YRKESHÖGSKOLAN NOVIA

Comparative Analysis of Dry and Wet Fermentation Processes for Biogas Production in Northernmost Norway

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Abstract

This thesis investigates biogas production in northern Norway, focusing on wet and dry fermentation methods. Stemming from the Boost Nordic Biogas initiative, in collaboration with Rå Biopark, the study aims to enhance biogas production in the region. By comparing wet and dry fermentation, it seeks to identify the most suitable approach for the unique challenges of northern Norway. The objectives include researching fermentation processes, conducting a comparative assessment, and evaluating feasibility.

First, the thesis delved into existing literature on biogas in Norway, followed by research of dry and wet technologies. Subsequently, three reactors were dimensioned to compare their sizes.

The study highlights significant disparities of up to 1000 m^3 between the anticipated and actual dimensions of digesters. These calculations are based on operating conditions at a mesophilic temperature of approximately 35°C, with a retention time of 25 days. For the second line, two digesters were designed: a wet technology digester with a capacity of 7686.67 m^3 and a dry technology digester with a capacity of 6478.34 m^3, illustrating the latter's advantage in size due to the lower water content in the feedstock.

While wet fermentation remains the preferred choice due to its maturity and efficiency, this study suggests allocating resources to further develop dry fermentation technology.

Language: English
Key Words: Anaerobic Digestion, Biogas, Dry Fermentation, Wet Fermentation, Renewable Energy, Norway

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GLOSSARY

Terms will be defined to facilitate the understanding of the material beforehand.

Anaerobic digestion: This is a biological process in which microorganisms break down organic materials in the absence of oxygen, producing biogas and digestate as by-products.

Biogas: A mixture of gases, primarily methane and carbon dioxide, produced through anaerobic digestion.

Moisture Content: Amount of water present in a material is typically expressed as a percentage of the total mass.

Dry Content: Portion of material that remains after removing all moisture, expressed as a percentage of the total mass.

Total Solids (TS): The combined mass of solids present in a material, including both organic and inorganic components, expressed as a percentage of the total mass.

Organic Loading Rate (OLR): The rate at which organic material is introduced into an anaerobic digestion system, typically measured in kilograms or tonnes per unit volume per day.

Substrates: Organic materials, such as agricultural residues, food waste, and sewage sludge, are fed into an anaerobic digestion system to produce biogas.

Digestate: The nutrient-rich residue is fed into an anaerobic digestion process, often used as a fertilizer or soil amendment.

County: A geographical and administrative division within a country often used for local governance purposes.

Inhibitor Toxins: Substances that interfere with the activity of microorganisms in anaerobic digestion, reducing biogas production and overall efficiency.

Units

m^3	Cubic meters
yr	Year
t	Tonne
kg/m^3	Density
m	Metre
ºC	Degree Celsius
W	Watt
h	Hour
mV	millivolts

1 Introduction

Biogas has emerged as a viable alternative for electricity, heat, and fuel production in regions with ample organic materials, fostering a trajectory toward carbon-neutral energy generation. Its adoption is widespread in Scandinavian countries and is gradually gaining traction in Southern Europe (BioKraft, 2022). Norway, with its commitment to becoming a low-emission society by 2050, stands at the forefront of this transition.

This thesis project originated from the Boost Nordic Biogas initiative, which is supported by Interreg Aurora and aims to enhance biogas production in the northern regions of Finland, Sweden, and Norway. Given that Rå Biopark is the foremost undertaking in northern Norway, collaboration with Rå Biopark is crucial for the project's success (BioFuel Region, 2024). Rå Biopark, is endeavoring to invest in an anaerobic biogas plant located in northern Scandinavia, an area where previous efforts have not succeeded. The primary focus of the examination lies in the collection of resources and the fermentation techniques employed. This thesis entails a thorough examination of both wet and dry fermentation methods.

Comparative analysis of dry and wet fermentation processes for biogas production in northernmost Norway is a critical area of research because of the region's unique environmental conditions. Biogas, a renewable energy source, is produced through the anaerobic digestion of organic materials. The choice between dry and wet fermentation methods has significant implications for biogas yield, process efficiency, and environmental impacts.

This study examined the specific challenges and opportunities for biogas production in the northernmost region of Norway, where cold temperatures and limited organic waste resources present distinct challenges for both dry and wet fermentation processes. By comparing the performance of these two methods in this unique context, I aim to provide valuable insights into the most suitable approach for biogas production for the biogas plant studied. Furthermore, the findings of this research will contribute to the development of sustainable energy solutions tailored to the specific needs of northern communities.

1.1 Objectives

The primary aim of this project was to conduct a feasibility study of wet and dry fermentation for biogas production in the northern region of Norway. This study aimed to assess the viability and potential benefits of implementing a single technology or a combination of them for biogas generation in this specific geographical context.

The following objectives were identified to achieve this overarching goal:

- Research into fermentation process literature.
- Identify the key parameters involved in fermentation for the functionality of such a project.
- Conduct a comparative assessment between dry and wet digesters, evaluating their respective dimensions and performance metrics.
- Assess the feasibility of implementing dry or wet fermentation biogas technology specifically tailored for a plant situated in northern Norway.

1.2 Disposition

This section will outline the chapters comprising this thesis, offering a brief overview of their content.

1. Introduction: introduces the background in which the thesis is situated, delineating its aims, objectives, and structure.
2. Study background: explores Norway's renewable energy efforts, highlighting its leading position in Europe's renewable electricity generation and delving into the country's challenges in meeting emission targets and its promotion of biogas as a sustainable solution defining the concept, clarifying the process, and identifying the key parameters.
3. Literature review: a comprehensive investigation of each technology has been made for a later comparison between them. Following with an in-depth examination of the feedstock employed in Norway has been undertaken, aiming to

specify those suitable for implementation within the studied region, delineating their characteristics, and assessing their respective availability.

4. Methodology: after the research, dimensioning of the digester has been made, considering two lines for treatment of the feedstock. One line is dedicated to sewage sludge while the other handles the remaining feedstock. The dimensioning of the second line encompasses both dry and wet technologies, facilitating a subsequent comparative evaluation. Then an energy consumption comparison of the two technologies.

5. Description of the planned plant in Norway: briefly describe the plant studied, including its location, ownership, and a concise overview of the planned sections. Additionally, the anticipated outcomes of the project are outlined.

6. Results and Discussion: a sensitivity analysis is conducted using the information explained within the thesis, recalling the objectives and aims presented at the outset of the study.

7. Conclusion: wrap up the discussion and will offer suggestions for further considerations.

8. References: list with all the references

9. Appendices: provide tables and calculations to complete the understanding of the thesis

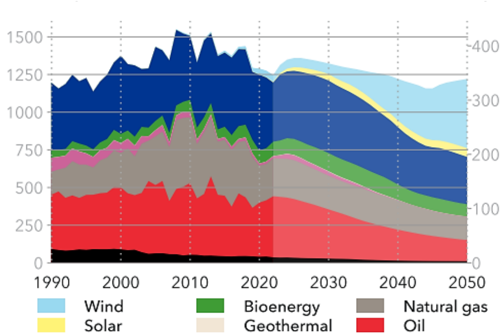
2 Study Background

In this section, the background regarding renewable energy in Norway is provided, followed by an exposition on biogas in their energy transformation process, and key parameters with a consecutive overview of the status of biogas in Norway are presented.

2.1 Renewable Energy Initiatives in Norway

Norway stands as an example of the potential renewable energy. With close to half of its total energy supply coming from renewable sources, the country boasts the highest share of renewable electricity generation in Europe. Hydropower remains the backbone of its energy consumption, contributing a staggering 88%. However, Norway recognizes the significance of diversification for long-term sustainability. The 2023 Energy Transition Norway 2050 report highlights Norway's failures to meet the greenhouse gas emission reduction targets set by the Paris Agreement. Despite political consensus on achieving 55% and 100% reductions by 2030 and 2050, respectively, Norway is projected to fall short with reductions of only 27% by 2030 and 80% by 2050 (Business Norway, 2024).

In 2023, Norway's total production was 145.9 TWh, as can be seen in Figure 1 which is divided between these three sources, hydropower with a percentage of 88%, as mentioned before, wind power with a share of 10,1% and following up with thermal power with 1,9%. While biomass plays a role in the renewable energy mix, primarily as a source of heat and liquid biofuels, still has numerous paths to go while it continues to grow (Norsk Industri, 2023).



Adjusted for gross electricity trade, using average European electricity mix
Historical data source: IEA WEB (2023), SSB (2023)

Figure 1. Norway's primary energy consumption by source, (Norsk Industri, 2023)

Norway has been actively promoting renewable energy sources, including biogas, to reduce its carbon footprint and achieve its climate goals.

Norway's commitment to a sustainable future extends beyond electricity generation. Recognizing the impact of the transport sector on emissions, the country has set ambitious goals. By 2050, they aim for all new city buses to be zero-emission or powered by biogas. To achieve this, government agencies like Enova and Innovation Norway provide crucial support. Enova offers financial subsidies for the production of biogas and biofuels, along with the purchase of biogas-powered vehicles and electric machinery. Innovation Norway further extends this support by providing grants for small-scale biogas and woodchip production in the agricultural sector (International Energy Agency, 2022).

Norway's renewable energy ambitions are underpinned by a robust policy framework designed to promote sustainable practices and reduce greenhouse gas emissions. This framework includes several key measures: the Renewable Energy Act (REA) which provides the legal framework for promoting renewable energy sources (Lovdata, 2023); the Green Certificate System, fostering collaboration with Sweden to incentivize renewable energy production (Energifakta Norge,2023); Feed-in Tariffs and Market-based Mechanisms ensuring smooth integration of renewables into the grid; Renewable Portfolio Standards (RPS) setting targets for renewable electricity generation; government support for Research and Development driving innovation; Environmental Regulations ensuring responsible operation of biogas plants; Promotion Through Quotas by grid operators; a Landfill Ban diverting organic waste from landfills to foster biogas generation (CCAC, 2024); and recent policies like the National Transport Plan and Urban Growth Agreements, targeting a 50% reduction in emissions by 2030, with a focus on using biogas for new city buses by 2025 (Samferdselsdepartementet, 2021). These measures collectively aim to accelerate Norway's transition towards a sustainable, low-carbon future.

2.2 Background Biogas production

Biogas is a renewable energy source that is produced through anaerobic digestion after organic materials are broken down by bacteria in an oxygen-free environment (EESI, 2023). The biogas will be primarily composed of methane, in a proportion ranging from 50% to 70%, and carbon dioxide, from 30% to 50%. The amount of methane and carbon dioxide varies depending on the type of organic substrate used and the pH of the reactor. Further other gases such as water vapor, hydrogen sulphide, etc, will also be found in smaller proportions (Digestion Anaerobia, 2014).

Anaerobic digestion is characterized by the existence of consecutive several stages and reactions, many of them happening at the same time, employed to degrade the substrate (Balasubramaniyam et al., 2008). This conversion of complex organic compounds is carried out in a sequence of four stages: Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis. During hydrolysis organic substrates such as lipids, proteins, carbohydrates, and inorganic compounds are converted into smaller components through the action of hydrolytic enzymes. The hydrolysis rate depends on the particle size and the percentage of lignocellulosic materials (Bennardi, n.d.). Then acidogenic bacteria, characterized by being fermentative, use these smaller compounds and produce short-chain carboxylic acids with low molecular weight and subproducts such as ethanol, carbon dioxide, methane, and hydrogen. These intermediate products resulting from the acidogenic stage will be transformed by acetogenic bacteria, obtaining hydrogen, carbon dioxide and acetic acid as the main products. The last stage will be the methanogenesis where the acetic acid, hydrogen and carbon dioxide are transformed into methane and carbon dioxide (Digestion Anaerobia, 2014). This transformation occurs through two reactions:

Acetoclastic Pathway:

$$\mathrm{CH_3COOH \rightarrow CH_4 + CO_2}$$

Hydrogenotrophic Pathway:

$$\mathrm{CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O}$$

Most of methane is produced through the stage of methanogenesis, around 70% of the methane is produced in general (Bennardi, n.d.).

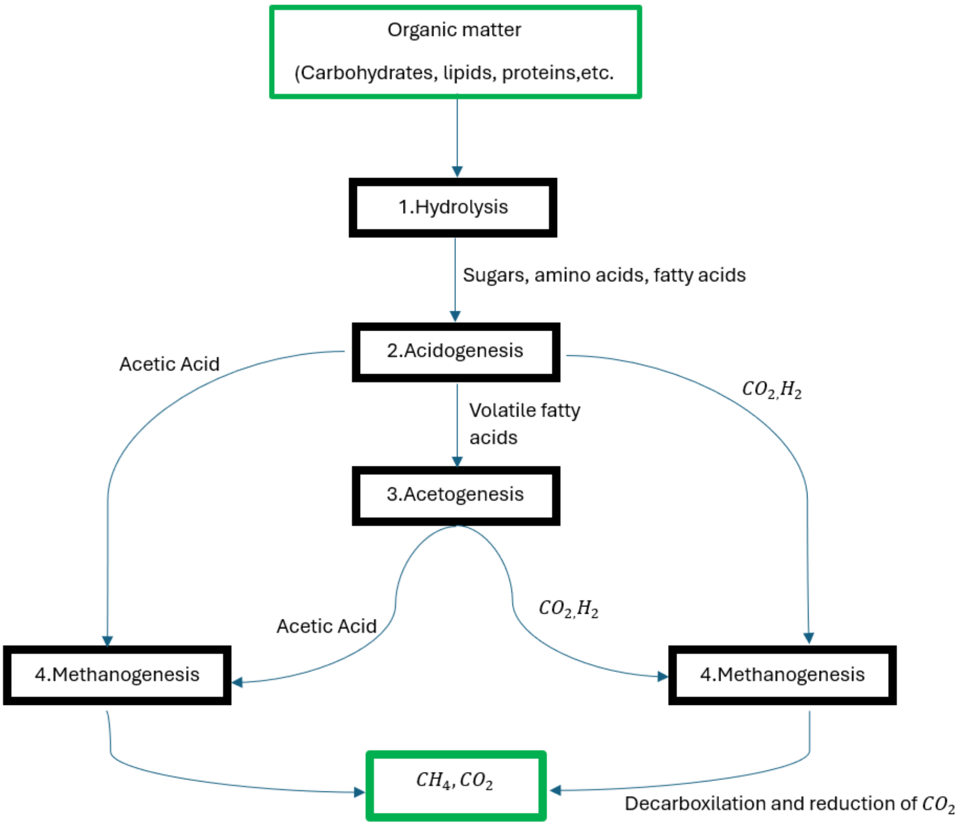


Figure 2. Scheme of anaerobic digestion, (author's own)

Anaerobic digestion will be significantly influenced by the conditions under which the process takes place. Generally, a distinction can be made between environmental parameters and operational parameters.

