic digestion modeling is complex since it involves a variety of physicochemical and biological parameters for an unsteady-state process. (Rafey, 2020). The International Water Association (IWA) Task Group created the ADM1 model (Anaerobic Digestion Model No 1) to mathematically model the anaerobic digestion process. It describes physical-chemical reactions with a huge number of constants and coefficients. Other models, such as mass balance models, black-box models for complex processes, and heuristic models, are also available and employed (D J Batstone et al., 2002; Dimitrova & Krastanov, 2012; Gerber & Span, 2008; Lübken et al., 2007).

Anaerobic digestion modeling allows researchers to track biogas production as organic matter is transformed over time. The hydrolysis stage involves solubilizing the substrate using extracellular enzymes secreted by some bacteria; this is not considered biological because there is no metabolism. Bacteria absorb and alter organic substrate during acidogenic, acetogenesis, and methanogenesis metabolic phases. Three phenomena define biokinetics: substrate consumption, bacterial growth and decay, methane production, and bacterial inhibition (Fedailaine et al., 2015).

The simplifying hypotheses considered are (1) Complete mixture of sludge in the mesophilic condition with temperature levels at 35 ◦C; (2) the biochemical reactions occur in the bioreactor; (3) a uniform composition in the reactor in a continuous stirred-tank reactor (CSTR); the reactor is a closed tank; and (4) established transitional arrangements, where the organic substrate is the factor limiting bacterial growth. Complete mixing occurs in the bioreactor while endogenous microorganism decay is ignored. The mass conservation law is used to create a mathematical model for microorganism growth, substrate decomposition, and biogas formation (Fedailaine et al., 2015; Mohammadi et al., 2021; Robescu et al., 2013).

4.1.1 Anaerobic digestion process material balance

The basis of all mathematical models is a mass balance for a specific state variable. Several literatures (Tchobanoglous et al., 2003; Agunwamba, 2001; Kiely, 1998; Reynolds and Richards, 1996; Tchobanoglous and Burton, 1991; Andrews, 1978, etc.) state the general form of a material balance expression as follows:

Rate of accumulation of material in the reactor	=	*Rate of material flow into reactor*	+	*Rate of appearance or disappearance of material due to reaction*	−	*Rate of material flow out of the reactor*

Mass balance of substrates degradation:

$$V\frac{dS}{dt} = Q_i S_i - Q_u S_u - r_n V \qquad 4.1$$

Where Q_i and Q_u are the flowrates of the input and output of the sludge ($L.d^{-1}$), respectively.

S_i and Su are the concentration of substrate at the inlet and outlet ($g.L^{-1}$).

V is the volume of the digester (L)

r_n: substrate degradation rate ($g.g^{-1}$), *Mass balance of microorganism's growth:*

$$V\frac{dX}{dt} = Q_i X_i - Q_u X_u + r_c V - r_d V \qquad 4.2$$

r_c: anaerobic microorganisms growth rate (g/l.d), r_d: anaerobic microorganisms decay rate (g/l.d),

X_i and X_u represent the anaerobic microorganism concentration at the entrance and the outlet ($g.L^{-1}$).

Mass balance of Methane production:

$$Q_i Z_i = Q_u Z_u - kV + V\frac{dZ}{dt} \qquad 4.3$$

Z_u is the methane concentration ($g.L^{-1}$).

K: coefficient rate of volatile organic compounds transformation into methane,

For modeling purposes, these assumptions are considered: Because methane production is negligible at the beginning and end of the process $Q_i Z_i = Q_u Z_u - kV + V\frac{dz}{dt}$, therefore:

$Q_i\, Z_i = Q_u\, Z_u = 0$ and $\frac{dZ}{dt} = K$;

$S_u = S$ (Substrate final is substrate instantaneous S).

Therefore, by simplifying the equation (3), (4), and (5) based on assumptions and dividing them by the volume, they become:

$$\frac{dS}{dt} = D(S_i - S_u) - r_n \quad 4.4$$

$$\frac{dX}{dt} = D(X_i - X_u) + r_C - r_d \quad 4.5$$

$$\frac{dZ}{dt} = K \quad 4.6$$

the anaerobic microorganism's growth rate is described as:

$$r_C : \mu X$$

Where μ is the specific microorganism growth rate,

the anaerobic microorganisms decay rate is described as

$$r_d : K_d X$$

The K_d represents the detachment rate constant of microorganisms (d^{-1}).

Then,

The equations can be written as:

$$\frac{dX}{dt} = D(X_i - X_u) + \mu X - K_d X \quad 4.7$$

However, at high concentrations of acetate, the acetolactic methanogenesis phase was found to be inhibited. As a result, a kinetic equation based on Haldane kinetics was proposed (Ntamukunzi, 2013). The Andrew relationship is used for calculating microorganism's specific growth rate for substrate inhibition (Robescu et al., 2013):

$$\mu = \mu_{max} \frac{1}{1 + \frac{K_s}{S} + \frac{S}{K_i}} \quad 4.8$$

Where,

K_s : half-saturation constant (g.L^{-1}).

K_i: coefficient of inhibition (g.L^{-1}).

The substrate degradation rate. 'r_n' is a set of three various parameters, namely r_{nx} , r_{ns} , *and* r_{nz} :

- New cell formation

$$r_{nx} = -\frac{1}{Y_x}\frac{dx}{dt} = -\frac{\mu X}{Y_x} \quad 4.9$$

Y_x: yield coefficient g.g^{-1},

- Energy provided for maintaining and growth of microorganisms

$$r_{ns} = K_{sx}X\mu + K_{mx}X\frac{S}{K_s + S} \quad 4.10$$

K_{sx}: substrate degradation rate to provide energy for growth of microorganisms (g.g^{-1}),

K_{mx}: substrate degradation rate to provide energy for the maintenance of microorganisms (g.g^{-1}).

- Product formation

$$r_{nc} = \frac{1}{Y_s}\ \frac{dZ}{dt} \quad 4.11$$

Y_s: methane production coefficient g/g.

By applying these parameters to equation (4.4), the mass balance of the substrate becomes as follows:

$$\frac{dS}{dt} = D(S_i - S_e) - \frac{\mu X}{Y_x} - K_{sx}X\mu - K_{mx}X\frac{S}{K_s + S} - \frac{1}{Y_s}\frac{dZ}{dt} \qquad 4.12$$

'K' is a coefficient for converting organic substrates into methane related to microorganisms' growth(g/g.d). It can be defined as equation (4.13)

$$K = Y_p \mu X \qquad 4.13$$

Y_p : methane production ratio (g/g)

Thus, the equation for methane concentration become:

$$\frac{dZ}{dt} = Y_p \mu X \qquad 4.14$$

In the next step, the mass and flowrate of methane and biogas are calculated from the below equations:

Mass of produced Methane:

$$M_{CH4} = Z \times V \qquad 4.15$$

M_{CH4} : the mass of methane (g), Z: Methane concentration g/l, V: volume(l).

Methane flowrate:

$$Q_{CH4} = \frac{M_{CH4}}{t} \qquad 4.16$$

Q_{CH4}; methane flowrate (g/d), t: retention time (day).

Biogas flowrate:

$$Q_{biogas} = \frac{Q_{CH4}}{0.6 \times \rho_{ch4}} \quad 4.17$$

Q_{biogas} : biogas flow rate (m^3/day), 60% is methane percentage in biogas by volume, ρ_{ch4} is methane density 0.717 (g/l).

4.1.2 Digester volume

The total volume of a digesting sludge is defined as the medium's flow rate and the hydraulic retention time.

stated mathematically as:

$$V_s = Q \times \theta_h \quad 4.18$$

where V = overall volume of the sludge, m^3

Q = influent sludge flow rate, m^3/day

θ_h = hydraulic retention time, days.

Head spaces ranging from 20% to 50% of the total volume of the reactor are commonly used.

4.2 Model Validation

The model's verification is essential since it verifies that the model results are accurate and reliable. Verification is done by comparing model results to results from other studies and implementation. After developing the AD model in INSEL, the model is calibrated by the data from other experimental works and studies (Fedailaine et al., 2015; Nakhla et al., 2006; Robescu et al., 2013). The prediction of the biogas generation by the model is carried out too.

Fedailaine, M. 2015 and Nakhala, G. 2006

In a study, Fedailaine, M. et al. developed the mathematical model of anaerobic digestion of organic waste on MATLAB software based on experimental parameters. The parameters and inputs used for the simulations are presented in Table 4-3 and 4-4, respectively. In this simulation, the generation time was based on 80 days. Results are compared with previous studies as follows:

Table 4-1: List of parameters

Parameters	Values and units	
μ_{max}	0.35	d^{-1}
D	0.29	d^{-1}
K_d	0.02	d^{-1}
K_s	150	g/l
K_i	0.5	g/l
Y_x	0.82	g/l
K_{mx}	0.4	g/g
K_{sx}	0.983	g/g
Y_p	4.35	g/g
Y_s	0.27	g/g

Table 4-2 demonstrates that the model results compared with results from Fedailaine 2015 and Nakhla 2006 present a similar amount of produced methane concentration.

Table 4-2: model inputs and comparison between the outputs

Input	INSEL model and (Fedailaine et al., 2015)	INSEL model and (Nakhla et al., 2006)
Si g/l	4	7.85
Xi g/l	2	2.833
Zi g/l	0	0
Day	80	80
Output		
Z g/l	1.83	3.95
INSEL; Z g/l	1.833	3.957

Figures 4-1 and 4-3 illustrate substrate consumption during digestion. By comparing Figures 4-1 and 4-2, it can be concluded that methane generation increases as the substrate are consumed in the process of digestion.

