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# Renewable Energy and Nutrient Valorization from Anaerobic Digestion – Resource-Efficient Solutions

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# Abstract

This thesis presents a comprehensive analysis aimed at understanding process performance, methane yield, and key influencing factors within the context of solid-state anaerobic digestion (SS-AD). SS-AD is used to treat organic material with high solids content, which can be challenging to address by alternative methods. The investigation involves modelling and simulation exploring mass and energy balances and the associated environmental implications. To achieve this, a waste management tool, ORganic WAste REsearch (ORWARE) was adapted and validated to suit the unique parameters of SS-AD operating under a plug-flow reactor configuration, representing a specific case study. The search of an optimal feedstock mix that enhances the digestion process and energy performance is highlighted. Findings suggest that feedstock selection significantly affects methane yield in SS-AD systems, and optimizing substrate mixtures can enhance process efficiency. Key considerations include biodegradability and lignocellulosic content. Operational parameters, such as temperature variations, impact the results from the model, while responsiveness of hydraulic retention time and organic loading rate remains limited. A further comparison between a liquid anaerobic digestion (L-AD) vs SS-AD is made, despite similar methane yields, SS-AD outperforms due to higher energy turnover. Additionally, effective management of digestate nutrients is crucial for its biofertilizer use. Beyond the biogas system, the thesis explores interconnected relationships between SS-AD inputs and outputs and their subsequent use as resources for a hydroponic greenhouse production system. The examination of system interconnections and their broader implications emphasizes the importance of comprehensive assessments when integrating biogas systems beyond their conventional applications.

**Keywords:** Solid-state anaerobic digestion, methane yield, digestate, systems analysis, modelling, life cycle assessment.

# Sammanfattning

Denna avhandling presenterar en omfattande analys som syftar till att förstå processprestanda, metanutbyte, och viktiga påverkande faktorer inom ramen för torrötning. Torrötning används för att behandla organiskt material med hög torrhalt, vilket kan vara svårt att hantera med alternativa metoder. Undersökningen omfattar modellering och simulering för att utforska mass- och energibalanser och därmed sammanhängande miljökonsekvenser. För att uppnå detta anpassades och validerades ett verktyg för avfallshantering ORganic WAste REsearch (ORWARE) för att passa en torrötnings-anläggning med pluggflödereaktor, vilket representerar en specifik fallstudie. En optimal råvarublandning som förbättrar rötningsprocessen och energiprestanda lyfts fram. Resultaten tyder på att valet av råmaterial avsevärt påverkar metanutbytet i torrötnings-system, och att optimera substratblandningar kan förbättra processeffektiviteten. Viktiga överväganden inkluderar biologisk nedbrytbarhet och lignocellulosahalt. Driftsparametrar, såsom temperaturvariationer, påverkar torrötning, medan känsligheten för hydraulisk retentionstid och organisk belastningshastighet i den modifierade pluggflödereaktor-konfigurationen förblir begränsad. I en jämförelse mellan våtrötning och torrötning så har både teknikerna liknande metanutbyten, men torrötning överträffar på grund av förbättrad energibalans. Avhandlingen undersöker dessutom aspekter bortom biogassystemet. Den utforskar de sammankopplade förhållandena mellan torrötning-utgångar och deras efterföljande användning som resursinsatser för ett hydroponiskt växthusproduktionssystem. Utforskningen av systemsammankopplingar och deras bredare implikationer belyser vikten av omfattande bedömningar när man integrerar biogassystem utöver deras konventionella tillämpningar.

**Nyckelord:** Torrötning, metanutbyte, biogödsel, systemanalys, modellering, livscykelanalys.

# Acknowledgements

I arrived in Sweden during a dark and cold winter, and at that moment, many thoughts ran through my head. One of them was: ‘What have I done?’ Happily, this adventure became, without a doubt, the most exciting I have ever had. I am fortunate and thankful to have navigated this academic adventure.

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A mi familia y amigos en México, o donde quiera que se encuentren: ustedes son mi fortaleza y acompañantes en mis aventuras. A Vita y Miguelito por darme las mejores herramientas para la vida, las cuales no son materiales. A Yaya, por tu apoyo y amor incondicional. A Yeyo, que eres como mi hijo y me animas en todo. A Vladi, el tío favorito; esta familia no sería igual sin ti. A los amores de mi vida, Sven, Ragnar y, por supuesto, Robert, que tuve que viajar miles de kilómetros para poder encontrarnos y formar una familia hermosa. Gracias.

# Appended Papers

This thesis is based on the work described in the following appended papers, which are referred to with Roman numerals.

### Paper I

Carlos-Pinedo, S., Wang, Z., & Eriksson, O. (2019). Methane yield from SS-AD: Experiences to learn by a full spectrum analysis at laboratory-, pilot- and full-scale. *Biomass and Bioenergy* (127): 105270. doi: 10.1016/j.biombioe.2019.105270

### Paper II

Carlos-Pinedo, S., Wang, Z., Eriksson, O., & Soam, S. (2020). Study of the Digestion Process at a Full-Scale Solid-State Biogas Plant by Using ORWARE: Model Modification and Implementation. *Waste Management* (107): 133-42. doi: 10.1016/j.wasman.2020.03.036

### Paper III

Carlos-Pinedo, S., & Wang, Z. (2022). Assessment of a full-scale solid-state anaerobic co-digestion: A multi-component substrate analysis by using ORWARE. *Waste Management* (146): 36-43. doi: 10.1016/j.wasman.2022.04.042

### Paper IV

Danevad, D., & Carlos-Pinedo, S. (2021). Exploring Interactions Between Fruit and Vegetable Production in a Greenhouse and an Anaerobic Digestion Plant – Environmental Implications. *Frontiers in Sustainability* (2): 1-10. doi: 10.3389/frsus.2021.770296

### Paper V

Carlos-Pinedo, S., Wang, Z., & Eriksson, O. Systems analysis of biogas and digestate utilization pathways with carbon capture: A Life Cycle Assessment and a Material and Energy Balance approach. (manuscript).

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# 1. Introduction

While waste management (WM) is considered a basic necessity, it often receives less attention than other essential services, such as shelter, food, and energy (UNEP, 2016). Currently, approximately 2.01 billion tonnes of municipal solid waste annually are generated worldwide. However, projections indicate a significant increase to 3.40 billion tonnes by 2050 (Kaza et al., 2018). Globally, approximately one-third of municipal solid waste is improperly managed, contributing significantly to 5% of global emissions (Kaza et al., 2018; UNEP, 2016). The remaining emissions are distributed among other sectors, with roughly 34% (20 $GtCO_2$-eq) of the world's net greenhouse gas (GHG) emissions originating from the energy sector, 24% (14 $GtCO_2$-eq) from industry, 22% (13 $GtCO_2$-eq) from agriculture, forestry, and other land use (AFOLU), and 15% (8.7 $GtCO_2$-eq) from transportation (IPCC, 2022). In 2015, the United Nations adopted 17 Sustainable Development Goals (SDGs) along with 169 targets as part of the 2030 Agenda. These goals and targets formed the basis for global collaboration aimed at eradicating poverty and hunger, addressing the effects of climate change, and promoting prosperity worldwide (UNDP, 2015). In the same year, the Paris Agreement established the global goal of limiting the average temperature increase to below 2 °C, with a more ambitious target of 1.5 °C, referring to sustained warming over an extended period (UNFCCC, 2017) (WMO, 2023).

Furthermore, the urgency of the climate change crisis, combined with the occurrence of pandemics and the recent Ukraine conflict, has highlighted the critical need to diversify energy sources and reduce dependence on fossil fuels, including gas supplies. In that sense, it has become clear that there is a need for increased development of local energy resources. Likewise, as global energy prices continue to rise, the concept of energy recovery from organic residues and waste streams is gaining increasing attention. Flexible energy generation and storage are the keys to the future of energy technology, guaranteeing a reliable energy supply and facilitating an efficient transition (Garcia et al., 2022). These transitions can include the adoption of biofuels for transportation, a notable decrease in overall fossil fuel consumption, minimal reliance on unabated fossil fuels, and the implementation of carbon capture, use, and storage (CCUS). Additionally, utilizing bioenergy with CCUS (BCCUS), and reducing food loss and waste are all viable mitigation options (IPCC, 2022).

On a global scale, the most significant waste category consists of food and green waste (EPA, 2018; Kaza et al., 2018). This waste stream can be managed through various methods, including biological treatments, which enable the valorization of organic waste. These technologies can generate valuable by-products such as soil amendments and/or liquid fertilizers. Additionally, anaerobic digestion (AD) can produce biogas, a valuable renewable energy source (Lin et al., 2014; Song et al., 2021; Yong et al., 2015). Treatment of solid waste through AD is a complex process that relies on a diverse microbial community including hydrolytic, acidogenic, acetogenic, and methanogenic microorganisms, each performing sequential steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Vavilin et al., 2008). Within this process, organic matter undergoes significant degradation, with the hydrolysis step being considered the rate-limiting step, especially when working with solid waste (García-Gen et al., 2015; Vavilin et al., 2008). The typical ratio of $CH_4$ to $CO_2$ in biogas is 60:40 under ideal conditions (Kythreotou et al., 2014). When the organic matter has a total solids (TS) content higher than 15% inside the digester/reactor, it is classified as dry, high-solids or solid-state AD (SS-AD), which could offer several advantages over liquid AD (L-AD), where the TS content is typically below 15% (Ge et al., 2016; Li et al., 2011; Yang et al., 2015). One advantage is that SS-AD produces a more concentrated digestate, resulting in reduced storage and transportation costs while also contributing to a smaller environmental footprint. Likewise, SS-AD is more resilient to process disturbances and is less susceptible to washout of microorganisms (Budzianowski, 2016; Zhang et al., 2017). However, SS-AD uses a solid medium to transfer substances, reducing the need for water but decreasing the contact between microorganisms and substrate which could lead to a drop in the biogas yield (Li et al., 2011).

Sweden has set a goal to ensure that, no later than 2023, at least 75% of food waste generated by households, catering kitchens, shops, and restaurants is sorted and treated biologically to recover biogas and nutrients (Energimyndigheten, 2021). In 2022, the total waste generation amounted to approximately 123 kilograms per person, with a total generation of 4,719,490 tonnes. Of these, 16% underwent biological treatment, either AD or composting (Avfall Sverige, 2022). Particularly, the use of biofuels such as biogas has consistently increased with a total of 4.8 TWh in 2021, including both domestically produced and imported sources. Almost half of the 281 biogas production facilities operating in Sweden are sewage treatment plants, while only 37 facilities are categorized as co-digestion plants, which digest different types of organic material like source-sorted food waste, slaughterhouse waste, manure, and energy crops, excluding sewage sludge (Energigas Sverige, 2023). Despite their lower number, most of the biogas production takes place in these types of co-digestion facilities. Additionally, only a few co-digestion plants operate using SS-AD conditions with examples located in Mörrum, Härnösand, Forsbacka, Jönköping, and Högbytorp (BRIGHT, 2017; Eisenmann, 2012; HZI, 2020a, 2020b; Persson et al., 2019; Westerholm et al., 2020). Given that these SS-AD technologies are relatively new in the country, it becomes important to investigate their process performance due to the unique advantages they offer, positioning them as a potential key technology for treating specific waste streams. While many studies have focused on the systems analysis of waste management technologies (Björklund, 2000; Boldrin et al., 2011; Eriksson & Bisaillon, 2011; Gentil et al., 2010; Hansen et al., 2006; Winkler and Bilitewski, 2007), to the best of the author's knowledge, limited research has been conducted in the specific area of full-scale SS-AD performance (Angelonidi & Smith, 2015; Chiumenti et al., 2018; Westerholm et al., 2020), and more specifically, their environmental performance (Feiz, 2016). Furthermore, establishing efficient pathways for the utilization of biogas and digestate remains a priority (Bose et al., 2022; Dahlgren, 2022; Farghali et al., 2022).

## 1.1. Aim and research questions

The aim of this thesis is to deepen the understanding of anaerobic digestion under solid-state conditions and assess the performance at full scale with respect to renewable energy production and nutrient recovery. To accomplish this goal, a systems analysis model was applied, which incorporates methodologies such as material flow analysis (MFA) and life cycle assessment (LCA). The evaluation of the biogas production system primarily focuses on examining material and energy performance, as well as environmental impacts.

Based on the aim of the thesis the following research questions (RQ) are addressed:

> RQ1. How do various factors, such as feedstock composition and operational parameters, affect methane yield in solid-state conditions?

An important aspect of understanding anaerobic digestion with high solid content substrate is about how various factors influence methane yield. Feedstock compositions vary widely, each with distinct characteristics. Investigating the impact of different feedstock compositions on methane yield is crucial for identifying the most promising mixtures in solid-state conditions. Furthermore, methane yield is also related to other operational parameters, such as temperature, hydraulic retention time (HRT), organic loading rate (OLR), and so on. Studying how variations in these operational parameters influence the process allows for the improvement of conditions to maximize methane yield.

> RQ2. What strategies can be implemented to enhance the production of biogas and digestate, and to minimize resource usage in full-scale SS-AD plants?

This question relates to the exploration of technical recommendations to enhance biogas, energy turnover, and the nutrient content of the digestate. Simultaneously, the aim is to minimize the consumption of resources, including materials and energy inputs at full-scale operation.

> RQ3. How can the biogas and digestate be processed and utilized, and what are the potential environmental implications associated with them?

This research question deals with the analysis of various scenarios within an expanded biogas system, which represents different uses of biogas as heat, electricity, or vehicle fuel, through different pathways and applications of digestate as organic fertilizer in different settings. The evaluation consists of material and energy analyses, along with an assessment of their environmental impacts. The inclusion of biogenic carbon, derived from biogas as a $CO_2$ source, is also considered.

Table 1 presents the interconnections between the research questions and the papers that were developed and included in this thesis.

Table 1. Connections between the research questions and different papers.

| RQ | Paper I | Paper II | Paper III | Paper IV | Paper V |
|---|---|---|---|---|---|
| RQ1 | x | x | | | |
| RQ2 | | x | x | | |
| RQ3 | | | | x | X |

## 1.2. Scope and delimitation

This thesis focuses on the analysis of a co-digestion biogas production system, primarily centered around a case study involving SS-AD in a full-scale production setting. Additionally, it includes different scenarios tailored to each paper's specific aims and scope. The production, sorting, and collection of feedstocks, as well as their transportation from the source to the SS-AD plant, are not within the scope of this thesis. It is assumed that the operation occurs under favorable conditions, ensuring stable biogas and digestate production, with microbiology analyses not included. Emissions related to the use of digestate include those associated with its application on arable land, and those resulting from the soil. The findings can be considered applicable and/or indicative of other similar conditions, and they have been contrasted with existing literature that examines comparable production systems. There are different categories for biogas systems, in this thesis, the "small-scale" term refers only to biogas produced in a laboratory-scale context or similar. Additionally, the investigated SS-AD case study works under specific plug-flow reactor conditions. In this thesis, resource efficiency is limited to the perspectives of material and energy performance, and for papers IV and V, it is evaluated through the environmental impact assessment.

The central focus of the analysis in the appended papers is situated in the digestion process, as shown in Figure 1. Other aspects, such as the processing and utilization of biogas and digestate, were incorporated to enhance and expand the overall system. The analysis starts with the digestion process and concludes with the integration of various product processing methods. The first system level (SL1) of the study covers the digestion process area, encompassing feedstock types and characteristics, methane production, digestate production, and an analysis of operational parameters such as temperature, HRT, and OLR. At this level, the reactor design analysis is also performed which allows for a better comparison of the actual biogas plant operating under specific plug-flow conditions. In addition to this, a comparison of the operation between high-solids (the SS-AD operations) conditions vs low-solids (L-AD) content is analyzed. The second level (SL2) of the study builds upon the processes from the first level, providing a more detailed analysis of methane yield and energy turnover concerning different feedstocks and their combinations. Additionally, it includes the examination of digestate processing and nutrient content assessment.

The final level (SL3) focuses on biogas processing and explores different options for its utilization, such as heat, electricity, and vehicle fuel. Heat and electricity generation involves a combined heat and power (CHP) system and solid oxide fuel cells (SOFCs). Vehicle fuel is assumed to be either compressed biogas (CBG) or liquefied biogas (LBG). This level also addresses reject management, dealing with impurities that are assumed to be present in the feedstock input, which are incinerated, and the resulting ashes are deposited in a landfill. Liquid digestate is assumed to be used as an organic fertilizer with direct application in arable land, and in a hydroponic greenhouse for fruit and vegetable production. Solid digestate is assumed to be utilized as biofertilizer through two options: as an amendment or as pellets. Additionally, the valorization of biogenic $CO_2$ is explored, with two primary options: as a growth enhancer in a hydroponic greenhouse, and as a resource for producing a supplementary cementitious material (SCMs), together with the ashes from the incinerated input rejects. Based on material and energy analyses, this level also considers environmental impacts.

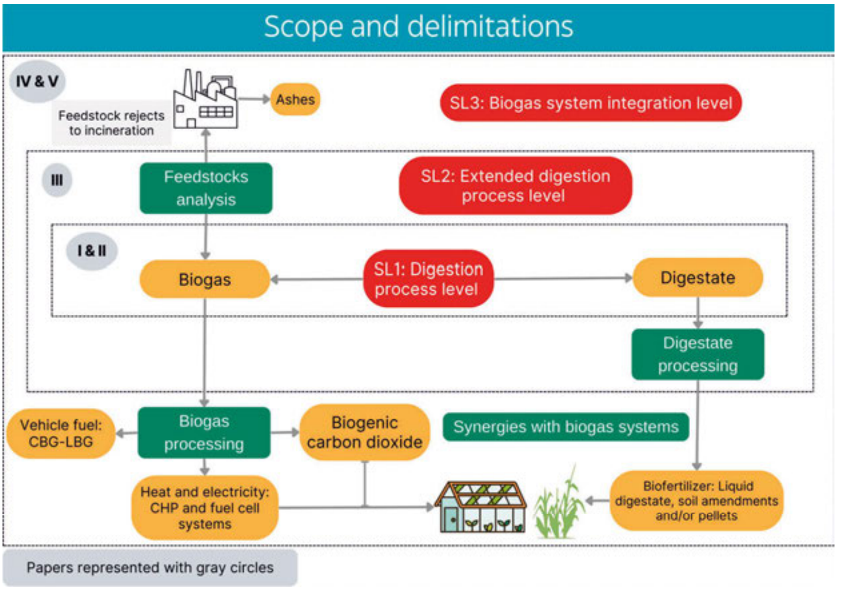



Figure 1. Scope and delimitations for different systems and papers.

## 1.3. Overview of papers and co-author statement

This thesis comprises five papers. The papers are briefly described and accompanied by a co-author statement.

### Paper I

The aim of this paper is to provide a comprehensive analysis of methane yield performance and the primary factors influencing it under SS-AD conditions at laboratory, pilot, and full scale. Additionally, it provides recommendations for enhancing methane yield at a full-scale level and contributes to the theoretical foundation for subsequent papers.

I was responsible for data collection and paper writing, while the analysis was conducted in collaboration with Zhao Wang and Ola Eriksson, who also provided supervision.

### Paper II

This paper aims to adapt and validate the ORWARE model for studying SS-AD under a plug-flow configuration to mimic the case study. This modification was required as the original ORWARE anaerobic digestion process was designed for different conditions. Additionally, it emphasizes and discusses the digestion performance distinctions between L-AD and SS-AD.

My primary responsibilities included model modification, data collection, and paper writing. I collaborated with Zhao Wang and Ola Eriksson on result analysis and certain sections of the paper. Ola Eriksson supervised the model design, and feedback on the manuscript was provided by Zhao Wang, Ola Eriksson, and Shveta Soam.

### Paper III

The purpose of this paper is to assess how various feedstocks and their combinations affect methane, digestate production and quality, and final energy turnover. This is crucial when environmental goals aim to reduce food waste, the primary feedstock in this case study. Additionally, the paper offers a detailed analysis of the nutrient content of the digestate and its processing. It also aims at analyzing different scenarios for reducing input resources, such as energy usage, while increasing biogas production and maintaining or improving digestate quality in terms of key nutrients.

Zhao Wang and I each contributed equally to the conceptualization of this paper, but I had the primary responsibility for data collection and writing. Both of us conducted the analysis of the results.

### Paper IV

This paper aims to conduct a comparative analysis of two tomato production systems within a Swedish context. The first system involves traditional greenhouse practices commonly used in Sweden. The second system explores the integration of products from an SS-AD plant, which includes biogas as an energy source for heat and electricity, $CO_2$ supply, and liquid digestate as a biofertilizer. The analysis focuses exclusively on the liquid fraction of the digestate since the greenhouse process corresponds to a hydroponics configuration. The evaluation of materials, energy usage, and environmental aspects are covered. Additionally, a sensitivity analysis is performed to assess the effects when utilizing a European electricity mix instead.

My contribution to this paper was mainly in the Material Flow Analysis while Daniel Danevad focused primarily on the Life Cycle Assessment method. However, we both made equal contributions to the conceptualization, data gathering, analysis, writing, and editing of the manuscript.

### Paper V

This paper aims to explore various utilization options for biogas and digestate, taking into consideration materials, energy, and environmental analysis. Additionally, it examines the potential utilization of the biogenic carbon derived from biogas. The study also expands with the integration of waste treatment technologies, such as the incineration of feedstock rejects, primarily plastics. The specific scenarios analyzed include the use of a landfill for the ashes resulting from the incineration process, the post-processing of solid digestate to produce soil amendments and pellets, and the upgrading of biogas. In the case of biogas, it is assumed to be deliverable as either CBG or LBLBG. Additionally, alternative scenarios explore the use of biogas solely for heat and electricity production. This paper adopts a system expansion perspective, which accounts for the compensation needed to produce the primary products of the system using alternative resources.

I made the main contributions to the conceptualization, data collection, writing, and analysis of results. The analysis was conducted in collaboration with Zhao Wang and Ola Eriksson, who also provided supervision.

# 2. Background

Within the subject of renewable energy and WM, few technologies hold as much promise as anaerobic digestion. This process not only enables the production of biogas, a renewable energy source, but also offers the opportunity for nutrient valorization. Moreover, the integration of biogas systems with BCCUS presents a chance to tackle climate change and work under circular economy principles. In this section, the main theoretical background will be described, with a focus on examining the current biogas systems approaches, presenting their versatile applications, and highlighting the synergies that can be realized by leveraging biogas systems in conjunction with other practices.

## 2.1. Biogas outlook

The Nordic Biogas Model as defined by the Biogas Research Center represents a comprehensive approach to biogas production (Biogas Research Center, 2022). Back in time, experimental biogas production from waste started in the 19$^{th}$ century, when the initial processes were primarily focused on municipal waste treatment and did not prioritize energy recovery. Subsequentially, biogas was employed for street lighting, and during and after World War II, it gained interest as a fuel source for vehicles and farm tractors (Mital, 1997). Today, the Nordic Biogas Model follows a similar approach along with nutrient recovery and more recently, the increased interest in coupling biogas systems to other industries such as food production (Lindfors et al., 2022). This model emphasizes the utilization of waste and residual products as substrates and the upgrading of biogas to biomethane, primarily for transportation purposes or injection into gas networks, often serving industries, altogether with the use of the digestate as biofertilizer (Biogas Research Center, 2022).