2.2.1 pH parameter

Let's commence by examining environmental parameters. The first factor for discussing is pH, where for the process to develop satisfactorily, the pH should not drop below 6.0 or rise above 8.0. The pH value in the digester not only determines biogas production but also its composition. A decrease in pH to a value below 6 results in biogas with low methane content and, therefore, lower energy qualities. Maintaining the pH near neutrality is crucial due to methanogenesis being considered the limiting stage of the process. Acidogens are significantly less sensitive to extreme pH values (Manual de biogas, 2011).

2.2.2 Redox potential

The next variable is the redox potential, used to describe a system's overall reducing or oxidizing capacity (Sondergaard, 2009). It must be sufficiently low for the strict methanogenic microorganisms to thrive, as these microorganisms require oxidation-reduction potentials below -300mV (Digestion Anaerobia, 2014).

2.2.3 C/N Ratio

Followed with the concept of nutrients described as the residues for digestion must have an appropriate ratio to facilitate the development of microorganisms involved in the process. The key elements to consider are nitrogen, carbon, and phosphorus. The C/N ratio should be around 30/1 and the C/P ratio should be 150/1 (Digestion Anaerobia, 2014).

2.2.4 Inhibitor toxins

The last environmental parameter is inhibitor toxins, where an increase in specific compounds in the biodigester can elevate the inactivity of microorganisms responsible for anaerobic digestion. The magnitude of the effect will depend on the nature and concentration of the inhibitory substance (Byosis group, 2017).

2.2.5 Temperature

Furthermore, operational parameters play an important role too, starting with temperature which significantly affects the anaerobic process. Reaction rates, anaerobic digestion, biogas composition, and potential damage to microorganisms depend on this parameter. The anaerobic process requires a minimum temperature of 4 to 5ºC to initiate and should not exceed approximately 80ºC. Depending on the working temperature three main groups are categorized (Wang et al., 2019). Table 1 illustrates that higher temperatures result in shorter biomass degradation process times.

Table 1. Range of temperatures and time of anaerobic fermentation.

Fermentation	Minimum	Optima	Maximum	Duration
Psychrophilic	4-10ºC	15-18ºC	20-25ºC	Around 100 days
Mesophilic	15-20ºC	25-25ºC	35-45ºC	30-60 days
Thermophilic	25-45ºC	50-60ºC	75-80ºC	10-15 days

(Bennardi, n.d)

Biogas production is sluggish and less efficient in the psychrophilic range, where cold temperatures inhibit the activity of methanogenic bacteria, rendering it less viable due to the large reactor dimensions required. In the mesophilic range, which is the most common temperature range for anaerobic digestion, biogas production is efficient and relatively stable, with optimal conditions around 35-37°C (Santa Fe, n.d). In contrast, the thermophilic range promotes faster biogas production due to the activity of thermophilic bacteria, but it also presents challenges such as sensitivity to temperature and pH fluctuations. Its main disadvantage lies in the energy cost and sensitivity to the heating system, requiring precautions such as preheating the substrate to minimize temperature variations (Cleanergy, n.d).

2.2.6 Agitation

Another parameter to consider is agitation, depending on the volume, characteristics of the digestate, and the residue, the power needed to cover will vary. Typically, the range varies between 30 W·h/m^3·day and 100 W·h/m^3·day. Mixing is important because achieves a homogenization of the feed substrate with the substrate undergoing digestion, ensures uniform distribution of heat and prevents foam formation and sedimentation. (Caminos et al., 2016).

2.2.7 Particle size

Moreover, particle size will be closely related to the rate of organic matter solubilization. A smaller particle size achieves an increase in available surface area, thus improving the biogas production in substrates with high fiber content and low biodegradability (South African Journal of Chemical Engineering, 2015).

2.2.8 Retention time

The next parameter is the retention time defined as the period during which the substrate remains in the anaerobic digestion system, subjected to the action of microorganisms. This time is calculated by dividing the reactor volume by the substrate feeding rate. It is an important measure as it determines the effectiveness of the digestion process and affects the quantity and quality of the biogas produced. A longer retention time may allow for greater degradation of organic matter and thus higher biogas production, but it can also increase operational costs (Biomasa Digestores, 2007).

2.2.9 Organic Loading Rate

Finally, the term organic loading rate refers to the amount of organic material, usually measured in terms of chemical oxygen demand or volatile solids, that is fed into the system per unit of time (g/L-d). This loading rate is a crucial factor in determining the efficiency and performance of the AD process. If the organic loading rate is too high, it can lead to process instability, inhibition of methane production, and accumulation of volatile fatty acids. On the other hand, if the loading rate is too low, it may underutilize the capacity of the system, implying a low concentration in the influents and/or a high retention time (Labatut & Pronto, 2018).

2.3 Overview of Biogas Production in Norway

Biogas production in Norway has gained significant traction in recent years, emerging as a sustainable solution to multiple environmental and energy challenges. Norway, known for its commitment to renewable energy and environmental conservation, has embraced biogas production as a vital component of its energy transition strategy. As it has been shown in their government support and policies described in Chapter 2.1.

Biogas plants are operational, with the world’s largest liquid biogas producer located near Trondheim. This eco-friendly fuel is already used in buses and waste collection vehicles, with aspirations to expand to heavy-duty trucks and even ships. From the latest report of

2023 made by the Norwegian Waste and Recycling Associations (Norwaste), Norway counts around 60 active biogas plants that produce 740 GWh. Notably, 63% of the biogas was upgraded to Compressed Biogas (CBG) and Liquefied Biogas (LBG), amounting to 456 GWh. Both LBG and CBG experienced increases of 5% and 1%, respectively, compared to 2022. The ownerships of these facilities are fairly distributed, with 47% under municipal management and 33% privately owned. The primary substrates utilized include sewage sludge, food waste, and fish silage. Furthermore, approximately 600,000 tons of biogas digestate were produced as a fertilizer. This industry contributed to a value creation of 1.480 billion NOK and employed for 1,258 full-time equivalents. Norway's biogas sector comprises 39 refueling stations, with an additional 40 stations in development, with CBG dominating the market at 79% (Biogasstatistikk, 2023).

Based on the 2023 report, there is a clear indication of the necessity for a biogas production facility in the Tromsø area. Currently, most biogas plants in Norway are situated in the southern region of the country, as it can be seen in Figure 2, this is primarily due to shorter distances and higher population density in that area. The establishment of a Tromsø station is slated for September 2025.

Figure 2. Location of biogas plants in Norway, (Biogasstatistikk, 2023)

3 Literature Review

In this chapter, a thorough examination of both dry and wet fermentation processes is presented, culminating in a summarising-comparison table. This is followed by an explanation of the feedstocks utilised in both Norway and the specific region, detailing their respective characteristics.

3.1 Dry Fermentation Process

3.1.1 Definition and overview

Dry fermentation, also called solid-state anaerobic digestion (SSAD) (Renergon, 2018), is a method for producing biogas from organic waste with high dry matter content ranging between 15% and a maximum of 40%. This versatile process can be executed in either a continuous or discontinuous system, offering flexibility to diverse operational setups (Weiland, 2010).

Dry anaerobic digestion systems excel in accommodating substrates rich in crop residues, household waste, and livestock manure. Unlike wet systems, dry fermentation systems do not require the need for organic matter movement or liquid addition (Bioferm, n.d). However, it is important to note that although they may not require liquid addition, the liquid within the digester still necessitates recirculation and percolation to ensure optimal bacterial activity.

3.1.2 Feedstock

The choice of feedstock depends on factors like local availability of raw material with a high solids content, the biomethane production potential, and economic aspects (Wang et al., 2023). Dry AD systems are particularly suited for organic wastes with low moisture content. Co-digestion of substrates, such as cattle slurry with fruit or vegetable waste, can enhance methane yields but requires careful feedstock control to prevent process instability (Rocamora et al., 2020).

Some parameters to consider regarding the feedstock influencing process efficiency are the carbon-to-nitrogen (C/N) ratio and total solids (TS) contents. Achieving an optimal C/N ratio, typically between 20 and 30, is essential for microbial growth and stable digestion (Bouallagui et al., 2009). Dry AD typically operates with high TS content, however high TS content can limit mass transfer between microbes and substrates, negatively impacting microbial metabolism and methane production (Wang et al., 2020).

3.1.3 Process management

3.1.3.1 Batch

Batch mode, also known as "garage-digesters" (BiogasWorld, 2024), is a process where all the substrate and nutrients are added at zero time or soon after inoculation takes place. Inoculum is a way of accelerating the start-up period. Commonly, previous batch digestate or sewage sludge are used as inoculum sources. Experts recommend a range from using 50% digestate as inoculum (Karthikeyan and Visvanathan, 2013) to ratios of 1:1.15 to 1:2.5 (Di Maria et al., 2012). Finding the balance between inoculum quantity and the substrate is crucial for optimizing batch-dry AD processes. Then the strategy of percolate recirculation is widely adopted to mitigate inhibition issues and accelerate the process. While various recirculation strategies exist, such as continuous or intermittent schemes, all have demonstrated increased methane yields compared to no recirculation (Chen et al., 2008). The mixture is discharged at the end of each batch digestion. Those kinds of digesters are characterized by low investment and a strong resistance to various substrates. The influent solid concentration is usually around 20% to 40% (He et al., 2019).

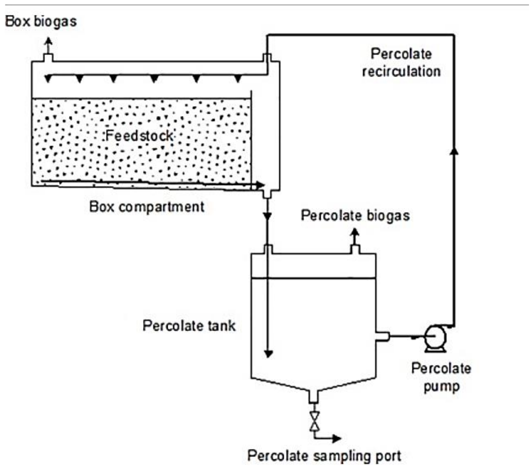


Figure 3. Scheme of a batch, "garage-type" reactor, (Cleaner Production, 2020).

3.1.3.2 Continuous

These digesters are designed to allow feedstock to flow through the digester in a continuous plug, ensuring that the oldest material is at the discharge end. They are typically used for liquid or semi-liquid feedstocks and can handle a range of solid concentrations

Biogas and methane production in continuous systems are determined by the organic loading rate (OLR) (Rocamora et al., 2020). OLR is a key design parameter for continuous dry AD systems, with optimum values typically higher than those in wet AD processes due to the higher total solids (TS) content of substrates (Karthikeyan and Visvanathan, 2013). However, high OLRs exceeding the digester's capacity can lead to reduced methane production and process disturbances due to the accumulation of volatile fatty acids and pH drops, hindering methanogenic activities and possibly causing process failure (Ganesh et al., 2013).

In these types of reactors impellers are used, blades or vanes that rotates causing the substrate to move or be pressurized, which allows a minimal mixing for a better performance. This minimal mixing allows to have a better contact between microorganisms and substrate (Patinvoh, 2017). In dry AD, mixing becomes more critical due to the high total solids content and some authors highlight potential negative effects as inhibition caused by intensive mixing (Singh et al., 2019). There is a notable lack of comprehensive studies addressing the effects of mixing, and opinions on the matter vary. Therefore, further research in this field is needed.

Nevertheless, some shortcomings, such as lower mass transfer due to a lack of mixing, thermal stratification, and solid sedimentation problems have been reported (Patinvoh, 2017).

Figure 4 depicts a prototype of a new plug flow reactor developed specifically for continuous dry digestion processes as part of a study aimed at investigating process stability.

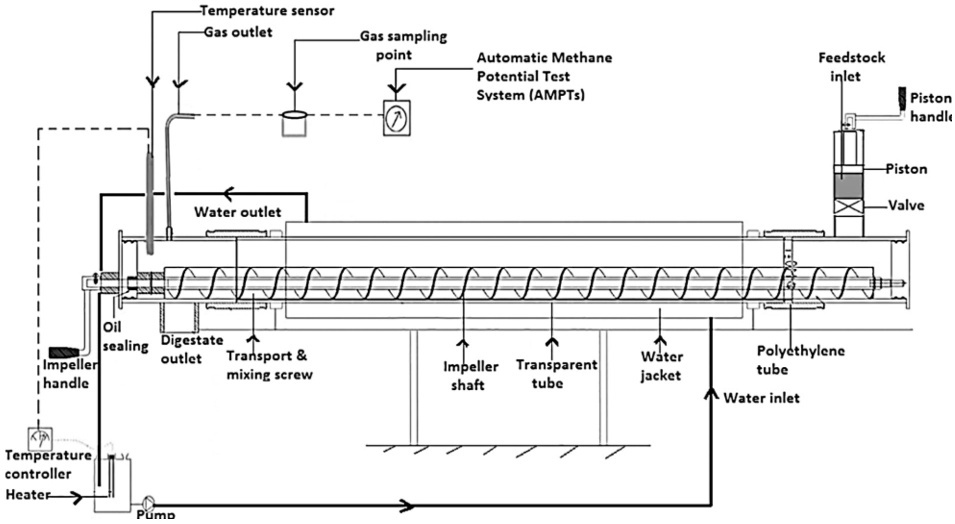


Figure 4. Plug flow reactor prototype (Bioresource Technology, 2017)

3.1.4 Process monitoring

Anaerobic digestion is a complex biochemical process driven by a diverse consortium of microorganisms, rendering it highly sensitive to pH conditions. In single-stage AD systems, pH fluctuations are typically influenced by volatile fatty acid (VFA) concentration and alkalinity. During the initial stages of batch AD reactors, pH tends to decrease due to rapid hydrolysis/acidification kinetics and organic acid buildup, but this decrease may be offset by ammonia production. Subsequently, pH increases as methanogenic archaea convert VFAs into methane. However, excessive acidification below pH 6.5 can negatively impact methanogenic activity, necessitating avoidance of such conditions.