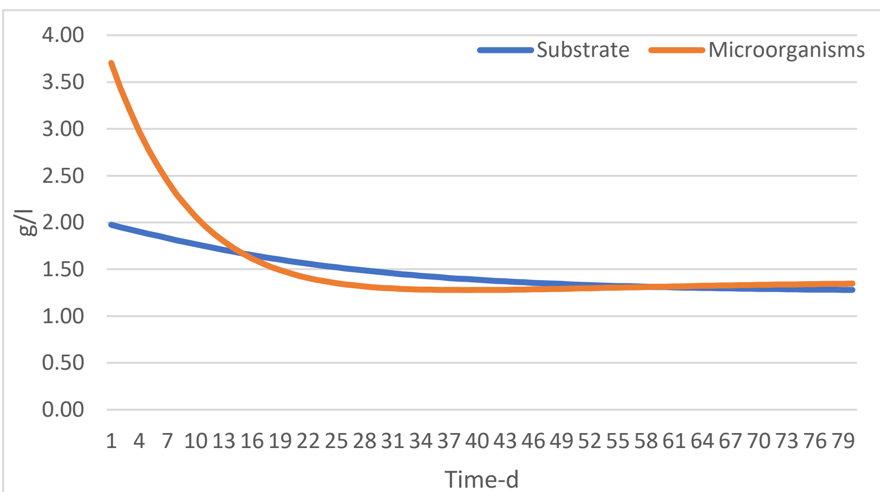

Figure4-1: Substrate's concentration, S and Microorganisms concentration, X based on Fedailaine data

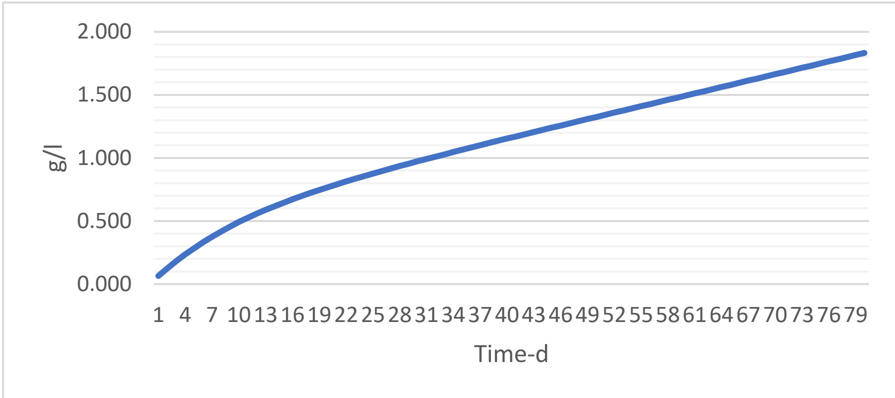

Figure 4-2Methane concentration based on Fadailine data

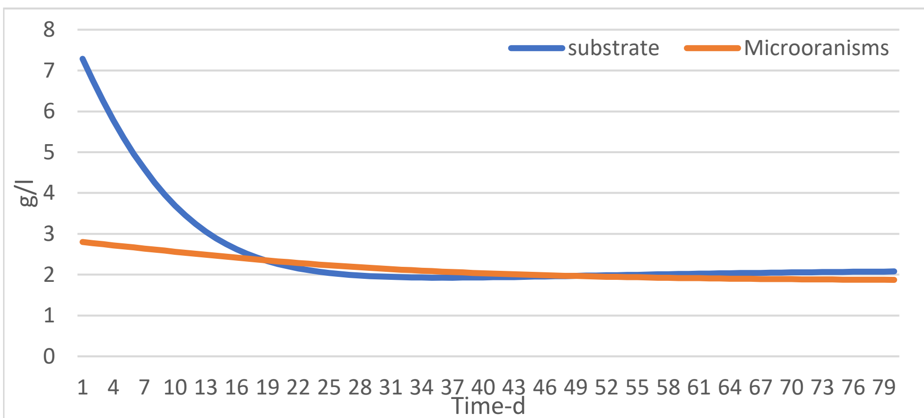

Figure 4-3 Substrate's concentration, S and Microorganisms concentration, X; based on Nakhla data

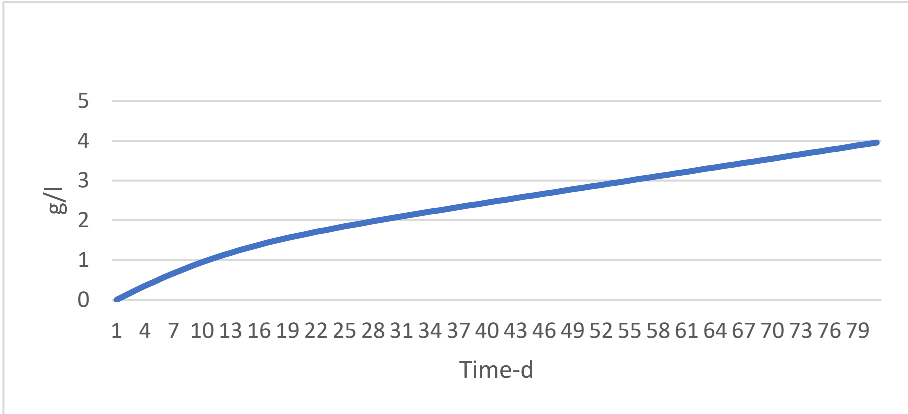

Figure 4-4 Methane concentration based on Nakhla 2006 data

Robescu. D et al. 2015

The other study is Robescu et al., which presents a biological anaerobic digestion model of wastewater sludge based on mass balance. The model was implemented in MATLAB-Simulink, using standard blocks from the Simulink library. The input data were obtained from the Wastewater Treatment Plant Contanța, South Romania. The results of this study were compared with outputs from the INSEL model, as shown in Table 4-5.

Table 4-3 List of parameters Robescu et al. 2015

Parameters	**Values and units**	
μ_{max}	0.35	d^{-1}
D	0.292	d^{-1}
K_d	0.02	d^{-1}
K_s	71	g/l
K_i	1.0	g/l
Y_x	0.82	g/l
K_{mx}	0.4	g/g
K_{sx}	0.983	g/g
Y_p	4.35	g/g
Y_s	0.27	g/g

Table 4-4 model inputs and comparison between the outputs

Input	INSEL model and Robescu et al., 2013
Si g/l	6
Xi g/l	3
Zi g/l	0
Time d	30
Output	
Z g/l	2.065
INSEL, Z g/l	2.055

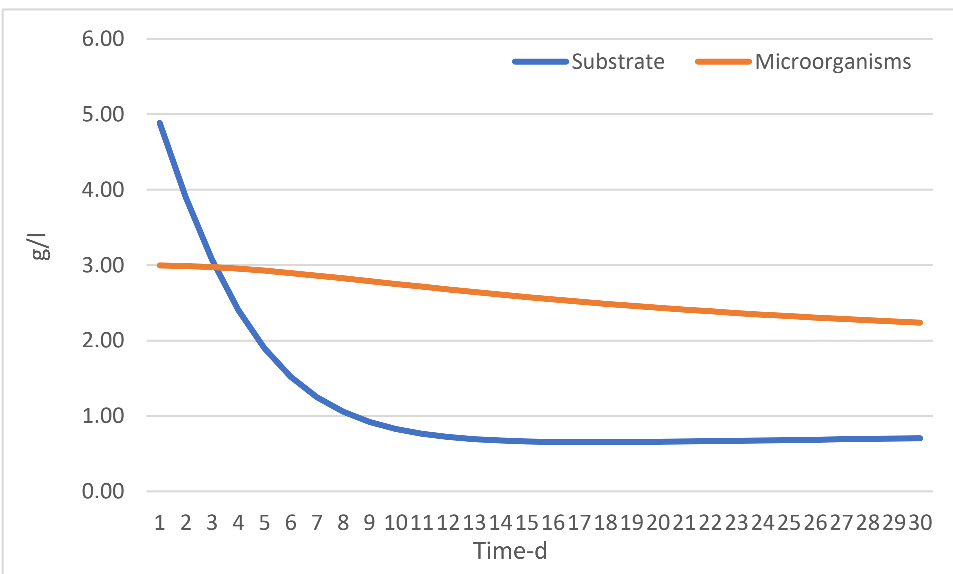

Figure 4-5: Substrate's concentration, S and Microorganisms concentration, X based on Robescu

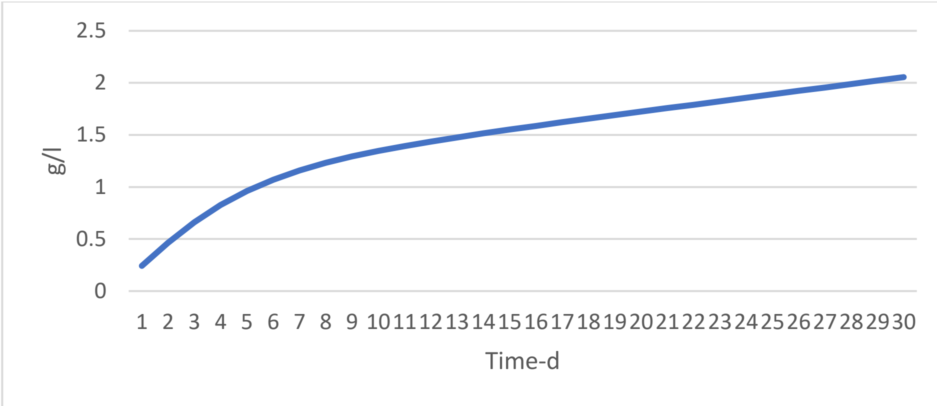

Figure 4-6 Methane concentration based on Robescu, 2013

4.3 Anaerobic Digestion Energy Balance

Anaerobic digestion is usually implemented for sludge stabilization, but its use in energy recovery has recently gained attention. Investigations showed that a significant part of the energy consumed in WWTP units could be supplied by the biogas produced (Silvestre et al., 2015). For wastewater plants smaller than 10,000 PE, the energy coverage is around 40%, while an energy autonomy between 68 and 100% has been suggested for plants larger than 100,000 PE (Gandiglio et al., 2017).