For instance, there has been an increase in biogas production in Denmark, reaching 4.7 TWh, which already accounts for 15% of total gas consumption. This places Denmark in second place in terms of biogas production per capita in Europe. Initially, biogas in Denmark was directly used for CHP generation. However, the current trend involves upgrading before injecting it into the national gas grid (IEA Bioenergy, 2021a). In Finland, biogas production accounts for approximately 2 TWh, where biogas is mainly used to power wind power plants and upgraded for vehicle fuel (IEA Bioenergy, 2021b). Norway has a modest biogas production of around 1 TWh, with a growing interest in its use as liquified biogas as vehicle fuel (IEA Bioenergy, 2021c). In Sweden, the national production of biogas alone reached 2.26 TWh, primarily used as vehicle fuel, which accounts for over 90% of gaseous transport fuel (IEA Bioenergy, 2021d). In all the examples mentioned, digestate is mainly used as a replacement for conventional fertilizers. In Europe, the concentration of biogas plants has been predominantly in Germany, contributing to approximately 87 TWh of biogas production (IEA Bioenergy, 2021e), initially prioritizing renewable electricity generation using crops as the main substrate. However, there is currently a shift towards adopting the Nordic model across countries, reflecting changes in energy production approaches.

### *2.1.1. Feedstock sources and characteristics*

A new goal for the European Union is to increase biomethane production to 35 bcm by 2030 (IEA, 2022). To achieve this target, national strategies should prioritize sustainable pathways, focusing on waste-based production from various sources such as agricultural and forest waste, food industry waste, and domestic organic waste among others (European Commission, 2022; IPCC, 2022). Aligning with this sustainability goal, Sweden is contributing to this effort. Sweden produced about 2 TWh of biogas in 2021. However, there is an ambitious proposal aiming to increase production to 15 TWh by 2030, with 12 TWh designated for transportation use and 3 TWh allocated for industrial applications. An initial target of 7 TWh, derived only from waste as the main feedstock is set (Energigas Sverige, 2018). Gustafsson and Anderberg (2022) suggested three scenarios aimed to analyze alternative approaches to reach the 7 TWh biogas goal. Their suggestions imply that achieving the goal would require digester volumes up to five times larger and up to 12 times more AD plants, resulting in a six to eight-fold increase in biofertilizer production. This could be realized through a combination of full-scale centralized biogas systems, primarily co-digestion plants known for their higher efficiency in biogas production, and decentralized production systems that effectively utilize agricultural feedstock distributed across the country while improving the utilization of digestate as biofertilizer. Decentralized production of energy has the potential to contribute to the development of rural areas and strengthen small and medium-sized enterprises (FNR, 2012). When predominantly utilizing municipal solid waste and agricultural waste, SS-AD configurations could play a crucial role as a more suitable technology (Ellacuriaga et al., 2021; Ge et al., 2016).

Moreover, sustainable feedstock availability for biogas production is projected to increase by 40% by the year 2040 (IEA, 2020). The main type of feedstock according to EBA's projections is in the first place sequential crops, followed by agricultural residues, manure, and food waste (EBA, 2022). While sequential cropping proves to be an effective soil management strategy by cultivating intermediate crops between two harvests, promoting soil fertility, carbon preservation, and erosion prevention without competing for agricultural land with food or feed crops (IEA, 2020), lignocellulosic material, which predominantly consists of cellulose (35-50%), hemicellulose (20-35%), and lignin (10-25%) (Sawatdeenarunat et al., 2015), presents its own challenges. Lignin, a significant component within lignocellulosic material, forms a natural barrier that contributes to the development of a highly resistant and recalcitrant biomass structure through intricate interactions among these three primary constituents (Philbrook et al., 2013). This structural complexity of lignocellulosic material has a direct impact on the production of biogas, as the quantity of biodegradable organic substances in the feedstocks, including fats, proteins, and carbohydrates, is intrinsically linked to its composition. Within these organic substances, extracted fractions of carbohydrates, proteins, and lipids represent the soluble components. Lipids are particularly attractive due to their high theoretical methane potential, yet excessive lipid content can impede microorganism activity (Ponsá et al., 2011). In contrast, proteins exhibit higher hydrolysis rates, leading to accelerated methane production, although an abundance of proteins can result in nitrogen excess (Neves et al., 2008). In Sweden, one type of feedstock that has gained attention is horse manure, primarily because of its abundance and specific nutrient characteristics (Mönch-Tegeder et al., 2014; Svenska Ridsport Förbundet, 2016; Wartell et al., 2012). For example, Eriksson et al. (2016b) compared different treatment technologies for horse manure and found that anaerobic digestion performs better in terms of global warming potential.

A couple of essential macronutrients for microorganisms are carbon (C) and nitrogen (N). Ensuring an ideal C:N ratio is another crucial element that impacts biogas yields. Inadequate ratios can result in problems like the buildup of total ammonia nitrogen (TAN) or the rapid consumption of nitrogen by methanogens, ultimately leading to reduced gas production (Li et al., 2011; Zeshan et al., 2012). The optimal C:N ratio typically falls within the range of 20 to 35, with 25 commonly employed (Mao et al., 2015). Co-digestion, the process of digesting various feedstock types in the same digester chamber, is a strategy that can be used to adjust the C:N ratio at an optimum level (Bao et al., 2023). Additionally, the selected feedstock should then be biodegradable, with a low proportion of lignocellulosic material, and maintain a balance in macro- and micronutrients (Kothari et al., 2014). SS-AD addresses challenges encountered in L-AD, including issues related to floating and stratification of fibers, making it particularly suitable for handling high solids biomass. Other advantages are the reduced energy requirements for heating and minimal digestate production (Brown et al., 2012). However, there can also be disadvantages to using feedstock with a high solid content, leading to a lower methane yield. One contributing factor is the restricted diffusion pathways, which can cause sugar accumulation and hinder substrate hydrolysis (Cui et al., 2011). Additionally, decreased mass transfer reduces substrate accessibility to microbes. Moreover, a reduction in microbial hydrolysis rate can occur within a range of 10% to 25% TS, and physical limitations related to liquid/gas mass transfer can arise at 30% TS (Abbassi-Guendouz et al., 2012).

### *2.1.2. Capacity and digestion configuration*

Laboratory and small-scale processes are commonly used to investigate the methane potential of specific feedstocks, providing greater flexibility in implementing pre-treatments (Angelidaki et al., 2009; Guendouz et al., 2010). These pretreatments offer better control over the levels of non-degradable compounds like lignin and facilitate the breakdown of cellulose and hemicellulose to extract soluble sugars, potentially enhancing methane yield. One common example of such scale processes is the biomethane potential (BMP) test. BMP tests are employed to assess the biodegradability of specific feedstocks, their potential for methane production (Angelidaki et al., 2009), and the influence of complex organic components in the feedstock, such as lignocellulosic materials. To conduct these tests accurately, precise control over various operational parameters is necessary. These parameters can include the inoculum/substrate ratio, temperature, quantity of lignocellulosic materials, HRT, and others (Angelidaki et al., 2009; Lesteur et al., 2010). Large-scale plants, on the other hand, can range in volume from hundreds to thousands of cubic meters, treating a variety of feedstocks usually in co-digestion settings (Energigas Sverige, 2023; Kumaran et al., 2016; Schimpf et al., 2013). Positioned between small- and full-scale biogas plants, pilot-scale are commonly used to evaluate the behavior of possible feedstocks and to assess their feasibility for upscaling to larger volumes (Rathnasiri, 2016). Achieving similar outcomes in full-scale processes as in the small-scale can be challenging due to limitations in specialized equipment, and the additional energy required for pre-treatments (Kothari et al., 2014).

In addition to this, full-scale SS-AD processes can have various reactor configurations, primarily as single-stage and "garage" type reactors, as well as plug flow reactor types (PFR) (Illmer & Gstraunthaler, 2009; Li et al., 2018). On the other hand, for L-AD, the commonly used configuration is the continuous stirred tank reactor (CSTR) type (Bolzonella et al., 2003). Both SS-AD and L-AD processes can operate under mesophilic conditions (around 35°C) or thermophilic conditions (around 55°C). The main difference between the PFR and CSTR models is that the latter maintains a constant concentration throughout the reactor due to complete mixing, while the PFR has radial mixing that results in the concentration being dependent on its position within the reactor (Levenspiel, 1999). During reactor design, both mass conservation and reaction rate principles should be applied. More specifically, when analyzing a system under SS-AD conditions, the effective volume of the reactor is affected by the mass removed as biogas (Jewell et al., 1993). In that regard, the reactor design equation should consider the removal or loss of biogas using the fermentation stoichiometry equation that represents the water hydrolytically consumed during biogas production.

Other operational parameters are important when evaluating the performance of a biogas system. One such parameter is the OLR, which quantifies the amount of volatile solids (VS), representing the organic substances, introduced into a digester over a given period in continuous feeding. Typically, an increase in OLR is indicative of higher methane production potential. However, incorporating a significant amount of daily fresh feedstock can bring about alterations within the digester, potentially causing temporary inhibition in the initial fermentation stages (Mao et al., 2015). Another critical factor is HRT, which represents the average duration of feedstock residence in the reactor. HRT is significant because it determines the average time available for the digestion process (Kumaran et al., 2016). Moreover, evaluation of performance of SS-AD and energy efficiency when operating at thermophilic conditions is important due to the energy input required to keep the operation temperatures inside the digester (Ge et al., 2016).

### *2.1.3. Renewable energy generation*

Biogas can be efficiently utilized for electricity and heat generation by combusting it in engines or turbines, or through supply to fuel cells. Moreover, with an upgrading method, it can serve as vehicle fuel, providing an alternative to fossil fuels for transportation needs (Leonzio, 2016; Vo et al., 2018).

#### *2.1.3.1. Electricity and heat production*

Internal combustion engines (ICEs) are usually used in CHP systems (Sun et al., 2015), and their electrical efficiencies are determined through the combustion of a hydrocarbon (fuel) (Carrette et al., 2000). Moreover, the heat generated as a byproduct in this process can be harnessed and employed for heating needs. In more sophisticated setups, this surplus heat can be employed to produce steam for various uses such as industrial processes or district heating systems. Different sizes of biogas plants with installed capacities of 29 to 2,425 $kW_{el}$ showed different electricity efficiencies ranging from 30.7 to 40.6% respectively, assuming that the electrical efficiency increases with the size of the plant (Walla & Schneeberger, 2008). In another work, the calculated net efficiencies for electricity and heat of a biogas plant producing 636 $Nm^3_{biogas}$/day were 20.4% and 12.5% respectively, with a total efficiency of 30.4% (Wu et al., 2016).

Fuel cells offer a distinct advantage over traditional combustion processes, as they directly convert the chemical energy of a fuel into electrical and heat energy without emitting pollutants into the atmosphere (Behling, 2013; Gandiglio et al., 2020). The advantages of high-temperature fuel cells enable internal hydrogen conversion, with methane reforming occurring at temperatures around 600-700 °C (Behling, 2013; Chiodo et al., 2015; Gandiglio et al., 2020; Siefert & Litster, 2014). SOFCs for example, have the capability of on-site methane reforming due to their higher operational temperature, 600-800 °C and 650-1,000 °C respectively (Behling, 2013; Carrette et al., 2000; Sun et al., 2015). For SOFC, it is important to maintain the $CO_2$ concentration as low as possible since it could act as a dilutant (Sun et al., 2015). Disadvantages of high-temperature fuel cells include challenges controlling gas and heat flows across the fuel stack, long start-up times, and high material costs (Budzianowski, 2016; Mehr et al., 2021; Siefert & Litster, 2014). SOCFs present electrical efficiencies ranging from 40% to 65% with total efficiencies of 70% to 90% when including the recovered heat (Mehr et al., 2021). In a previous study, the maximum useful energy generated by various biogas-to-electricity technologies operating at a 1 $MW_{el}$ biogas production scale was investigated. The study reported efficiency yields of 19% for micro gas turbines, 26% for ICE, and 58% for SOFC (Siefert & Litster, 2014).

#### *2.1.3.2. Biomethane*

There is a growing trend in bio-sourced gas production plants focusing on the production of biomethane instead of biogas. Biomethane is viewed as a versatile energy carrier suitable for various sectors, including transport, industry, power, and heating (Bioenergy Europe, 2022). Upgrading biogas to enhance its methane content, usually called biomethane, can be done using several methods, including water scrubbing, pressure swing adsorption (PSA), membrane separation, and chemical absorption, among others. The selection of the appropriate upgrading technology depends on the quality of the biogas and the desired methane content. Chemical absorption with amine as a solvent has been widely used since it has high $CO_2$ selectivity and low methane losses (Bauer et al., 2013; Sánchez Bas et al., 2022; Sun et al., 2015). The process operates at atmospheric pressure, and its efficiency can reach up to 98% in terms of $CO_2$ recovery. The regeneration of the absorbent incurs heat consumption of around 0.55 kWh/Nm$^3$ which could account for up to 30% of the total energy consumption, with electricity consumption of about 0.14 kWh/m$^3$ (Bauer et al., 2013; Garcia et al., 2022). Currently, biomethane can be used as vehicle fuel following the obligation specified in Article 25 of the Renewable Energy Directive (RED) (European Commission, 2022). The purity of the biomethane for use in vehicles should be approximately 97% methane and cleaned from other contaminants such as siloxanes and sulphur (f3, 2016; Swedish Standards Institute, 2017). After upgrading, biomethane can be transported in the form of compressed biogas (CBG) or liquified biogas (LBG). CBG is compressed to 200 bar with an associated energy consumption ranging from around 0.02-0.03 kWh per MJ of biomethane, and about 0.03-0.04 kWh for LBG (Dahlgren, 2022; Gustafsson et al., 2020). Nevertheless, it is important to note that biogas may not be a feasible transport fuel option in all regions, especially where substrate availability is limited (Lundmark et al., 2021).

As an example, Wu et al. (2016) stated that biomethane exhibits higher energy efficiency compared to the system using CHP and SOFC pathways. This difference arises because biomethane is directly obtained from the upgrading process, while the biogas utilization system with CHP and SOFC pathways generates electricity and heat as output energy carriers through secondary conversion, which is discounted compared to the biomethane fuel. Furthermore, the biogas CHP and SOFC pathways consume some of the output energy to fulfill the system's energy requirements. Nevertheless, the total plant efficiency of the system utilizing the SOFC pathway exceeds that of the CHP pathway by 2.5%.

#### *2.1.4. Biofertilizer production*

The digestion process also produces a nutrient-rich product suitable for use as a biofertilizer. In Sweden, almost all digestate is utilized in agricultural land, reducing the need for conventional fertilizers and imported phosphorus (P) (Energimyndigheten, 2021). The main application for digestate is its direct use as biofertilizer, however, the amounts typically produced in biogas systems are usually larger than the required land area (Farghali et al., 2022). In that sense, separation into solid and liquid fractions is commonly used to reduce the volume, storage, and costs of transportation (IEA Bioenergy, 2012). Regarding the digestate analysis, the Swedish regulation (SPCR120) regarding the use of digestate as organic fertilizer considers certain limits. These limits are set at 22 kg of P/ha/y, calculated as a five-year average, and 150 kg $NH_3/NH_4^+$-/ha/y (with a maximum of 170 kg $NH_3/NH_4^+$-/ha/y depending on soil type) (Avfall Sverige, 2007). According to the SPCR120 regulation, when applying digestate as fertilizer, it is important to adhere to specific values for heavy metals.

#### *2.1.4.2. Liquid digestate*

The liquid fraction of digestate is characterized by its high content of total nitrogen (TN), typically in the range of 65-75%, ammonium nitrogen ($NH_4$-N), which can be as high as 70-80%, and potassium (K), also ranging from 70-80%, 70-80% (Akhiar et al., 2017; IEA Bioenergy, 2015). This liquid biofertilizer offers a viable alternative to conventional fertilizers for supporting fruit and vegetable growth. However, elevated ammonium levels can be harmful to plants, especially highly sensitive crops like tomatoes, when concentrations exceed approximately 10% of the total nitrogen (Stoknes et al., 2016). Consequently, various studies have emphasized the need for a nitrification process when applying digestate (Pelayo Lind et al., 2021; Sonneveld & Voogt, 2009). For instance, Bergstrand et al. (2020) stated that the use of liquid digestate as a biofertilizer for the cultivation of vegetables, pak choi, in hydroponic greenhouses could be feasible after post-processing such as the nitrification of the digestate. Interestingly, the ammonium content can be advantageous for fostering microalgal growth, representing a valuable resource for the production of biochemicals and biofuels (Xia & Murphy, 2016).

#### *2.1.4.1. Solid digestate*

In addition to climate change, soil degradation stands as one of the most pressing environmental problems we currently face (Matuštík et al., 2020). In that sense, soil amendments can be used to improve soil quality with respect to both its structural composition and biochemical functioning (Maiti & Ahirwal, 2019). Among these, organic soil amendments are those derived from the decomposition of biomass such as manure or digestate. The valuable nutrients present in the solid fraction of digestate make it a good option for soil amendment. These organic amendments are rich in organic matter as well as microelements (Ca, Fe, and Zn) and macroelements (C, N, P, and K), which can increase soil fertility and promote microbial growth (Maiti & Ahirwal, 2019; Palansooriya et al., 2023; Stanturf et al., 2021). Particularly, the solid fraction of the digestate is primarily characterized by significant quantities of organic matter as volatile solids (VS), 55-65%, P, 55-65%, and carbon (C) (IEA Bioenergy, 2015). Consequently, solid-liquid separation represents a viable option in situations where the application of phosphorus to nearby farmland is limited, allowing for the transportation of the solid phase to regions facing a phosphorus deficiency (Feiz et al., 2022). Regarding the analysis of solids, in the evaluation presented by Akhiar et al. (2017), it was found that the solid fraction of digestate has the highest variability in comparison with the other fraction in terms of VS/TS ratio, i.e., 37% to 77%, the figure of 37% being related to feedstocks with high biodegradability such as fruits and vegetables. And, for specific PFR conditions, a ratio, VS/TS, was found between 51% to 78%, mainly corresponding to agricultural feedstocks and municipal solid waste.

To convert solid digestate into a suitable soil amendment, techniques like composting can be used, or alternative post-treatment methods that ensure maturity and a reduction in phytotoxicity (Lu & Xu, 2021; Marcato et al., 2009). An alternative option for utilizing solid digestate involves its processing into pellets. These pellets can replace conventional fertilizers, offering the advantage of reducing emissions during the spreading phase as compared to not having any post-treatment to the digestate (Eriksson et al., 2016a). Producing pellets offers additional advantages such as diminishing volume and generating a marketable product, similar as for soil amendment. However, a drawback lies in the energy demand for the drying and pelletization process, which can be as high as approximately 60 kWh per tonne of digestate (Bisaillon et al., 2010).

## 2.2. Synergies with biogas systems

The concept of biogas systems has been discussed by various authors, each presenting different approaches. For instance, Feiz et al. (2020) have outlined a comprehensive framework for defining system boundaries within the context of biogas production systems. This framework consists of several distinct levels, each addressing specific aspects of the system. At the core is the biogas plant level, which encompasses all activities related to digestion, gas treatment, and digestate handling. Expanding on this, the extended biogas plant level includes factors in the transportation to and from the biogas plant, considering the broader logistics involved. Moving upstream and downstream, the biogas production system level encompasses processes linked to the utilization of biogas products. Lastly, the biogas production system plus substitution effects level introduces a system expansion, incorporating considerations such as the substitution of biomethane and digestate for mineral fertilizers and fossil fuels. This framework offers a comprehensive approach to defining the scope and boundaries of biogas systems, facilitating a thorough assessment of their environmental and operational aspects. Olsson and Fallde (2015) argue that the biogas system is dynamic, with no well-defined boundaries. Instead, it is driven by the need to address specific issues, such as WM services, a solution to air pollution through the use of biogas, or to address energy crises, among others, making biogas systems a complex system to study, involving various actors. Incorporating the concept of the circular economy into the perspective of biogas systems suggests that biogas offers much more than just a renewable fuel. This perspective proposes several additional product benefits, including the production of biofertilizers, the establishment of local circular economic cycles, and enhanced energy security. Due to these advantages, the concept of biogas solutions is sometimes utilized (Hagman & Eklund, 2016; Ottosson et al., 2020).

Biogas systems can provide additional resources for food production systems beyond digestate. For instance, the raw biogas can be introduced into a CHP system to produce both electricity and heat. Additionally, the $CO_2$ stream, separated from the biogas, can be utilized to improve the growth of plants. In that sense, biogas systems can be designed to capture and utilize biogenic $CO_2$

from the biogas upgrading that can be used in various industrial applications(Cordova et al., 2022). Some authors have named this process as the pre-combustion pathway for the enhancement of biogas (Garcia et al., 2022). The capture and utilization of $CO_2$ derived from biogas production hold substantial environmental advantages, potentially transforming it into a negative emissions technology. Through the capture of $CO_2$ that would otherwise be released into the atmosphere, carbon capture and utilization (CCU) has the potential to decrease overall GHG emissions associated with the production of biomethane (Varling et al., 2023). The potential applications for CCU are wide and include the production of bio-based chemicals, materials, and fuels (IEA, 2019). In the same context, carbonation of ashes from incineration could be an option for both capturing $CO_2$ and valorizing the ashes for the possibility of creating a new product (Nam et al., 2012; Rendek et al., 2006; Schnabel et al., 2021).

As previously stated, biogas and food production systems, by their nature, can create interconnections between their main products (Kervroëdan et al., 2022; Mirata et al., 2017). The waste generated in the food industry such as greenhouses can vary in composition, but focusing on processing leaves and branches as feedstock for an SS-AD plant can be advantageous (Li et al., 2018, 2016; Maaoui et al., 2020; Stoknes et al., 2016). This waste typically exhibits fibrous characteristics, is relatively dry, and has the potential to provide structural support within the digester's waste matrix. For instance, Li et al. (2016) analyzed the co-digestion of tomato residues with dairy manure and corn stover, resulting in an increase in the methane yield of 415 $L/kg_{VS}$, while inhibition occurred when adding more than 40% of tomato residues in the input mixture. Other system analyses of biogas systems with some form of integration with their products and other areas/industries have been evaluated. For example, Lindkvist et al. (2019) explored five food industry cases under distinct scenarios, encompassing by-product use, anaerobic digestion, and heat and power generation. Varling et al. (2023) performed an LCA for biogas systems, encompassing biogas combustion, the process of upgrading to natural gas quality, CCUS, direct utilization of CO2, and methanation.