Maintaining an appropriate pH range is crucial for AD process stability. Alkalinity, indicative of the system's buffering capacity, plays a crucial role in preventing drastic pH changes. Research suggests that increasing alkalinity through bicarbonate addition can elevate operating pH levels, leading to improved methane production (Ward et al., 2008).

As it was detailed in Chapter 2.2 Biogas background temperature significantly influences the fermentation process. In the context of dry AD, the adoption of thermophilic temperatures may be less common due to the need for stringent process control and detailed study. Consequently, mesophilic operations are more popular due to its stability and cost-effectiveness (Labatut et al., 2014).

In both dry and wet anaerobic digestion (AD) systems, inhibitory issues are prevalent, but dry AD systems are more susceptible to the accumulation of inhibitors. This susceptibility is attributed to factors such as high organic loading rates (OLR) and total solids (TS) content, coupled with low or absent mixing, leading to inadequate homogenization (Abbassi-Guendouz et al., 2012). Consequently, inhibitors like fatty acids and ammonia tend to accumulate more readily. Despite this, dry AD exhibits a higher tolerance to inhibitors compared to wet AD systems and can operate effectively at elevated concentrations of volatile fatty acids (VFA) or ammonia (Dong et al., 2010).

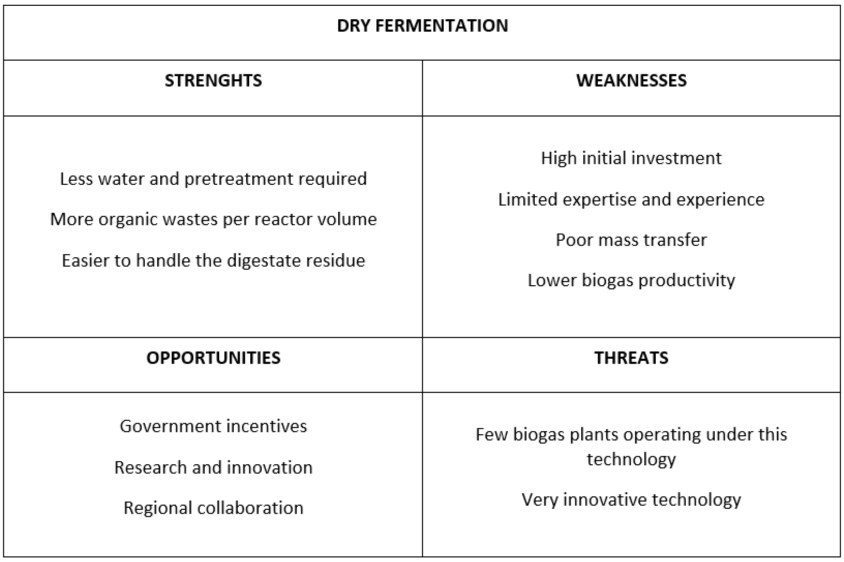
3.1.5 Challenges and opportunities

Dry AD technology offers several advantages, such as less pretreatment, reduced digester volume allowing to process more organic wastes per reactor volume (Pavintoh, 2017), improved feedstock flexibility, and enhanced handling of low moisture digestate (Wang et al., 2023). Moreover, its merits extend to the reduced or absence, in some cases, of moving parts within the reactor, mitigated volatile solids loss during pretreatment, augmented Organic Loading Rate (OLR), cost-effectiveness in pretreatment procedures, and diminished heat requirements. These attributes collectively position the dry AD technology as a promising avenue (Vandevivere et al., 2002). Furthermore, in dry anaerobic digestion, issues like foam, sedimentation, and surface crust are absent, eliminating the need for energy-intensive stirring equipment (Schäfer et al., 2006).

However, challenges persist, particularly on the technical and economic fronts. One significant obstacle lies in optimizing mass transfer. The yield stress of anaerobically digested solid waste increases exponentially with total solids (TS) content, hindering both mass transfer and homogenization, thereby elevating energy consumption (Wang et al., 2023), resulting in lower biogas productivity compared to wet technology (Vandevivere et al., 2002). Moreover, heat and material transfer are highly sensitive to temperature and pH fluctuations, rendering them susceptible to toxic shocks, which may require prolonged contact times for recovery (Lopez, 2013).

For a better understanding of the strengths and weaknesses of dry fermentation technology a SWOT table was made, in order to have a visual representation of the factors just described. Emphasizing in while it has a consistent strength, such as less water and pretreatment required this is counterpart by having a lower biogas productivity and taking a high risk because of the lack of experience in this type of plants.

Table 2. SWOT Analysis for Dry Fermentation



DRY FERMENTATION	
STRENGHTS	**WEAKNESSES**
Less water and pretreatment required More organic wastes per reactor volume Easier to handle the digestate residue	High initial investment Limited expertise and experience Poor mass transfer Lower biogas productivity
OPPORTUNITIES	**THREATS**
Government incentives Research and innovation Regional collaboration	Few biogas plants operating under this technology Very innovative technology

(Author's own)

3.2 Wet Fermentation Process

3.2.1 Definition and overview

In contrast to dry processes, wet fermentation systems operate with a dry matter content not exceeding 15%, necessitating the addition of liquid for the movement of organic material. These systems entail multiple pretreatment steps for biomass and organic waste input, including the separation of non-organic materials, liquefaction, sand separation, and sanitization. Primarily utilized for anaerobic digestion of sewage sludge, manure, or other liquid inputs, solid residues must be diluted to achieve a concentration of 10 to 15% solid matter (Lopez, 2013). Typical wet fermentation systems consume 10-30% of the energy generated for plant operation, with additional energy required for wastewater treatment processes. This highlights the considerable energy demands associated with wet fermentation systems compared to their dry counterparts (Bioferm, n.d).

3.2.2 Process conditions

The type of incoming material for wet fermentation systems primarily caters to liquid inputs, although solid materials can be accommodated provided they undergo dilution. However, if the substrate mix proves too dry, additional water or materials with lower dryness, such as septic tank sludge, may be required to achieve optimal conditions.

In the presence of inert compounds like plastics, glass, or sand within the feed, digesters may encounter several challenges. These compounds can accumulate at the bottom of the digester, reducing its useful volume, while also posing risks of damage to pumps, mixers, and potential blockages in pipes

Process stability is crucial for the efficient operation of wet fermentation systems. An unbalanced feed can lead to acidosis issues, necessitating the shutdown of the installation. In such cases, the entire system may need to be halted, with drainage and restart procedures extending over 2 to 3 months, emphasizing the significant downtime and potential disruptions associated with process instability (Lopez, 2013).

3.2.3 Advantages and disadvantages

The advantages of wet fermentation systems are manifold, excelling in substrate homogenization, enhancing the overall efficiency of the digestion process, and resulting in improved biogas production (Marjolaine, 2022). Another notable advantage is the reduction in residence time required for the digestion process, further optimizing operational efficiency and output (Lopez, 2013) and the equipment to handle slurries is cheaper (Vandevivere et al., 2002).

Wet fermentation systems, while offering various advantages, also come with notable disadvantages. One such drawback is the necessity to add liquid to reduce the dry matter content of the mixture, which can complicate the handling and processing of feedstock. Moreover, these systems require robust and costly mixing equipment to ensure proper homogenization and efficient digestion. The significant energy requirements of the facility to run pumps and agitators further add to the operational costs (Marjolaine, 2022). Additionally, wet fermentation systems typically yield digestate with lower dry matter content, altering practices for land application and potentially necessitating additional investments in storage and handling facilities. The need for significant recirculation equipment and the cost associated with digestate dehydration pose further challenges (Lopez, 2013).

Figure 5 illustrates the complexity of wet AD technology, showing all the stages that the feedstock has to go through, in the simplest way.

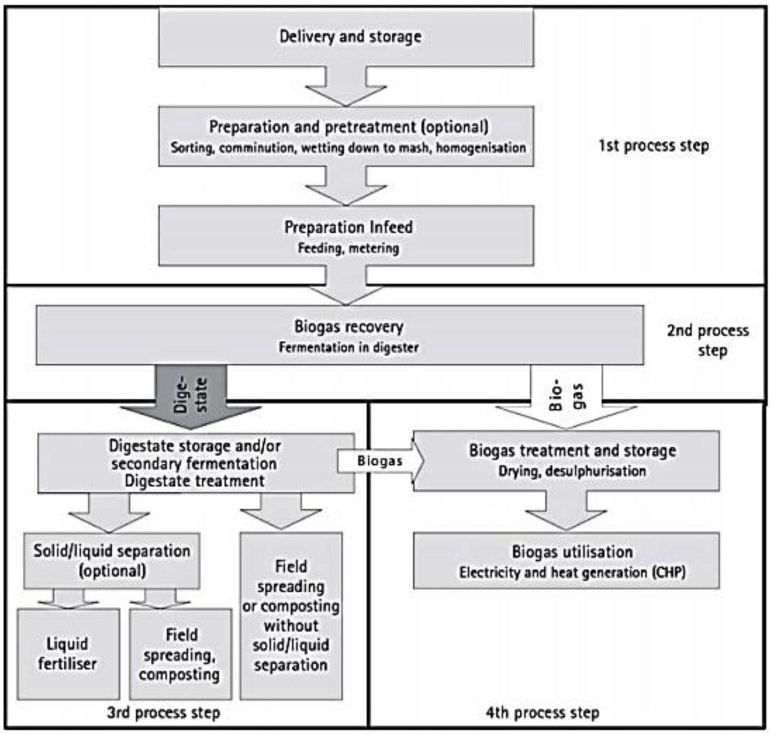


Figure 5. General process of biogas through wet fermentation, (Guide Biogas, 2010)

As well as the dry fermentation section, a SWOT analysis for wet fermentation has been made too. In the following Table 3 a compilation of some important aspects of this technology has been covered to have a visual representation of what it was described in this section. Highlighting certain key aspects underscores the process's strengths, such as its high gas production rate and versatile feedstock options, as well as its weaknesses, including energy intensity and challenges in digestate management. Opportunities for improvement include technological advancements and integration with wastewater treatment, while threats stem from regulatory constraints and public perception concern

Table 3. SWOT Analysis for Wet Fermentation

WET FERMENTATION	
STRENGHTS	**WEAKNESSES**
High gas production rate Versatile feedstock options Efficient mixing and substrate distribution Nutrient-rich digestate	Energy-intensive Digestate management challenges Sensitivity to feedstock composition
OPPORTUNITIES	**THREATS**
Technological advancements Integration with wastewater treatment	Regulatory Constraints Public perception and acceptance

(Author's own)

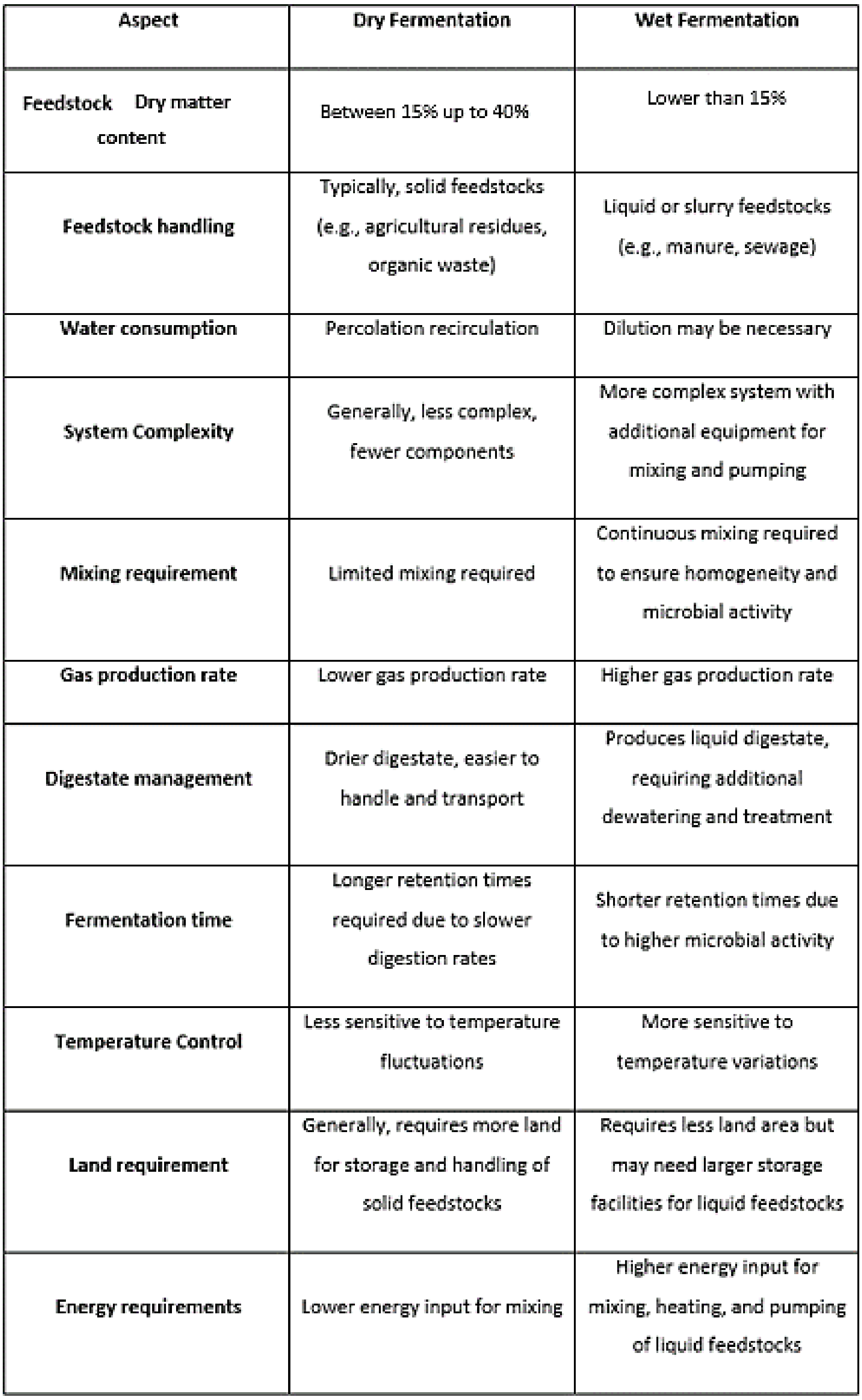
3.3 Comparison Between the Two Processes

Transitioning from dry anaerobic digestion (AD) technology to wet fermentation systems, the advantages and drawbacks of each process become apparent. Dry AD technology offers a range of benefits, including reduced pretreatment requirements, smaller digester volumes, and improved handling of low moisture digestate. Additionally, the absence of moving parts within the reactor eliminates issues like foam, sedimentation, and surface crust, reducing the need for energy-intensive stirring equipment. However, challenges arise concerning mass transfer optimization, leading to a lower biogas productivity compared to wet technology.