4.3.1 Energy (Electrical and Thermal) production from biogas

In anaerobic digestion, energy is primarily produced as biogas and microbial heat to a minor extent (Lübken et al., 2007), which is neglected in this study. The electrical and thermal energy production from biogas was calculated considering a Combined Heat and Power (CHP) engine, or co-generation, which receives the monthly biogas production rates to deliver power 4.19 and heat 4.20, as follows:

$$EE_g = BY \times Y_{CH4} \times P_{calCH4} \times \eta_E \times t_{we} \times t_{wd}^{-1} \times 0.9 \qquad 4.19$$

$$TE_g = BY \times Y_{CH4} \times P_{calCH4} \times \eta_T \times t_{we} \times t_{wd}^{-1} \qquad 4.20$$

EE_g: electrical energy generation ($kJ.d^{-1}$)

TE_g: Thermal energy generation ($kJ.d^{-1}$)

BY: Biogas production rate ($m^3.d$), Y_{CH4}: methane content (60%), P_{calCH4}: methane heating value (34,020 $kJ.m^{-3}$), η_E: electric efficiency of the CHP engine (35%), η_T: thermal efficiency of the CHP engine (60%), t_{we}: the working hours per month of the CHP engine (666.7 $h \cdot month^{-1}$, with a total of 8000 $h \cdot year^{-1}$), t_{wd}: the hours that the digester is producing biogas (considering 24 h per day and 30 days per month), 0.9 is a factor taken into account for the CHP engine's auto-consumption (10% of the total electric energy generated). (Data extracted from (Igoni, 2016; Silvestre et al., 2015; Claudia Wendland, 2008). The amount of the produced heat related to the anaerobic activity of microorganisms in anaerobic digestion is insignificant that could be neglected.

4.3.2 Energy (Thermal) consumption

The required energy for pasteurization and mesophilic digestion are calculated on a monthly basis considering the average monthly temperature at a given location according to equations 4.21 and 4.22:

$$q_T = Q_s \times \rho \times (T_D - T_s) \times C_P \qquad 4.21$$

$$q_L = A_w \times (T_D - T_A) \times U_w + A_F \times (T_D - T_F) \times U_F + A_R \times (T_D - T_A) \times U_R \qquad 4.22$$

Where,

q_T : energy required for heating the raw sludge (kJ·d^{-1}),Q_S: BW and KW flowrate (m^3·d^{-1}), ρ: BW and KW sludge density (999.5 kg·m^{-3}) (Andreoli et al., 2007), T_D: is the operating temperature of the digester (mesophilic 35 ºC), T_S: sludge's temperature was considered 10 ºC higher than the average monthly environmental temperature, and Cp is the specific heat value (4.18 kJ. ºC $^{-1}$.kg^{-1}). q_L: energy required for maintaining the anaerobic reactor's temperature (kJ.d^{-1}), A_W, A_F, A_R , are the surface area of the walls, floor, and roof respectively (m^2), T_A (ºC): the average monthly environmental temperature; and U_W, U_F, U_R the heat transfer coefficients of walls, floor, and roof (kJ.d^{-1}m^{-2}K^{-1}). (Igoni, 2016; Metcalf and Eddy, 2004). Assuming that the reactor was cylindrical in design, with a diameter two times greater than its height, and was made of concrete with a 300 mm thick wall plus brick facing.

The heat requirements were determined on a monthly basis using the Montreal average temperature. Table 4-5 and figure 4-7 presents the monthly average temperature information based on the Montreal weather station website.

Table 4-5Montréal monthly average temperature in 2019

Avg. Temp	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	-10.4	-8.5	-2.9	5.3	12	18.2	23.5	20.9	16.1	9.8	-1.9	-4.4

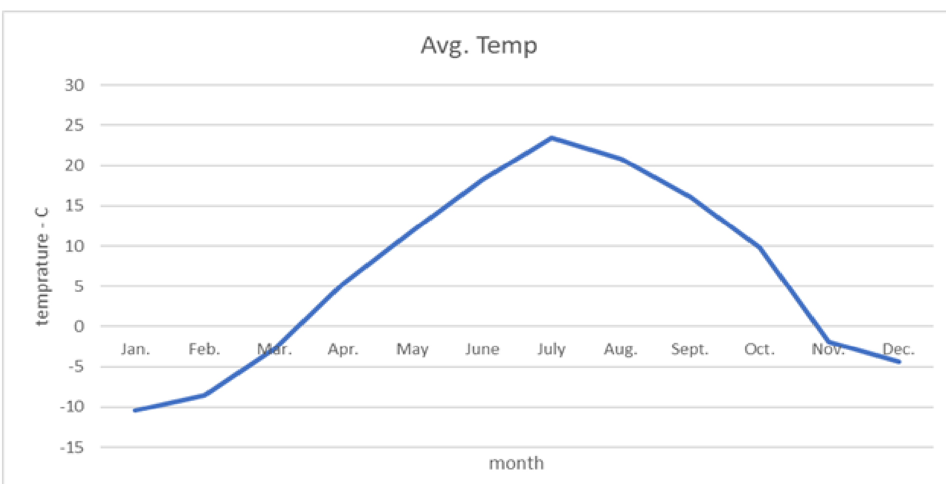

Figure 4-7: Montreal monthly average temperature in 2019

4.4 Biogas Digestate Gasification

In the proposed system, first of all, the digestate should be dewatered and dried to a minimum dryness of 45-55 % digested sludge in order to low moisture tolerance in the reactor (Lacroix et al., 2014; Oladejo et al., 2019) to increase the gasification chemical efficiency and facilitate solids handling (Dussan & Monaghan, 2018). After drying, the digestate is fed to the gasifier, in which preheated air is used as an agent.

Each type of biowaste has different characteristics that determine how well it performs as a fuel. Moisture (the amount of drying required before energy recovery will be determined by the moisture content of biomass), ash (ash content represents the non-combustible material present), volatile matter, proximate analysis, calorific value, and bulk density are the most relevant parameters associated with thermal conversion (Barco-Burgos et al., 2021). The technique of proximate analysis is used to determine the moisture content, ash content, and fixed carbon in biomass. On the other hand, ultimate analysis is a technique for determining the chemical composition of biomass.

Few research works are available in the literature concerning the gasification of sewage sludge digestate. The relevant data concerning these publications have been collected in Table 4-6.

Gasification of sludge takes place at temperatures from 750 ◦C-1100 ◦C (Lumley et al., 2014). In order to analyze the gasification process, a user-friendly mathematical model for biomass gasification processes was developed by one of the CERC team Ph.D. students in the equation solver program Engineering Equation Solver (EES). The model can forecast the producer gas composition, yield, and heating value for specific biomass. The developed model has been validated with experimental published data of other authors, which can be used to evaluate various gasification processes and variations in fuel and operating conditions (Puig-Arnavat et al., 2012)

Table 4-6: proximate and ultimate analysis of fecal sludge and sewage sludge

	Fecal sludge	**Sewage sludge**	**REF.**
Proximate analysis (%ds)			
Volatile solids	44.4-74	51-58	(Byrne et al., 2014; Hafford et al., 2018)
Fixed Carbon	9.1	8-11.8	(Byrne et al., 2014; Hafford et al., 2018)
Ash content %	47-58.7	41.3±8.9	(Hafford et al., 2018), https://phyllis.nl/
Moisture %	8.1-59.6	6.6-77	(Byrne et al., 2014; Onabanjo et al., 2016)
Ultimate analysis (%ds)			
Carbon	27.8-49	36-39	(Gałko & Król, 2018; Hafford et al., 2018; Judex et al., 2012)
Oxygen	19-34	22-36	(Hafford et al., 2018; Onabanjo et al., 2016)
Hydrogen	4.2-7.06	3.6-6.3	(Hafford et al., 2018; Onabanjo et al., 2016)
Nitrogen	3.2-6.87	1.02-7	(Hafford et al., 2018; Onabanjo et al., 2016)
Sulfur	0.7-1.7	0.66-1.8	(Hafford et al., 2018; Onabanjo et al., 2016)

Chapter 5 Case Study

Montreal, Canada's second-largest municipality, has developed strategies and goals to become more sustainable. The city faces three major sustainable development concerns on its path to achieving sustainability and carbon reduction goals (Samadzadegan, 2021, *Ensemble pour une métropole durable*, 2016)

- Reduce the dependence on fossil fuels and GHG emissions by 80% by the year 2050 compared to the year 1990 baseline.
- Provide and improve access to services and facilities across city neighborhoods and the equitable distribution of resources across all dwellings.
- To become a best practices model for other cities in sustainable development.