## 2.3. Environmental systems analysis

Environmental systems analysis employs a systems approach to describe and assess the environmental impacts of various activities. In this context, a system comprises two or more interacting components within a shared domain working toward a common goal or function (Björklund, 2000). Systems are not isolated but linked to others through inputs and outputs (Boyd, 2001), making the behavior of one component affect others within the entire system. Additionally, systems analysis is usually performed as a sequential activity by integrating various levels of analysis of different sub-systems. LCA is a methodology for assessing the possible environmental effects of a product over its entire life cycle (ISO, 2006), which consists of four primary stages: definition of goal and scope, inventory analysis, impact assessment, and interpretation (Azapagic, 2018; ISO, 2006). As part of the inventory analysis, life cycle inventory (LCI) is a list of all different inputs and outputs from the processes studied. The results of the LCI are a comprehensive aggregation of the resources consumed (inputs) and emissions generated (outputs) by the product throughout its entire life cycle, relative to the defined functional unit (FU) (Finnveden et al., 2009). As stated by Clavreul et al. (2012), decisions regarding attributional and consequential LCA approaches and the inclusion of specific impact categories, are considered methodological choices rather than uncertainties. On the other hand, MFA is a method used to analyze and quantify the flow of materials through systems. In a more specific definition, MFA is a systematic assessment of flows and stocks of different materials through a certain period in a certain region, where materials can be defined as chemical elements, compounds, products, etc. (Azapagic, 2018).

As biogas systems are integrated into diverse contexts, challenges related to feedstock quality, the correct management of digestion operation parameters, and overall profitability can commonly appear (Ammenberg & Feiz, 2017). In this context, adopting a systems analysis approach which studies the interconnections between different components or areas, proves advantageous (Boyd, 2001; Kondusamy et al., 2021). Moreover, utilizing analytical modeling and simulation tools offers numerous benefits when evaluating the environmental performance of integrated solid WM technologies from a systems analysis perspective. These tools not only save valuable time and resources by reducing the need for extensive real-world testing but also simplify the evaluation process, thereby minimizing costs associated with implementing and testing various strategies (Shiflet & Shiflet, 2014).

Several specific environmental systems analysis tools have been developed to analyze waste management systems. These tools include EASETECH (Environmental Assessment of Solid Waste Systems and Technologies) (Clavreul et al., 2014; Kirkeby et al., 2006), ORWARE (ORganic WAste REsearch) (Dalemo et al., 1997; Eriksson et al., 2002), IFEU (UMBERTO) (Gómez & Amelung, 2004), WRATE (Waste and Resources Assessment Tools for the Environment) (Gentil, 2006), IWM2 (Integrated Waste Management) (McDougall et al., 2001), WISARD (Waste Integrated Systems Assessment for Recovery and Disposal) (Kirkeby et al., 2006), LCA-IWM (The Use of Life Cycle Assessment Tool for the Development of Integrated Waste Management Strategies for Cities and Regions with Rapid Growing Economies) (den Boer et al., 2007), EPIC/CSR (Environment and Plastics Industry Council, Corporations Supporting Recycling) (McDougall et al., 2001) and MSW-DST (Integrated Solid Waste Management-Decision Support Tool) (Thorneloe et al., 2007; Weitz et al., 1999), most of which are extensively documented in literature. These models are capable of handling various waste fractions simultaneously, enabling the modeling of complete systems. One of the main advantages of using ORWARE lies in its flexibility to modify sub-models and process units, as well as the option for changing the mathematical model equations governing the material and mass flow at a process level, making the model adaptable to different scenarios. ORWARE also allows the study of different pre-treatments to enhance specific waste treatment methods (Carlsson et al., 2015). Moreover, prospective studies and the integration of waste treatment into other systems, such as district heating energy systems, have also been realized (Eriksson et al., 2014). Other WM systems analysis using ORWARE are described in the following references: Assefa et al. (2005b); Baky & Eriksson (2003); Björklund et al. (1999a), (1999b); Dalemo et al. (1998); Eriksson et al. (2016a), (2016b), (2005); Eriksson & Baky (2010); Hadin et al. (2017); Hansen et al. (2006).

In assessment studies, results are inevitably affected by uncertainties originating from factors such as data variability, measurement errors, inaccurate estimations, missing or unrepresentative data, and modeling assumptions (Gentil et al., 2010). Huijbregts (1998) categorized LCA uncertainties into parameter uncertainties (arising from inherent variability, measurement imprecision, or data limitations), scenario uncertainties (resulting from choices made when constructing scenarios), and model uncertainties (related to the mathematical equations employed in LCA calculations). Epistemic uncertainty is linked to limitations in data collection, measurement, and modeling due to gaps in knowledge and understanding, potentially introducing bias or imprecision into the analysis (Clavreul et al., 2012). This often necessitates improved measurement techniques and a deeper comprehension of the system under investigation. Sensitivity analysis is a common modeling approach used to gauge how alterations in input variables influence model outcomes, while scenario analysis systematically modifies assumptions to assess their impact (Björklund, 2000; Clavreul et al., 2012). In contrast, stochastic uncertainty arises from the intrinsic variability of natural systems or processes, characterized by randomness or probabilistic behavior. Statistical analyses are employed to quantify and comprehend the extent of variability within the studied system.

# 3. Materials and methods

This thesis utilized a systems-oriented approach to investigate the potential for biogas and digestate production in a specific system. The analysis involved multiple levels of examination, focusing on material and energy flows and their environmental impacts. To achieve a thorough understanding of the process, various methods were utilized, including MFA, substance flow analysis (SFA), and LCA. The ORWARE model, which is a model to evaluate different WM technologies, served as the primary tool in papers II, III, IV, and V. To gain insight into the key factors and parameters required for optimizing the system, a literature review was conducted due to the limited availability of scientific information on the specific technology of AD process under solid-state conditions at that time (Zhang et al., 2016). Paper I is then a literature review focusing on the methane yield at various SS-AD scales, using a content analysis approach. Furthermore, a literature analysis was done for the purpose of obtaining input data for the different methodologies such as the MFA and LCA performed in the appended papers. Also, relevant documentation and statistics from various institutions were consulted whenever applicable.

To collect additional data for modeling, simulation, and result analysis, a variety of communication approaches were utilized. These methods included conducting personal interviews, engaging in direct one-on-one discussions, participating in meetings, and exchanging emails with the biogas plant staff members and executives. The main purpose of these interactions was to gather operational data and other relevant input, while also gaining valuable insights into the company's production methods and practices. Additionally, efforts were made to establish contact with farmers who utilize the biogas plant's biofertilizer to understand their specific application procedures for crops. Moreover, insights into greenhouse operating conditions were shared with other companies in the same field.

## 3.1. Content analysis

Paper I corresponds to a literature review that aims to consolidate existing research on SS-AD processes at different operational scales: small/laboratory, pilot, and full-scale. The main focus was to systematically assess what factors influence the methane yield at the mentioned scales and what possible strategies there are to improve it. The content analysis method was then chosen to be the primary approach for the literature assessment. This is a mixed method that aims to classify patterns, themes, and key concepts, and to identify the conceptual content of a particular topic of analysis, in addition to contributing to the development of new insights in the field (Seuring & Müller, 2008).

The content analysis methodology includes material collection, descriptive analysis, category selection, and material evaluation (Philipp, 2014), see Figure 2. In gathering materials, only academic sources including books and peer-reviewed articles published in scientifically indexed journals from databases and search engines like Scopus, ScienceDirect, and Google Scholar were examined. The selection of categories was guided by keyword searches focused on dry-AD and SS-AD processes, feedstock type, process scale, methane yield, factors influencing methane yield, and enhancements or improvements. After reviewing the collected material, 37 articles were chosen under the aforementioned criteria, as shown in Table 2.

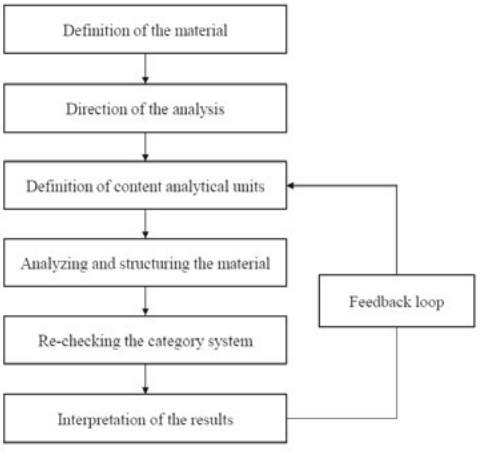



Figure 2. General content analysis procedural method, adapted from Philipp (2014).

Table 2. Sampled articles (x37) for SS-AD configurations.

| **Scale** | **Article number (n)** | **n/37** |
|---|---|---|
| Small-scale (0.17-50 L) | 19 | 51.3% |
| Pilot-scale (0.69-53 $m^3$) | 7 | 18.9% |
| Full-scale (735-2,200 $m^3$) | 11 | 29.7% |

Information was restructured for the sake of comparison, such as the conversion of units. It also included the distinctive properties of the feedstocks, such as TS and VS, as well as key components like carbohydrates, proteins, and lipids.

The quantitative part of the analysis of the data was done with the open-source BoxPlotR. The box plot served as a graphical representation of the numeric information, in this case, data about methane yield, HRT, temperature, and OLR, between the different scales. This method was selected as it is robust in the presence of skewness and outliers. In this case, it contains information about the median and interquartile range. Therefore, it is a good method to use since data of methane yield, for example, depends on different parameters, making it a data set with extreme values, sometimes being difficult to compare among processes, e.g., different feedstock's origins, scales, operational temperature, etc. The box limits were indicated with the 25th and 75th percentile, and whiskers extended 1.5 times (Nuzzo, 2016).

## 3.2. Systems studied and assumptions

The base case study corresponds to a full-scale AD plant located in Forsbacka, Sweden, and owned by Gästrike Ekogas AB. The general process diagram can be seen in Figure 3, starting from the pre-treatment of the feedstock to the processing of the digestate and biogas. Collection and transportation of waste from the source to the AD plant were excluded from the analysis. This plant works under SS-AD conditions with a variety of feedstocks like biowaste, BW, (mainly food waste), green waste, GW (mainly grass, leaves, small branches, etc.), food slurry, and grease waste, FS/GS, and horse manure. The main design characteristics of the process are presented in Table 3.

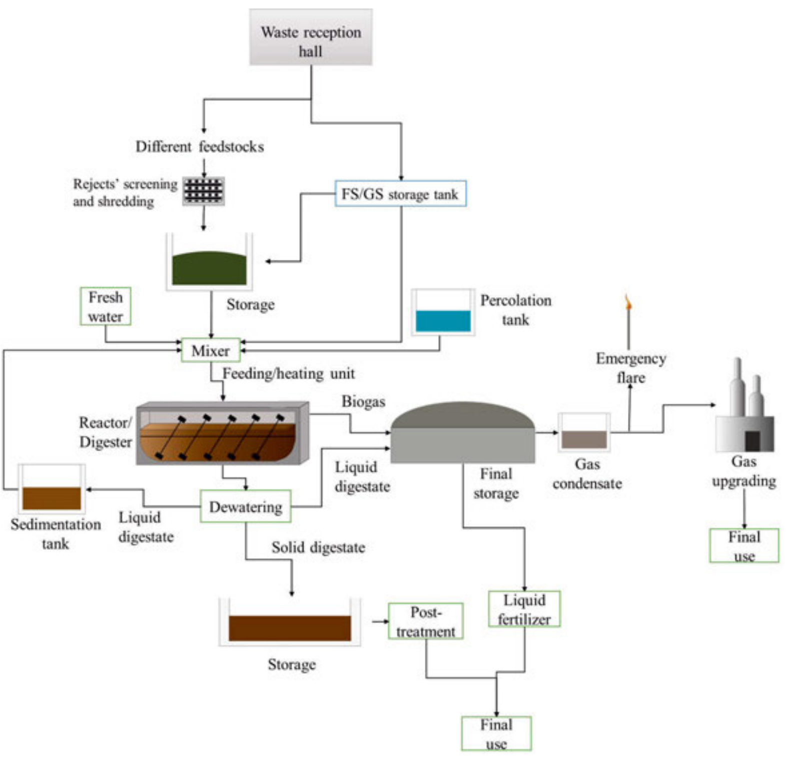



Figure 3. Process diagram of the full-scale SS-AD plant at Forsbacka, Gävle, Sweden.

Table 3. Design parameters of the studied SS-AD plant (Thöni, 2016).

| Parameter | Amount/Description |
|---|---|
| Waste treatment capacity (tonne/year) | 25,000 |
| Digester volume ($m^3$) | 2,250 |
| Retention time (days) | 36 |
| Operational temperature (°C) | 55 |
| Total solids (%) | 27 |
| Raw gas ($m^3$/year) | 4,400,000 |
| Liquid digestate (tonne/year) | 13,500 |
| Solid digestate (tonne/year) | 3,500 |

At the time that this research started, the biogas plant had not yet worked at its full capacity, therefore, the type of feedstock and quantities varied from paper to paper as shown in Table 4.

Table 4. Feedstocks analyzed in different papers.

| Feedstock in tonnes per year* | Paper II | Paper III | Paper IV | Paper V |
|---|---|---|---|---|
| Biowaste | 11,341 | 11,341 | 15,000 | 18,483 |
| Green waste | 2,835 | 2,835 | 2,200 | 2,500 |
| Food slurry/Grease sludge | 632 | 632 | 200 | 243 |
| Structural material** | - | - | 2,300 | - |
| Horse manure | - | - | 670 | 1,096 |
| Wood chips as bedding | - | - | 330 | 540 |
| Slaughterhouse waste | - | - | 50 | 25 |
| **Total waste** | **14,808** | **14,808** | **20,750** | **22,887** |

*The amounts of feedstock represent only the base-case scenario for each paper.
**Structural material is waste that could not be degraded and used as a recycled waste input for the digestion process.

The amount of feedstock was adapted for each paper during the research time. Moreover, in paper II, the proportions of BW and GW were changed from 100-0% to 0-100%, the temperatures between 45 °C and 70 °C, and changes in HRT from between 10 to 60 days. These variations were performed as part of a sensitivity analysis. In papers III and IV, different types of feedstocks and their effects on the methane yield were studied. In paper III, different quantities of horse manure were incorporated along with their corresponding proportion of bedding material, which accounted for approximately one-third of the total mixture. The study examined two types of bedding, namely wood chips, and straw, see Table 5.

Table 5. Different feedstocks analyzed in scenarios (Sc) in paper III.

| Feedstock (t/year) | Sc A | Sc B | Sc C | Sc D |
|---|---|---|---|---|
| Biowaste | 11,341 | 11,341 | 11,341 | - |
| Green waste | 2,835 | - | - | - |
| FS/GS | 632 | 632 | 632 | 632 |
| Horse manure | - | 2,126 | 2,126 | 10,632 |
| Wood chips | - | 709 | - | 3,544 |
| Straw | - | - | 709 | - |

In paper IV, the addition of waste from a hydroponic greenhouse growing tomatoes was analyzed. The hydroponic greenhouse corresponds to a model based on different assumptions such as a size of 2 ha, tomato yield of 84.4 kg/m$^2$, and an estimated waste generation of about 17 kg/m$^2$, mainly composed of green leaves and small branches. The analyzed systems and their connections are represented in Figure 4.

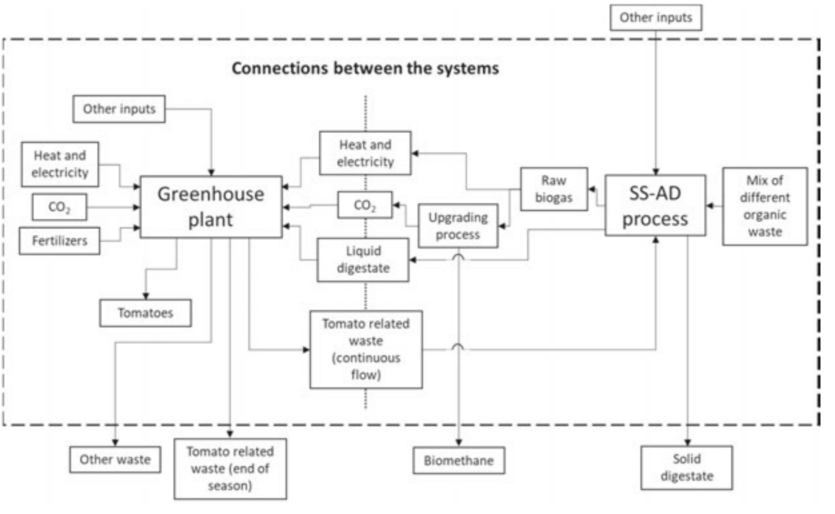



Figure 4. Connections between the anaerobic digestion system and the greenhouse system.

In paper V, the integration of secondary waste technologies such as incineration and landfilling was studied in addition to the AD process. Incineration of contaminants such as plastics in the input feedstock and the solid fraction of the digestate (assumed to contain significant impurities and unsuitable for use as a biofertilizer) were included, see Figure 5. Consequently, landfilling was employed to treat the ashes generated from the incineration facility. Alternative scenarios were developed, including pre-sorting of impurities/plastics, enabling the reuse of the solid fraction of the digestate as a soil amendment or as pellets, Figure 6. Furthermore, different applications of biogas, such as LBG, and the generation of heat and electricity, were explored as illustrated in Figure 7. Cleaning of the biogas is done by a chemical absorption technology, heat is supplied by a gas boiler, and the electricity and heat are produced with a SOFC process and CHP system. For papers IV and V, it was assumed that $CO_2$ can be recovered after the upgrading of the biogas. In paper IV, $CO_2$ is considered to be used for growing enhancer in a greenhouse, while for paper V the captured $CO_2$ was assumed to be utilized in the maturation of ashes produced in the incineration of the rejects of the feedstock (impurities/plastics).

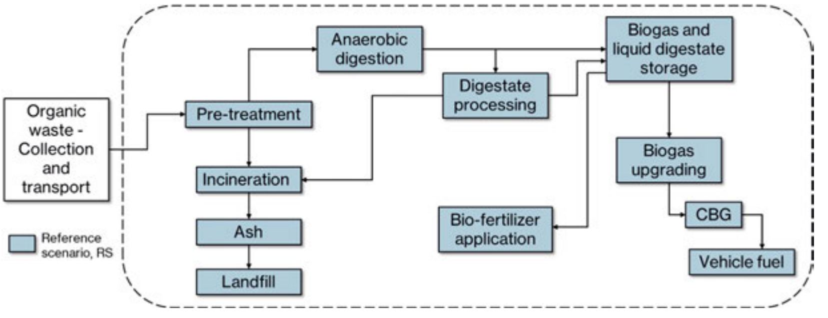



Figure 5. Diagram of Reference Scenario, RS, for paper V.

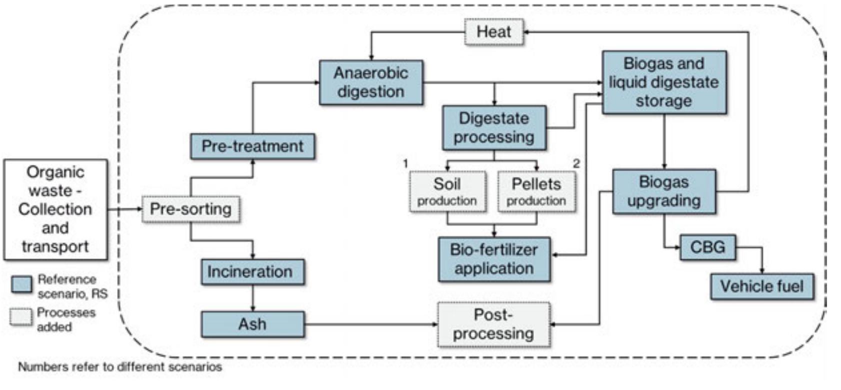



Figure 6. Representation of scenarios 1 and 2, for paper V.

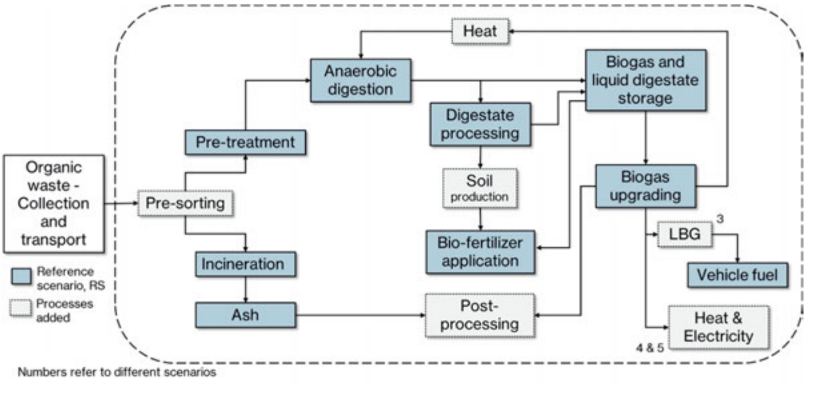



Figure 7. Representation of scenarios 3, 4 and 5, for paper V.

Regarding the composition of the feedstock used in the simulations, Table 6, the low values of heavy metals contributed to the expectations of not exceeding the permissible limits specified in the regulation. These values were provided as averages from the representative component of different feedstock, obtained from the ORWARE dataset.

## 3.3. The ORWARE model

The ORWARE model is a software tool developed in MATLAB and utilizes the Simulink interface to analyze the environmental and economic systems of various WM strategies (Dalemo et al., 1997). It can calculate the energy balance, emissions, and products generated by WM alternatives. The model consists of sub-models that focus on specific WM methods such as incineration with energy recovery, sanitary landfill, composting, and AD. It also includes the transport of the waste and use of compost or biofertilizers (Eriksson et al., 2002). ORWARE considers factors such as nutrient composition, carbon content, water content, as well as TS and VS among others. In this sense, the model employs a dataset of 74 substances that describes all composition flows in the system. By utilizing this dataset as input, the sub-models can calculate the turnover of materials, energy, and financial resources. The sub-models and material flows, represented as arrows, can be seen in Figure 8. ORWARE utilizes substance flow analysis (SFA), MFA, and LCA as the main methodologies for environmental impacts and material resources analysis. The WM system of Stockholm and Uppsala served as references for the construction of the original sub-models. However, these sub-models are designed to be adaptable and can be modified to suit any chosen WM system, whether it currently exists or as a hypothetical system. In practice, the sub-models are not limited to specific scenarios and offer flexibility in their application to different WM contexts (Eriksson et al., 2002).

In ORWARE, different subcategories are defined in order to simplify the analysis of various WM. Waste collection, transport, incineration, landfill, composting, and AD among others, represent the core system. The resources to the core system are represented as the upstream process, while the waste-derived products are part of the downstream process (Assefa et al., 2005a). The comparison between scenarios/WM alternatives should be the same, however, depending on the design of the scenarios, output-related functional units may be included. To maintain consistency in functional units across all scenarios, it becomes necessary to expand the system to incorporate the compensatory system. Representation of the WM systems together with the different processes adapted to this thesis is illustrated in Figure 9.