Conversely, wet fermentation systems showcase strengths in substrate homogenization, resulting in enhanced biogas production and operational efficiency. They also require less residence time for the digestion process and feature cheaper equipment to manage slurries. Nonetheless, the necessity to add liquid to reduce dry matter content complicates feedstock handling, while robust mixing equipment adds to operational costs. Furthermore, wet fermentation systems yield digestate with lower dry matter content, necessitating additional investments in storage and handling facilities. Despite these hurdles, wet fermentation systems remain viable options for organic waste management, offering distinct advantages over dry AD technology.

In the following Table 4 a summary of this advantages categorized in sections for a better comparison between specific requirements of each fermentation technique has been made. Wet fermentation is the dominant technology nowadays, mainly because of having a higher gas production rate but the interest of dry technology due to the less water requirement and energy input in is gaining attention to develop in an industrial scale.

Table 4. Comparison table between Dry and Wet Fermentation



Aspect	**Dry Fermentation**	**Wet Fermentation**
Feedstock Dry matter content	Between 15% up to 40%	Lower than 15%
Feedstock handling	Typically, solid feedstocks (e.g., agricultural residues, organic waste)	Liquid or slurry feedstocks (e.g., manure, sewage)
Water consumption	Percolation recirculation	Dilution may be necessary
System Complexity	Generally, less complex, fewer components	More complex system with additional equipment for mixing and pumping
Mixing requirement	Limited mixing required	Continuous mixing required to ensure homogeneity and microbial activity
Gas production rate	Lower gas production rate	Higher gas production rate
Digestate management	Drier digestate, easier to handle and transport	Produces liquid digestate, requiring additional dewatering and treatment
Fermentation time	Longer retention times required due to slower digestion rates	Shorter retention times due to higher microbial activity
Temperature Control	Less sensitive to temperature fluctuations	More sensitive to temperature variations
Land requirement	Generally, requires more land for storage and handling of solid feedstocks	Requires less land area but may need larger storage facilities for liquid feedstocks
Energy requirements	Lower energy input for mixing	Higher energy input for mixing, heating, and pumping of liquid feedstocks

Source: Author’s own

3.4 Feed Materials Specifications

Norway has a significant potential for sustainable biomass for biofuel production, estimated between 30 and 40 TWh by 2030. This potential mainly comes from forestry, agriculture, households, industry, and business waste, which, if collected, could have significant positive environmental effects, and help reduce greenhouse gas emissions in the transportation sector.

Considering a conservative conversion rate, where over 50% of the energy contained in biomass is converted into biofuel, it is estimated that by 2030, between 16 and 20 TWh of biofuel could be produced using available Norwegian biomass. This represents a step towards a more sustainable economy and a reduction in dependence on fossil fuels in the transportation sector (Om ZERO, 2016).

As illustrated in the chart below, the biogas production figures for 2022 in Norway reveal that food waste is the leading contributor, followed by animal fertilizer and fish waste. Notably, there is no available data for biogas production from sewage sludge (Statistisk Sentralbyra, 2022).

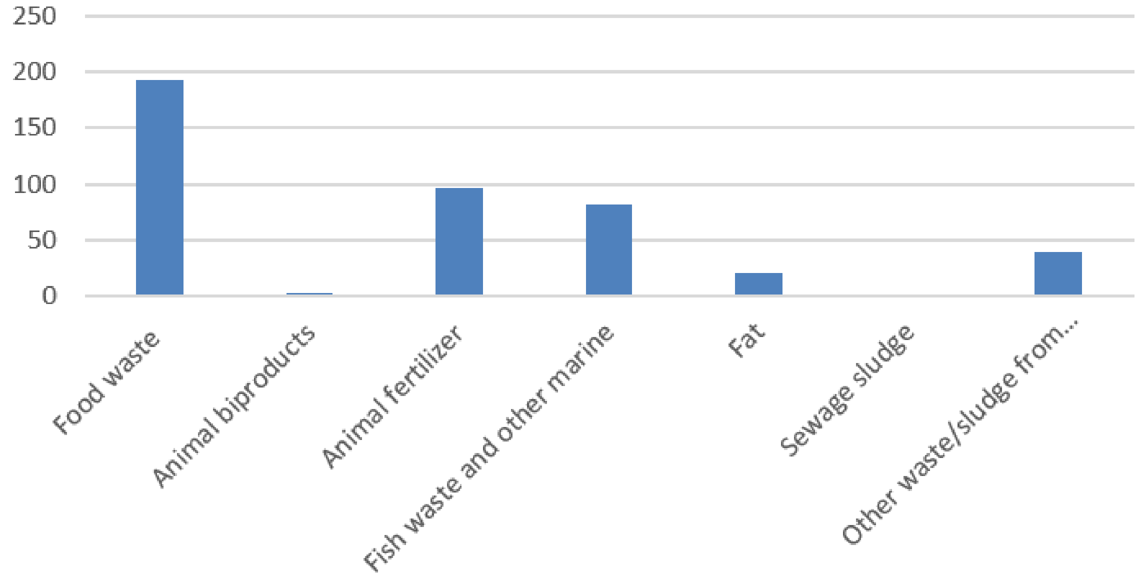


Figure 6. Biogas production from feedstock in Norway 2022, (Adapted from Statistisk Sentralbyra, 2022).

In Tromsø County, the available feedstock includes sewage sludge, organic waste, fish industry waste, grease and oils, brewery waste, and animal waste. As illustrated in the chart below, the distribution of available feedstock in the Tromsø region reveals that organic waste (OW) and household waste combined constitute the largest source, followed by fish waste and sewage sludge. A notable difference is observed in animal waste compared to the average distribution in Norway. This variance in the Tromsø region can be attributed to the dispersed population and reduced agricultural farm activity.

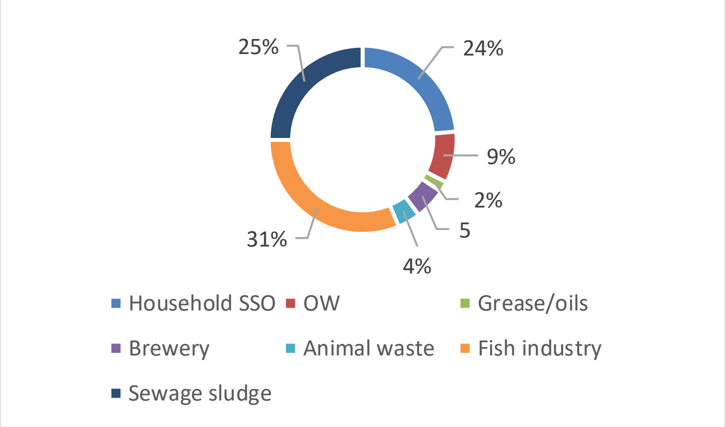


Figure 7. Percentage in wet tonnes per year available feedstock in the Tromsø region, (adapted from Ford, 2023).

3.4.1 Sewage sludge

Sewage sludge, also referred to as biosolids, is a semi-solid material produced as a byproduct of wastewater treatment processes. When wastewater is treated at sewage treatment plants, solids are removed from the water through processes like sedimentation, filtration, and biological treatment. The remaining solid material, known as sewage sludge, contains a mixture of organic and inorganic matter, including human waste, bacteria, chemicals, and debris that were present in the wastewater (Sewage sludge, 2023).

In the county of Nordland exists 333 facilities and within the county of Tromsø there are 25 facilities (The Norwegian PRTR, 2024). The byproducts generated by these facilities can be repurposed at the Rå Biopark plant to produce biogas, effectively transforming waste into valuable resources.

3.4.2 Organic Waste and Household HoReCa

Organic waste refers to any waste material that originates from living organisms and is biodegradable. This type of waste includes various types of organic matter, such as food scraps, yard waste (such as grass clippings and leaves), agricultural waste, animal waste, paper products, and biodegradable plastics. Organic waste is typically rich in carbon and nutrients (Sun and Yu, 2023).

In the Tromsø region of Norway, organic waste serves as a significant resource to produce biogas. Households actively participate in the collection and segregation of organic waste at the source, a practice that has been established since around 2001 (Recolection,2017). This long-standing tradition has fostered considerable experience and acceptance among the population. Collection of organic waste from households typically occurs once per week, with some cases occurring once every two weeks. Additionally, organic waste from the hospitality sector, including hotels, restaurants, and catering facilities, contributes to the biogas production stream (Ford, 2023). However, this waste often contains impurities and contaminants and is delivered in solid form, typically contained in plastic bags. Furthermore, the local food production industry, encompassing sectors such as dairy and algae production, generates various byproducts that also contribute to the organic waste feedstock for biogas production (Price, 2013).

3.4.3 Fish industry

Fish waste from the fish industry refers to the byproducts generated during the processing of fish, including parts of fish that are not used for human consumption, such as heads, bones, scales, fins, and internal organs. These waste materials can be rich in organic matter and nutrients, making them suitable feedstock for biogas production (Coppola et al., 2021).

Within the jurisdiction of Tromsø County, the production of biogas from fish waste is a significant aspect of the local economy and waste management practices. One key source of fish waste is the recirculating aquaculture system (RAS) fish farms, which utilize state-of-the-art technology to produce Atlantic salmon. These fish farms recirculate water in tanks, resulting in the production of fish sludge as the primary waste product (OECD, 2021). Fish sludge consists of feed residues and feces from land-based RAS hatcheries, and its volume depends on the production growth cycle of the fish, peaking during certain seasons. Additionally, fish silage, a byproduct of mortality events in salmon production, is treated with formic acid and ensiled for use in biogas production (Ford, 2023). The Tromsø region also processes fish waste further to produce various products such as oil, fish protein concentrate (FPC), and cake, which undergo heating and mechanical separation processes before being utilized as feedstock for biogas production.

3.4.4 Grease/oils

Grease and oils serve as a valuable feedstock for biogas production owing to their high lipid content. Derived from various sources such as food processing industries, restaurants, and wastewater treatment plants. Co-digestion with other organic materials, such as food waste or sewage sludge, enhances biogas production efficiency by providing a balanced nutrient mix. However, depending on the source, grease and oils may require pre-treatment, such as emulsification or heating, to optimize their digestibility by microorganisms. Overall, utilizing grease and oils for biogas production not only diverts waste from landfills but also generates renewable energy, contributing to environmental sustainability (Hunter et al., 2012).

3.4.5 Brewery

Brewery waste refers to the byproducts and residues generated during the brewing process in breweries. This waste typically includes spent grains, hops residue, yeast slurry, trub (sediment), and wastewater discharged from cleaning equipment and facilities (Missana et al., 2022). These sub-products are characterized by their high suspended solids content and stickiness (Carlini et al., 2021).

3.4.6 Animal waste

In the region, considering the prevailing living conditions, animal waste predominantly consists of byproducts from cattle and goats, reflecting the most prevalent agricultural practices in the area (Ford, 2023).

Cattle slurry is a liquid mixture of cattle excrement and urine, devoid of any bedding material. Meanwhile, goat manure sourced from nearby farmers includes goat excrement along with straw bedding. Both goat manure and cattle slurry are rich in organic matter and nutrients, such as nitrogen and phosphorus, making them valuable resources for agricultural purposes. These materials can be utilized as fertilizers to improve soil fertility and crop yields. Additionally, they can be processed through anaerobic digestion to produce biogas (Font-Palma, 2019).

4 Methodology

This next chapter involves the calculations for each reactor discussed, within their hypothetical configuration, and ends with a comparison of energy consumption between the two technologies.

4.1 Assumed quantities and compositions

The feedstock quantities outlined in the preceding chapter have been sourced from the Rå Biopark data provided by the company. Given the diverse array of feedstock types available, a decision was made to categorize them into groups based on their similar characteristics, facilitating a more streamlined analysis.