This study considered the anaerobic co-digestion of blackwater and kitchen waste for a district in Montreal's Lachine-East borough figure 5-1. Lachine-East is a former industrial hub surrounded on the south by the Lachine Canal, west by 6th Avenue, north by Victoria Street, and east by the Canadian Pacific Railway line. This project spans 63.8 hectares and is currently undergoing re-zoning for an eco-district development with an estimated 10,000 residents on the east side of Lachine. The potential of methane production from co-digestion of blackwater and kitchen waste and associated energy consumption and methane generation via anaerobic digestion was analyzed for this district. A decentralized blackwater and kitchen refuse treatment system was proposed towards the sustainability goal.

To assess which percentage of the overall district energy demand could be covered with the co-digestion process, z. The resulting electricity demand of the Lachine-Est district is shown below.

Table 5-1: Lachine-Est eco-district electricity demand in year

Heating Demand ($kWh.m^2$)	Cooling Demand ($kWh.m^2$)	Plug loads Electricity ($kWh.m^2$)	Total electricity for heating(MWh)	Total electricity for cooling(MWh)	Total plug load electricity (MWh)	District electricity (MWh)
32	10	29	2006	835	7274	10115

Figure 5-1: Case study, Lachine East

5.1 Determination of the characteristics and daily loads of blackwater and kitchen refuse

Different toilet flushing systems impact the energy recovery potential of blackwater. Traditional toilet flush systems use 9 liters of water every flush, dual flush systems use 3 or 6 liters of water per flush, and vacuum flush toilets use 0.5 to 1.2 liters of water per flush. Vacuum toilets use less water and generate higher organics. Collecting blackwater separately and combining it with water-saving toilets (e.g., vacuum toilets) produces a concentrated stream (less than 30% of total household wastewater consumption) that contains the majority of contaminants (i.e., more than 50% of organic content and 80–95 percent of nutrients can be recovered) (Katarzyna Kujawa-Roeleveld & Zeeman, 2006). (Remy & Jekel, 2007) used a life cycle evaluation to analyze various ecological performance and sustainability systems. They cited significant benefits of the vacuum technology and blackwater AD system, particularly in chemical fertilizer substitution and reduced eutrophication of the receiving waterways.

Organic loads of blackwater and food waste varied in the different studies, and the quantity highly depends on diet and region. A study in Singapore indicated that 5 liters of brown water (only feces) and 200 g food waste per capita are produced daily (Rajagopal et al., 2013). While Rose et al.2015, estimated the median fecal wet mass production is 128 g/cap.d for the high-income population and 250 g/cap.d for low-income countries with a large minimum and maximum range of 51–796 g/cap.d and median urine generation rate of 1.42 l/cap.d. In 2018, the produced food waste in Canada was 250-340 g/cap.d (Zhang et al., 2019). The reported load ratio was 5 l

BW/cap.d and 500 g FW/cap.d production in China. Reported results from Flintenbreite, a pilot project in Luebeck, Germany, from the year 2000 and with 350 to 400 inhabitants, showed that the discharge of vacuum toilets consumes 0.7 to 1 liter per flush, and the addition of kitchen refuse to the blackwater assumed 40g KR per liter BW (C. Wendland et al., 2007). Kujawa-Roeleveld et al. 2003, estimated that daily faeces production is 138 g and 0.7 liters of flush water of vacuum toilets for one individual, 1.5 l/cap.d is urine, and kitchen refuses generation is 0.2 l/cap.d. These variations can be associated with the region and toilet type, which shows the BW and KR production ranges between 5.2 l/cap.d and 8.5 l/cap.d.

There is a lack of information about BW and KR characteristics in Montreal and reliable related indicators. Also, we could not perform laboratory analysis for model validation within the study. The blackwater and kitchen refuse discharge rate for inhabitants is assumed according to literature values of 8.5 l/cap.d (Claudia Wendland et al., 2014). According to Wendland et al., 2007, about 0.60% of the total discharged rate (8.5 l/cap.d) is assumed to be collected and considered the main discharge (5.2 l/cap.d). Due to Bautista et al. 2020., Otterpohl et al. 2003, in consideration of the daily loads of BW, the values were 35 to 45% lower than the loads reported for human excreta. Two factors are primarily responsible for the variations, The housing estate Lachine district is a residential area, so employed residents are not present for the majority of the day, and a fraction of the residents are children who generate a lower amount of excreta and are not at home for half of the day.

5.2 Methane generation

According to Elmitwalli et al.2006, about 71 - 73% of inlet sludge are organic compounds, which fit a typical organic matter range in municipal wastewater ranging from 65 to 80% (Elmitwalli et al., 2006b; Robescu et al., 2013; C. Wendland et al., 2007). In an anaerobic system, the majority of biodegradable organic matter in the waste, typically 70% to 90%, is converted to biogas (Torretta et al., 2014). On a bench scale, the tests with untreated blackwater indicate 87 percent of total COD biodegradability after 20 days of HRT. However, blackwater and kitchen refuse combination contains 85-96% biodegradable organic matter (Elmitwalli et al., 2006a; C. Wendland et al., 2007). For the particulate COD, the efficiency is 94% even higher. Thus, an increasing HRT of above 20 days leads to a slightly higher overall efficiency. Therefore, in this study, the amount of 18.7 g/l COD is assumed to be organic matter, and this value is used to calculate the concentration of inlet substrate, and 12.7 g/l is considered for microorganisms' concentration.

As introduced in the previous chapter, blackwater (BW) anaerobic co-digestion with kitchen refuse (KR) can be a very important step of Ecological Sanitation (ECOSAN). The developed model is a part of a proposed decentralized system for achieving an Eco-district goal. Two scenarios have been considered: anaerobic digestion of blackwater without kitchen refuse, The other is the anaerobic digestion of blackwater with kitchen refuse. The results are compared to investigate the impact of co-digestion on biogas generation.

5.3 Model Result

The implemented model can be utilized as a stand-alone model or in combination with other models to study an entire urban energy system. The system presented in this thesis is intended to be simple to comprehend and adaptable to new applications. When running the model with input and parameter values presented in Table 5-2 and 5-3, the following results are obtained and shown in Figures 5-2 and 5-3.

Table 5-2: Model parameters

Parameters	Value and units		Reference
μ_{max}	0.48	d^{-1}	(Robescu et al., 2013; Tomei et al., 2009)
D	0.29	d-1	(Fedailaine et al., 2015; Robescu et al., 2013)
K_d	0.01	d-1	(Robescu et al., 2013; Sötemann et al., 2005)
K_s	120	g/l	(Feng et al., 2006; Tomei et al., 2009)
K_i	1.5	g/l	(Siegrist et al., 2002)
Y_x	0.82	g/l	(Fedailaine et al., 2015; Robescu et al., 2013)
K_{mx}	0.4	g/g	(Fedailaine et al., 2015; Robescu et al., 2013)
K_{sx}	0.983	g/g	(Fedailaine et al., 2015; Robescu et al., 2013)
Y_p	0.27	g/g	(Fedailaine et al., 2015; Robescu et al., 2013)

Table 5-3: Model input and output for Blackwater and mixture of Blackwater and kitchen refuse

Input	Blackwater	Blackwater and Kitchen refuse
Si g/l	10.3	18.7
Xi g/l	7.1	12.7
Zi g/l	0	0
Time d	20	20
Z g/l	3.3	6.43

Table 5-2 shows the performance of AD of pure blackwater and blackwater and kitchen refuse at HRT of 20 days. When the BW was digested alone, the methane production was lower than when the blackwater was treated with kitchen refuse. The generated methane concentration is 3.3 g/l for BW only and 6.43 g/l for BW with KR. The difference is because the decreased substrate and microorganism concentration affected the methane concentration, which means that as the initial concentration of substrates increased, methane production was significantly increased.

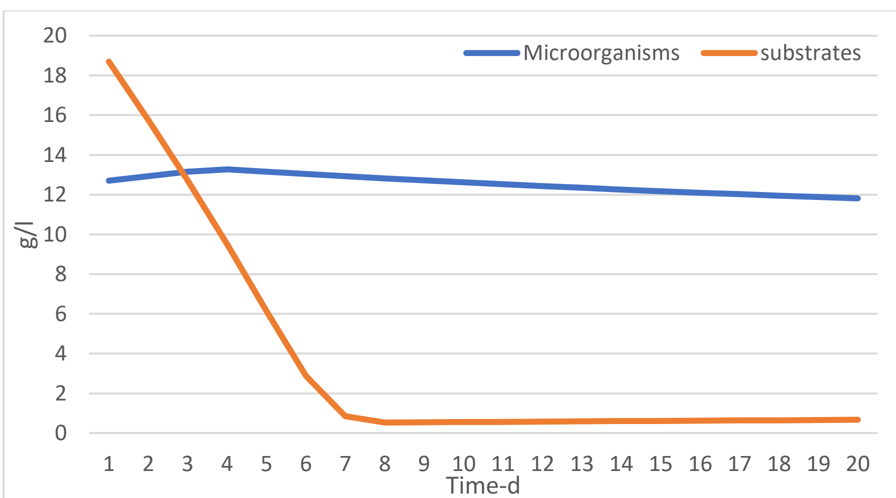

Figure 5-2: Output from model simulation, Substrate (S), and Microorganisms (X) concentration.