Table 6. Chemical characteristics of the main feedstocks used in the papers.

| **Component (kg/kgTS)** | **Biowaste** | **Green waste** | **FS/GS** | **Horse manure** | **Wood chips** | **Straw** | **Slaughterhouse waste** |
|---|---|---|---|---|---|---|---|
| Total solids ratio, TS | 2.7E-01 | 4.2E-01 | 3.6E-02 | 2.4E-01 | 8.4E-01 | 8.8E-01 | 4E-01 |
| Volatile solids, VS | 8.5E-01 | 8.8E-01 | 9.4E-01 | 8.9E-01 | 9.1E-01 | 8.3E-01 | 7.5E-01 |
| C-lignin | 2.9E-02 | 1.4E-01 | 0.0E+00 | 2.2E-02 | 1.7E-01 | 1.8E-01 | 0.0E+00 |
| C-starch & sugar | 9.7E-02 | 3.5E-02 | 4.3E-02 | 1.1E+00 | 1.0E+00 | 1.2E-01 | 1.0E-03 |
| C-fat | 1.4E-01 | 0.0E+00 | 6.7E-01 | 6.7E-03 | 0.0E+00 | 1.6E-02 | 2.2E-01 |
| C-protein | 6.6E-02 | 1.8E-02 | 0.0E+00 | 1.9E-02 | 0.0E+00 | 3.6E-02 | 2.2E-01 |
| C-cellulose | 1.1E-01 | 2.7E-01 | 0.0E+00 | 2.9E-01 | 3.4E-01 | 1.3E-01 | 0.0E+00 |
| Total Nitrogen, N-tot | 2.3E-02 | 7.0E-03 | 2.5E-02 | 1.5E-02 | 8.0E-03 | 6.0E-03 | 3.3E-02 |
| Ammonium nitrogen, NH3/NH4+-N | 2.6E-03 | 0.0E+00 | 0.0E+00 | 8.1E-04 | 0.0E+00 | 0.0E+00 | 0.0E+00 |
| Phosphorus, P-tot | 3.9E-03 | 1.0E-03 | 3.0E-03 | 1.2E-03 | 2.7E-04 | 8.2E-04 | 1.6E-02 |
| Potassium, K | 9.2E-03 | 5.0E-03 | 2.0E-03 | 1.9E-03 | 2.2E-03 | 2.8E-03 | 7.4E-03 |
| Lead, Pb | 3.8E-06 | 1.3E-05 | 0.0E+00 | 1.1E-06 | 1.8E-05 | 0.0E+00 | 8.4E-06 |
| Cadmium, Cd | 1.4E-07 | 1.6E-07 | 0.0E+00 | 1.0E-07 | 3.4E-07 | 0.0E+00 | 2.6E-07 |
| Mercury, Hg | 2.1E-08 | 4.0E-08 | 0.0E+00 | 1.0E-08 | 2.1E-07 | 0.0E+00 | 6.7E-07 |
| Copper, Cu | 1.6E-05 | 1.6E-05 | 0.0E+00 | 1.4E-05 | 3.4E-05 | 0.0E+00 | 4.9E-05 |
| Chromium, Cr | 7.5E-06 | 1.0E-05 | 0.0E+00 | 4.7E-06 | 3.4E-05 | 7.5E-06 | 1.0E-05 |
| Nickel, Ni | 3.8E-06 | 5.4E-06 | 0.0E+00 | 3.1E-06 | 4.2E-06 | 0.0E+00 | 8.8E-06 |
| Zinc, Zn | 4.5E-05 | 6.7E-05 | 0.0E+00 | 5.5E-05 | 4.4E-04 | 0.0E+00 | 4.1E-04 |

Maximum concentration of heavy metals in digestate according to SPCR120: 1.00E-04 kgPb/kgTS, 1.00E-06 kgCd/kgTS, 1.00E-06 kgHg/kgTS, 6.00E-04 kgCu/kgTS, 1.00E-04 kgCr/kgTS, 5.00E-05 kgNi/kgTS, and 8.00E-04 kgZn/kgTS.

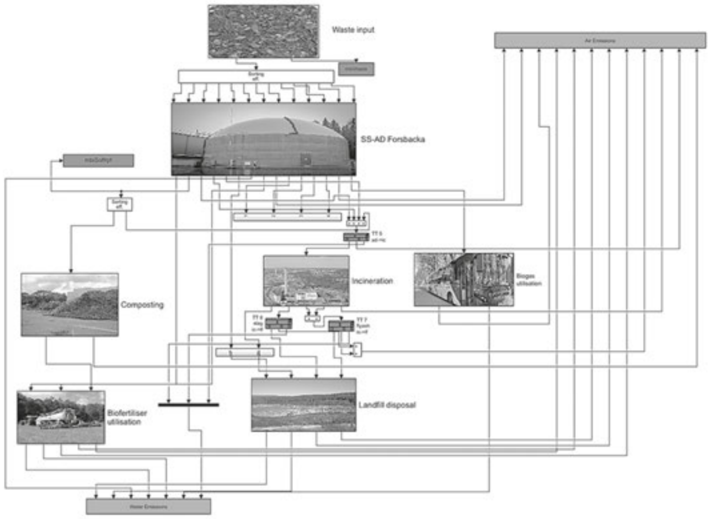



Figure 8. Graphical representation of the ORWARE model in the Simulink interface for this thesis.

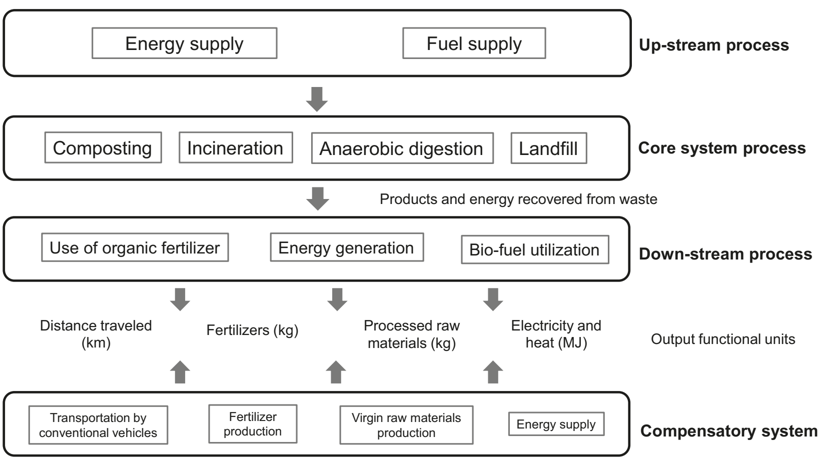



Figure 9. Waste management systems in ORWARE modified for this thesis and adapted from (Assefa et al., 2005a). Note: Waste generation and its collection and transportation were not included in this thesis.

The AD sub-model was initially designed based on the Continuous Stirred Tank Reactor (CSTR) configuration, which is used to model a specific chemical reaction (Dalemo, 1996). However, in order to accurately represent the SS-AD plant being studied, a new reactor design equation for a Plug Flow Reactor (PFR) was necessary. A more detailed description of the utilized parameters can be found in paper II. The newly added PFR design to the AD sub-model was then used as the representative model for the base-case system, SS-AD process, in papers III, IV, and V.

### 3.3.1. Material flow analysis

Similar to the reactor design theory, MFA is based on the principle of mass conservation, meaning that inputs, outputs, losses, and/or stocks must be balanced. On the other hand, SFA is a specific type of MFA that tracks a particular substance of interest. However, occasionally the two terms are used interchangeably (Azapagic, 2018). The objective of flow analysis is to identify any missing or hidden flows within a system, track the origins of environmental issues related to substances and materials across the lithosphere, biosphere, and technosphere, and screen for potential concerns that warrant further investigation using other analytical methods (Björklund, 2000). When examining multiple substances or components within a system, it can be helpful to enhance interpretation by converting flows of various substances into comparable metrics, such as aggregating them into environmental impact categories, a practice commonly employed in LCA. In ORWARE, the material balance for specific substances, e.g., carbon and nutrient content, and pollutants/emissions, are calculated across the entire WM system, usually represented by arrows, see Figure 8. These calculations are based on the type of input dataset provided, e.g., type of treated feedstock/waste, which in turn allows the calculation of energy, environmental impacts, and economics.

### 3.3.2. Life cycle assessment

For this thesis, the LCI database in ORWARE is constituted by different data on peer-reviewed journal articles, technical articles, technical reports, and other databases such as EcoInvent (Assefa et al., 2005a; Dalemo et al., 1997; Eriksson et al., 2002). The global warming potential 100 years (GWP100) was based on the IPCC 2021 characterization method, while the rest of the indicator categories used the midpoint CML-IA baseline V3.08/V3.06 characterization factors.

One of the objectives of LCA is to describe the environmentally significant physical flows to and from a life cycle and its component parts (Ekvall, 2020; Finnveden et al., 2009). In the case of paper IV, this approach was employed to assess the environmental impacts associated with tomato production within distinct contexts, represented by scenarios and sensitivity analysis. SimaPro/EcoInvent served as the designated LCA tool for conducting this study. Another aim of this methodology is to elucidate how environmentally significant physical flows may alter in response to potential decisions (Finnveden et al., 2009). In paper V, the LCA approach was utilized to determine the environmental consequences of various processing methods and end uses for the products of the biogas system. As part of the aim, the identification of critical processes and their relationships was crucial to facilitate potential system improvements.

The functional unit (FU) serves as a standardized reference unit that defines the system under examination, enabling the comparison of the performance of various products or processes. The FU is typically defined in terms of the service provided by the system and is used to normalize the impacts of different systems (ISO, 2006). In this thesis, the total amount of waste, presented in Table 4, was analyzed, but the FU utilized in papers II, III, and V was expressed as 1 tonne of treated waste. Additionally, the output-related functional units for paper V were included as a result of the different analyzed scenarios: compensatory heat and electricity, vehicle fuel, conventional fertilizers, and production of cement. For paper IV, the FU was set to 1 kg of fresh bulk tomato.

# 4. Results

In this chapter, the main findings and outcomes are presented derived from the research aim and methodologies outlined in the previous chapters. To ensure clarity and facilitate a structured understanding of the results, each section within this chapter corresponds to a specific research question.

## 4.1. Methane yield at solid-state conditions: Factors & parameters

Understanding anaerobic digestion with high solid content substrate involves exploring how different factors influence methane yield, RQ1. Feedstock compositions vary significantly, each type having its distinct characteristics. Investigating how different feedstock compositions impact methane yield could give insight into identifying the most promising mixtures. Additionally, methane yield is closely linked to several operational parameters. Therefore, a comprehensive understanding of the interaction between feedstock composition and operational parameters is important for improving the digestion process and enhancing methane production. This part of the results corresponds to the first studied level, SL1 in Figure 1.

### *4.1.1. Production scales and feedstock composition*

As a starting point, it was essential to comprehend how the SS-AD process works under different conditions. In paper I, a review encompassing different processes across different scales was conducted. A total of 37 peer-reviewed articles were selected, spanning from laboratory (small) to full-scale, as shown in Table 2. From these articles, 45 cases were analyzed, indicating that methane yield tends to be higher in small-scale settings compared to pilot and full-scale cases, even with similar types of feedstocks, see Table 7.

Table 7. Feedstock type and maximum methane yield retrieved from the literature review, paper I.

| **Scale** | **Main feedstock type** | **Max. $CH_4$ yield ($m^3/t_{VS}$)** | **Reference** |
|---|---|---|---|
| Small-scale (0.17-50 L) | 55% food waste-45% crops and lignocellulosic waste | 531 (from food waste) | (Qiao et al., 2011) |
| Pilot-scale (0.69-53 $m^3$) | Mainly mixed waste as the OFMSW* | 327 | (Zeshan et al., 2012) |
| Full-scale (735-2,200 $m^3$) | Mainly mixed waste as the OFMSW* | 400 | (Bolzonella et al., 2006) |

*OFMSW: Organic fraction of the municipal solid waste.

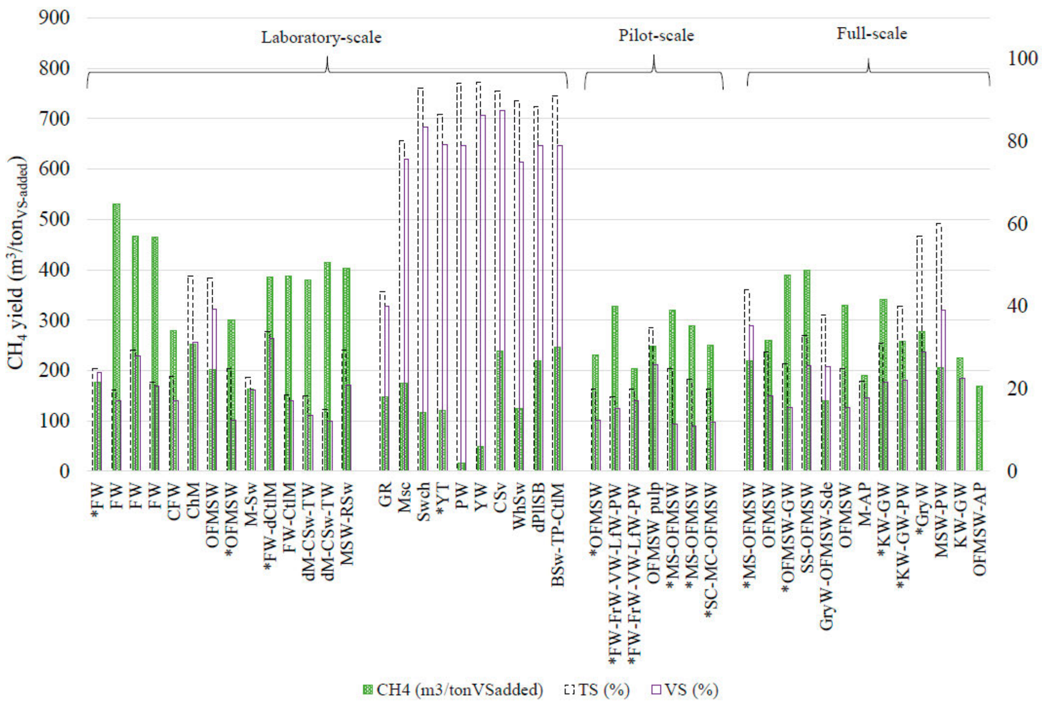
Different feedstock types were analyzed in paper I, indicating that an SS-AD process has the capability to utilize a wide range of them. The main feedstocks include food waste, garden waste, agricultural waste, forest residues, and energy crops. Feedstocks also vary in their biodegradable content, primarily consisting of organic materials like carbohydrates, lignocellulosic substances, proteins, and lipids. Consequently, the methane potential differs based on the quantities of these main components as presented in Table 8.

Table 8. Theoretical methane potential, adapted from Neves et al. (2008).

| Component | Time for 50% methanation (days) | Methane yield ($m^3/t_{VS}$) | Hydrolysis constants (Kh values ($day^{-1}$) |
|---|---|---|---|
| Lipids | 14.8 | 430 | 0.005-0.7 |
| Proteins | 5.9 | 390 | 0.015-0.8 |
| Carbohydrates | 3.0 | 370 | 0.025-2.0 |

Regarding the C/N, results in paper I show that C:N ratios ranging from 14 to 27 tend to yield the highest methane production, though slightly lower than the ideal value often mentioned in the literature (Li et al., 2011; Mao et al., 2015; Zeshan et al., 2012). Typically, feedstocks like crop waste contain significant amounts of C, whereas feedstocks such as food waste or manure contain substantial amounts of N.

By examining the chemical composition of the feedstocks used in the papers (see Table 6), it becomes apparent that certain feedstocks possess desirable components for biogas production. The comparison between different feedstocks and their chemical composition is presented in Figure 10. This comparison was made by using values presented in Table 6. One such feedstock is biowaste, which contains approximately 50% starch and sugars in comparison to the other feedstocks, positioning it as an ideal feedstock, as highlighted in paper II.




*Thermophilic conditions (SS-AD processes without * were performed at mesophilic conditions). Note: FW, Food waste; CFW, Cooked food waste; ChM, Chicken manure; OFMSW, Organic fraction of municipal solid waste; M, Manure; Sw, Straw; dCtlM, Dairy cattle manure; CtlM, Cattle manure; dM, Dairy manure; CSw, Corn straw; TW, Tomato waste; MSW, Municipal solid waste; RSw, Rice straw; GR, Giant reed; Msc, Miscanthus; Swch, Switchgrass; YT, Yard trimmings; PW, Paper waste; YW, Yard waste; CSv, Corn stover; WhSw, Wheat straw; dPllSB, Dried pellets of sugar beets; FrW, Fruit waste; VW, Vegetable waste; LfW, Leaf waste; MS-OFMSW, Mechanically sorted-OFMSW; SC-OFMSW, separately collected-OFMSW; GW, Green waste; GryW, Grey waste; Sde, Sludge; AP, agricultural products; KW, Kitchen waste; MSW, Municipal solid waste.

Figure 10. Relation between methane yield, TS and VS in different feedstocks at laboratory-, pilot- and full-scale process, in paper I.

#### 4.1.2. Operational parameters

In paper I, it was suggested that by controlling the physical properties of feedstocks and adjusting operational parameters in the digestion process, higher methane yields can be achieved. However, when comparing the temperature process among the reviewed articles, the influence of thermophilic (~55 °C) and mesophilic (~35 °C) conditions across scales gave inconsistent results. In other words, it provided no clear relationship between the different temperatures, the methane yield and the size of the process, i.e., small, pilot, and full-scale. Nevertheless, individual scale analysis indicates a significant 22.6% increase in methane yield under thermophilic conditions at full-scale compared to mesophilic conditions, based on the statistical analysis presented in paper I. Regarding the amount of TS inside the reactor, paper I proposes several improvements that can be implemented to address mass transfer limitations and optimize the SS-AD process. These include the utilization of flow recirculation, biogas recirculation, and premixing techniques.

Paper II simulated multiple scenarios to analyze the effects of feedstock and specific operational parameters on the modified PFR configuration within the anaerobic sub-model. It was noted that the model exhibits limited sensitivity to HRT and temperature variations, but high sensitivity to composition of feedstock, specific to co-digestion of biowaste (BW), and green waste (GW), see Figure 11.

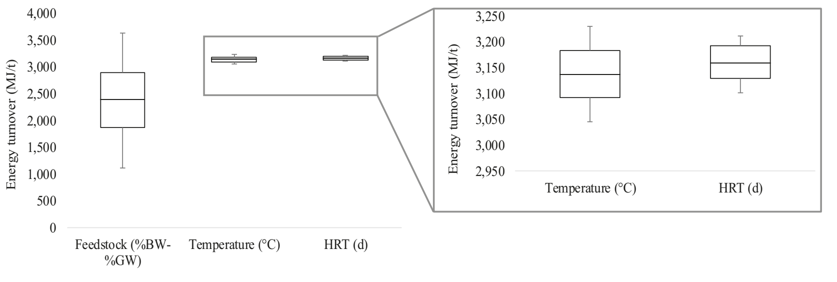



Figure 11. Sensitivity analysis for different parameters such as feedstock composition, temperature and hydraulic retention time in paper II.

Additionally, there are various configuration modes for operating SS-AD processes (André et al., 2018). In paper II, the results of methane yield in the different analyzed scenarios showed no significant differences between L-AD and SS-AD.

### 4.2. Performance analysis in terms of biogas and digestate for a full-scale SS-AD

This chapter presents results related to RQ2, proposing strategies to enhance biogas and digestate production while minimizing input resources like materials and energy at SS-AD plants. This part of the results corresponds to the second studied level, SL2 in Figure 1.

### *4.2.1. Co-digestion*

Co-digestion processes, as proposed in the literature (Bao et al., 2023), are strategies for balancing nutrients in the digester and enhancing biogas production. In this sense, several scenarios were built to assess the model's sensitivity to changes in feedstock. From the results presented in paper II, the model was found to be sensitive when analyzing changes in the proportions of feedstock, specifically between BW and GW. Seven scenarios were constructed to analyze changes in proportions of feedstock, moving from 100% BW to 0% GW, to 0% BW to 100% GW. These changes had a significant impact on electricity and heat consumption, methane production, and the overall energy turnover. BW, which contains a higher nutrient content compared to green waste GW, as shown in Table 6, contributes significantly to methane production. Consequently, when the proportion of BW in the input feedstock mix is reduced, it is expected that the methane yield will decrease, as presented in Table 9.

Table 9. Sensitivity analysis of energy production based on different proportions of feedstocks in paper II.

| **Parameter (MJ/$t_{treated\ waste}$)** | **Sc 1** | **Sc 2** | **Sc 3** | **Sc 4** | **Sc 5** | **Sc 6** | **Sc 7** |
|---|---|---|---|---|---|---|---|
| Methane | 4,000 | 3,574 | 3,091 | 2,853 | 2,616 | 2,145 | 1,620 |
| Heat | -305 | -314 | -339 | -352 | -364 | -389 | -413 |
| Electricity | -63 | -66 | -70 | -72 | -74 | -78 | -80 |
| Energy turnover | 3,600 | 3,156 | 2,640 | 2,386 | 2,133 | 1,630 | 1,076 |

Negative values represent the energy consumption in the AD process.

As described in section 2.1.1, when moving towards a more carbon-neutral environment, efforts should be focused on finding sustainable feedstocks that do not compete with food production and, at the same time, reducing the amount of food waste. The simulation results presented in Table 10 demonstrate that replacing GW with horse manure leads to an increase in methane production and energy turnover, at least for scenarios B (Sc B) and C (Sc C). This can be attributed to the distinctive characteristics of the feedstocks outlined in Table 6 and illustrated in Figure 12, where horse manure is shown to have significantly lower lignin and cellulose contents compared to GW. In addition to the energy benefits gained by replacing GW with horse manure in scenarios B and C, there is also a reduction in the requirement for fresh water input. This reduction is due to the lower TS content of horse manure compared to GW, Table 6.

Table 10. Simulation results from the scenarios studied in paper III.

| Parameter | Sc A | Sc B | Sc C | Sc D |
|---|---|---|---|---|
| Methane (MJ/$t_{treated\ waste}$) | 3,570 | 3,730 | 3,677 | 2,455 |
| Electricity need (MJ/$t_{treated\ waste}$) | -61 | -61 | -61 | -72 |
| Heat need (MJ/$t_{treated\ waste}$) | -352 | -353 | -352 | -436 |
| Energy turnover (MJ/$t_{treated\ waste}$) | 3,156 | 3,316 | 3,264 | 1,947 |
| Recirculation flow (t/year) | 1,275 | 1,372 | 1,328 | 1,334 |
| Fresh water for dilution (L/$t_{waste}$) | 4.4 | 0 | 0 | 304 |

It is important to note that horse manure consists of bedding materials such as wood chips and straw, which contain substantial amounts of both lignin and cellulose. In the model, lignin is classified as slowly degradable organics (Dalemo, 1996). In the case of exclusive digestion of horse manure, as seen in scenario D (Sc D), the advantages of replacing green waste (GW) are lost. In such situations, there is a need for an alternative type of feedstock that can be used in co-digestion and provide different components, such as proteins (Neves et al., 2008), given the high cellulose content of horse manure plus bedding, Figure 12.