Among these groups, fish waste constitutes the largest portion, followed by organic waste and sewage sludge. Furthermore, a comprehensive table detailing the properties and compositions of each group has been compiled and can be referenced in the appendix of this thesis under the title "Feedstock parameters". Subsequent calculations will draw upon the data presented in this table.

Table 5. Quantities of the feedstock used per year.

Feedstock	Wet tonne per year	Consistency
Sewage sludge	15800	Solid
Organic waste & Household HoReCa	20500	Solid
Fish wastes	19700	semisolid
Grease/oils	1150	Liquid
Brewery	3450	semisolid
Animal waste (goat manure and cattle slurry)	2500	semisolid

(Ford, 2023)

4.2 Equipment sizing

For sizing the digesters, there are preliminary calculations first, as it depends on the quality, quantity, and type of available biomass, as well as the digesting temperature (Energypedia, 2015).

This biogas plant model entails the construction of two separate lines, each requiring its digester. One digester will specifically process sewage sludge as the primary feedstock, while the second line will manage a variety of other biomasses (Ford, 2023). To facilitate a comprehensive comparison between the two technologies, the upcoming chapter will focus on dimensioning the first line for sewage sludge, employing wet techniques suited to its liquid nature. The second line will be dimensioning a reactor for each case of wet and dry technologies, to make a comparison between them afterwards, facilitating the handling of diverse feedstocks. In short, one system will feature reactors solely under wet AD technology, while the other will incorporate the line 1 under wet AD and line 2 under dry AD technology.

All calculations will consider the plant's operation for 52 weeks per year, totalling 365 days annually. Operating at a mesophilic temperature of approximately 35°C (Ford, 2023), the retention time for the feedstocks in both lines will be set at around 25 days. It's worth noting that the Hydraulic Retention Time (HRT) initially approximates the highest value found in the literature search for the type of process. So the analysis will be based on a high retention time, so it always can go lower and will be refined as more data is gathered once the process commences. Initially, this might result in a larger digester size, but adjustments will be made to ensure optimal efficiency.

4.2.1 Line 1 dimensioning, sewage sludge

The initial calculation will pertain to sewage sludge, sourced from Table 5. According from the table, sewage sludge has an annual availability of 15,800 wet tonnes.

First, it is needed to calculate how much daily substrate input the digester will have. So, knowing the annual availability, an average of it has been done.

$$\frac{15800\ \text{wet tonnes}}{365\ \text{days}} = 43{,}28\,\frac{\text{wet tonnes}}{\text{day}}$$

Next, to determine the volume of the digester, we need to convert the tonnage to cubic meters. This conversion will utilize the density of sewage sludge, which is provided in Table 9 located in the Appendix, specifying a density of 721 $\mathrm{kg/m^3}$.

$$43{,}28\,\frac{\text{wet tonnes}}{\text{day}} \cdot \frac{10^3\text{kg}}{1\text{t}} \cdot \frac{1\text{m}^3}{721\ \text{kg}} = 60{,}02\text{m}^3/\text{day}$$

The size of the digester is determined by the chosen retention time (HRT) and the quantity of daily substrate input, denoted as Sd. All the calculations from now on are based on the following reference, Guardado-Chacón, 2007.

$$\mathrm{V_d} = \mathrm{S_d} \cdot \mathrm{HRT}\ [\mathrm{m}^3] \tag{1}$$

Considering a daily substrate input of $60{,}02\mathrm{m^3/day}$ and a retention time of approximately 25 days the resulting volume is calculated to be $1500{,}69\mathrm{m^3}$.

$$\mathrm{V_d} = 60{,}02\,\frac{\mathrm{m}^3}{\mathrm{day}} \cdot 25\ \mathrm{days} = 1500{,}69\ \mathrm{m}^3$$

It is necessary to calculate one third more volume for the digester due to the need to provide an additional margin to accommodate any unexpected variation in biogas production, as well as to allow for a reserve space for the temporary storage of organic materials before processing (Willfors, 2024). Reactor volume can be calculated from the digester volume as:

$$\mathrm{V_r} = \mathrm{V_d} + \tfrac{1}{3} \cdot \mathrm{V_d} \tag{2}$$

$$\mathrm{V_r} = 1500{,}69\ \mathrm{m}^3 + \frac{1}{3} \cdot 1500{,}69\ \mathrm{m}^3 = 2000{,}92\ \mathrm{m}^3$$

Once these preliminary calculations are done, specific equations are used to determine the sizing parameters of the digester. The type of digester will have the structure shown in Figure 8 as it is one of the most commonly utilized designs.

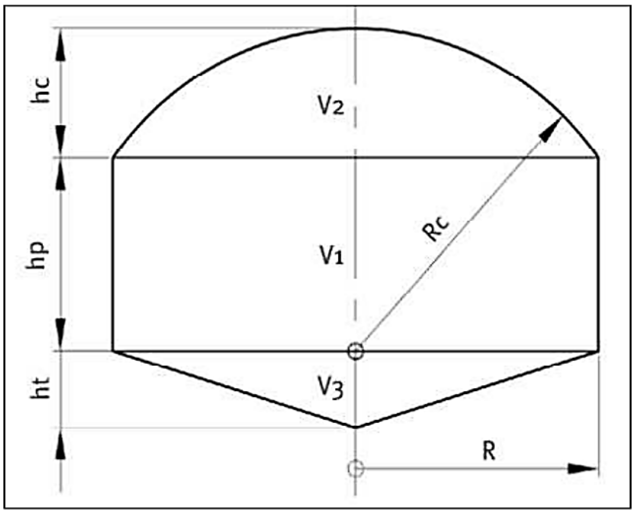


Figure 8. Scheme of the basic measures for the dimensioning of the fixed dome digester (Guardado-Chacón, J.A., 2007)

The formulas are based on the calculation of the three fundamental parts of this type of digester: the conical, cylindrical, and spherical parts. The calculations start with the previously determined $\mathrm{V_r}$, and then proceed to the following this table:

Table 6. Formulas used for the calculation of the fixed dome digester for line 1

Parameter calculated	Formula	Result
Basic radio	$R = \sqrt[3]{\frac{V_r}{(\pi)\cdot(1{,}121)}}\ [m]$ (3)	8,28 m
Proportional unit	$U = \frac{R}{4}$ [m] (4)	2,07 m
Dome radio	$R_c = (5) \cdot (U)$ [m] (5)	10,35 m
Cylindrical diameter	$D = (8) \cdot (U)\ [m]$ (6)	16,56 m
Dome height	$h_c = (2) \cdot (U)\ [m]$ (7)	4,14 m
Wall height	$h_p = (3) \cdot (U)\ [m]$ (8)	6,21 m
Base cone height	$h_t = (0{,}15) \cdot (U)\ [m]$ (9)	0,3105 m
$\mathbf{V_1}$	$V_1 = (R^2) \cdot \pi \cdot h_p\ [m^3]$ (10)	1338 m^3
$\mathbf{V_2}$	$V_2 = \left(\frac{h_c}{3}\right) \cdot R_c \cdot \pi \cdot (h_c)^2\ [m^3]\ (11)$	770 m^3
$\mathbf{V_3}$	$V_2 = \left(\frac{h_t}{3}\right) \cdot \pi \cdot (R)^2\ [m^3]$ (12)	22,30 m^3

(Adapted from Guardado-Chacón, 2007)

4.2.2 Line 2 dimensioning, remaining feedstock in a wet system

To initiate the dimensioning of this second line, we need to ascertain the daily substrate input for the system. All calculations are documented in the appendix of this thesis, under the subtitle of line 2 dimensioning in a wet system, where the input for each feedstock is calculated individually and then summed up, resulting in a total of 230,60 m^3.

Next, we refer back to equation (1) which was previously used to calculate the volume of the digester.

$$\mathrm{V_d} = 230{,}60\,\frac{\mathrm{m}^3}{\mathrm{day}} \cdot 25\ \mathrm{days} = 5765\ \mathrm{m}^3$$

Similarly, the volume of the reactor is calculated using equation (2) as before, where an additional one-third volume is required for the digester to accommodate unexpected variations in biogas production, yielding a result of 7686,67 m^3.

$$\mathrm{V_r} = 5765\ \mathrm{m}^3 + \frac{1}{3} \cdot 5765\ \mathrm{m}^3 = 7686{,}67\ \mathrm{m}^3$$

Once these preliminary calculations are done, the equations for the dimension of the digester will be the same as the ones shown in Table 6 for the sewage sludge line.

The result of the new dimensions for this digester will be the following:

Table 7. Formulas used for the calculation of the fixed dome digester for line 2

Parameter calculated	Formula	Result
Basic radio	$R = \sqrt[3]{\frac{V_r}{(\pi)\cdot(1,121)}}\ [m]$ (3)	12,97 m
Proportional unit	$U = \frac{R}{4}$ [m] (4)	3,24 m
Dome radio	$R_c = (5)\cdot(U)$ [m] (5)	16,2 m
Cylindrical diameter	$D = (8)\cdot(U)\ [m]$ (6)	25,92 m
Dome height	$h_c = (2)\cdot(U)\ [m]$ (7)	6,48 m
Wall height	$h_p = (3)\cdot(U)\ [m]$ (8)	9,72 m
Base cone height	$h_t = (0{,}15)\cdot(U)\ [m]$ (9)	0,486 m
$\mathbf{V_1}$	$V_1 = (R^2)\cdot\pi\cdot h_p\ [m^3]$ (10)	5144,76 m^3
$\mathbf{V_2}$	$V_2 = \left(\frac{h_c}{3}\right)\cdot R_c\cdot\pi\cdot(h_c)^2\ [m^3]\ (11)$	4616,03 m^3
$\mathbf{V_3}$	$V_2 = \left(\frac{h_t}{3}\right)\cdot\pi\cdot(R)^2\ [m^3]$ (12)	85,74 m^3

(Adapted from Guardado-Chacón, 2007)

4.2.3 Line 2 dimensioning, remaining feedstock in a dry system

To conduct a comparative analysis of dry and wet systems in this thesis, it was dimensioned a digester using dry technology. This necessitates converting the feedstock into dry content. To obtain this value, research has been conducted on the percentage of moisture content and dry content, that can be found in Table 9 of Appendix I, from which an approximation of the daily input substrate has been derived.

This approximation has been made because the known data was assumed to already have all the water content needed for the wet system, so for this case there is a “removal” of that extra content in the data to use an approximation of what the feedstock input will be for a dry AD system.

The daily input substrate is estimated to be around 194,35 m^3. Achieving this figure involved numerous calculations, detailed in the appendix of this document, which can be found under the subtitle line 2 dimensioning in a dry system.

Using equation (1), a result of 4858,75 m^3 is obtained.

$$V_d = 194{,}35\,\frac{m^3}{day}\cdot 25 \text{ days} = 4858{,}75 \text{ m}^3$$

The reactor volume can be calculated from the digester volume using equation (2). For the moment there isn't any literature that could certify the necessity of having a headspace of a dry digester but will be calculated as well because is most likely to have it.

The result is the following equation:

$$V_r = 4858{,}75 \text{ m}^3 + \frac{1}{3}\cdot 4858{,}75 \text{ m}^3 = \ 6478{,}34 \text{ m}^3$$

4.3 Configurations systems

In this section, systems of two configurations are considered, one regarding line 1 and line 2 with both processes under wet fermentation processes, see Figure 9, and the second configuration is line 1 under wet fermentation and line 2 under dry fermentation process according to Figure 10.

The first configuration proposed involves both reactors operating under wet conditions, which, according to the literature review and from the discussions held with Andreas Willfors, emerges as the most feasible option. This approach is widely employed in Scandinavian countries, signifying its proven effectiveness (Willfors, 2024). A notable advantage is the uniformity it offers in system operations, allowing for the utilizations of shared pre-treatment and post-treatment facilities. This standardization streamlines processes while accommodating variations in the characteristics of the processed feedstock.

Furthermore, considering the specific regional context of the biogas plant under study, there is merit in subdividing line 2's feedstock processing. By allocating the remaining feedstock to Line 2, utilizing two reactors instead of one, it can effectively manage the substantial volume involved, amounting to 7686,67 m^3. This subdivision allows for the construction of two smaller reactors, each with a capacity of 3843,34 m^3. The benefit of this approach lies in its energy efficiency; maintaining optimal temperature levels becomes more manageable with two smaller reactors operating in parallel, reducing the energy demand for heating up compared to a single large reactor.

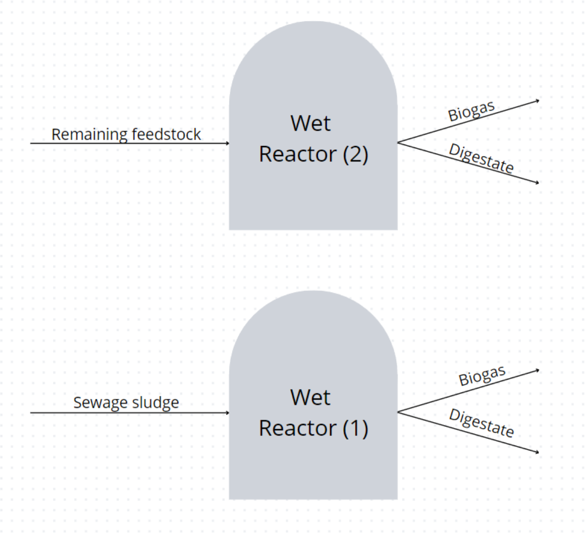


Figure 9. System configuration option 1, (author's own)

An alternative involves one reactor operating under wet conditions, fed by sewage sludge, while the second operates under dry conditions. This approach minimizes water usage, with the option to utilise percolate recirculation from the same dry reactor suggested by some authors, described in Section 3.1.2.2.1 Batch in Chapter 3 about the literature review, claiming that this technique improves the production of methane. Additionally, this configuration requires fewer materials for the construction of Line 2, as its volume is significantly smaller compared to Line 2 in the first option, with a volume difference of approximately 1000 m^3.