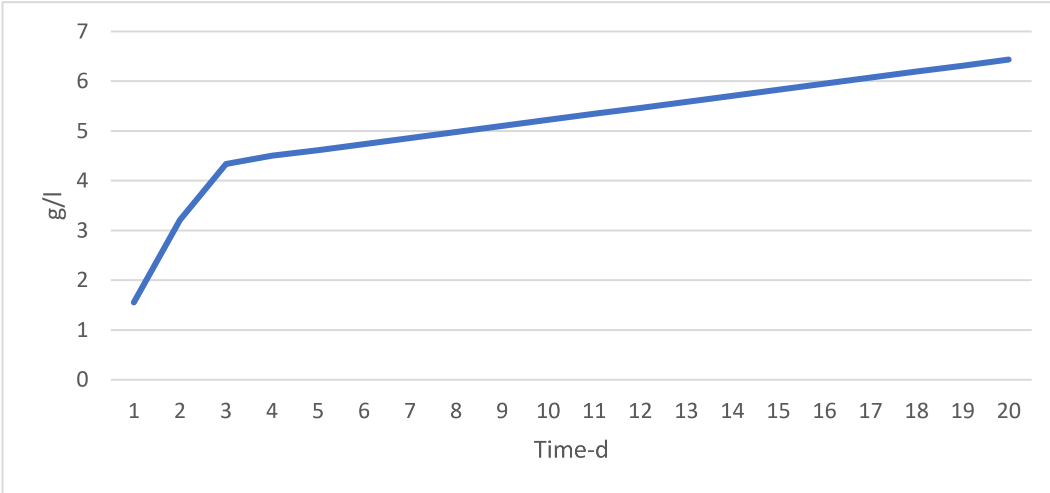

Figure 5-3: Generated methane concentration (g/l)

Figures 5-2 and 5-3 show the graphs generated by the model. Figure 5-2 depicts the evolution of the organic substrate (S) and microorganism (X) concentrations, which corresponds to the microorganisms' degradation of the organic substrate, and Figure 5-3 depicts the simulation results representing the concentration of generated methane by anaerobic digestion of blackwater and kitchen waste over the course of 20 days. The microorganisms consume the organic substrate as food to generate biogas in the first phase, and the trend of substrate concentration shows a slope due to the degradation of the soluble substrate, causing biomass growth to decrease. The three main biological stages are acidogenesis, acetogenesis, and methanogenesis. Various species of anaerobic microorganisms degrade complex organic materials during these periods. Anaerobic digestion is a lengthy process in which microorganisms must produce new cells and remove bacteria as a function of time (Fedailaine et al., 2015). The biodegradation process is finished when the organic substrate is wholly consumed. The production of biogas is the next step. The biological activity corresponds to the time when microorganisms degrade, resulting in an increase in methane production. The results demonstrate that at the end of the period, methane production reaches a concentration of roughly 6.45 g l^{-1}.

The model output is compared for validation with the results from the Wendland study. By calculating the generated biogas and methane using Eq 3-15, 3-16, and 3-17, the estimated produced biogas was calculated 442 m^3/d or 44.2 l/cap.d and produced methane was 26.4 l/cap.d, very close to the Wendland et al. study results of 27 l/cap.d. The methane yields are proportional to the rate of breakdown of the organic substrate, the number of microorganisms present, capita, and day. This simulation allows us to keep track of the digestion process and methane production.

As can be derived from Figure 5-4, the initial substrate and microorganism concentration directly impact methane generation. However, time is also an essential factor in biogas production, but initial substrates concentration is more significant.

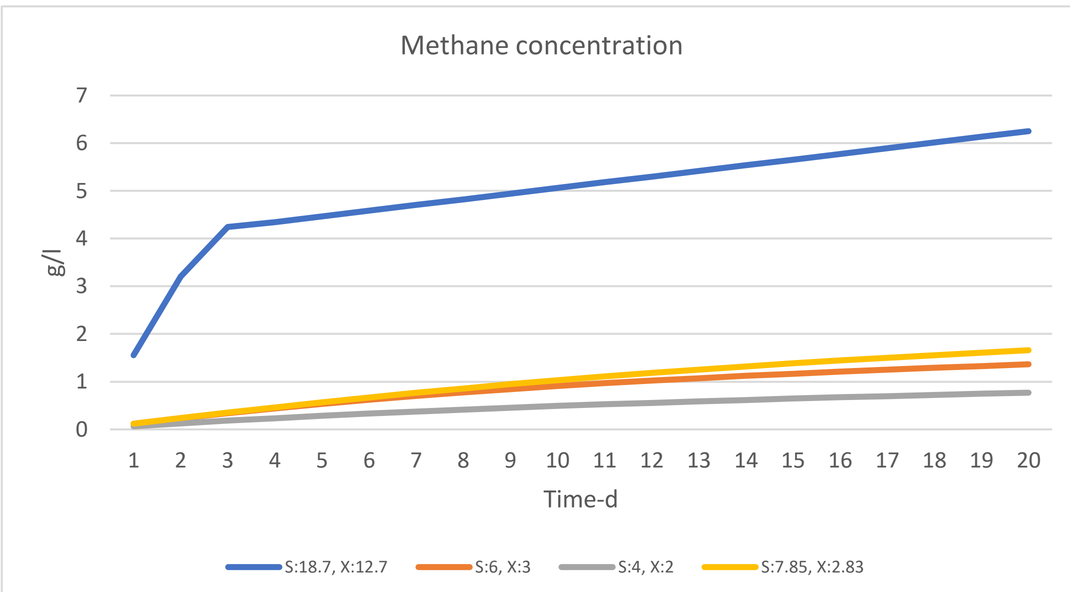

Figure 5-4: Methane concentration based on the initial substrates and microorganisms' concentration

5.4 Reactor sizing

The assumed blackwater and kitchen refuse discharge rate is 5.2 (l/cap/d). The total discharged rate for the districts is:

$$Q_T = 10000 \times (5 + 0.2) = 52000 \text{ l.d}^{-1} = 52 \text{ m}^3\text{.d}^{-1}$$

In this study, the amount of sludge has been assumed equal to the discharged rate. To determine the digester's volume (Eq.3-18),

$$V = 52\ m^3.d^{-1} \times 20\ day = 1040\ m^3$$

Commonly, headspaces range from 20% to 50% of the total reactor volume (Casallas-Ojeda et al., 2020).

5.5 Energy balance (generation and consumption)

Table 4-7 presents thermal energy requirements that correspond to the energy demands for maintaining the anaerobic digester temperature (q_L) and heating the sludge (q_T) which were calculated based on the monthly average temperature. Two different scenarios were considered for calculating the thermal energy demand with insulation of the walls U_W 7.10^{-4} kJ. $S^{-1}m^{-2}K^{-1}$ (0.7 W/m^2k) and without insulation 45.10^{-4} $kJ.s^{-1}m^{-2}K^{-1}$ (4.5 W/m^2k).The value for the floor U_F was 17.10^{-4} $kJ.s^{-1}m^{-2}K^{-1}$ (1.7 W/m^2k) due to the fact that the digester's floor was below ground level and in touch with dry earth, and the values for the roof U_R were 40.10^{-4} $kJ.s^{-1}m^{-2}K^{-1}$ (4 W/m^2k) and 18.10^{-4} $kJ.s^{-1}m^{-2}K^{-1}$ (1.8 W/m^2k) with and without insulation, respectively, assuming a cover thickness of 300 mm concrete for non-insulation scenario (Metcalf and Eddy, 2004).

Table 5-4: Thermal Energy consumption of anaerobic BW and KR digestion with and without insulation (kWh.d -1)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	Without Insulation											
q_T	2126.3	2012.1	1675.8	1183.3	780.8	408.4	90.1	246.3	534.6	913.0	1615.7	1765.9
q_L	1265.3	1211.9	1054.4	823.8	635.3	460.9	311.9	385.0	520.0	697.2	1026.3	1096.6
	With Insulation											
q_T	2126.3	2012.1	1675.8	1183.3	780.8	408.4	90.1	246.3	534.6	913.0	1615.7	1765.9
q_L	407.1	389.9	339.1	264.7	203.9	147.7	99.6	123.2	166.7	223.9	330.0	352.7

Table 5-4 shows that the lowest thermal energy demand is for July 402 $kWh.d^{-1}$ and 189.7 $kWh.d^{-1}$, respectively, without and with insulation. In the same way, in the coldest month of the year (January), the thermal energy requirement is 3391.6 $kWh.d^{-1}$ for non-insulation and 2533.4 $kWh.d^{-1}$ for the condition considering insulation. As shown in Table 5-4, the thermal energy demand with insulation significantly reduces that of the non-insulation situation.

Likewise, Eq 4.19 and 4.20 were used for estimating the generated energy by a CHP engine fueled with the produced biogas from the anaerobic digestion of the blackwater and kitchen refuse. The results show that the plant produces more thermal energy than electricity. The electrical energy generation (EE_g) is 731.1 $kWh.d^{-1}$, while thermal energy generation (TE_g) is 1392.5 $kWh.d^{-1}$. Figure 5-5 shows the estimated thermal and electrical energy generation and thermal energy requirements in kWh per day. Although the energy consumption in the cold months of the year exceeds the energy production, in the warm months, the CHP unit's energy covers the heat demand, and in addition to offsetting the demand for heating, there is an extra amount of electrical and thermal energy. The excess TE_g and EE_g generated at this point can be used for various reasons, such as delivering heat and electricity to office buildings. Indeed, electrical energy could be sent to the public grid, generating additional revenue, whereas thermal energy is usually not used outside the AD plant's self-consumption (Monlau et al., 2015). The biogas flow rate, which is directly proportional to the organic matter concentrations in the feed sludge, significantly impacts the energy output.