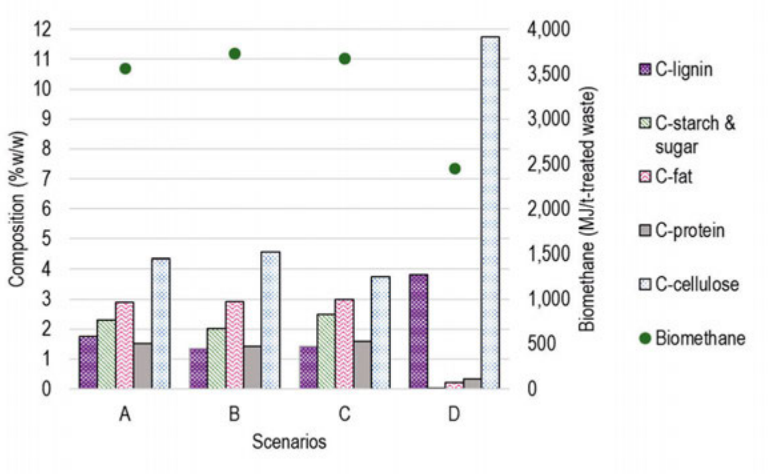



Figure 12. Comparison of different main carbon components and the biomethane production in the studied scenarios in paper III.

### 4.2.2. *Digestate processing*

The results from the simulations from the comparison between L-AD and SS-AD are presented in Table 11. The main distinctions between the scenarios are the amount of liquid digestate, influenced by the addition of water to achieve the low total solids (TS) content of 9% required by L-AD, and the utilization of electricity and heat, resulting in the final energy turnover. As the L-AD process requires more water, the handling of additional liquid during the dewatering of the digestate increases electricity consumption. Additionally, there is greater heat consumption required for heating the additional water. Despite achieving similar values, the energy turnover is, on average, 10% greater for SS-AD.

Table 11. Simulations results of SS-AD and L-AD in paper II.

| Scenarios | Methane production ($MJ/t_{waste}$) | EnT ($MJ/t_{waste}$) | L-dig (t/year) |
|---|---|---|---|
| SS-AD (HRT = 36 d, T = 55 °C) | 3,569 | 3,156 | 10,029 |
| L-AD (HRT = 15 d, T = 35 °C) | 3,339 | 2,849 | 39,000 |
| L-AD (HRT = 15 d, T = 55 °C) | 3,448 | 2,769 | 39,168 |
| L-AD (HRT = 25 d, T = 35 °C) | 3,460 | 2,936 | 39,185 |
| L-AD (HRT = 25 d, T = 55 °C) | 3,527 | 2,791 | 39,293 |

Regarding the analysis of the digestate, the content of nutrients, mainly organic carbon, TN, ammonia and ammonium nitrogen ratio ($NH_3/NH_4^+$-N), P and K were retrieved from the model for both liquid and solid fractions. The analysis in paper III adhered to the Swedish regulations outlined in SPCR120 concerning the application of digestate as an organic fertilizer, as discussed in section 2.1.4. The simulation results indicate that scenarios A and D may lead to nitrogen surplus when applying the liquid fraction of digestate, see Table 12. Only the analysis of scenarios A and D is presented since scenarios B and C are similar to each other and do not show the possible excess in nitrogen.

Table 12. Analysis of nitrogen in the digestate according to the Swedish regulations.

| Scenarios | Liquid fraction (kg $NH_3/NH_4^+$-N-/ha/y) | Solid fraction (kg $NH_3/NH_4^+$-N-/ha/y) | Total digestate including both fractions (kg $NH_3/NH_4^+$-N-/ha/y) |
|---|---|---|---|
| A | 155 | 39 | 104 |
| D | 515 | 130 | 261 |

When considering the option of only spreading the solid fraction of digestate, there may be a deficiency in nitrogen content, which could potentially fail to meet the desired requirements. Implementing a post-treatment process for the liquid fraction of digestate demands the consumption of energy and/or resources. Opting for nutrient recycling in its most straightforward form involves directly applying the entire digestate, bypassing the necessity for fraction separation. In the case of scenario A, the digestate already aligns with regulatory stipulations. By avoiding any fraction separation, a potential for increasing the energy turnover could be achieved, that is, decreasing the electricity consumption for the digestate processing by around 50%. However, in the case of scenario D, the direct application of digestate is not optimal since it contains high amounts of nitrogen. Further options for its use would be more suitable in such cases.

## 4.3. Processing and utilization of SS-AD products and their environmental impacts

This chapter focuses on the processing and utilization of biogas and digestate, as well as their associated environmental impacts, addressing the scope of RQ3. Within this context, papers IV and V present alternative pathways and explore the interconnectedness between the SS-AD system and other relevant systems. This part of the results corresponds to the final studied level, SL3 in Figure 1.

### *4.3.1. Impact assessment of the use of biogas and digestate*

Paper IV investigates the connections between a hydroponic greenhouse growing tomatoes and the SS-AD plant. The key connections established between the two systems involve the utilization of biogas as a heating and $CO_2$ source in the greenhouse, while the digestate serves as a valuable organic fertilizer. Results are divided into two parts, the first one dealing with MFA findings, while the second part deals with the environmental impacts from a LCA perspective. In addition to this, the analysis considered two main scenarios: the reference system, which represents a hydroponic greenhouse with typical inputs and outputs commonly found in Sweden, and the combined system, representing connections between the greenhouse and an SS-AD plant, Figure 4.

According to the simulation results, the quantity of tomato-related waste (TRW) has a minimal impact on the SS-AD plant; outcomes concerning biogas and digestate can be seen in Table 13. The marginal decrease in biomethane production per ton of treated waste can be ascribed to the insufficient nutrient content in TRW, in this paper assumed to be equal to the composition of green waste, which fails to generate substantial biogas quantities and leads to a dilution effect within the waste mixture.

Table 13. Material flow analysis results from the digestion process.

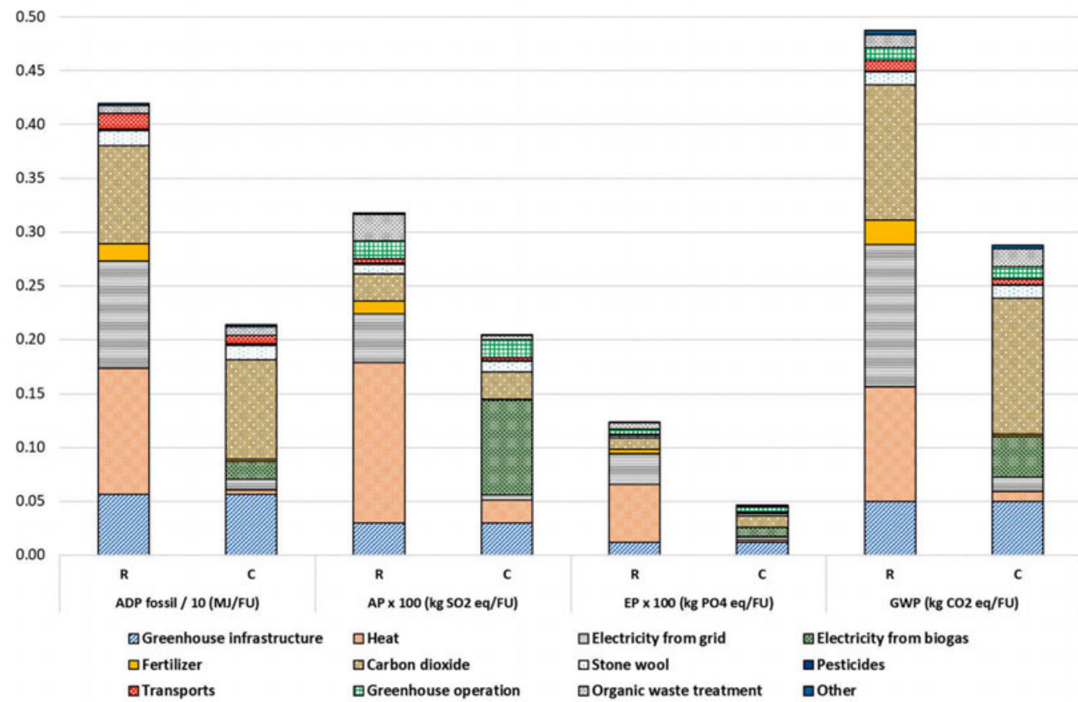
| Parameter | Current SS-AD | SS-AD w/TRW |
|---|---|---|
| Biomethane (MJ/$t_{treated\ waste}$) | 3,641 | 3,609 |
| $CO_2$ (kg/ $t_{treated\ waste}$) | 108 | 107 |
| Liquid fraction of digestate (kg/ $t_{treated\ waste}$) | 752 | 749 |
| Solid fraction of digestate (kg/ $t_{treated\ waste}$) | 345 | 353 |

Similarly, both $CO_2$ emissions and liquid digestate experience minor decreases, while solid digestate exhibits an increase, potentially influenced by undegraded lignocellulosic matter present in the tomato leaves. In the same context, the use of TRW had only a minor impact on the chemical characteristics of the liquid digestate, which can replace 100% nitrogen, 45% of P, and 29% of K in the greenhouse process.

Regarding the LCA results, the combined system performs better than the reference system, Figure 13. The most substantial reduction comes from the decreased impact per unit of energy, as demonstrated by the reduced heat and electricity impacts in the combined system for all selected categories (with the exception of acidification potential for electricity). This effect is attributed to the nature of biogas, characterized by its low emissions and resource utilization.

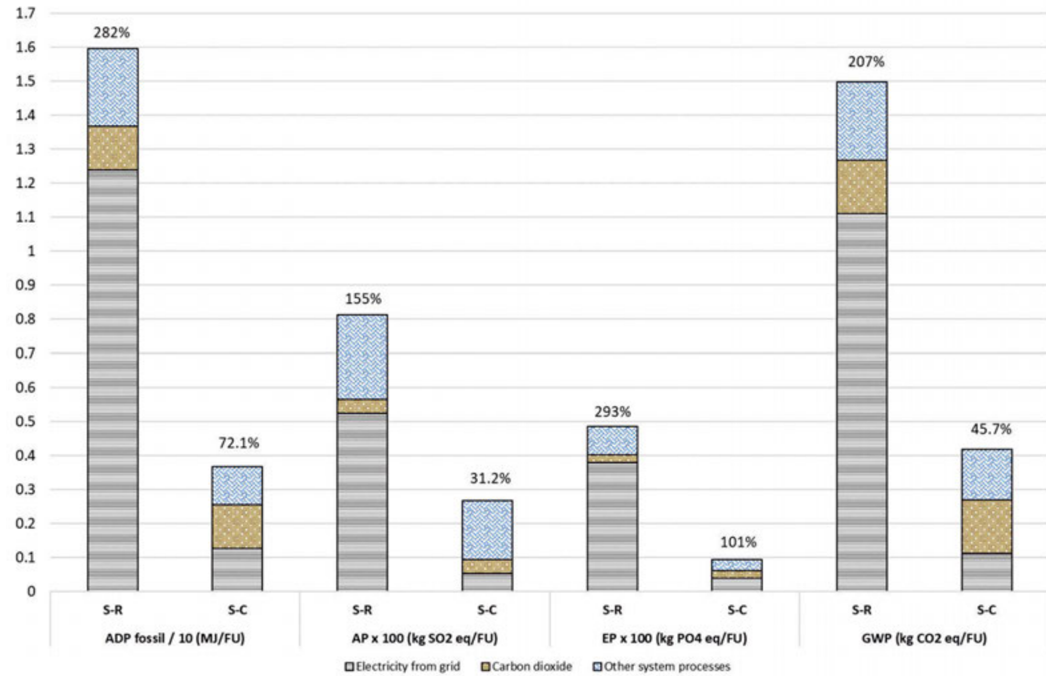
Significant findings were also observed from the sensitivity analysis, where different electricity sources are considered. Specifically, the analysis compares the European electricity mix instead of the Swedish mix. The results show a significant reduction in environmental impacts. For example, in terms of abiotic depletion of fossil fuels (ADP), the systems exhibit an increase in emissions of 282% more for the reference system (S-R) when using the European mix and 72% for the combined system (S-C). This trend is consistent with the other analyzed impact categories, such as global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP), as illustrated in Figure 14. This emphasizes the importance of adopting a clean electricity source as a proactive approach to mitigating adverse environmental consequences.

Regarding the results from paper V, the results consider the primary energy use, GWP, AP, and EP potentials. As illustrated in Figure 9, the core system includes different WM technologies. For this specific analysis, the core system is comprised by the digestion process, the biogas upgrading, digestate and compost transportation (the soil amendment and pellets are represented as the compost product), incineration and associated transportation, landfill disposal, utilization of biogas in buses and cars, biofertilizer application, emissions from arable land, carbon sink, utilization of biogas as an input for the combined heat and power (CHP) system, as well as for the fuel-cell (SOFC), and internal biogas use in a boiler. Conversely, the compensatory system includes production of heat, mainly by using biomass, production of electricity (based on the marginal Swedish mix), production of vehicle fuel, and production of conventional fertilizers. When the impacts of certain areas in the core system are not significant, they were gathered in the "Other" category in Figure 15, Figure 16, Figure 17, and Figure 18.




Abiotic depletion of fossil fuels (ADP), Acidification potential (AP), Eutrophication potential (EP), Global warming potential (GWP). Note: only some impact categories were selected from paper IV and used in this thesis.

Figure 13. LCA results comparing both systems, reference system (R) and the combined system (C).




Abiotic depletion of fossil fuels (ADP), Acidification potential (AP), Eutrophication potential (EP), Global warming potential (GWP). Note: only some impact categories were selected from paper IV and used in this thesis.

Figure 14. Sensitivity analysis based on different electricity mixes, European vs. Swedish. Sensitivity analysis for the reference scenario (S-R), and sensitivity analysis for the combined systems (S-C).

Furthermore, different scenarios were built according to Figure 6 and Figure 7, described in Table 14.

Table 14. Scenarios description for paper V.

| **Scenarios** | **Description** |
|---|---|
| RS | This scenario represents the reference case where the biogas is mainly upgraded to produce vehicle fuel, CBG. The liquid digestate is used as a biofertilizer, and the solid digestate is assumed to be incinerated due to impurities in the input feedstock such as plastics. |
| Sc1 | Scenario 1, Sc1, represents the case where pre-sorting of plastics occurs before digestion. In this scenario, solid digestate can be valorized and used as a biofertilizer, primarily in the form of soil amendments. Simultaneously, a fraction of the biogas is used to produce heat for internal use. |
| Sc2 | Scenario 2, Sc2, is similar to Sc1 but with the difference of using the solid digestate as pellets. |
| Sc3 | Scenario 3, Sc3, represents the utilization of biogas as LBG, with the use of solid digestate remaining the same as in Sc1. |
| Sc4 | Scenario 4, Sc4, assumes the use of biogas for heat and electricity production from a CHP system. Solid digestate remaining the same as in Sc1. |
| Sc5 | Scenario 5, Sc5, represents the production of heat and electricity from a SOFC system. Solid digestate remains the same as in Sc1. |

When comparing the primary energy use between the core system to the compensatory processes, the production of compensatory electricity has the highest impact, followed by the compensatory production of vehicle fuel in scenarios 4 and 5 (Sc4 and Sc5) which stands out as the scenarios where biogas is utilized for heat and electricity generation instead of as vehicle fuel, see Figure 15. The AD process is the primary contributor to primary energy use in the core system with 0.42 MJ/$t_{waste}$, as it treats most of the waste. In particular, Sc2 exhibits high energy consumption due to the production of pellets, 0.18 MJ/$t_{waste}$, which is more energy intensive compared to soil production. Another significant area is biogas upgrading, with the processing of biogas as LBG being the second most energy intensive.

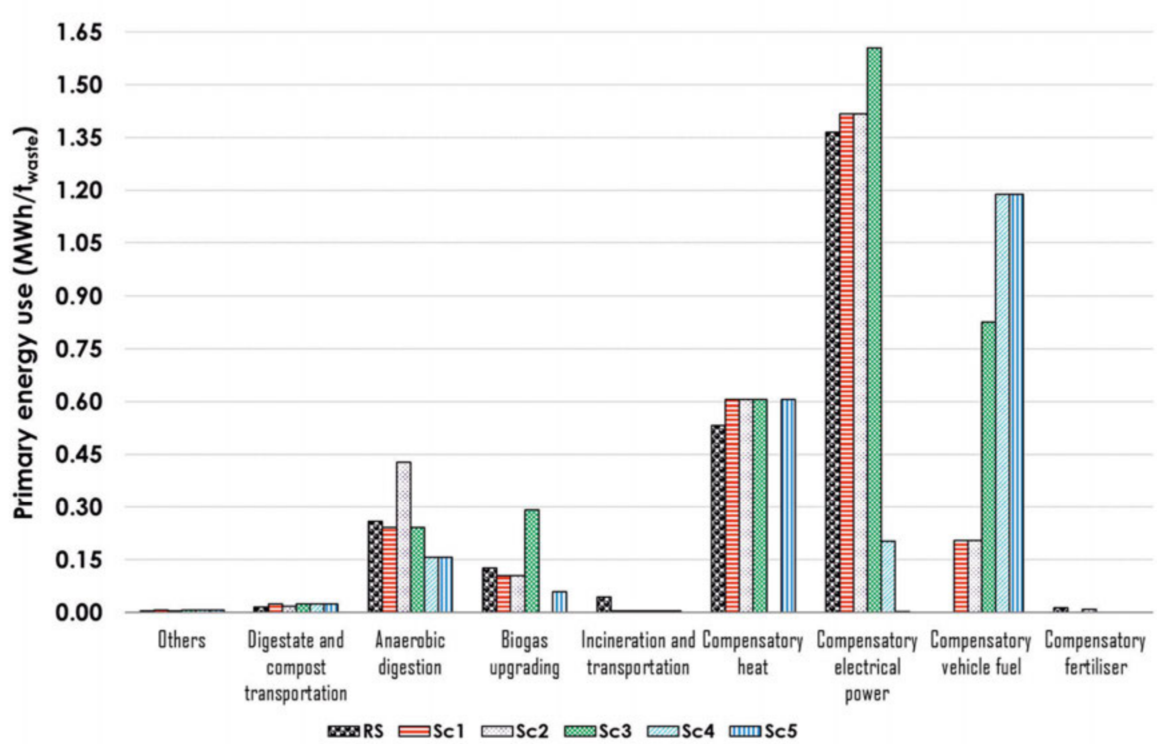



Figure 15. Primary energy use results for the analyzed scenarios in paper V.

The pre-sorting process can lead to a cleaner input feedstock, simultaneously reducing the environmental impacts of incineration and enhancing the system's carbon sink, as presented in Figure 16. The amount of solid digestate that could be valorized with the pre-sorting treatment accounts for approximately a total of 4,857 tonnes. Additionally, processing the solid digestate into pellets leads to reduced impacts associated with digestate and soil amendment (compost) transport. This is because pellets are a more compact product compared to soil amendments, as seen in the comparison between scenarios 1 and 2 (Sc1 and Sc2). Moreover, using the solid digestate as a biofertilizer, whether as a soil amendment or pellets, increases the carbon sink. High emissions are related to Sc4 with the use of CHP system when biogas is combusted, generating 94.2 $kgCO_2$-eq/$t_{waste}$. Overall, this scenario represents the highest impacts regarding the GWP, even including the benefits of the carbon sink. According to the comparison between the core system and the compensatory system, the core system has the highest impacts regarding GWP. The comparison is based on energy production primarily derived from biomass, natural gas (fossil), and wind power, as represented by the Swedish marginal mix. The production of heat in the compensatory system is based on the use of biomass.

In terms of the AP and EP results, the majority of the impacts can be attributed to the emissions resulting from the application of biofertilizers and the soil emissions, particularly for EP, see Figure 18, which is influenced by the soil type, in this case clay. Within the ORWARE model, it was assumed that fertilizer efficiencies for ammonium and organically bound nitrogen were set at 80% and 30%, respectively. This means that 70% of the organically bound nitrogen has the potential to be emitted into the environment (Dalemo et al., 1998). In both AP and EP, the compensatory electricity has the higher impact, related to the energy source production, of which 41% comes from fossil natural gas.

In all scenarios, the raw biogas production remained consistent at 4,891 MJ per tonne of waste processed. Regardless of the scenario, the nutrient composition within the liquid and solid digestate remained unchanged. Table 15 presents the specific levels of nitrogen, phosphorus, and potassium from the system.

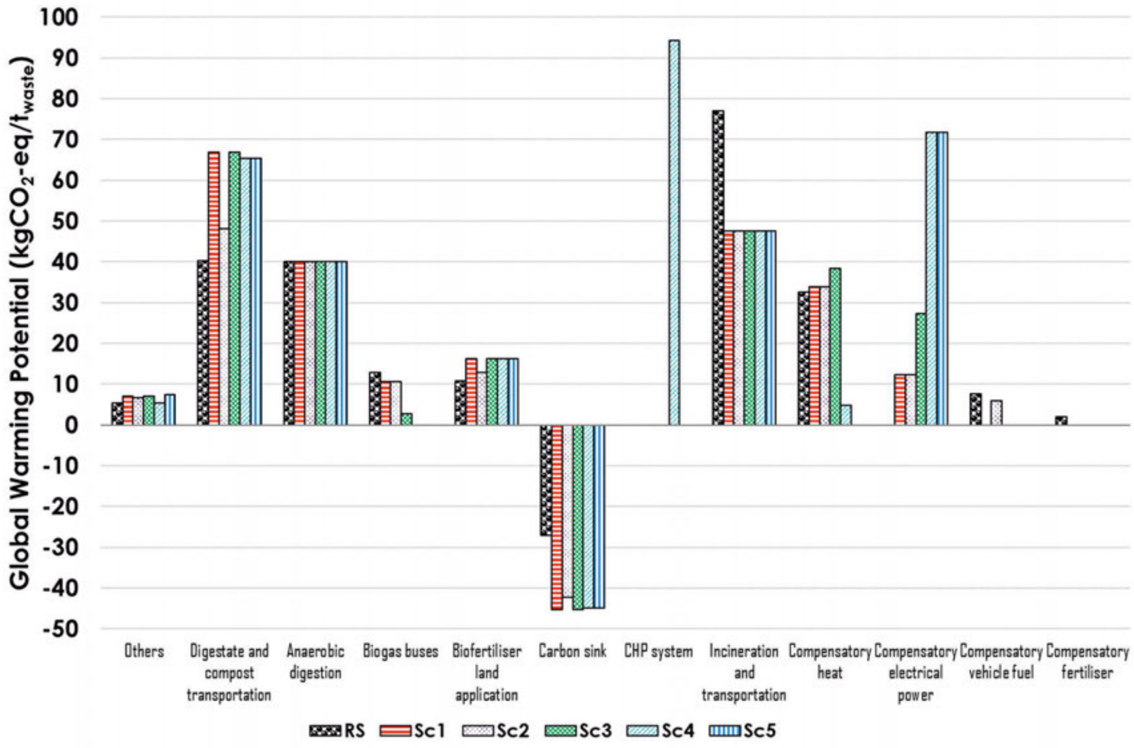



Figure 16. Global warming potential results from different scenarios in paper V.