However, a key challenge lies in the fact that dry technology is still in the development stages. Implementing such an innovative approach may risk delaying the construction schedule of the plant.

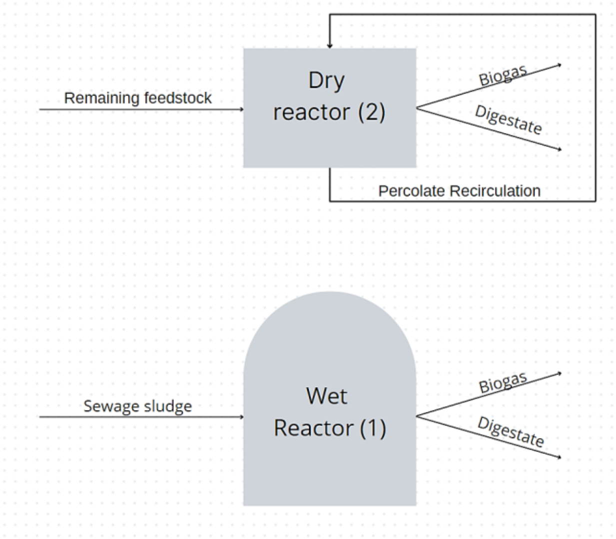
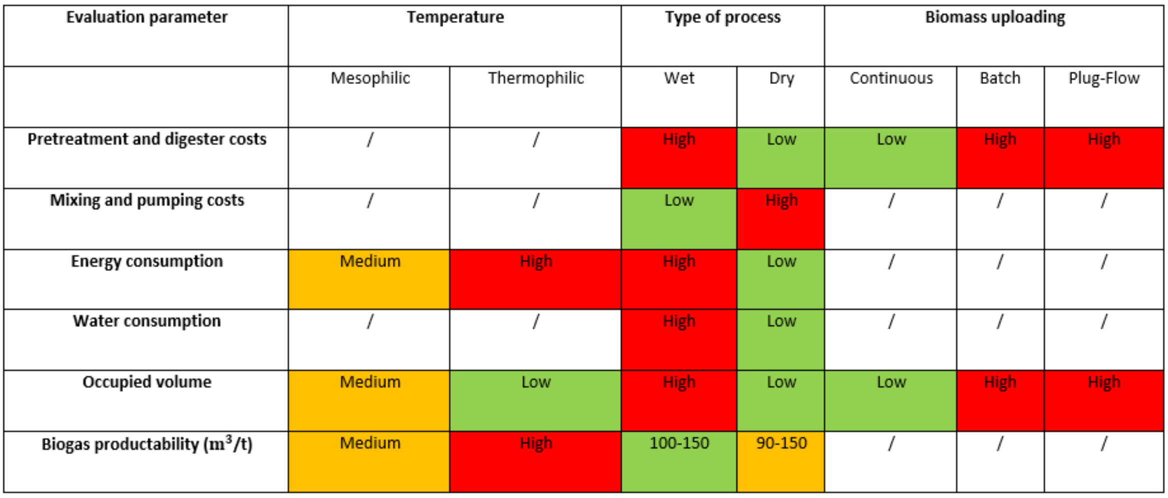


Figure 10. System configuration option 2, (author's own)

4.4 Energy Consumption

When considering dry versus wet fermentation in a cold climate area, energy consumption plays a crucial role. Considering Table 8 it can be said that wet processes generally entail higher pre-treatment and reactor costs, but offset this with lower expenses for mixing and pumping systems, alongside robust biomethane producibility. However, these processes necessitate greater water usage, thereby escalating the need for thermal power to heat the incoming biomass. The presence of higher total solids content in the organic fraction of municipal solid waste (OFMSW) has inclined towards dry fermentation, requiring less thermal power and water. Nonetheless, the dry process entails more intricate pumping systems and yields a lower biomethane output (Masala, F. et al, 2022). It's important to note that energy consumption is influenced by factors such as temperature range, with mesophilic conditions typically offering the most favorable balance between energy efficiency and biomethane yield. Additionally, variations in biomass loading techniques, such as continuous, batch, or plug flow reactors, contribute to differences in energy consumption and overall process efficiency.

Table 8. Evaluation parameters for energy consumption



Evaluation parameter	Temperature		Type of process		Biomass uploading		
	Mesophilic	Thermophilic	Wet	Dry	Continuous	Batch	Plug-Flow
Pretreatment and digester costs	/	/	High	Low	Low	High	High
Mixing and pumping costs	/	/	Low	High	/	/	/
Energy consumption	Medium	High	High	Low	/	/	/
Water consumption	/	/	High	Low	/	/	/
Occupied volume	Medium	Low	High	Low	Low	High	High
Biogas productability (m^3/t)	Medium	High	100-150	90-150	/	/	/

(Adapted from Masala et al, 2022)

In cold climate areas, insulation, and heating systems are crucial considerations for both wet and dry fermentation processes. Insulation helps maintain stable temperatures within the system, while heating systems prevent the freezing of water lines or digester contents, ensuring uninterrupted operation (Yang et al., 2019). The presence of liquid in wet fermentation aids in temperature regulation compared to the dry process, where temperature control can be more challenging (Wang et al., 2019).

Furthermore, feedstock considerations play a significant role in determining the feasibility of fermentation processes in cold climates. Certain feedstocks may be better suited to withstand low temperatures and maintain microbial activity, thus influencing process efficiency.

Maintenance and monitoring become even more critical in cold climates to prevent issues such as freezing, equipment failure, or reduced microbial activity due to temperature fluctuations. Regular inspection and upkeep are essential to ensure the smooth operation of fermentation systems in these challenging conditions (Shrestha & Shrestha, 2019).

Referring to Table 8, a grading system assigning 2 points to green boxes, 1 point to orange boxes, and zero to red ones provides valuable insights. From this assessment, it can be inferred that, currently, the mesophilic temperature range appears to be the most favourable. Additionally, the dry fermentation process emerges as the preferred option, despite its lower biogas yield. As for biomass uploading methods, continuous input appears to be the most optimal based on the parameters considered.

5 Description of the Planned Plant in Norway

Rå Biopark is a Norwegian industrial project considered the largest environmental cooperation project in Northern Norway. Behind this project are six waste companies: Hålogaland Ressursselskap IKS, Remiks Miljøpark AS, Reno Vest IKS, Avfallsservice AS, Lofoten Avfallsselskap IKS, and Finnmark Ressursselskap (LASA, 2023). This facility is expected to transform around 60,000 tonnes of organic waste, sludge, and fish waste from households and businesses across approximately 41 municipalities into approximately five million liters of biogas in this new plant in Skibotn. In this place, there is already an existing composting plant, owned by Origo Skibotn AS, but in two years, this process will be discontinued. So, Rå Biopark plans to replace open-air composting with biogas production in a closed facility (Johansen., E, 2024). A section of the site has already been allocated as the designated plot for the plant's construction, spanning approximately 31,000 square meters (Lindbach, 2024).

Figure 12. Geographical map of surroundings of the location (site marked with blue circle), (Lindbach, 2024)

Figure 11. Planned distribution and view of the plant, (HRS, 2022)

The waste processing facility is designed with two units for the waste line, each equipped with digesters capable of parallel operation. These digesters will have a combined volume of approximately 10,000 cubic meters. Additionally, the sludge processing line consists of one digester with a volume of 3,500 cubic meters. Accounting with three lines of reception. The decay process is planned to occur in the mesophilic temperature range of 38-40°C, although consideration is given to potentially adopting a thermophilic process operating at temperatures of 48-55°C. Stirring within the tanks can be achieved through various mixing systems, including gas stirring, mechanical stirring, or pumping. Heating is facilitated by circulating the biomass through a heat exchange system (Statforvalteren, 2023).

Then biogas produced in the decomposition tanks undergo condensation removal and purification before being collected in a gas balloon and fed through an upgrading facility to produce liquid biofuel (LBG). The substrate is dewatered separately for waste and sludge lines before the rejected water is sent to a common evaporation plant. Sludge bioresidues are incinerated, while other bioresidues are dried.

In the evaporation plant, rejected water is disinfected at temperatures exceeding 100°C, producing concentrate and condensate. The condensate is predominantly utilized as process water within the biogas plant, for dilution of incoming waste, and for cleaning pretreatment equipment. The remaining purified wastewater will be discharged, preferably after additional purification due to its relatively high levels of COD and nitrogen. This post-treatment of rejected water, along with sanitary wastewater cleaning from the plant, will be carried out via infiltration into local gravel and sand beds at a loose mass crest west of the biogas plant (Lindbach, 2024).

Ventilation air from the biogas plant will be collected and directed to two odour treatment plants. One, located in the waste reception hall, employs photooxidation and activated carbon, while the second, handling substrate processing air, consists of a water scrubber and mineral biofilter.

As can be illustrated in Figure 13 the principal elements that constitute this plant and their function are halls 1, 2, and 3 constitute halls for the reception and pre-treatment of waste as well as the post-treatment of bio-residue. Tanks 12-17 constitute buffer and decay tanks. PR1 between the tanks marks the pump room. Markings 30-33 show the area set to contain equipment for upgrading, liquefaction, and storage of biogas (Norconsult, 2023).

Figure 13. Sketch of plant components that together make up the biogas plant, (Norconsult AS, 2023)

With an initial budget of NOK 300 million, Rå Biopark faces cost escalations primarily attributed to fluctuations in NOK exchange rate. Nonetheless, the project remains committed to its core objective of harnessing cutting-edge technology to convert waste materials into approximately five million liters of liquid biogas annually (LASA, 2023).

This biogas output is equivalent to the energy consumption of 2,500 households per year and will contribute significantly to Norway's biogas utilization, accounting for 10% of the country's total usage. In alignment with sustainability objectives, Rå Biopark claims that all transportation of food waste to the Skibotn facility will be conducted using biogas-powered vehicles (Remiks,2023).

Furthermore, the project has secured NOK 18 million in support from Enova, facilitating the acquisition of 15 biogas vehicles and the establishment of three filling stations in Tromsø, Bjerkvik, and Alta (HRS, 2022). Construction is anticipated to commence around May 2024, although there is a likelihood of a delay until June. It is envisaged that the facility will be operational by mid-2026. (Statforvalteren, 2023).

6 Discussion

In these sections, the thesis results about the aims and objectives are explored, followed by the thesis limitations, while the next section assesses the inconsistencies within the evaluation results. Lastly, a sensitivity analysis is carried out, to understand what influences most in the process and make the difference.

6.1 Aim and objectives result

Considering all the research conducted about the initial objective of the thesis, which pertains to the potential benefits of dry or wet technologies in the northern region of Norway, the thesis aligns with the required aim. Concerning the four objectives outlined at the onset of the research, most of them have been accomplished.

The initial objective was to delve into the literature on the fermentation process, and this goal has been achieved. By reading this thesis, even someone unfamiliar with fermentation would gain insight into the essential aspects of this process.

The next objective was to identify the key parameters involved in fermentation; this aim was fulfiled as well. Within the thesis, the essential parameters are delineated, followed by a sensitivity analysis that identifies the parameters most influential in fermentation and the ones that distinguish between the two processes.

Then, the objective of conducting a comparative analysis between dry and wet digesters, evaluating their respective dimensions and performance metrics has been completed. Where a dimensioning of each type of digester has been done, considering the most suitable feedstocks for each of them, and then presenting the type of configurations that could be done, followed by a comparison between the energy consumption to make a final assumption of which technology is better.

The final objective is to evaluate the feasibility of implementing either dry or wet fermentation biogas technology, specifically tailored for a plant situated in northern Norway. This objective proved to be the most challenging, given the complexities arising from the unique location of the biogas plant. Making decisive choices between the two technologies was particularly intricate. Although both options present advantages, they also come with their own set of challenges. Additionally, the absence of region-specific feedstock data further complicated the assessment. Perhaps with a more comprehensive study and access to accurate data, a decision could be reached, but not for this thesis.

6.2 Limitations

For the development of this thesis, several limitations have been encountered regarding the desired outcome. Firstly, concerning the literary search, limitations arose as some information was only accessible through paid means, which is not covered by the institution. Consequently, certain information that appeared interesting could not be thoroughly investigated. Another obstacle encountered in conducting this search was the scarcity of studies in the dry technology field, with most ending up repeating or drawing the same conclusions. Additionally, as this technology is still in development, many studies were incomplete, and access to information was restricted in some cases. The last significant limitation pertained to the data used for calculations, which had to be sourced from various places, resulting in a high margin of error in the outcome.

6.3 Inconsistencies within the assessment's results

In this thesis, several inconsistencies have been identified. While the weight of available feedstock is accurately reported, the absence of additional information concerning the characteristics of each feedstock introduces a notable discrepancy. This lack of detail stems from the utilization of data sourced from diverse regions globally, resulting in inconsistencies throughout the final assessment. Furthermore, the development of a theoretical framework posed challenges due to the extensive range of information available and the disparities among authors' findings. Additionally, certain data may require updating as further research and studies emerge, further complicating the synthesis of a cohesive thesis.

6.4 Suggestions for assessment improvements

It would be beneficial to obtain the precise dry and moisture content of each feedstock, along with their chemical characteristics, necessitating the use of laboratory analysis. This comprehensive dataset would enable the calculation of biogas production and methane yield. Determining retention times proves challenging as they are continually adjusting based on the performance of the feedstock. However, in this thesis, a higher retention time was chosen for both reactors to facilitate a more comparative analysis. Nonetheless, the wet reactor should most likely have a shorter retention time, as suggested by some literature.