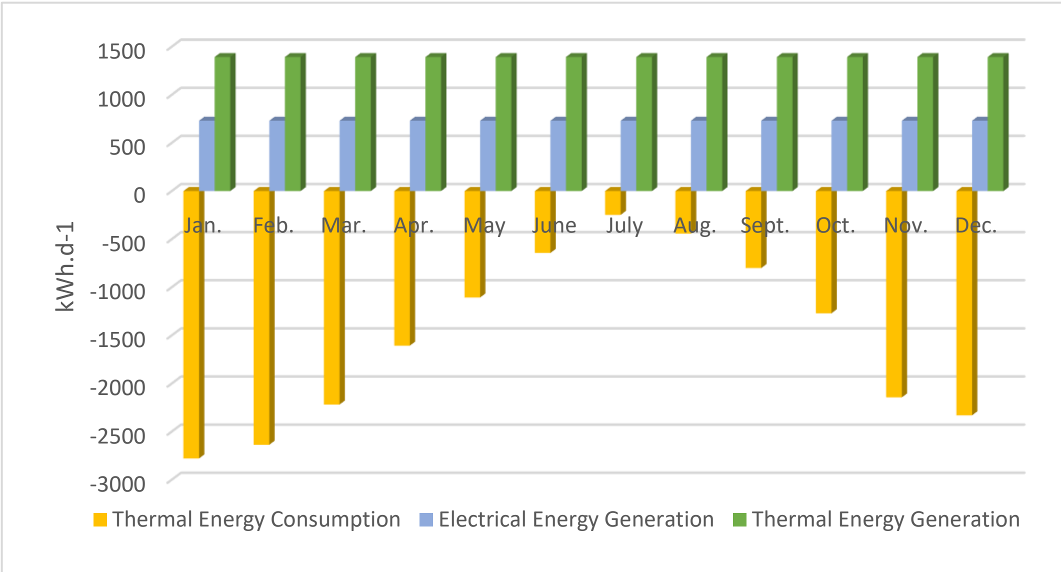

Figure 5-5: Energy generation and Consumption of Anaerobic co-digestion of BW and KR.

The Sankey diagram of Figure 5-6 reveals that the generated biogas has a total yearly energy output of 775 MWh, divided into 266.8 MWh of electricity generation and 508.2 MWh of thermal energy generation. By considering insulation, the generated heat can provide approximately 92% of the required Thermal Energy (TE) anaerobic co-digestion of blackwater and kitchen waste (551.3 $MWh.yr^{-1}$). According to the findings, the thermal energy (TE) recovered in the CHP engine could be enough to meet the heat demand of mesophilic anaerobic reactors for a year except for colder months. However, sustainability could be achieved by adopting some approaches such as increasing the organic matter loading, sludge preheating, or optimizing the reactor size for minimizing energy wasted through heat transfer since the ambient temperature is a decisive factor in AD energy consumption.

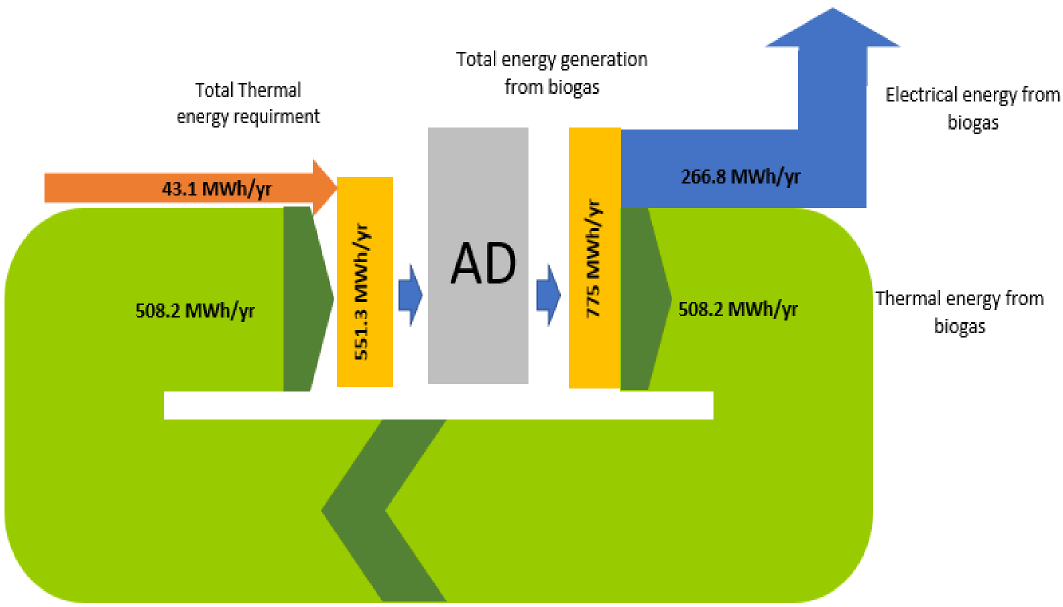

Figure 5-6: Sankey diagram of anaerobic co-digestion yearly energy generation and consumption.

5.6 Digestate management

After anaerobic digestion of blackwater and kitchen refuse sludge, the digestate still contains a significant liquid fraction of more than 70%. Therefore, the digestate should be dewatered and dried further to be suitable for gasification. however, any energy needed for dewatering and drying would reduce the energy production. In this work, the energy demand for dewatering and drying is not considered.

The chemical composition of Blackwater and Kitchen-refuse digestate is presented in Table 5-5. The approximate estimated numbers are taken from Table 4-6 as an average amount. We use this information as an input for the gasification model figure 5-7. This study focuses on investigating further energy generation after coupling gasification and anaerobic digestion of BW and KR.

Table 5-5 Proximate and ultimate analysis

	BW and KR digestate
Ash content %	50
Moisture %	10
Proximate analysis (%ds)	
Volatile solids	45
Fixed Carbon	9
Ultimate analysis (%ds)	
Carbon	38
Oxygen	28
Hydrogen	5
Nitrogen	6.2
Sulfur	1.2

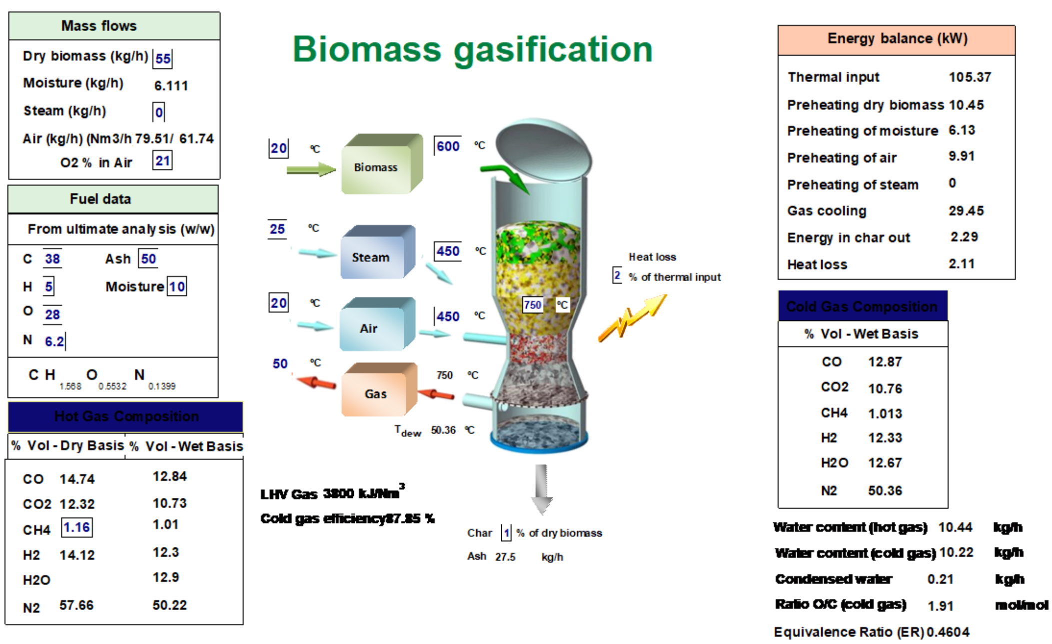

Figure 5-7: Developed gasification model in EES

In many studies, such as (Calise, Cappiello, et al., 2020), the mass variation due to gas generation is neglected; it is assumed that the input flowrate is equal to the output digestate (V_{in}= V_{out}). Likewise, (Hertel et al., 2015) mentioned that the initial masses are transformed only by a small portion into biogas between 1.3 and 4.4 % of input mass so that the digestate amount stays comparable to the input. In the same way, in this study, the mass variation of input and output was low. After solid/liquid separation, the digestate requires further drying in order to reduce the moisture of the gasifier feedstock. After the dewatering and drying process, the dry digestate is estimated at 55 kg/h. Figure 5-8 illustrates BW and KR digestate treatment cycle.