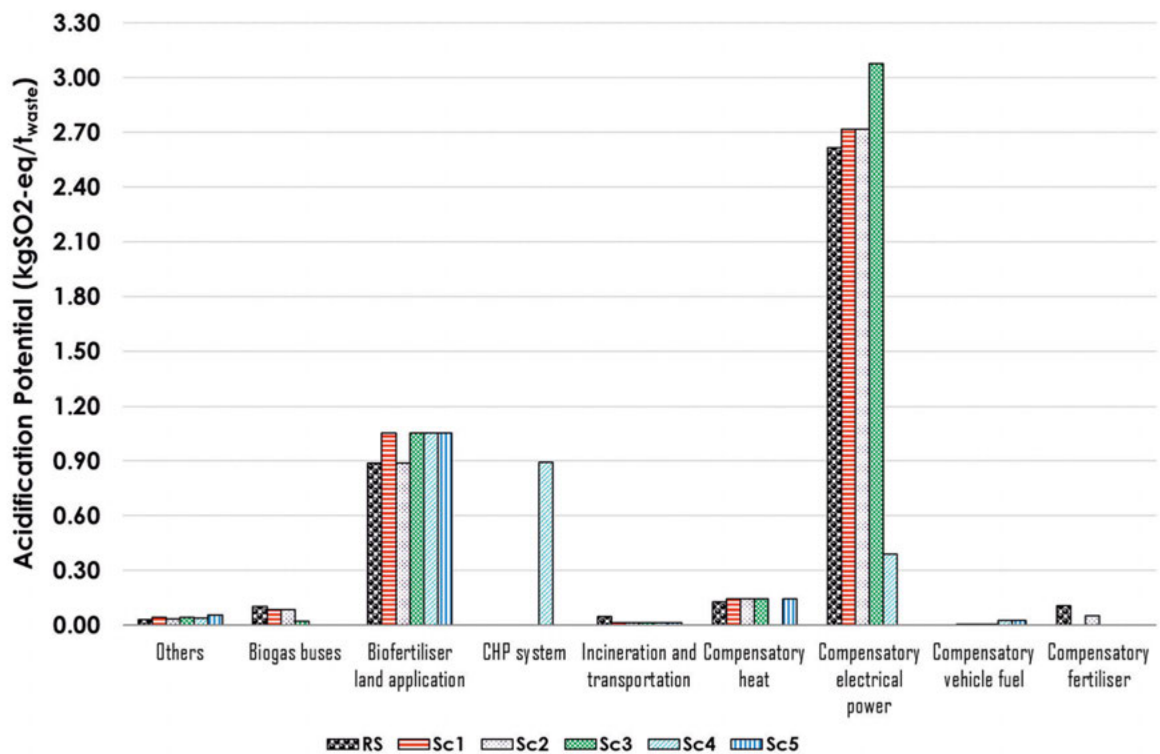



Figure 17. Acidification potential results for different scenarios in paper V.

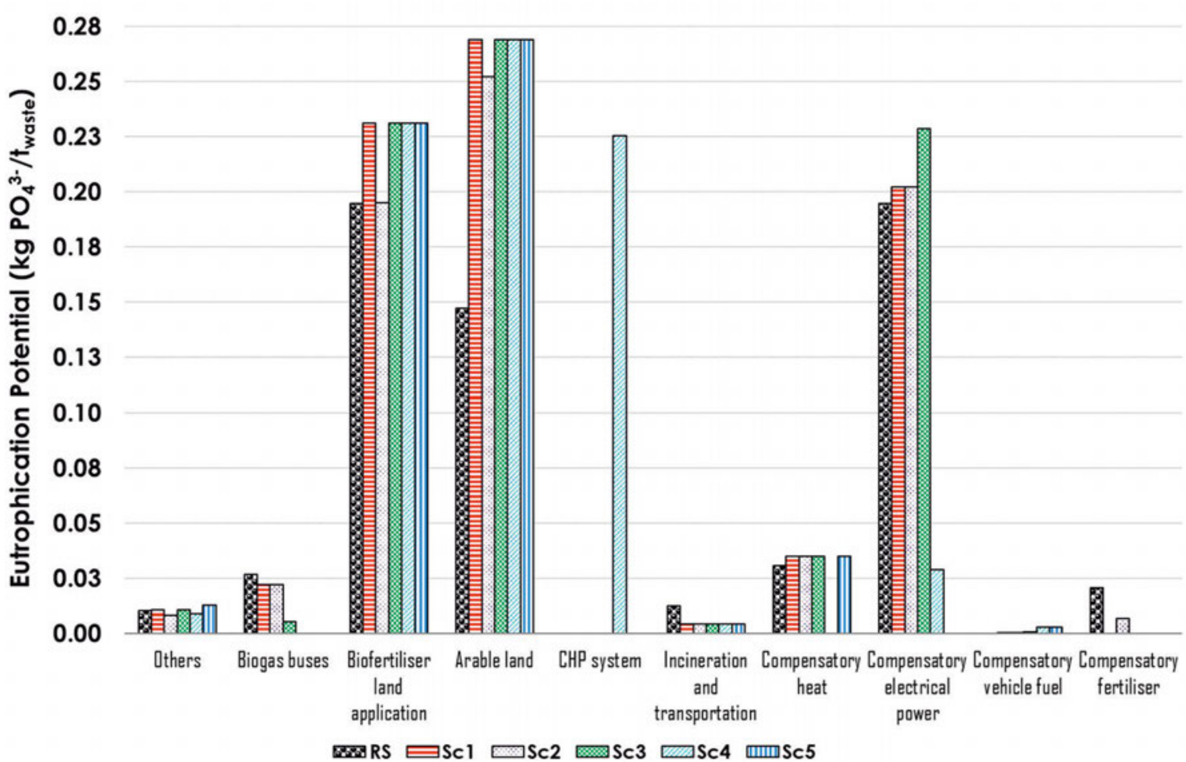



Figure 18. Eutrophication potential results for different scenarios in paper V.

Table 15. Results from simulations in ORWARE and its comparison to the operational data.

| Nutrient (tonne/year) | Liquid fraction | Solid fraction |
|---|---|---|
| Total nitrogen | 128 | 34 |
| Ammonium nitrogen | 107 | 19 |
| Total phosphorus | 16 | 11 |
| Total potassium | 56 | 10 |

In terms of the energy balance, the RS scenario demonstrates the highest energy output, despite the need to compensate for heat and electricity generation in comparison to scenarios 4 and 5, see Figure 19. The RS provides the highest energy turnover, with Sc4, which has the highest heat production of 3,219 MJ/$t_{waste}$, in second place. Within this analysis, diesel is utilized as the fuel for transportation within the core system, such as the transportation of digestate. However, this diesel usage is quite minimal and does not significantly impact the results.

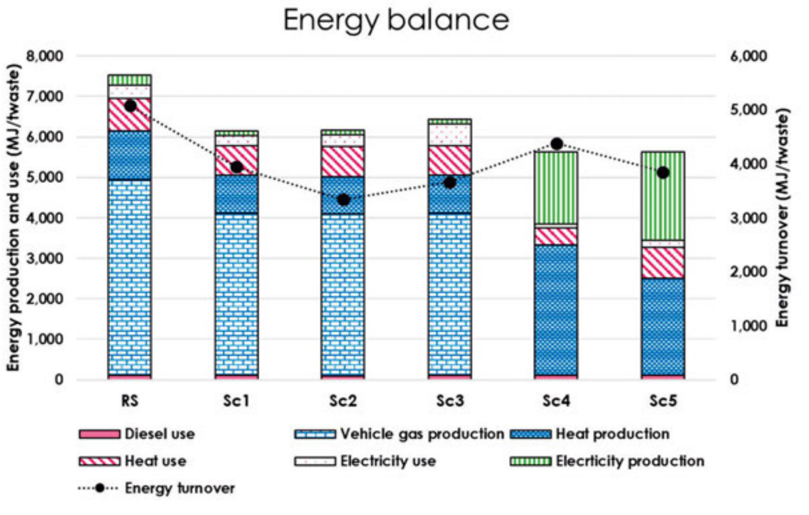



Figure 19. Energy balance for different scenarios in paper V.

#### 4.3.2. *Biogenic carbon*

Biogenic $CO_2$ is gaining attention as an important product from AD due to its possible applications replacing conventional $CO_2$ sources. In Paper IV, $CO_2$ captured from the upgrading of the biogas is used as a growing enhancer for tomatoes. However, due to the unavailability of specific LCI data for the implementation of biogenic $CO_2$ as a growth enhancer under similar conditions, the same LCI dataset was used for both the reference and the combined systems, giving similar results. Nevertheless, the $CO_2$ derived from the AD process is specifically important in achieving environmental benefits. By avoiding long transportation distances of the common $CO_2$ source in this paper (IV), and instead, utilizing a more local source from the SS-AD plant, the overall environmental impact is further reduced, Figure 13.

According to the findings in paper V, the incineration of impurities and rejects can yield approximately 114.4 tonnes of ashes. By applying the ratio provided by Rendek et al. (2006) for capturing 24 liters of $CO_2$ per kilogram of ashes in an accelerated carbonation process, scenarios 1, 2, 3, and 5, which are related to biogas upgrading, have the potential to capture approximately 5 tonnes of $CO_2$. However, this amount is relatively low when compared to the total $CO_2$ that can be separated during the upgrading process, which amounts to 2,657 tonnes of $CO_2$. Therefore, it is advisable to explore other options to either replace or complement the accelerated carbonation process.

# 5. Discussion

This chapter presents a discussion of the main findings in the papers, with a specific focus on the research questions.

## 5.1. Methane yield from solid-state anaerobic digestion

The analysis of methane production for a specific quantity of a given feedstock used was conducted through a literature review and different modelling scenarios. Small-scale processes, ranging from 0.17-50 L and using food waste as a primary feedstock, demonstrated the highest methane yield, achieving 531 $m^3CH_4/t_{VS}$ (Qiao et al., 2011). According to the chemical composition retrieved from the dataset in ORWARE (see Table 6), food waste, referred to as biowaste in this thesis, is notable for its high content of starch and sugars, proteins, and lipids, which makes it a good choice for biogas production. However, in line with environmental goals, there is a need to reduce food waste in order to decrease potential GHG emissions and preserve resources for its production (Energimyndigheten, 2021; Jordbruksverket, 2021). Other potential feedstocks for SS-AD processes include agricultural waste (IEA, 2020). Nevertheless, this type of waste contains significantly large amounts of lignocellulosic materials, which can hinder methane production (Sawatdeenarunat et al., 2015). In full-scale processes, agricultural waste, mainly manure and straws, is often combined with other feedstock in a co-digestion process, such as the organic fraction of municipal solid waste (OFMWS) (refer to Figure 10). This practice can help improve nutrient balance, such as the C:N ratio, and enhance methane yield (Li et al., 2011; Zeshan et al., 2012). However, the methane yield given by pilot and full-scale, mainly operating under co-digestion conditions, may not reach similar methane production as for the small-scale setups, at least based on the cases analyzed and presented in Table 7 and in Figure 10. Considering the scenarios proposed by Gustafsson and Anderberg (2022), which suggest the development of more large co-digestion plants and decentralized plants using mainly agricultural waste, it becomes necessary to consider pre-treatment methods to improve methane production. Additionally, a further energy analysis should be carried out to assess its efficiency.

The chemical composition of feedstocks plays a key role in successful biogas production. In addition, the physical properties of feedstocks and operational parameters in the digestion process also significantly impact methane yields (Ellacuriaga et al., 2021). However, the relationship between temperature, methane yield, and process scale is complex, with no straightforward correlations as presented in paper I. In addition to this, the influence of temperature and HRT variations in the model did not have significant effect on the overall energy use due to the linearity of the mathematical models used in ORWARE (Dalemo et al., 1997). Nonetheless, most Swedish SS-AD plants could opt for thermophilic conditions as a mean to avoid external hygienization method, although the potential risks of ammonia inhibitions, especially when working with food waste streams, need consideration (Persson et al., 2019).

The high solid content in biomass greatly affects methane yield, requiring solutions to address mass transfer limitations. The results of the review study, paper I, suggest solutions like flow recirculation, biogas recirculation, pre-mixing techniques, and pre-treatments for lignocellulosic feedstocks. The latter is particularly relevant when considering the implementation of more decentralized biogas systems that utilize agricultural waste with high lignocellulosic content. To this, more biogas systems could be built with an SS-AD configuration, which enables better handling of the high-solids feedstocks. The transition from L-AD (with a CSTR mathematical reactor design) to SS-AD (with a PFR mathematical reactor design) configuration process is another factor addressed in the model. The changes in reactor design and equations are presented in paper II.

## 5.2. Process performance analysis of solid-state anaerobic digestion

Sweden's goal to achieve 7 TWh of biomethane production from waste aligns with the EU's target of 35 bcm by 2030 (European Commission, 2022). To reach this goal, we must explore waste-based feedstocks that do not compete with food production (EBA, 2022; European Parliament, 2009). Additionally, part of the global sustainability goals is aimed at reducing food waste. A comprehensive understanding of the various feedstocks, nutrient analysis, energy efficiency, and potential optimization strategies is then important.

Horse manure has gained attention primarily due to its abundance and specific nutrient characteristics (Eriksson et al., 2016b; Mönch-Tegeder et al., 2014; Wartell et al., 2012). To explore the effects of replacing BW with horse manure, and addressing concerns related to GW containing heavy metals due to urban pollution, different scenarios were constructed in paper III. Adjusting the feedstock proportions, specifically, the inclusion of horse manure with bedding, BW, and GW, has significant implications on electricity and heat consumption, methane production, and overall energy turnover. As detailed in Table 10, the substitution of GW with horse manure significantly enhances biomethane production and energy turnover, largely due to differences in lignin and cellulose content, as demonstrated in Table 6. In addition to this, the higher amounts of TS from GW in comparison to horse manure with bedding leads to greater demand for fresh water to adjust the operational TS, see Table 3. Consequently, this leads to increased electricity consumption for the dewatering of digestate and higher heat consumption for heating the digester. However, when only working with horse manure and bedding as the main feedstock, scenario D, the methane yield decreases. Horse manure generally offers good alkalinity which stabilizes the biogas process, but it has a relatively low energy content (Carlsson et al., 2013). Therefore, it is better suited as a feedstock for co-digestion processes rather than for mono-digestion (Ammenberg & Feiz, 2017).

Analyzing the nutrient content of the digestate is essential for its proper management and utilization. It is noteworthy that scenarios A and D, in paper III, exhibit nitrogen excess when spreading the liquid fraction and nitrogen deficiency when spreading solely the solid fraction, requiring compliance with Swedish regulations (SPCR120). In that sense, the direct application of the digestate would meet the required regulations and could increase energy turnover when avoiding fraction separation of the digestate. Still, digestate dewatering depends on the location of the specific biogas plant, determining whether it can be spread near the facility without dewatering or if is essential for improved transportation efficiency (Pöschl et al., 2010). On the other hand, specific soil nutrient compositions can require solid-liquid separation, providing a viable solution when the application of phosphorus to nearby farmland is restricted. In such cases, the solid phase can be transported to regions facing phosphorus deficiency (Feiz et al., 2022). The strategy of separating digestate fractions could be viable for biogas plants because the energy input required for digestate processing, specifically using screw-press technology, is relatively low compared to the total energy input needed for the entire biogas plant (Pöschl et al., 2010). In the studied scenarios in papers II and III, however, transportation and application of the digestate was not included.

The performance of the digestion process in SS-AD and L-AD configurations shows distinct differences. SS-AD exhibits a 10% higher energy turnover, even though the methane yield is similar in both configurations, as previously reported in the literature (Chiumenti et al., 2018). This energy turnover encompasses the energy used for the digestion process, the digester heating, the dewatering of the digestate, and the energy recovered from the biogas. However, a comprehensive assessment should include a more thorough understanding of the process performance in terms of energy input and total energy turnover. This entails considering the processing of biogas for its final use, whether as vehicle fuel or as input for heat and electricity generation. Additionally, another critical aspect is the transportation of digestate to arable land or other final destinations. Furthermore, environmental, and economic analyses should be integral to the comprehensive assessment, accounting for potential pre-treatments for lignocellulosic biomass when used as a feedstock. This consideration is particularly relevant when utilizing agricultural waste, such as crops, as one of the primary proposed feedstocks for sustainable biogas production (EBA, 2022).

## 5.3. Beyond the anaerobic digestion from a system perspective

In this studied level, the environmental impacts between a hydroponic greenhouse primarily focused on tomato cultivation and an SS-AD plant is evaluated. The primary aim is to understand how these two systems can be interlinked to enhance sustainability in food production systems and biogas systems. One of the key connections established between these systems involves the utilization of biogas as a multifaceted resource within the greenhouse. The biogas produced in the SS-AD plant serves a dual purpose, acting both as a heating source and a supplier of $CO_2$, which is essential for enhancing plant growth (Oreggioni et al., 2019). Simultaneously, the digestate produced by the SS-AD plant serves as a valuable biofertilizer, offering a sustainable alternative to conventional fertilizers. Two main scenarios are considered: the reference system, which mirrors a typical hydroponic greenhouse with inputs and outputs commonly found in Sweden, with heat provided by the energy recovery from wood chips (Jordbruksverket, 2018) and the Swedish electricity mix (Treyer, 2019), and the combined system, illustrating the connections between the greenhouse and an SS-AD plant. Figure 4 provides an illustrative representation of these scenarios. Results indicate that, when using TRW as an additional feedstock for the SS-AD plant, the increase in biogas production is somewhat limited, primarily due to the insufficient nutrient content in TRW. This insufficiency results in a slight reduction in biomethane production per tonne of treated waste and a dilution effect within the waste mixture. It is important to note that more precise data is needed to accurately represent real conditions, as the chemical characteristics of TRW were obtained from the ORWARE dataset.

As Figure 13 shows, a noticeable reduction in heat production occurs when using biogas as a heat source. However, the extent of this reduction may also vary depending on the type of crop being cultivated. Burg et al. (2021) noted that growing lettuce instead of tomatoes requires less heating. This raises questions about the choice of crops for cultivation in Sweden. Specifically, tomatoes were chosen as a focal point, considering that a significant portion of them are imported (Jordbruksverket, 2022). Further analysis is needed to understand the trade-off between energy use for cultivating crops and the nutritional value they provide. Similarly, the use of TRW in the SS-AD plant has limited impact on the chemical characteristics of the resulting digestate. Assuming a nitrification efficiency of 75%, it becomes feasible to replace a substantial portion of the essential nutrients required by tomato plants, particularly nitrogen, phosphorus, and potassium. Particularly, the SS-AD plant can provide the total amount of $CO_2$ needed by the greenhouse, whereas TRW alone can only supply 5.7% of this requirement. In their study, Oreggioni et al. (2019) explored the feasibility of utilizing $CO_2$ for tomato production and found it to be technically viable and economically favorable compared to $CO_2$ geological storage. However, the study assumed the permanent capture of $CO_2$ by tomatoes, similar to geological storage, which could potentially lead to an overestimation of the benefits.

Analyzing the environmental impact from an LCA perspective, the combined system, which represents the interconnection between the greenhouse and the SS-AD plant, shows improved environmental performance compared to the reference system. This enhancement is particularly clear in categories related to energy efficiency, such as lower heat and electricity impacts across all categories. This reduction in impact is primarily attributed to the low emissions and resource consumption associated with biogas utilization. Nevertheless, GHG emissions from cropping systems should be evaluated based on biomass productivity to compare systems with diverse production services. For instance, the inclusion of biogas systems can offer a wide range of production services, such as biomass productivity, e.g., sequential crops for biogas production, and nitrogen fertilization autonomy (Kervroëdan et al., 2022).

Food waste, denoted as BW, has been recognized for its favorable attributes as a feedstock, including high biogas yield, accessibility, profitability, and substantial GHG emission reductions. Nevertheless, the presence of plastics, often used for packaging, in this feedstock poses challenges and renders it unsuitable for biofertilizer production (Ammenberg & Feiz, 2017; Carlsson et al., 2013). In paper V, pre-sorting is proposed to clean up the input feedstock and for further valorization of the solid fraction of the digestate. Comparing the core system with compensatory processes, the findings highlight the energy consumption variations across scenarios. This difference can be attributed to various factors, such as energy-intensive pellet production, biogas upgrading processes, and waste sent for incineration. Furthermore, scenarios involving the use of solid digestate as a biofertilizer present improvements, particularly in terms of GWP related to carbon sink. In a broader context, taking into account various factors that can influence energy supply and its fluctuations, such as pandemics and conflicts, there is a growing interest in exploring alternative applications of biogas beyond the conventional Nordic model, as described in section 2.1. Specifically, the focus is on its potential for heat and electricity production through different pathways. It is important to note that this exploration of alternative applications does not diminish the significance of using biogas as a vehicle fuel, as reducing emissions from the transportation sector remains a critical strategy in mitigating climate change (Lindfors et al., 2022).

In the context of vehicle fuel, paper V assesses two options for processing and utilizing biogas: CBG and LBG. In Figure 19, the highest energy turnover is associated with the RS scenario, where biogas is upgraded and used as a vehicle fuel. Similarly, Varling et al., (2023) found that biogas upgrading allows for the recovery of 80–85% of the energy content of the biogas, being the best scenario in terms of the energy assessment. This means that by avoiding other processes such as pre-treatments, energy can be saved. However, in terms of GWP, scenario 2 could be more beneficial. This scenario involves the use of CBG and includes the valorization of solid digestate as pellets, which reduces the impacts of transportation due to the reduced volumes. In contrast, digestate management can significantly impact the feasibility of operations, potentially acting as a barrier to entry for new biogas plants. This, in turn, has economic implications and can restrict production scalability (Mirata et al., 2017). On the other hand, given that the $CO_2$ derived from biomethane is already separated, it is essential to utilize this readily available resource for CCS purposes. In the context of investigating its potential for accelerating the carbonation of ashes, which could offer a viable utilization for these materials, the option did not yield significant results in terms of $CO_2$ capture.

## 5.4. Uncertainties and limitations

Uncertainties in ORWARE involve not only inherent variability in key parameters but also challenges associated with data gaps. Data gaps are a common issue in modelling and simulation due to the difficulty of acquiring comprehensive statistics or precise measurements of process parameters. In some cases, data from external databases, such as EcoInvent, are incorporated to fill these gaps. While this approach might not eliminate uncertainties entirely, it is more favorable than leaving the model with significant gaps. It is important to note that spatial variability, or the variation of emissions in different geographic locations and their impact on background concentrations, is not explicitly considered in ORWARE. Additionally, all calculations within the model are based on yearly averages, which may not capture temporal variations. This assumption is closely related to the model's reliance on stable biogas production and average values as its foundation (Björklund, 2000).