6.5 Sensitivity Analysis

While both dry and wet anaerobic digestion processes share common parameters that influence biogas production, the sensitivity and optimal ranges of these parameters vary between the two technologies. In dry anaerobic digestion, moisture content is pivotal, affecting porosity and microbial activity, while temperature regulation is crucial for optimal kinetics while pH control and hydraulic retention time play significant roles in wet AD to sustain microbial communities in liquid substrates. Both processes are sensitive to feedstock composition, C/N ratio, and process design. Understanding these sensitivities is crucial for optimizing biogas production and ensuring the economic viability of anaerobic digestion systems

7 Conclusion

By evaluating the comparative analysis of dry and wet fermentation processes for biogas production in northernmost Norway aimed to provide a comprehensive understanding of the advantages and disadvantages of each method within the context of the unique environmental conditions of the region. Northernmost Norway is characterised by extremely cold temperatures, long winters, and limited access to resources, presenting substantial challenges for biogas production systems, impacting their efficiency and effectiveness.

Throughout this thesis, dry fermentation stands out for being less sensitive to temperature fluctuations, less water requirement, and needs a lower energy input compared to wet anaerobic digestion outlines by having a higher biogas productivity, shorter retention times, and an efficient mixing and substrate distribution. While both technologies have their numerous advantages it is not without their challenges that counterpart those.

In determining the preferred technology, key considerations include digester sizing, energy consumption, and adaptability to the subarctic climate. Discrepancies in digester dimensions between theoretical calculations and practical applications underscore the complexity of matching technology to local conditions.

Initially, it was observed that the digester designed for sewage sludge, referred to as "line 1" in this thesis, was undersized by 1000 m^3 compared to Ra Biopark's planned capacity. This discrepancy may stem from incomplete characterization data for the feedstocks. These calculations are based on operating conditions at a mesophilic temperature of approximately 35°C, with a retention time of 25 days However, for the second line, two digesters were dimensioned: one utilizing wet technology with a total capacity of 7686.67 m^3, and the other employing dry technology with a capacity of 6478.34 m^3, reflecting a discrepancy of one thousand cubic meters due to the lower water content in the feedstock outlining one of the dry technology advantages regarding the size of the digester. Comparing these calculations with the real digesters planned shows that their digesters for the second line will be around ten thousand cubic meters. This big difference is due to the same reason as before.

So, when it comes to deciding which technology is better for the unique climate conditions, it is difficult to stipulate one sole answer. On one side, wet technology is much more developed and therefore more efficient meanwhile dry technology has a bright future, and more research is needed. Consequently, for a project with these characteristics that is already very developed, the suggestion will be to stick with the plan of using wet fermentation but pay attention to it and give some resources to develop dry fermentation. Principally, dry fermentation needs fewer water requirements, making it a favourable option for implementation. So, the water could be used for other essential purposes.

In essence, while wet fermentation remains the current preference due to its maturity, there is merit in nurturing the potential of dry fermentation to diversify and improve biogas production in northernmost Norway's challenging environment.

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9 Appendices

In this section, additional information regarding the results research and the calculations done for the dimensions of the reactors will be compilated to further facilitate the reader's comprehension of the findings.

Appendix I. Feedstock parameters

Table 9. Feedstock parameters

Feedstock	Dry matter content (%)	Volatile solids (%)	Biogas yield (m^3/wet tonne)	Methane content (%)	C/N ratio	Moisture content (%)	Dry content (%)	Density (kg/ m^3)	References
Sewage sludge	10	60-80	270-540	50-70	20/1	n.a	n.a	721	(Neumann et al., 2016; Aqua-Calc, 2024)
Organic waste & Household HoReCA	30,1	90,1	100-300	50-70	14.8	60	15	481	(Aqua-Calc, 2024, Alkarimiah, 2019; Uddin et al., 2021)
Fish wastes	30	60-80	100-300	50-70	10/1-20/1	70	23	721	(Aqua-Calc, 2024; Alkarimiah, 2019; Kebe et al., 2021)
Grease/oils	1-5	100	20-200	60-80	n.a	n.a	n.a	n.a	Aqua-Calc, 2024; Alkarimiah, 2019
Brewery	10-20	70-80	200-400	50-70	Low C/N (high C content)	80	20-25	432	(Aqua-Calc, 2024; Alkarimiah, 2019; González-García et al., 2018)
Animal waste (goat manure and cattle slurry)	15	60-80	100-300	50-70	10/1-20/1	65%	20%	400	Aqua-Calc, 2024; Alkarimiah, 2019; Zhang et al, 2013; Rahman et al., 2008)

(Author’s own)

Appendix II. Reactors calculations

Line 1 dimensioning in a wet system, sewage sludge

The steps followed for the dimensioning are the following:

1. The volume of the reactor is calculated, in this case is 2000,92 m^3 previously calculated in the main text in Chapter 4.2. Equipment Sizing.

2. The basic radio is calculated

$$\mathrm{R} = \sqrt[3]{\frac{\mathrm{V_r}}{(\pi)\cdot(1{,}121)}} \rightarrow \quad \mathrm{R} = \sqrt[3]{\frac{2000{,}92}{(\pi)\cdot(1{,}121)}} = 8{,}32 \text{ m} \tag{3}$$

The constant 1.121, is derived from experimental data, facilitates the correlation between the fundamental radius and the overall volume of the digester (Guardado-Chacón, 2007).

3. The proportional unit is calculated in meters and R is the radius just dimensioned.

$$\mathrm{U} = \frac{\mathrm{R}}{4} \rightarrow \mathrm{U} = \frac{8{,}32}{4} = 2{,}08 \text{ m} \tag{4}$$

4. The rest of the parameters are determined

a. Proportions calculations

Dome radio: $\mathrm{R_c} = (5)\cdot(\mathrm{U}) \rightarrow \mathrm{R_c} = (5)\cdot(2{,}08) = 10{,}41$ m (5)

Cylindrical diameter: $\mathrm{D} = (8)\cdot(\mathrm{U}) \rightarrow \mathrm{D} = (8)\cdot(2{,}08) = 16{,}64$ m (6)

Dome height: $\mathrm{h_c} = (2)\cdot(\mathrm{U}) \rightarrow \mathrm{h_c} = (2)\cdot(2{,}08) =$ 4,16 m (7)

Wall height: $\mathrm{h_p} = (3)\cdot(\mathrm{U}) \rightarrow \mathrm{h_p} = (3)\cdot(2{,}08) =$ 6,24 m (8)

Base cone height: $h_t = (0{,}15) \cdot (U) \rightarrow \; h_t = (0{,}15) \cdot (2{,}08) = 0{,}312$ m (9)

b. Partials volumes

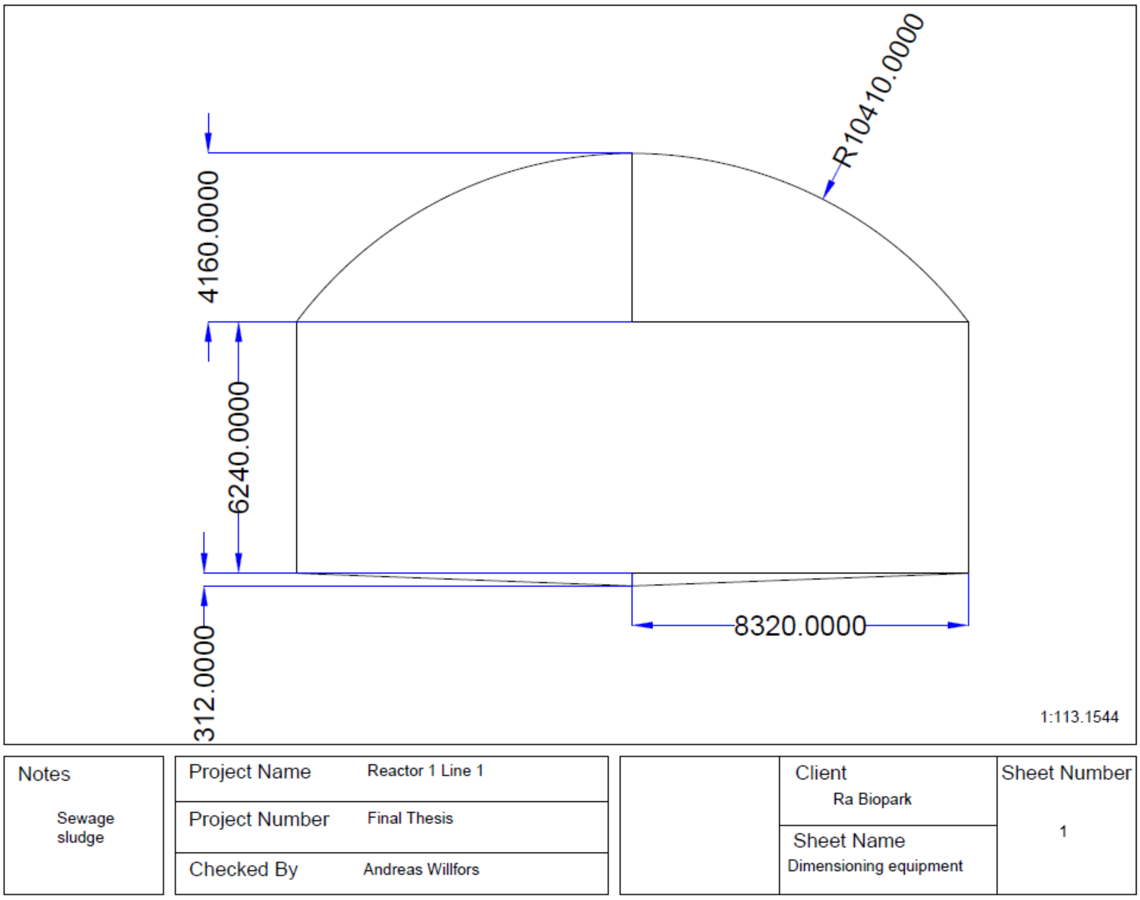
$$V_1 = (R^2) \cdot \pi \cdot h_p = (8{,}32)^2 \cdot \pi \cdot 6{,}24 = 1357 \ \ m^3 \ (10)$$

$$V_2 = \left(\frac{h_c}{3}\right) \cdot R_c \cdot \pi \cdot (h_c)^2 = \left(\frac{4{,}16}{3}\right) \cdot 10{,}41 \cdot \pi \cdot (4{,}16)^2 = 770 \ m^3 \ (11)$$

$$V_3 = \left(\frac{h_t}{3}\right) \cdot \pi \cdot (R)^2 = \left(\frac{0{,}312}{3}\right) \cdot \pi \cdot (8{,}32)^2 = 22{,}30 \ \ m^3 \ (12)$$

All the formulas and procedure used are based from the reference (Guardado-Chacón, 2007).

To facilitate comprehension of the recently calculated dimensions, a schematic of the design has been drafted. This visual aid not only simplifies the grasp of the dimensions but also facilitates comparisons between the sizes of the digester.



Notes: Sewage sludge
Project Name: Reactor 1 Line 1
Project Number: Final Thesis
Checked By: Andreas Willfors
Client: Ra Biopark
Sheet Name: Dimensioning equipment
Sheet Number: 1

Figure 14. AutoCAD layout of Reactor 1., (author's own) *

*All measurements are in mm in the design

Line 2 dimensioning in a wet system

For the correct dimensioning of this reactor, it is needed to know how much daily substrate will be. Knowing that there are different feedstocks, the volume occupied for each feedstock has been calculated. For these calculations. It will be considered that the data of each feedstock used has already the percentage of water required in a wet system, as indicated in Table 5, found in the main text in Chapter 4.1.

The steps followed in order to calculate the daily input substrate, start retrieving the available data for each type of feedstock, then the numbers given are for year-round, so it was divided into 365 days, the result obtained is the daily input per day.

$$\text{Organic waste} = \frac{20500 \text{ wet tonnes}}{365 \text{ days}} = 56{,}16 \text{ wet tonnes per day}$$

Then, it is needed to convert the result obtained before into meters cubic, because the equation of digestor volume requires that the substrate input is in meters cubic.

$$56{,}16 \frac{\text{T}}{\text{day}} \text{OW} \cdot \frac{1000\text{kg}}{1\text{T}} \cdot \frac{1 \text{ m}^3}{481\text{kg}} = 116{,}76 \text{ m}^3$$

$$\text{Fish waste} = \frac{19700 \text{ wet tonnes}}{365 \text{ days}} = 53{,}97 \text{ wet tonnes per day}$$

$$53{,}97 \frac{\text{T}}{\text{day}} \text{FW} \cdot \frac{1000\text{kg}}{1\text{T}} \cdot \frac{1 \text{ m}^3}{721\text{kg}} = 74{,}85 \text{ m}^3$$

$$\text{Brewery} = \frac{3450 \text{ wet tonnes}}{365 \text{ days}} = 9{,}45 \text{ wet tonnes per day}$$

$$9{,}45 \frac{\text{T}}{\text{day}} \text{B} \cdot \frac{1000\text{kg}}{1\text{T}} \cdot \frac{1 \text{ m}^3}{432\text{kg}} = 21{,}87 \text{ m}^3$$

$$\text{Animal waste} = \frac{2500 \text{ wet tonnes}}{365 \text{ days}} = 6{,}85 \text{ wet tonnes per day}$$

$$6{,}85 \frac{\text{T}}{\text{day}} \text{AW} \cdot \frac{1000\text{kg}}{1\text{T}} \cdot \frac{1 \text{ m}^3}{400\text{kg}} = 17{,}12 \text{ m}^3$$

Once all the feedstocks' weights are in cubic meters, a sum of them has been done, so a final number of the total daily input substrate for the wet AD system has been calculated

Total daily input substrate = 116,76 + 74,85 + 21,87 + 17,12 = 230,60 m^3

$$\text{Total of daily input substrate is } \mathbf{230,60\ \ m^3}$$

Next, it is calculated the volume of the digester.

$$\mathrm{V_d} = \mathrm{S_d} \cdot \mathrm{HRT}\ [\mathrm{m}^3] \qquad (1)$$

$$\mathrm{V_d} = 230{,}60\,\frac{\mathrm{m}^3}{\mathrm{day}} \cdot 25\ \mathrm{days} = 5765\ \mathrm{m}^3$$

Similarly, the volume of the reactor is calculated using equation (2) as before, yielding a result of 7686,67 m^3.

$$\mathrm{V_r} = \mathrm{V_d} + \tfrac{1}{3} \cdot \mathrm{V_d} \qquad (2)$$

$$\mathrm{V_r} = 5765 + \frac{1}{3} \cdot 5765 = 7686{,}67\ \mathrm{m}^3$$

Then the dimensions of the reactor are calculated in the same way as line 1, as a fixed dome digester.