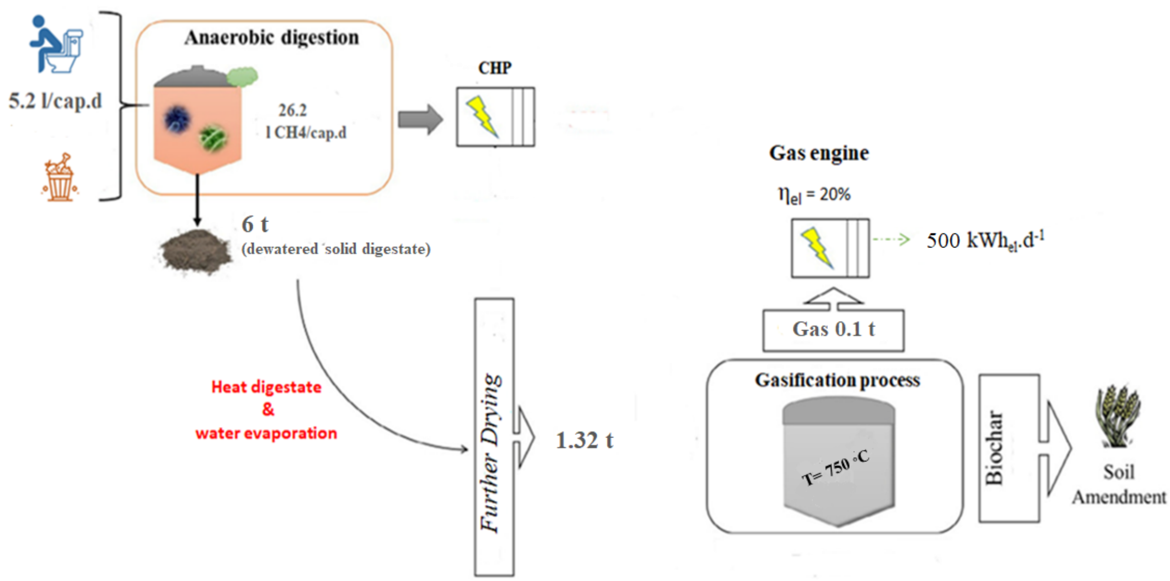

Figure 5-8: Blackwater and Kitchen refuse digestate management.

The syngas is produced at around 750°C using 55 kg.h^{-1} of dry digestate in the gasification model. According to the model outputs, 104.7 kg syngas is produced with the lower heating value is about 3.8 MJ/Nm^3, which provides a reliable value in comparison with the (Gałko & Król, 2018) study, which reported a lower heating value range of combustible syngas due to sewage sludge gasification is about 3.1 to 3.8 MJ/Nm^3. In the study of (Ramachandran et al., 2017), syngas with LHV of 4 MJ/Nm^3 was generated from sewage sludge and woody biomass co-gasification. According to model results, by utilizing the gas derived from digestate gasification, daily electrical production of 500 kWh_{el}.day^{-1} is expected, assuming an electrical efficiency of 20% of the combustion engine. According to the successfully commercialized biomass gasification power plants, the self-consumption ratio of electricity for biomass gasification power plant was about 10% (Guo et al., 2021).

Biochar has the potential to be employed as an energy source, a low-cost adsorbent, a soil improver, carbon sequestration, and a climate impact mitigator. Indeed, biochar used as soil fertilizer has been shown to increase water and nutrient retention in soil (Monlau et al., 2015). There is another possibility of adding biochar as a potential for enhancing biomethane production (Salman et al., 2017).

5.7 Greywater treatment and reuse

According to the report on drinking water use in Ville de Montreal 2017, the domestic water usage determined 308 liters per capita in a day. Household purposes that demand drinking water comprise personal hygiene (19-30%), toilet flushing (30%), dishwashing and laundry (20%), exterior maintenance, pool and garden care (10-30%), cooking and consumption (1-10%). By considering the number of residents, the annual drinking water consumption for the Lachine district equals about 1,124,200 m³. By implementing vacuum toilets, the drinking water demand can be reduced significantly as they only need 0.75-1.2 L per flushing compared to 18-20 L of conventional toilets reported in Montreal (Ouellet, 2005). The drinking water demand for vacuum toilet flushing is about 21,900 m^3, in which the water consumption for conventional flushing toilets is around 346,750 m^3.

Based on data by (Claudia Wendland, 2008), the electricity consumption for the advanced vacuum system is about 19 kWh_{el} per person in a year. The total electricity consumption for toilet flushing in Lachine-Est is estimated to be about 190 MWh in a year.

In decentralized systems, for greywater collection, gravity sewer systems were supposed to be used. However, in the conventional collecting system, greywater is transported through gravity to the nearest pumping station and then pumped to a centralized wastewater treatment plant (CWWTP) which requires more energy than a decentralized plant for pumping. For example, in California, pumping water in a 16-kilometer tunnel with a 600-meter lift required 2.4 kWh/m^3 electrical energy (Stokes & Horvath, 2009).

According to the (Kobayashi et al., 2020) study, additional tap water reduction would be reached through reusing greywater. Recycling greywater usage to substitute part of the household purposes garden care and cleaning (112,420 m^3), laundry (168,630 m^3), and toilet flushing of vacuum toilets (21,900 m^3) thus the drinking water demand can be reduced to 821,250 m^3, which corresponds to a reduction of about 27% tap water. In addition to the tap water savings with greywater reuse, a 14-25% leakage loss from the conventional drinking water distribution system is expected. The water loss from the decentralized distribution systems was assumed to be negligible due to the small size of the network.

The most significant contributor to the impacts of tap water supply was confirmed to be the energy used for water treatment and distribution. The estimated values range for Ontario is a total of 1.43-1.76 kWh/m^3 for both treatment and distribution and 0.61 kWh/m^3 for Atlanta (Kobayashi et al., 2020). Thus, considering the water savings resulting from implementing the vacuum toilets and greywater reuse, about 187.7-433 MWh could be saved annually, about (1.8-4%) of the Lachine district's total electricity consumption. Because of the high energy consumption of traditional water treatment and distribution, the Global Warming potential advantages of reduced water demand greatly outweighed the additional impacts of greywater distribution systems for reuse.

5.7.1 Energy consumption and CO_2 emission in conventional and decentralized reuse systems

A great deal of energy is used during wastewater treatment, resulting in considerable CO_2 emissions. CO_2 emissions from wastewater treatment are determined by the amount of energy consumed at each process stage. Municipal wastewater is typically treated to pass primary, secondary, and sometimes tertiary treatment levels, followed by disinfecting. Primary treatment is almost standard among different wastewater treatment plants and consists of wastewater collection, filtration, screening, chemical treatment, grit removal, and sedimentation. The literature contains a wide range of data on the primary treatment process energy intensity. In Canada, raw wastewater collection and pumping energy intensity are between 0.02 and 0.1 kWh/m^3. As with the primary settling, the energy consumption associated with this process, between 0.008-0.009 kWh/m^3. Different values are used when analyzing secondary wastewater treatment for several countries. The average electrical energy usage may range between 0.2 and 2.07 kWh/m^3 (Bodík & Kubaská, 2013). However, the amount of electricity required varies depending on the type of treatment. The aeration system is the most energy-intensive procedure. The average aeration consumption is between 0.18 and 0.8 kWh/m^3 (Longo et al., 2016). The amount of energy used during tertiary treatment is determined by the level of treatment required and applied to the effluents. According to the literature assessment, the tertiary treatment consumes more energy than the primary and secondary treatments (Matos et al., 2014). Granular medium filtration, microscreens, membrane microfiltration, and ultrafiltration are all examples of tertiary treatment methods (Ministry of the Environment Conservation and Parks, 2021). Carbon emissions depend on the energy mix of the location of the WWTP. In Quebec, electricity is nearly carbon-free, but according to Enerdata 2019, in Canada, the average value for 2018 is 150 g of CO_2 emitted per kWh of power was used to calculate CO_2 emissions.

Table 5-6: Energy consumption and CO_2 emission from conventional WWT system for the case study district.

Treatment process	Energy consumption (kWh/m^3)	Energy consumption variation interval (kWh/d)	CO_2 emissions variation intervals (kgCO_2/day)
Primary			
Sedimentation	0.008-0.009	19-22	3-3
Secondary			
Aeration system	0.18-0.82	443-2,020	66-303
Sludge recirculation	0.005-0.008	12-19	2-3
Clarification	0.5-1.5	1,232-3,696	185-554
Tertiary			
Ultrafiltration	0.5-3	1,232-7,392	185-1109
Disinfection			
UV-B or chlorine	0.045-0.066	103-162	0-24
Total		3,041-13,311	441-1996

For a decentralized greywater reuse system, the treatment system will combine a primary and secondary treatment, followed by disinfection, to meet the water quality criteria for greywater reuse in irrigation.

Table 5-7: Energy consumption and CO_2 emission from decentralized greywater treatment.