Addressing scenario uncertainties in the model becomes more complex due to the relationship between data gaps and the reliance on external databases. When constructing different scenarios, the model must deal with not only the inherent uncertainties tied to specific assumptions but also those introduced by incomplete or unrepresentative data from external sources. The data collected from the biogas plant was obtained across various years during the research, introducing uncertainties and occasionally constraining the scope of certain papers. Additionally, more sample analysis and measurements are needed for the facilities, the SS-AD plant in this case, so that it will be possible to easily evaluate effects of changes through time.

Model uncertainties, while associated with the mathematical equations and models used in the assessment, are also influenced by the quality and completeness of the data integrated into these equations. Furthermore, it is worth noting that the mathematical models in ORWARE are linear, which means they may not entirely represent real-world behavior. Lastly, ORWARE's approach to addressing these uncertainties involves encouraging further research and the development of improved measurement techniques. By actively working to fill these knowledge gaps, the model aims to reduce epistemic uncertainties over time and enhance the accuracy of its predictions (Clavreul et al., 2012). Despite these uncertainties, ORWARE gives valuable results and can be used in the decision-making process of different waste management processes (Assefa et al., 2005a, 2005b; Baky & Eriksson, 2003; Björklund et al., 1999b; Eriksson & Baky, 2010).

One significant limitation of this research is associated with the methodology employed, which primarily focuses on assessing the energy and environmental performance of the systems under investigation while omitting economic and social factors. Incorporating these aspects into the examination could have provided additional insights for decision-makers and facilitated the evaluation and comparison of the results. However, this limitation was primarily a result of constraints related to data availability and time restrictions.

## 5.5. Future research

Economic analysis of different utilization pathways for the SS-AD products is an important aspect that should be addressed. Environmental systems analysis is only a small part of the decision-making process. Moreover, the social aspect should be considered, particularly when waste generation is influenced by individual and group behaviors, especially in the context of a circular economy that emphasizes waste reduction.

The interconnections between biogas systems and other technologies play a crucial role in reducing input resources (Mirata et al., 2017). Besides its heating value, biomethane holds the potential for producing valuable platform chemicals like hydrogen and methanol (Farghali et al., 2022). Currently, the demand for such chemicals is low, but it is expected to increase. In an integrated biorefinery model, algae, for example, can convert $CO_2$ into carbon-rich lipids, protein, and carbohydrates (Xia & Murphy, 2016). These can be further processed through fermentation, anaerobic digestion, or pyrolysis to yield ethanol, biogas, or biochar, respectively. By integrating various process technologies, the SS-AD technology, for example, can potentially generate its own feedstock, making it a self-sufficient or at least partially self-sustaining process.

Presently, most commercial applications involve the direct use of $CO_2$. However, new pathways are being explored to transform $CO_2$ into fuels, chemicals, and building materials. Currently, the most well-established application is to boost yields in industrial greenhouses. This method has proven to be highly effective, with the capacity to increase yields by 25% to 30% (IEA, 2019). In the context of this research, an analysis of various utilization pathways should be conducted to select the most suitable option for the system under examination.

# 6. Concluding remarks

Co-digestion processes handle diverse type of feedstock, each possessing unique characteristics. Examining the impact of the different nutrient content, in addition to variations in operational parameters, could facilitate understanding optimal conditions for maximizing methane yield. The following are the conclusions related to the methane yield at SS-AD conditions:

- While food waste, rich in starch, sugars, proteins, and lipids, is an excellent choice for biogas production, environmental goals necessitate exploring alternative feedstocks.
- Co-digestion of agricultural waste, such as manure and straws, with other feedstock like the organic fraction of municipal solid waste (OFMWS), can improve nutrient balance and methane yield.
- The relationship between temperature, methane yield, and process scale is complex, and variations in temperature and HRT did not significantly affect overall energy use in the mathematical model used.
- SS-AD vs. L-AD process did not present a significant difference in terms of methane yield regarding the simulation results.

The following conclusions are related to exploring technical recommendations aimed at enhancing energy turnover while minimizing resource consumption, including materials and energy inputs, during full-scale operation:

- Replacing certain feedstocks with horse manure can have significant positive implications on electricity and heat consumption, methane production, and overall energy turnover.
- SS-AD exhibits a 10% higher energy turnover in comparison to L-AD from the simulation results. However, this energy analysis only takes into consideration the energy used in the digestion process and the dewatering of the digestate.
- By avoiding the separation of liquid and solid fractions of the digestate, energy turnover could be increased, potentially saving up to 50% of the electricity required for digestate processing.

Lastly, conclusions regarding the environmental performance of the SS-AD products within different applications in an expanded biogas system:

- The combined system, representing the interconnection between a hydroponic greenhouse and an SS-AD plant, shows improved environmental performance compared to the reference system, particularly in categories related to energy efficiency.
- Using biogas as CBG for vehicle fuel and incinerating the solid digestate offers the highest energy turnover. However, scenarios where the solid digestate is valorized as biofertilizer, especially as

pellets, show the best environmental performance in terms of GWP.

- Investigating the potential of biogas for accelerating the carbonation of ashes for $CO_2$ capture did not yield significant results.

# References


Abbassi-Guendouz, A., Brockmann, D., Trably, E., Dumas, C., Delgenès, J.P., Steyer, J.P., Escudié, R., 2012. Total solids content drives high solid anaerobic digestion via mass transfer limitation. Bioresour. Technol. 111, 55–61. https://doi.org/10.1016/j.biortech.2012.01.174

Akhiar, A., Battimelli, A., Torrijos, M., Carrere, H., 2017. Comprehensive characterization of the liquid fraction of digestates from full-scale anaerobic co-digestion. Waste Manag. 59, 118–128. https://doi.org/10.1016/j.wasman.2016.11.005

Ammenberg, J., Feiz, R., 2017. Assessment of feedstocks for biogas production, part II—Results for strategic decision making. Resour. Conserv. Recycl. 122, 388–404. https://doi.org/10.1016/j.resconrec.2017.01.020

André, L., Pauss, A., Ribeiro, T., 2018. Solid anaerobic digestion: State-of-art, scientific and technological hurdles. Bioresour. Technol. 247, 1027–1037. https://doi.org/10.1016/j.biortech.2017.09.003

Angelidaki, I., Alves, M., Bolzonella, D., Borzacconi, L., Campos, J.L., Guwy, A.J., Kalyuzhnyi, S., Jenicek, P., van Lier, J.B., 2009. Defining the biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays. Water Sci. Technol. 59, 927. https://doi.org/10.2166/wst.2009.040

Angelonidi, E., Smith, S.R., 2015. A comparison of wet and dry anaerobic digestion processes for the treatment of municipal solid waste and food waste. Water Environ. J. 29, 549–557. https://doi.org/10.1111/wej.12130

Assefa, G., Björklund, A., Eriksson, O., Frostell, B., 2005a. ORWARE: An aid to environmental technology chain assessment. J. Clean. Prod. 13, 265–274. https://doi.org/10.1016/j.jclepro.2004.02.019

Assefa, G., Eriksson, O., Frostell, B., 2005b. Technology assessment of thermal treatment technologies using ORWARE. Energy Convers. Manag. 46, 797–819. https://doi.org/10.1016/j.enconman.2004.04.011

Avfall Sverige, 2022. Swedish Waste Management 1–47.

Azapagic, A., 2018. Environmental Systems Analysis, in: Kutz, M. (Ed.), Handbook of Environmental Engineering. John Wiley & Sons, 1–12. https://doi.org/10.1201/b18873

Baky, A., Eriksson, O., 2003. Systems Analysis of Organic Waste Management in Denmark.

Bao, R., Wei, Y., Guan, R., Li, X., Lu, X., Rong, S., Zuo, X., Yuan, H., 2023. High-solids anaerobic co-digestion performances and microbial community dynamics in co-digestion of different mixing ratios with food waste and highland barley straw. Energy 262, 125529. https://doi.org/10.1016/j.energy.2022.125529

Bauer, F., Hulteberg, C., Persson, T., Tamm, D., 2013. Biogas upgrading – Review of commercial technologies.
Behling, N.H., 2013. Chapter 2 - Fuel Cells and the Challenges Ahead, in: Behling, N.H. (Ed.), Fuel Cells. Elsevier, 7–36. https://doi.org/https://doi.org/10.1016/B978-0-444-56325-5.00002-8
Bergstrand, K.J., Asp, H., Hultberg, M., 2020. Utilizing anaerobic digestates as nutrient solutions in hydroponic production systems. Sustain. 12, 1–12. https://doi.org/10.3390/su122310076
Bioenergy Europe, 2022. Statistical Report 2022. Brussels.
Biogas Research Center, 2022. Samhällsvillkor och Strategier [WWW Document]. URL https://www.biogasresearchcenter.se/forskning/
Bisaillon, M., Sundberg, J., Eriksson, O., 2010. Systemstudie Avfall i Göteborg. Project Report WR 21, Waste Refinery, SP Sveriges Tekniska Forskningsinstitut, pp. 1654e4706. ISSN.
Björklund, A., 2000. Environmental System Analysis of Waste Management : Experiences from Applications of the ORWARE Model.
Björklund, A., Bjuggren, C., Dalemo, M., Sonesson, U., 1999a. Planning biodegradable waste management in Stockholm. J. Ind. Ecol. 3, 43–58. https://doi.org/10.1162/108819899569683
Björklund, A., Dalemo, M., Sonesson, U., 1999b. Evaluating a municipal waste management plan using ORWARE. J. Clean. Prod. 7, 271–280. https://doi.org/10.1016/S0959-6526(99)00086-4
Boldrin, A., Neidel, T.L., Damgaard, A., Bhander, G.S., Møller, J., Christensen, T.H., 2011. Modelling of environmental impacts from biological treatment of organic municipal waste in EASEWASTE. Waste Manag. 31, 619–630. https://doi.org/10.1016/j.wasman.2010.10.025
Bolzonella, D., Battistoni, P., Mata-Alvarez, J., Cecchi, F., 2003. Anaerobic digestion of organic solid wastes: process behaviour in transient conditions. Water Sci. Technol. 48, 1–8.
Bolzonella, D., Pavan, P., Mace, S., Cecchi, F., 2006. Dry anaerobic digestion of differently sorted organic municipal solid waste : a full-scale experience. Water Sci. Technol. 53, 23–32. https://doi.org/10.2166/wst.2006.232
Bose, A., O'Shea, R., Lin, R., Long, A., Rajendran, K., Wall, D., De, S., Murphy, J.D., 2022. The marginal abatement cost of co-producing biomethane, food and biofertiliser in a circular economy system. Renew. Sustain. Energy Rev. 169, 112946. https://doi.org/10.1016/j.rser.2022.112946
Boyd, D.W., 2001. Systems Analysis and Model Synthesis. Syst. Anal. Model. 3–33. https://doi.org/10.1016/b978-012121851-5/50001-0
BRIGHT, 2017. Härnösand, Sweden [WWW Document]. Projects. URL https://www.bright-renewables.com/project/harnosand/
Brown, D., Shi, J., Li, Y., 2012. Comparison of solid-state to liquid anaerobic digestion of lignocellulosic feedstocks for biogas production. Bioresour. Technol. 124, 379–386. https://doi.org/10.1016/j.biortech.2012.08.051

Budzianowski, W.M., 2016. A review of potential innovations for production, conditioning and utilization of biogas with multiple-criteria assessment. Renew. Sustain. Energy Rev. 54, 1148–1171. https://doi.org/10.1016/j.rser.2015.10.054

Burg, V., Golzar, F., Bowman, G., Hellweg, S., Roshandel, R., 2021. Symbiosis opportunities between food and energy system: The potential of manure-based biogas as heating source for greenhouse production. J. Ind. Ecol. 25, 648–662. https://doi.org/10.1111/jiec.13078

Carlsson, M., Holmström, D., Bohn, I., Bisaillon, M., Morgan-Sagastume, F., Lagerkvist, A., 2015. Impact of physical pre-treatment of source-sorted organic fraction of municipal solid waste on greenhouse-gas emissions and the economy in a Swedish anaerobic digestion system. Waste Manag. 38, 117–125. https://doi.org/10.1016/j.wasman.2015.01.010

Carlsson, M., Holmström, D., Lagerkvist, A., Bisaillon, M., 2013. Förbehandling av biogassubstrat i systemanalys, Waste Refinery.

Carrette, L., Friedrich, K.A., Stimming, U., 2000. Fuel Cells: Principles, Types, Fuels, and Applications. ChemPhysChem 1, 162–193.

Chiodo, V., Galvagno, A., Lanzini, A., Papurello, D., Urbani, F., Santarelli, M., Freni, S., 2015. Biogas reforming process investigation for SOFC application. Energy Convers. Manag. 98, 252–258. https://doi.org/10.1016/j.enconman.2015.03.113

Chiumenti, A., da Borso, F., Limina, S., 2018. Dry anaerobic digestion of cow manure and agricultural products in a full-scale plant: Efficiency and comparison with wet fermentation. Waste Manag. 71, 704–710. https://doi.org/10.1016/j.wasman.2017.03.046

Clavreul, J., Baumeister, H., Christensen, T.H., Damgaard, A., 2014. An environmental assessment system for environmental technologies. Environ. Model. Softw. 60, 18–30. https://doi.org/10.1016/j.envsoft.2014.06.007

Clavreul, J., Guyonnet, D., Christensen, T.H., 2012. Quantifying uncertainty in LCA-modelling of waste management systems. Waste Manag. 32, 2482–2495. https://doi.org/10.1016/j.wasman.2012.07.008

Cordova, S.S., Gustafsson, M., Eklund, M., Svensson, N., 2022. Potential for the valorization of carbon dioxide from biogas production in Sweden. J. Clean. Prod. 370, 133498. https://doi.org/10.1016/j.jclepro.2022.133498

Cui, Z., Shi, J., Li, Y., 2011. Solid-state anaerobic digestion of spent wheat straw from horse stall. Bioresour. Technol. 102, 9432–9437. https://doi.org/10.1016/j.biortech.2011.07.062

Dahlgren, S., 2022. Biogas-based fuels as renewable energy in the transport sector: an overview of the potential of using CBG, LBG and other vehicle fuels produced from biogas. Biofuels 13, 587–599. https://doi.org/10.1080/17597269.2020.1821571

Dalemo, M., 1996. The ORWARE Simulation Model- Anaerobic Digestion and Sewage Plant Sub-Models. Uppsala, Sweden.

Dalemo, M., Sonesson, U., Björklund, A., Mingarini, K., Frostell, B., Jönsson, H., Nybrant, T., Sundqvist, J.O., Thyselius, L., 1997. ORWARE - A simulation model for organic waste handling systems. Part 1: Model

description. Resour. Conserv. Recycl. https://doi.org/10.1016/S0921-3449(97)00020-7
Dalemo, M., Sonesson, U., Jönsson, H., Björklund, A., 1998. Effects of including nitrogen emissions from soil in environmental systems analysis of waste management strategies. Resour. Conserv. Recycl. 24, 363–381. https://doi.org/10.1016/S0921-3449(98)00064-0
den Boer, J., den Boer, E., Jager, J., 2007. LCA-IWM: A decision support tool for sustainability assessment of waste management systems. Waste Manag. 27, 1032–1045. https://doi.org/10.1016/j.wasman.2007.02.022
EBA, 2022. EBA Statistical Report 2022 [WWW Document]. Eur. Biogas Assoc. URL https://www.europeanbiogas.eu/SR-2022/EBA/
Eisenmann, 2012. MÖRRUM BIOGAS PLANT.
Ekvall, T., 2020. Attributional and consequential life cycle assessment. Sustainability Assessment at the 21st century 42–62. https://doi.org/10.5772/intechopen.89202
Ellacuriaga, M., Cascallana, J.G., González, R., Gómez, X., 2021. High-solid anaerobic digestion: Reviewing strategies for increasing reactor performance. Environ. - MDPI 8. https://doi.org/10.3390/environments8080080
Energigas Sverige, 2023. Biomethane in Sweden - market overview and policies.
Energigas Sverige, 2018. National Biogas Strategy 2.0. Sweden.
Energimyndigheten, 2021. Produktion av biogas och rötrester och dess användning år 2021. Energimyndigheten och Energigas Sverige ER 2020:25, 29.
EPA, 2018. National Overview: Facts and Figures on Materials, Wastes and Recycling [WWW Document]. URL https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials
Eriksson, O., Baky, A., 2010. Identification and testing of potential key parameters in system analysis of municipal solid waste management. Resour. Conserv. Recycl. 54, 1095–1099. https://doi.org/10.1016/j.resconrec.2010.03.002
Eriksson, O., Bisaillon, M., 2011. Multiple system modelling of waste management. Waste Manag. 31, 2620–2630. https://doi.org/10.1016/j.wasman.2011.07.007
Eriksson, O., Bisaillon, M., Haraldsson, M., Sundberg, J., 2016a. Enhancement of biogas production from food waste and sewage sludge - Environmental and economic life cycle performance. J. Environ. Manage. 175, 33–39. https://doi.org/10.1016/j.jenvman.2016.03.022
Eriksson, O., Bisaillon, M., Haraldsson, M., Sundberg, J., 2014. Integrated waste management as a mean to promote renewable energy. Renew. Energy 61, 38–42. https://doi.org/10.1016/j.renene.2012.04.024
Eriksson, O., Frostell, B., Assefa, G., Granath, J., Carlsson, M., Baky, A., Thyselius, L., 2002. ORWARE - A simulation tool for waste management. Resour. Conserv. Recycl. 36, 287–307. https://doi.org/10.1016/S0921-3449(02)00031-9

Eriksson, O., Hadin, Å., Hennessy, J., Jonsson, D., 2016b. Life cycle assessment of horse manure treatment. Energies 9, 1–19. https://doi.org/10.3390/en9121011

Eriksson, O., Reich, M.C., Frostell, B., Björklund, A., Assefa, G., Sundqvist, J.O., Granath, J., Baky, A., Thyselius, L., 2005. Municipal solid waste management from a systems perspective. J. Clean. Prod. 13, 241–252. https://doi.org/10.1016/j.jclepro.2004.02.018

European Commission, 2022. Implementing REPowerEU Action Plan, RePowerEU plan.

European Parliament, 2009. Directive on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Offic. J. Eur. Union 47, L 140/16, date: 5.6.2009. 1, 32–38.

f3, 2016. Biomethane from Biogas. Biofuel fact sheet.

Farghali, M., Osman, A.I., Umetsu, K., Rooney, D.W., 2022. Integration of biogas systems into a carbon zero and hydrogen economy: a review. Environ. Chem. Lett. 20, 2853–2927. https://doi.org/10.1007/s10311-022-01468-z

Feiz, R., 2016. Systems Analysis for Eco-Industrial develompent: Applied on Cement and Biogas production systems. Linköping University.

Feiz, R., Johansson, M., Lindkvist, E., Moestedt, J., Påledal, S.N., Ometto, F., 2022. The biogas yield, climate impact, energy balance, nutrient recovery, and resource cost of biogas production from household food waste—A comparison of multiple cases from Sweden. J. Clean. Prod. 378. https://doi.org/10.1016/j.jclepro.2022.134536

Feiz, R., Johansson, M., Lindkvist, E., Moestedt, J., Påledal, S.N., Svensson, N., 2020. Key performance indicators for biogas production—methodological insights on the life-cycle analysis of biogas production from source-separated food waste. Energy 200. https://doi.org/10.1016/j.energy.2020.117462

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle Assessment. J. Environ. Manage. 91, 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

FNR, 2012. Guide to Biogas: From production to use, Fachagentur Nachwachsende Rohstoffe e. V. (FNR) FNR,.

Gandiglio, M., Lanzini, A., Santarelli, M., Acri, M., Hakala, T., Rautanen, M., 2020. Results from an industrial size biogas-fed SOFC plant (the DEMOSOFC project). Int. J. Hydrogen Energy 45, 5449–5464. https://doi.org/10.1016/j.ijhydene.2019.08.022

García-Gen, S., Sousbie, P., Rangaraj, G., Lema, J.M., Rodríguez, J., Steyer, J.P., Torrijos, M., 2015. Kinetic modelling of anaerobic hydrolysis of solid wastes, including disintegration processes. Waste Manag. 35, 96–104. https://doi.org/10.1016/j.wasman.2014.10.012

Garcia, J.A., Villen-Guzman, M., Rodriguez-Maroto, J.M., Paz-Garcia, J.M., 2022. Technical analysis of CO2capture pathways and technologies. J. Environ. Chem. Eng. 10, 108470. https://doi.org/10.1016/j.jece.2022.108470

Ge, X., Xu, F., Li, Y., 2016. Solid-state anaerobic digestion of lignocellulosic biomass: Recent progress and perspectives. Bioresour. Technol. 205, 239/249. https://doi.org/10.1016/j.biortech.2016.01.050

Gentil, E., 2006. WRATE Waste LCA for Municipal Waste Strategies.

Gentil, E.C., Damgaard, A., Hauschild, M., Finnveden, G., Eriksson, O., Thorneloe, S., Kaplan, P.O., Barlaz, M., Muller, O., Matsui, Y., Ii, R., Christensen, T.H., 2010. Models for waste life cycle assessment: Review of technical assumptions. Waste Manag. 30, 2636–2648. https://doi.org/10.1016/j.wasman.2010.06.004

Gómez, J.M., Amelung, M., 2004. Automated generation of environmental reports with Umberto. Manag. Environ. Qual. An Int. J. 15, 258–267. https://doi.org/10.1108/14777830410531234

Guendouz, J., Buffière, P., Cacho, J., Carrère, M., Delgenes, J.P., 2010. Dry anaerobic digestion in batch mode: Design and operation of a laboratory-scale, completely mixed reactor. Waste Manag. 30, 1768–1771. https://doi.org/10.1016/j.wasman.2009.12.024

Gustafsson, M., Anderberg, S., 2022. Great expectations—future scenarios for production and use of biogas and digestate in Sweden. Biofuels 14, 93–107. https://doi.org/10.1080/17597269.2022.2121543

Gustafsson, M., Cruz, I., Svensson, N., Karlsson, M., 2020. Scenarios for upgrading and distribution of compressed and liquefied biogas — Energy, environmental, and economic analysis. J. Clean. Prod. 256, 120473. https://doi.org/10.1016/j.jclepro.2020.120473

Hadin, Å., Hillman, K., Eriksson, O., 2017. Prospects for increased energy recovery from horse manure - A case study of management practices, environmental impact and costs. Energies 10, 1935. https://doi.org/10.3390/en10121935

Hagman, L., Eklund, M., 2016. The role of biogas solutions in the circular and bio-based economy. Biogas Res. Cent. Öst. BRC Raport, 32.

Hansen, T.L., Christensen, T.H., Schmidt, S., 2006. Environmental modelling of use of treated organic waste on agricultural land: a comparison of existing models for life cycle assessment of waste systems. Waste Manag. Res. 24, 141–152. https://doi.org/10.1177/0734242X06062485

Huijbregts, M.A.J., 1998. Application of uncertainty and variability in LCA, a general framework for the analysis of uncertainty and variability in life cycle assessment. Int. J. Life Cycle Assess. 3, 273–280.

HZI, 2020a. Jönköping/Sweden Decarbonising Regional Traffic with Biogas.