The steps followed for the dimensioning are the following:

5. The volume of the reactor is calculated, in this case is 7686,67 m^3 previously calculated in the main text.

6. The basic radio is calculated

   $$\mathrm{R} = \sqrt[3]{\frac{\mathrm{V_r}}{(\pi)\cdot(1{,}121)}} \rightarrow \mathrm{R} = \sqrt[3]{\frac{7686{,}67}{(\pi)\cdot(1{,}121)}} = 12{,}97\ \mathrm{m} \qquad (3)$$

   The constant 1.121, is derived from experimental data, facilitates the correlation between the fundamental radius and the overall volume of the digester (Guardado-Chacón, 2007.

7. The proportional unit is calculated in meters and R is the radius just dimensioned.

$\mathrm{U} = \frac{\mathrm{R}}{4} \rightarrow \mathrm{U} = \frac{12{,}97}{4} = 3{,}24\ \mathrm{m}$ (4)

8. The rest of the parameters are determined

    c. Proportions calculations

$\mathrm{R_c} = (5) \cdot (\mathrm{U}) \rightarrow \mathrm{R_c} = (5) \cdot (3{,}24) = 16{,}2\ \mathrm{m}$ (5)

$\mathrm{D} = (8) \cdot (\mathrm{U}) \rightarrow \mathrm{D} = (8) \cdot (3{,}24) = 25{,}92\ \mathrm{m}$ (6)

$\mathrm{h_c} = (2) \cdot (\mathrm{U}) \rightarrow \mathrm{h_c} = (2) \cdot (3{,}24) = 6{,}48\ \mathrm{m}$ (7)

$\mathrm{h_p} = (3) \cdot (\mathrm{U}) \rightarrow \mathrm{h_p} = (3) \cdot (3{,}24) = 9{,}72\ \mathrm{m}$ (8)

$\mathrm{h_t} = (0{,}15) \cdot (\mathrm{U}) \rightarrow \mathrm{h_t} = (0{,}15) \cdot (3{,}24) = 0{,}486\ \mathrm{m}$ (9)

    d. Partials volumes

$\mathrm{V_1} = (\mathrm{R}^2) \cdot \pi \cdot \mathrm{h_p} = 5144{,}76\ \ \mathrm{m}^3$ (10)

$\mathrm{V_2} = \left(\frac{\mathrm{h_c}}{3}\right) \cdot \mathrm{R_c} \cdot \pi \cdot (\mathrm{h_c})^2 = 4616{,}03\ \ \mathrm{m}^3$ (11)

$\mathrm{V_3} = \left(\frac{\mathrm{h_t}}{3}\right) \cdot \pi \cdot (\mathrm{R})^2 = 85{,}74\ \ \mathrm{m}^3$ (12)

All the formulas used are based from the reference (Guardado-Chacón, 2007).

To facilitate comprehension of the recently calculated dimensions, a schematic of the design has been drafted.

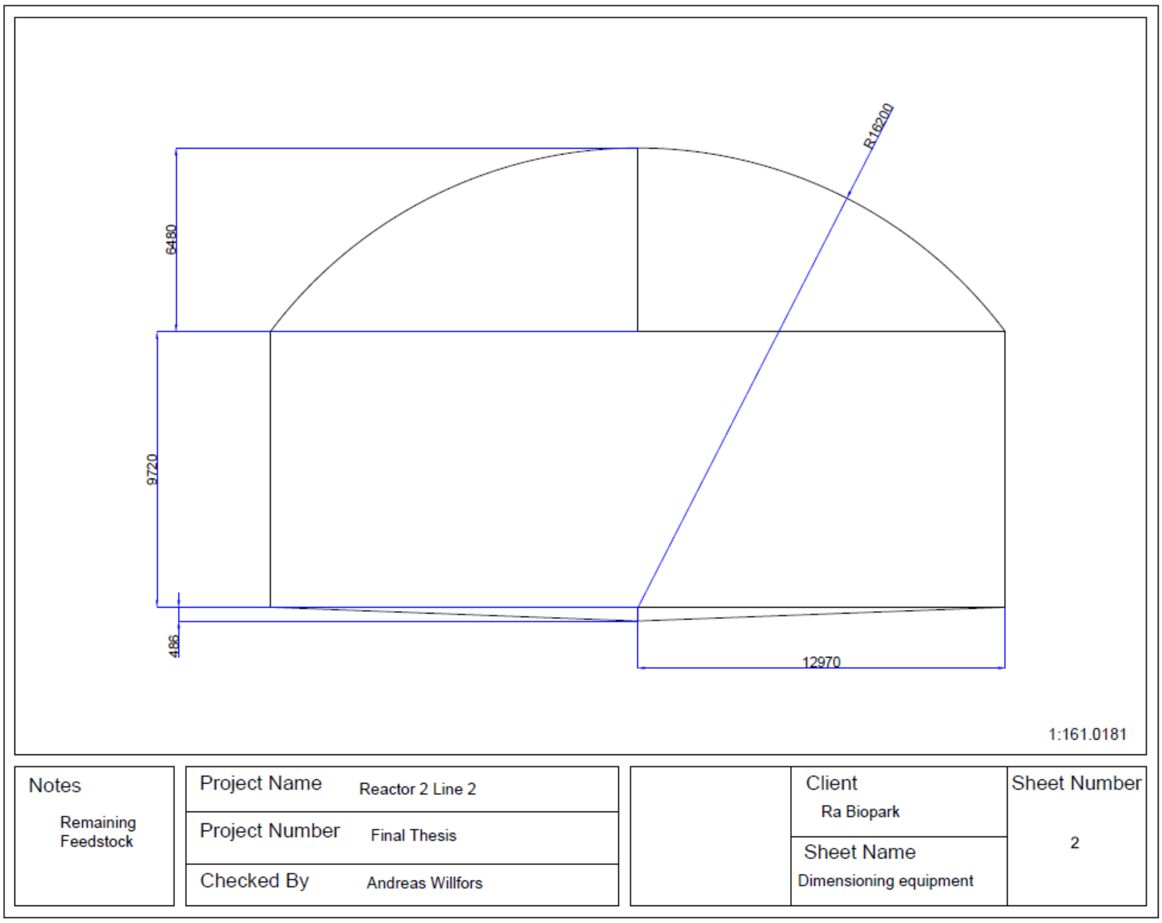


Figure 15. AutoCAD layout of Reactor 2, (author's own) *

*All measurements are in mm in the design

Line 2 dimensioning in a dry system

In line 2, it was assumed that the weight data for each feedstock, from Table 5, in a wet system already included the necessary water. For a dry system, we need to estimate the quantity of each feedstock without the additional water. To do this, we must know the normal dry matter content and the water content of each feedstock.

The moisture content determines the percentage of water in the feedstock. The moisture content for each feedstock has been retrieved from Table 9 in the appendix as well as the dry matter content. For the calculations of feedstock input this formula is used:

$$\text{Total input weight} = \text{dry matter content} + \text{water content}$$

Organic waste:

The wet tonne per year is multiplied by the percentage of moisture content.

$20500 \cdot 0{,}6 = 12300$ t moisture content in OW

The percentage of dry content is multiplied by the wet tonne per year.

20500·0,15=3075 t dry content in OW

Then the number obtained is summmed up with the water content

$$\text{Total input weight} = 3075 + 12300 = 15375 \frac{\text{t}}{\text{year}}$$

Next, the average dry tonnes per day are calculated and then multiplied by the density of each feedstock for having the final value in m^3.

$$15375 \frac{\text{dry tonnes}}{\text{year}} \cdot \frac{1 \text{ year}}{364 \text{ days}} \cdot \frac{1000 \text{ Kg}}{1 \text{ tonne}} \cdot \frac{1 \text{ m}^3}{481 \text{ Kg}} = 87{,}81 \text{ m}^3$$

The same procedure will apply to the remaining feedstock.

Fish waste:

19700 wet tonnes · 0,7=13790 moisture content of FW

19700 wet tonnes · 0,23= 4531 tonne dry content of FW

Total input weight= 13790 +4531 = 18321 $\frac{\text{t}}{\text{year}}$

$$18321 \frac{\text{dry tonnes}}{\text{year}} \cdot \frac{1 \text{ year}}{364 \text{ days}} \cdot \frac{1000 \text{ Kg}}{1 \text{ tonne}} \cdot \frac{1 \text{ m}^3}{721 \text{ Kg}} = 70 \text{ m}^3$$

Brewery waste:

3450 wet tonnes · 0,8=2760 moisture content of BW

3450 wet tonnes · 0,2= 690 tonne dry content of BW

Total input weight= 2760 +690 = 3450 tonnes $\frac{\text{t}}{\text{year}}$

$$3450 \frac{\text{dry tonnes}}{\text{year}} \cdot \frac{1 \text{ year}}{364 \text{ days}} \cdot \frac{1000 \text{ Kg}}{1 \text{ tonne}} \cdot \frac{1 \text{ m}^3}{432 \text{ Kg}} = 21{,}94 \text{ m}^3$$

Animal waste:

2500 wet tonne · 0,65=1625 moisture content of AW

2500 wet tonne · 0,65= 500 tonne dry content of AW

Total input weight= 1625 + 500 = 2125 tonnes

$$2125\ \frac{\text{dry tonnes}}{\text{year}} \cdot \frac{1\text{ year}}{364\text{ days}} \cdot \frac{1000\text{ Kg}}{1\text{ tonne}} \cdot \frac{1\text{ m}^3}{400\text{ Kg}} = 14{,}6\ \text{m}^3$$

All the values obtained are summed up.

Total substrate input= 87,81+70+21,94+14,6= **194,35** $\mathbf{m^3}$

So, the final value will be around 194,35 m^3 of daily input.

The illustration presented depicts potential dimensions for the digester, differing from the previously calculated dimensions for the other two digesters. These dimensions warrant thorough discussion to determine the most suitable size for the location and available installation space. It may be prudent to assess whether the proposed size necessitates dividing it into two reactors for more manageable disposition and dimensions.

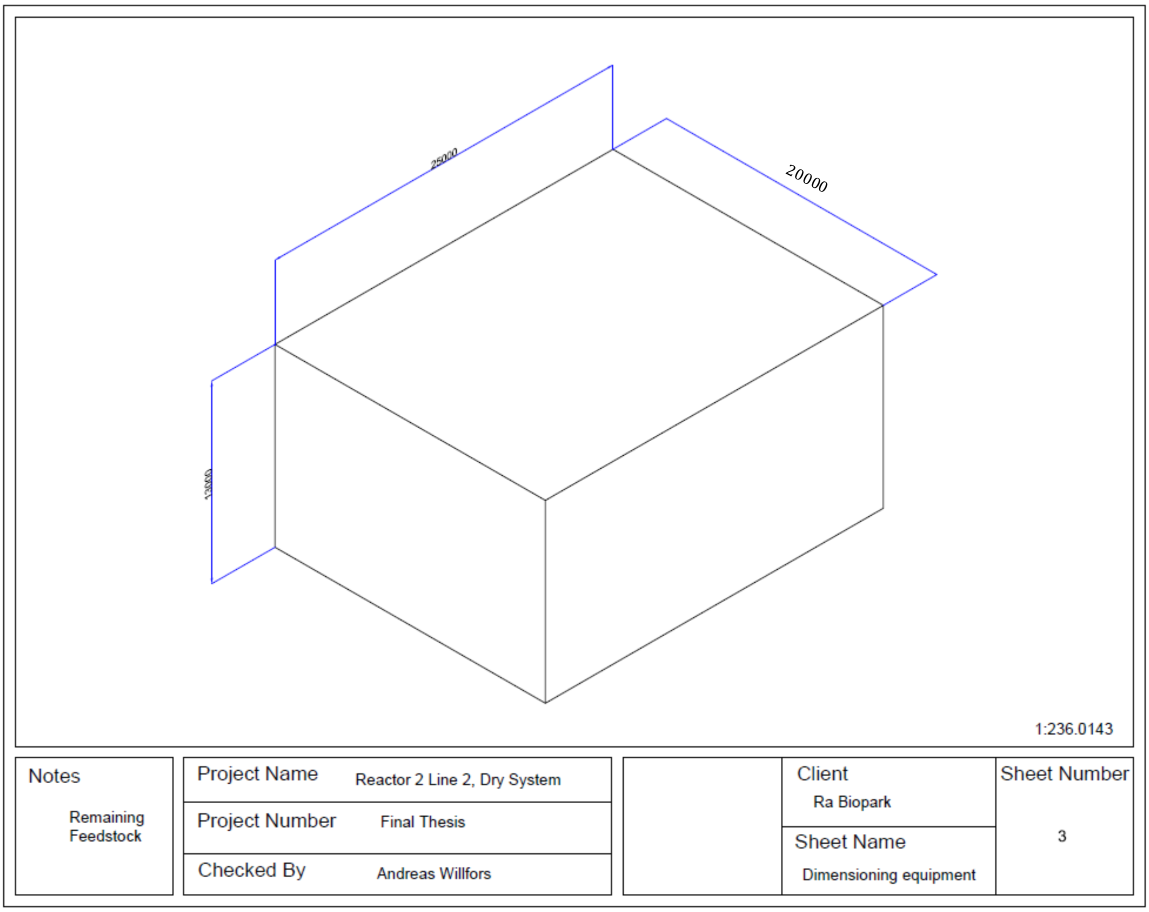


Figure 16. AutoCAD Layout Reactor 2 Dry system, (author’s own) *

*All measurements are in mm in the design