Treatment process	Energy consumption (kWh/m^3)	Energy consumption variation interval (kWh/d)	CO_2 emissions variation intervals ($kgCO_2$/day)
Primary			
Gravity and filter	0	0	0
Secondary			
Membrane bioreactor	0.4-1.8	616-2,775	92-416
Disinfection			
UV-B or chlorine	0.045-0.066	69-101	10-15
Total		668-2,873	102-431

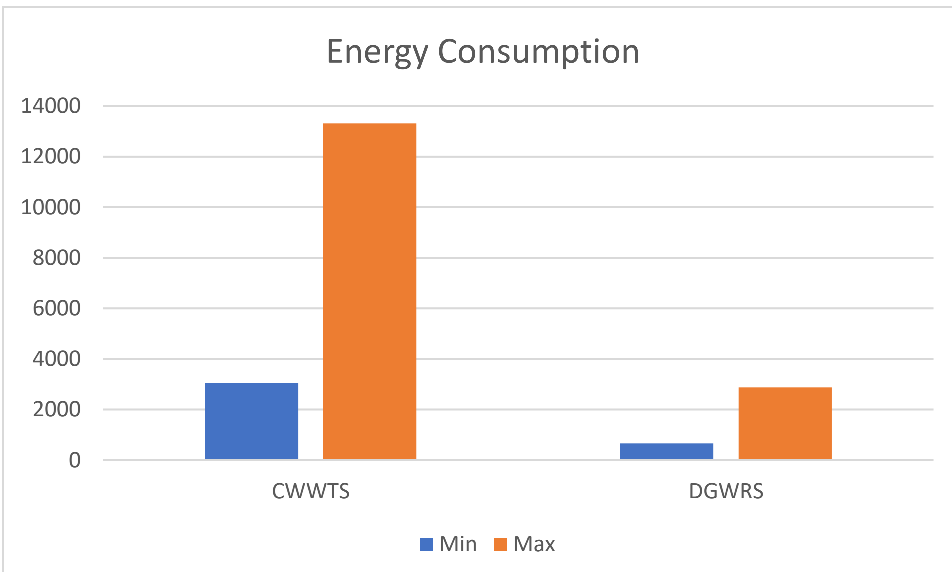

Figure 5-9 Energy consumption in CWWTS and DGWRS.

As shown in Figure 5-9, a conventional wastewater treatment system (CWTS) will consume between 3,041 and 13,311 kWh/day of energy and produce carbon emissions between 441 and 1,996 kg CO_2/day. As shown in Table 5-7, a decentralized greywater reuse system (DGWRS) will consume between 668 and 2,873 kWh/day of energy and will lead to values of CO_2 emission between 102 and 431 kg CO_2/day. Implementing a greywater reuse system will save 2,373-10,438 kWh/day of energy and reduce 339-1,565 kg CO_2/day. From the results presented here, it may be argued that a greywater treatment system is an optimum solution in terms of energy consumption and CO_2 emissions. It is worthy of mentioning that the main characteristics of both streams should be discussed in terms of water quality and the degree of treatment necessary. This form of analysis was not included in the study, but it could help future research because it will provide an average number for each system's energy consumption and CO_2 emissions.

5.8 Conclusion

Decentralized sanitation, also known as new or sustainable sanitation, is a resource-recovery and reuse-based wastewater treatment system intended to mitigate current challenges. The profits come from greywater's recovery and reuse of water sources, as well as blackwater's and kitchen wastes' nutrients use and bioenergy generation.

To develop, design, and control such decentralized systems, mathematical models are an efficient and cost-effective way. Even a simple model, such as the one used in this study, has proven extremely useful for design purposes, such as estimating digester volume, biogas production, degradation rate, or feed flow rate. The biological AD model was successfully implemented and applied to blackwater and kitchen refuse AD plant. The accuracy of model predictions was compared, and the simulation output correlated very well with other practical examples. The design of biological reactors primarily aims to determine the size and type of reactor and method of operation best suited for a given treatment process. This work initially set out to design a digester to treat blackwater and kitchen refuse with resultant biogas production, but it became necessary first to investigate the energy potential of BW and KR. In addition, a system is proposed that can be integrated with other technologies, such as the gasification process. The high organic content of the BW and KR found in this work predisposes the waste as a promising product for biogas generation.

The model's results suggest that with anaerobic co-digestion of 5.2 l/cap/day of blackwater and kitchen refuse, the methane generation potential is around 26.3 l/cap/day, which is consistent with experimental research.

In terms of energy, a CHP unit's energy might be used to offset the heat requirement of an anaerobic digester during the summer months. The biogas flow rate, which is directly proportional to the organic matter concentrations in the feed sludge, significantly impacts energy output. The higher the substrate concentration, the more surplus energy is produced. The simulation results aid in the construction of biogas units and the investigation of AD's energy consumption and generation potential, which is critical for the decentralized treatment of organic waste streams in households. For the case study investigated, a total biogas production of 442 m^3/d could be obtained for an eco-district with 10,000 inhabitants, which would mean a total energy production of 775 MWh per year.

If the biogas is combusted in a cogeneration engine, the heat can provide up to 92 percent of the digester's total thermal energy. In addition, 1.6 kWh electrical energy per m^3 biogas can be produced. The case study with 10,000 inhabitants results in total heat production of 508 MWh and total electrical energy production of 267 MWh per year. The energy generation is determined mainly by the amount of organic matter in the sludge, whereas the system's operation primarily determines its energy consumption. The amount of energy consumed is determined not only by the size of the plant but also by design and technology. The energy production potential of BW and KR, as well as the required energy for anaerobic digestion, were explored in this study, and digestate management and energy utilization for downstream processes were evaluated.

The integration of the gasification process with anaerobic digestion using BW and KR digestate management results in digested sludge reduction and syngas generation with a LHV of 3.8 MJ/Nm^3, showing further energy recovery potential. By gasifying the digestate, a maximum of 102 kg syngas could be produced, which can generate about 500 kWh_{el}/day. Coupling AD and gasification process can lead to an increase of 64% in electricity generation compared with stand-alone AD process.

Establishing source-separated wastewater flows could lead to a noteworthy reduction of energy and greenhouse gas emissions. The reuse system could save 2,373 to 10,438 kWh/day of energy, depending on many assumptions. Greywater reuse helps reduce the carbon footprint between 339 to 1,565 kg CO_2/day and produces water savings and less water drinking water demands. It could be shown that the produced electricity from the coupling of anaerobic digestion and gasification almost compensates for the electricity demand of the decentral greywater reuse system.

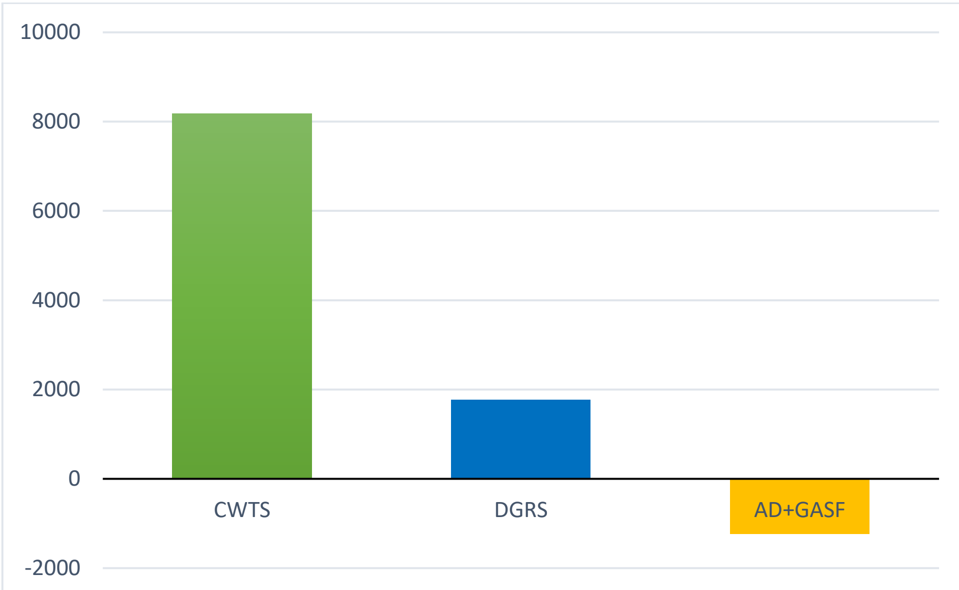

Figure 5-10: average energy consumption of CWT and DGRS and energy generation of AD+GASF

By comparing the energy generation results to Lachine eco-districts electricity demand of 1.01 MWh per year and capita, the anaerobic digestion could cover 2.2% of the electricity demand of a district with a 10,000 population. The total electricity from the combined system of AD and gasifier could cover 4.3%. The combination of anaerobic digestion (AD) and gasification not only solves the digestate disposal problem in the stand-alone AD project but also provides a significant amount of energy.

In conclusion, improving internal energy efficiency through process and technological upgrades, as well as wisely utilizing available incoming energy, could lead to the implementation of a "zero energy" wastewater treatment plant concept in the near future, which not only reduces facilities' energy footprint but also allows for the recovery of wastewater-embedded resources for reuse.

5.9 Future research needs

The following recommendations for future works are made in light of the findings and conclusions drawn from this research.

- Blackwater and kitchen refuse digestion in pilot-scale and commercial-scale should be constructed, and other models or experiments with other biowastes should be developed.

- In order to produce the desired syngas for power production or other products, further fundamental study on the influence of BW and KR sludge in gasification is required.

- The by-product of the digestion process should be investigated for further re-use, perhaps as fertilizer.

- In order to enhance the performance of the digesters, the optimization of treatment processes should be considered.

- A life cycle assessment and a techno-economic analysis should be conducted for the coupling of the biological process of anaerobic digestion (AD) with the gasification process.

- Climate mitigation, balancing sustainability issues with water quality, reliability, risks, and costs are required.

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