HZI, 2020b. Högbytorp, SWE [WWW Document]. References. URL https://www.hz-inova.com/projects/hoegbytorp-swe/

IEA, 2022. Scaling up biomethane in the European Union: Background paper.

IEA, 2020. Outlook for biogas and biomethane. Prospects for organic growth. IEA Publ. 1–93.

IEA, 2019. Putting CO 2 to Use. International Energy Agency.

IEA Bioenergy, 2021a. Implementation of bioenergy in Denmark – 2021 update. IEA Bioenergy 1–15.

IEA Bioenergy, 2021b. Implementation of bioenergy in Finland – 2021 update. IEA Bioenergy.

IEA Bioenergy, 2021c. Implementation of bioenergy in Norway – 2021 update. Ctry. Reports.
IEA Bioenergy, 2021d. Implementation of bioenergy in Sweden – 2021 update, Country Reports.
IEA Bioenergy, 2021e. Implementation of bioenergy in Germany – 2021 update. IEA Bioenergy.
IEA Bioenergy, 2015. Nutrient Recovery by Biogas Digestate Processing.
IEA Bioenergy, 2012. Quality management of digestate from biogas plants used as fertiliser. IEA Bioenergy - Task 37 40.
Illmer, P., Gstraunthaler, G., 2009. Effect of seasonal changes in quantities of biowaste on full scale anaerobic digester performance. Waste Manag. 29, 162–167. https://doi.org/10.1016/j.wasman.2008.02.005
IPCC, 2022. Synthesis report of the IPCC sixth assessment report (AR6). Longer Report, European University Institute.
ISO, 2006. ISO 14040:2006 Environmental Management – Life Cycle Assessment – Principles and Framework.
Jewell, W.J., Cummings, R.J., Richards, B.K., 1993. Methane fermentation of energy crops: Maximum conversion kinetics and in situ biogas purification. Biomass and Bioenergy 5, 261–278. https://doi.org/10.1016/0961-9534(93)90076-G
Jordbruksverket, 2022. Hur stor andel av livsmedlen som säljs på marknaden är producerade i Sverige ?
Jordbruksverket, 2021. Food loss in Sweden.
Jordbruksverket, 2018. Energianvändning i växthus 2017 Statistikrapport 2018:05 [Energy use in greenhouses 2017 Statistics report 2018:05].
Kaza, S., Yao, L., Tata-Bhada, P., Van Woerden, F., 2018. What A Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Urban Development Series. Washington. DC: World Bank. https://doi.org/10.1596/978-1-4648-1329-0. License: Creative Commons Attribution CC BY 3.0 IGO
Kervroëdan, L., Houben, D., Guidet, J., Denier, J., Dulaurent, A.M., Marraccini, E., Deligey, A., Journel, C., Lamerre, J., Faucon, M.P., 2022. Agri-Environmental Assessment of Conventional and Alternative Bioenergy Cropping Systems Promoting Biomass Productivity. Front. Agric. Sci. Eng. 9, 284–294. https://doi.org/10.15302/J-FASE-2021435
Kirkeby, J.T., Birgisdottir, H., Hansen, T.L., Christensen, T.H., Bhander, G.S., Hauschild, M., 2006. Environmental assessment of solid waste systems and technologies: EASEWASTE. Waste Manag. Res. 24, 3–15. https://doi.org/10.1177/0734242X06062580
Kondusamy, D., Kaushal, M., Ahlawat, S., Rajendran, K., 2021. Chapter 16 - The role of techno-economic implications and governmental policies in accelerating the promotion of biomethane technologies, in: Aryal, N., Mørck Ottosen, L.D., Wegener Kofoed, M.V., Pant, D. (Eds.), Emerging Technologies and Biological Systems for Biogas Upgrading. Academic Press, pp. 447–466. https://doi.org/https://doi.org/10.1016/B978-0-12-822808-1.00016-7

Kothari, R., Pandey, A.K., Kumar, S., Tyagi, V. V., Tyagi, S.K., 2014. Different aspects of dry anaerobic digestion for bio-energy: An overview. Renew. Sustain. Energy Rev. 39, 174–195. https://doi.org/10.1016/j.rser.2014.07.011

Kumaran, P., Hephzibah, D., Sivasankari, R., Saifuddin, N., Shamsuddin, A.H., 2016. A review on industrial scale anaerobic digestion systems deployment in Malaysia: Opportunities and challenges. Renew. Sustain. Energy Rev. 56, 929–940. https://doi.org/10.1016/j.rser.2015.11.069

Kythreotou, N., Florides, G., Tassou, S.A., 2014. A review of simple to scientific models for anaerobic digestion. Renew. Energy 71, 701–714. https://doi.org/10.1016/j.renene.2014.05.055

Leonzio, G., 2016. Upgrading of biogas to bio-methane with chemical absorption process: Simulation and environmental impact. J. Clean. Prod. 131, 364–375. https://doi.org/10.1016/j.jclepro.2016.05.020

Lesteur, M., Bellon-Maurel, V., Gonzalez, C., Latrille, E., Roger, J.M., Junqua, G., Steyer, J.P., 2010. Alternative methods for determining anaerobic biodegradability: A review. Process Biochem. 45, 431–440. https://doi.org/10.1016/j.procbio.2009.11.018

Levenspiel, O., 1999. Chemical Reaction Engineering, Third Edit. ed, Chemical Engineering Science. John Wiley & Sons. https://doi.org/10.1016/0009-2509(80)80138-2

Li, Y., Park, S.Y., Zhu, J., 2011. Solid-state anaerobic digestion for methane production from organic waste. Renew. Sustain. Energy Rev. 15, 821–826. https://doi.org/10.1016/j.rser.2010.07.042

Li, Yangyang, Li, Yu, Zhang, D., Li, G., Lu, J., Li, S., 2016. Solid state anaerobic co-digestion of tomato residues with dairy manure and corn stover for biogas production. Bioresour. Technol. 217, 50–55. https://doi.org/10.1016/j.biortech.2016.01.111

Li, Yangyang, Xu, F., Li, Yu, Lu, J., Li, S., Shah, A., Zhang, X., Zhang, H., Gong, X., Li, G., 2018. Reactor performance and energy analysis of solid state anaerobic co-digestion of dairy manure with corn stover and tomato residues. Waste Manag. 73, 130–139. https://doi.org/10.1016/j.wasman.2017.11.041

Lin, L., Yang, L., Xu, F., Michel, F.C., Li, Y., 2014. Comparison of solid-state anaerobic digestion and composting of yard trimmings with effluent from liquid anaerobic digestion. Bioresour. Technol. 169, 439–446. https://doi.org/10.1016/j.biortech.2014.07.007

Lindfors, A., Hagman, L., Eklund, M., 2022. The Nordic biogas model: Conceptualization, societal effects, and policy recommendations. City Environ. Interact. 15, 100083. https://doi.org/10.1016/j.cacint.2022.100083

Lindkvist, E., Karlsson, M., Ivner, J., 2019. System analysis of biogas production—Part II application in food industry systems. Energies 12. https://doi.org/10.3390/en12030412

Lu, J., Xu, S., 2021. Post-treatment of food waste digestate towards land application: A review. J. Clean. Prod. 303, 127033. https://doi.org/https://doi.org/10.1016/j.jclepro.2021.127033

Lundmark, R., Anderson, S., Hjort, A., Lönnqvist, T., Ryding, S.O., Söderholm, P., 2021. Establishing local biogas transport systems: Policy incentives and actor networks in Swedish regions. Biomass and Bioenergy 145. https://doi.org/10.1016/j.biombioe.2020.105953

Maaoui, M., Boukchina, R., Hajjaji, N., 2020. Environmental life cycle assessment of Mediterranean tomato: case study of a Tunisian soilless geothermal multi-tunnel greenhouse. Environ. Dev. Sustain. 23, 1242–1263. https://doi.org/10.1007/s10668-020-00618-z

Maiti, S.K., Ahirwal, J., 2019. Chapter 3 - Ecological Restoration of Coal Mine Degraded Lands: Topsoil Management, Pedogenesis, Carbon Sequestration, and Mine Pit Limnology, in: Pandey, V.C., Bauddh, K. (Eds.), Phytomanagement of Polluted Sites. Elsevier, pp. 83–111. https://doi.org/https://doi.org/10.1016/B978-0-12-813912-7.00003-X

Mao, C., Feng, Y., Wang, X., Ren, G., 2015. Review on research achievements of biogas from anaerobic digestion. Renew. Sustain. Energy Rev. 45, 540–555. https://doi.org/10.1016/j.rser.2015.02.032

Marcato, C.E., Mohtar, R., Revel, J.C., Pouech, P., Hafidi, M., Guiresse, M., 2009. Impact of anaerobic digestion on organic matter quality in pig slurry. Int. Biodeterior. Biodegrad. 63, 260–266. https://doi.org/10.1016/j.ibiod.2008.10.001

Matuštík, J., Hnátková, T., Kočí, V., 2020. Life cycle assessment of biochar-to-soil systems: A review. J. Clean. Prod. 259. https://doi.org/10.1016/j.jclepro.2020.120998

McDougall, F., White, P., Franke, M., Hindle, P., 2001. Integrated solid waste management: A life cycle inventory, Oxford, UK.

Mehr, A.S., Lanzini, A., Santarelli, M., Rosen, M.A., 2021. Polygeneration systems based on high temperature fuel cell (MCFC and SOFC) technology: System design, fuel types, modeling and analysis approaches. Energy 228, 120613. https://doi.org/10.1016/j.energy.2021.120613

Mirata, M., Eklund, M., Gundberg, A., 2017. Industrial symbiosis and biofuels industry: business value and organisational factors within cases of ethanol and biogas production, Report No 2017:11, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels.

Mital, K.M., 1997. Biogas systems: policies, progress and prospects. New Age International (P) Limited, Publishers, India.

Mönch-Tegeder, M., Lemmer, A., Oechsner, H., 2014. Enhancement of methane production with horse manure supplement and pretreatment in a full-scale biogas process. Energy 73, 523–530. https://doi.org/10.1016/j.energy.2014.06.051

Nam, S.Y., Seo, J., Thriveni, T., Ahn, J.W., 2012. Accelerated carbonation of municipal solid waste incineration bottom ash for CO2 sequestration. Geosystem Eng. 15, 305–311. https://doi.org/10.1080/12269328.2012.732319

Neves, L., Gonçalo, E., Oliveira, R., Alves, M.M., 2008. Influence of composition on the biomethanation potential of restaurant waste at mesophilic temperatures. Waste Manag. 28, 965–972. https://doi.org/10.1016/j.wasman.2007.03.031

Nuzzo, R.L., 2016. The Box Plots Alternative for Visualizing Quantitative Data. PM R 8, 268–272. https://doi.org/10.1016/j.pmrj.2016.02.001

Olsson, L., Fallde, M., 2015. Waste(d) potential: A socio-technical analysis of biogas production and use in Sweden. J. Clean. Prod. 98, 107–115. https://doi.org/10.1016/j.jclepro.2014.02.015

Oreggioni, G.D., Luberti, M., Tassou, S.A., 2019. Agricultural greenhouse CO2 utilization in anaerobic-digestion-based biomethane production plants: A techno-economic and environmental assessment and comparison with CO2 geological storage. Appl. Energy 242, 1753–1766. https://doi.org/10.1016/j.apenergy.2019.03.045

Ottosson, M., Magnusson, T., Andersson, H., 2020. Shaping sustainable markets—A conceptual framework illustrated by the case of biogas in Sweden. Environ. Innov. Soc. Transitions 36, 303–320. https://doi.org/10.1016/j.eist.2019.10.008

Palansooriya, K.N., Dissanayake, P.D., Igalavithana, A.D., Tang, R., Cai, Y., Chang, S.X., 2023. Converting food waste into soil amendments for improving soil sustainability and crop productivity: A review. Sci. Total Environ. 881, 163311. https://doi.org/https://doi.org/10.1016/j.scitotenv.2023.163311

Pelayo Lind, O., Hultberg, M., Bergstrand, K.J., Larsson-Jönsson, H., Caspersen, S., Asp, H., 2021. Biogas Digestate in Vegetable Hydroponic Production: pH Dynamics and pH Management by Controlled Nitrification. Waste and Biomass Valorization 12, 123–133. https://doi.org/10.1007/s12649-020-00965-y

Persson, E., Westerholm, M., Schnurer, A., Nordin, A., Tamm, D., Nordberg, U., 2019. Dry anaerobic digestion of food waste - Report 2019:609.

Philbrook, A., Alissandratos, A., Easton, C.J., 2013. Biochemical Processes for Generating Fuels and Commodity Chemicals from Lignocellulosic Biomass. Environ. Biotechnol. - New Approaches Prospect. Appl. 39–64. https://doi.org/http://dx.doi.org/10.5772/55309

Philipp, M., 2014. Qualitative Content Analysis: theoretical foundation, basic procedures and software solution. https://doi.org/10.1016/S1479-3709(07)11003-7

Ponsá, S., Gea, T., Sánchez, A., 2011. Anaerobic co-digestion of the organic fraction of municipal solid waste with several pure organic co-substrates. Biosyst. Eng. 108, 352–360. https://doi.org/10.1016/j.biosystemseng.2011.01.007

Pöschl, M., Ward, S., Owende, P., 2010. Evaluation of energy efficiency of various biogas production and utilization pathways. Appl. Energy 3305–3321. https://doi.org/10.1016/j.apenergy.2010.05.011

Qiao, W., Yan, X., Ye, J., Sun, Y., Wang, W., Zhang, Z., 2011. Evaluation of biogas production from different biomass wastes with/without hydrothermal pretreatment. Renew. Energy 36, 3313–3318. https://doi.org/10.1016/j.renene.2011.05.002

Rathnasiri, P.G., 2016. Dynamic Modelling and Simulation of Pilot Scale Anaerobic Digestion Plant Treating Source Separated Food Waste and Effect of Recycling Sludge. Procedia Environ. Sci. 35, 740–748. https://doi.org/10.1016/j.proenv.2016.07.082

Rendek, E., Ducom, G., Germain, P., 2006. Carbon dioxide sequestration in municipal solid waste incinerator (MSWI) bottom ash. J. Hazard. Mater. 128, 73–79. https://doi.org/10.1016/j.jhazmat.2005.07.033

Sánchez Bas, M., Aragón, A.J., Torres, J.C., Osorio, F., 2022. Purification and upgrading biogas from anaerobic digestion using chemical asborption of CO 2 with amines in order to produce biomethane as biofuel for vehicles: a pilot-scale study . Energy Sources, Part A Recover. Util. Environ. Eff. 44, 10201–10213. https://doi.org/10.1080/15567036.2022.2143957

Sawatdeenarunat, C., Surendra, K.C., Takara, D., Oechsner, H., Khanal, S.K., 2015. Anaerobic digestion of lignocellulosic biomass: Challenges and opportunities. Bioresour. Technol. 178, 178–186. https://doi.org/10.1016/j.biortech.2014.09.103

Schimpf, U., Hanreich, A., Mähnert, P., Unmack, T., Junne, S., Renpenning, J., Lopez-ulibarri, R., 2013. Improving the Efficiency of Large-Scale Biogas Processes : Pectinolytic Enzymes Accelerate the Lignocellulose Degradation. J. Sustain. Energy Environ. 4, 53–60.

Schnabel, K., Brück, F., Mansfeldt, T., Weigand, H., 2021. Full-scale accelerated carbonation of waste incinerator bottom ash under continuous-feed conditions. Waste Manag. 125, 40–48. https://doi.org/10.1016/j.wasman.2021.02.027

Seuring, S., Müller, M., 2008. From a literature review to a conceptual framework for sustainable supply chain management. J. Clean. Prod. 16, 1699–1710. https://doi.org/10.1016/j.jclepro.2008.04.020

Shiflet, A.B., Shiflet, G.W., 2014. Introduction to Computational Science_ Modeling and Simulation for the Sciences, Second Edi. ed. Princeton University Press.

Siefert, N.S., Litster, S., 2014. Exergy & economic analysis of biogas fueled solid oxide fuel cell systems. J. Power Sources 272, 386–397. https://doi.org/10.1016/j.jpowsour.2014.08.044

Song, S., Lim, J.W., Lee, J.T.E., Cheong, J.C., Hoy, S.H., Hu, Q., Tan, J.K.N., Chiam, Z., Arora, S., Lum, T.Q.H., Lim, E.Y., Wang, C.H., Tan, H.T.W., Tong, Y.W., 2021. Food-waste anaerobic digestate as a fertilizer: The agronomic properties of untreated digestate and biochar-filtered digestate residue. Waste Manag. 136, 143–152. https://doi.org/10.1016/J.WASMAN.2021.10.011

Sonneveld, C., Voogt, W., 2009. Plant nutrition of greenhouse crops, Springer. Springer, London New York.

Stanturf, J.A., Callaham, M.A., Madsen, P., 2021. Chapter 1 - Soils are fundamental to landscape restoration, in: Stanturf, J.A., Callaham, M.A.

(Eds.), Soils and Landscape Restoration. Academic Press, 1–37. https://doi.org/https://doi.org/10.1016/B978-0-12-813193-0.00001-1

Stoknes, K., Scholwin, F., Krzesiński, W., Wojciechowska, E., Jasińska, A., 2016. Efficiency of a novel "Food to waste to food" system including anaerobic digestion of food waste and cultivation of vegetables on digestate in a bubble-insulated greenhouse. Waste Manag. 56, 466–476. https://doi.org/10.1016/j.wasman.2016.06.027

Sun, Q., Li, H., Yan, J., Liu, L., Yu, Z., Yu, X., 2015. Selection of appropriate biogas upgrading technology-a review of biogas cleaning, upgrading and utilisation. Renew. Sustain. Energy Rev. 51, 521–532. https://doi.org/10.1016/j.rser.2015.06.029

Svenska Ridsport Förbundet, 2016. Horses and sustainable development [WWW Document]. Lövsta Stuteri. URL https://lovsta-images.b-cdn.net/lovsta-stuteri/Horsesandsustainability.pdf (accessed 6.23.21).

Swedish Standards Institute, 2017. SS 16723-2:2017 Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network - Part 2: Automotive fuels specification.

Thöni, 2016. TTV – High solids anaerobic digestion from Thöni Forsbacka / Gävle (SE).

Thorneloe, S.A., Weitz, K., Jambeck, J., 2007. Application of the US decision support tool for materials and waste management. Waste Manag. 27, 1006–1020. https://doi.org/10.1016/j.wasman.2007.02.024

Treyer, K., 2019. Market for electricity, medium voltage, SE, Allocation, cut-off by classification. Ecoinvent database version 3.6.

UNDP, 2015. Transforming our world: The 2030 agenda for sustainable development A/RES/70/1, Research and Global Sustainability - Proceedings of the 6th International Congress on the Environment, AS 2016. https://doi.org/10.1201/b20466-7

UNEP, 2016. Global Waste Management Outlook, Global Waste Management Outlook. https://doi.org/10.18356/765baec0-en

UNFCCC, 2017. The Paris Agreement [WWW Document]. URL https://unfccc.int/process-and-meetings/the-paris-agreement

Varling, A.S., Christensen, T.H., Bisinella, V., 2023. Life cycle assessment of alternative biogas utilisations, including carbon capture and storage or utilisation. Waste Manag. 157, 168–179. https://doi.org/10.1016/j.wasman.2022.12.005

Vavilin, V.A., Fernandez, B., Palatsi, J., Flotats, X., 2008. Hydrolysis kinetics in anaerobic degradation of particulate organic material: An overview. Waste Manag. 28, 939–951. https://doi.org/10.1016/j.wasman.2007.03.028

Vo, T.T.Q., Wall, D.M., Ring, D., Rajendran, K., Murphy, J.D., 2018. Techno-economic analysis of biogas upgrading via amine scrubber, carbon capture and ex-situ methanation. Appl. Energy 212, 1191–1202. https://doi.org/10.1016/j.apenergy.2017.12.099

Walla, C., Schneeberger, W., 2008. The optimal size for biogas plants. Biomass and Bioenergy 32, 551–557. https://doi.org/10.1016/j.biombioe.2007.11.009

Wartell, B.A., Krumins, V., Alt, J., Kang, K., Schwab, B.J., Fennell, D.E., 2012. Methane production from horse manure and stall waste with softwood bedding. Bioresour. Technol. 112, 42–50. https://doi.org/10.1016/j.biortech.2012.02.012

Weitz, K., Barlaz, M., Ranjithan, R., Brill, D., Thorneloe, S., Ham, R., 1999. Life Cycle Management of Municipal Solid Waste. Int. J. Life Cycle Assess. 4, 195–201.

Westerholm, M., Liu, T., Schnürer, A., 2020. Comparative study of industrial-scale high-solid biogas production from food waste: Process operation and microbiology. Bioresour. Technol. 304, 122981. https://doi.org/10.1016/j.biortech.2020.122981

Winkler, J., Bilitewski, B., 2007. Comparative evaluation of life cycle assessment models for solid waste management. Waste Manag. 27, 1021–1031. https://doi.org/10.1016/j.wasman.2007.02.023

WMO, 2023. Global Annual to Decadal Climate Update, World Metereological Organization.

Wu, B., Zhang, X., Shang, D., Bao, D., Zhang, S., Zheng, T., 2016. Energetic-environmental-economic assessment of the biogas system with three utilization pathways: Combined heat and power, biomethane and fuel cell. Bioresour. Technol. 214, 722–728. https://doi.org/10.1016/j.biortech.2016.05.026

Xia, A., Murphy, J.D., 2016. Microalgal Cultivation in Treating Liquid Digestate from Biogas Systems. Trends Biotechnol. 34, 264–275. https://doi.org/10.1016/j.tibtech.2015.12.010

Yang, L., Xu, F., Ge, X., Li, Y., 2015. Challenges and strategies for solid-state anaerobic digestion of lignocellulosic biomass. Renew. Sustain. Energy Rev. 44, 824–834. https://doi.org/10.1016/j.rser.2015.01.002

Yong, Z., Dong, Y., Zhang, X., Tan, T., 2015. Anaerobic co-digestion of food waste and straw for biogas production. Renew. Energy 78, 527–530. https://doi.org/10.1016/j.renene.2015.01.033

Zeshan, Karthikeyan, O.P., Visvanathan, C., 2012. Effect of C/N ratio and ammonia-N accumulation in a pilot-scale thermophilic dry anaerobic digester. Bioresour. Technol. 113, 294–302. https://doi.org/10.1016/j.biortech.2012.02.028

Zhang, Q., Hu, J., Lee, D.J., 2016. Biogas from anaerobic digestion processes: Research updates. Renew. Energy 98, 108–119. https://doi.org/10.1016/j.renene.2016.02.029

Zhang, W., Lang, Q., Pan, Z., Jiang, Y., Liebetrau, J., Nelles, M., Dong, H., Dong, R., 2017. Performance evaluation of a novel anaerobic digestion operation process for treating high-solids content chicken manure: Effect of reduction of the hydraulic retention time at a constant organic loading rate. Waste Manag. https://doi.org/10.1016/j.wasman.2017.03.034

**Papers**
Associated papers have been removed in the electronic version of this thesis.
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