

# **Alternative Solutions for Handling Biogas Digestate in Norway: Mass and Energy Balances**

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## **DEGREE THESIS**

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### **Abstract**

Increasing municipal solid waste (MSW) poses a significant environmental challenge. Globally, 2.24 billion tons of MSW are generated annually, leading to an average of 0.79 kilograms per person per day. Biogas plants offer a promising solution, generating renewable energy while producing digestate - a valuable fertilizer. However, efficient digestate handling, particularly for transportation and application, remains crucial.

The current thesis deals with a planned biogas project in Norway, called Rå Biopark, delving into strategies aimed at enhancing digestate treatment. Leveraging mass and energy balances, the study offers a comprehensive picture of material flow and energy consumption throughout the process. This investigation yielded significant results, including the production of 8,820 tons/year of biochar, 1,350 tons/year of fertilizer pellets, and 1,344 tons/year of ammonium crystals.

Furthermore, the thesis explores alternative digestate treatment methods, analyzing their operational efficiencies and potential for producing desired end-products. Excel templates were developed to facilitate future modifications based on acquired data. To conclude, this research aims to advance sustainable digestate management within Rå Biopark. Further research into the of digestate treatment technologies and the refinement of modeling techniques holds promise for continued advancements in sustainable waste management.

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Language: English

Key Words: Digestate treatment, Biogas plants, Biofertilizers, Municipal Solid Waste.

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## Glossary

### Acronyms

|                |  |
|----------------|--|
| <i>WM</i>      | Water mass                               |
| <i>WM_d</i>    | Water mass digestate                     |
| <i>WM_r</i>    | Water mass removed                       |
| <i>WM_s</i>    | Water mass solid fraction                |
| <i>DM</i>      | Dry matter                               |
| <i>E</i>       | Energy consumed                          |
| $\Delta H$     | Enthalpy of water (heat of vaporization) |
| $\bar{C}_p$    | Specific heat capacity of a substance    |
| $\Delta T$     | Temperature increase                     |
| VS             | Volatile solids                          |
| TS             | Total solids                             |
| <i>m_f</i>     | Feedstock mass                           |
| <i>V_{CH4}</i> | Methane volume                           |
| <i>MSY</i>     | Methane Specific Yield                   |
|                | <i>V_b</i> Volume biogas produced        |
| <i>E_p</i>     | Energy production                        |
| <i>GMB</i>     | Global mass balance                      |

### Units

|     |                |
|-----|----------------|
| t   | Tons           |
| kWh | Kilowatt-hour  |
| GWh | Gigawatt-hour  |
| kg  | Kilograms      |
| g   | gram           |
| J   | Joules         |
| °C  | Degree Celsius |

## 1 Introduction

In contemporary times, a situation wherein the production of organic waste is constantly increasing is confronted. As the world's population continues to grow, reaching an estimated 9.8 billion people by 2050 (Li, 2023), the Municipal Solid Waste (MSW) daily produced at homes, businesses, and institutions is considerably increasing as a result. Every year, the world generates a staggering 2.24 billion tons of MSW, which translates to an average of 0.79 kilograms of waste produced by each person daily (Topics, 2018). Moreover, escalating trends in municipal solid waste are evident, with projections indicating an increase from 2.3 billion tons in 2023 to 3.8 billion tons by 2050 (Moore, 2024).

Given the significant negative impact of MSW, it is imperative to implement comprehensive and sustainable MSW management strategies to effectively manage and mitigate the associated environmental and societal impacts. Uncontrolled waste dumping is no longer acceptable today, and even controlled landfill disposal and incineration of organic waste are not considered optimal practices. Instead, there is a growing imperative to prioritize strategies that encompass energy recovery, nutrient recycling, and organic matter reuse.

In addressing the challenges of MSW management, various methods have been explored, each offering unique advantages and applications. Among these methods, anaerobic digestion (AD) stands out as a promising solution, capable of transforming organic matter into biogas, while also providing valuable fertilizer for agricultural use. Biogas typically refers to a gas obtained through the degradation of organic matter by bacteria in the absence of oxygen (Bhatia, 2014).

The leftover material from a biogas plant, called digestate, holds potential as a valuable fertilizer. However, its immediate application next to the plant can be challenging due to the lack of nearby agricultural fields, necessitating transportation to other locations for spreading. Moreover, this bioresidue poses handling difficulties due to its high water content. Efforts are focused on reducing moisture content to enhance handling and transportation efficiency, thereby concentrating and drying the fertilizer for practical use. (Eu-Supply.com, 2024).

The task for this thesis came to be from the project Boost Nordic Biogas, funded by Interreg Aurora, who wants to increase biogas production in the northern parts of Finland, Sweden and Norway. Since Rå Biopark represents the largest initiative in northern Norway, it is important for the project to cooperate with Rå Biopark. Boost Nordic Biogas wanted to investigate the mass and energy balance of the Rå Biopark case and explore alternative solutions to facilitate increased biogas production and enhanced digestate handling in Norway. However, as Rå Biopark faces with the mentioned challenge, the importance of digestate treatment becomes paramount. In response, this thesis focuses on optimizing digestate handling for the project; providing a comprehensive picture of material flow and energy consumption throughout the digestate treatment process. This allows for identifying areas with excess material or wasted energy, ultimately leading to a more efficient system for Rå Biopark. Moreover, it delves also exploring alternative methods for digestate handling and analyzing their operational efficiencies to enhance the production of desired end products. Through a comprehensive examination of technologies and quantitative modeling, this study seeks to contribute to the advancement of sustainable waste management practices within the Rå Biopark project.

### **1.1 Aims and objectives**

The aim of the thesis is to tackle the challenge of effectively treating digestate within the Rå Biopark project. This involves exploring an alternative solution for digestate management due to the absence of nearby farmlands, while also examining the mass and energy balances of the process. This objective will be pursued by exploring and analyzing alternative methods within their operational processes to enhance the efficiency of obtaining the final desired products.

To achieve this, some objectives have been established as follows:

- Research and analyse alternative technologies for handling digestate.
- Perform mass balance analyses within the Rå Biopark process.
- Conduct energy demand assessments for each stage of the digestate management process at Rå Biopark.

- Apply quantitative parameters to model the technologies employed by the company, aiming to enhance the achieved outcomes.

## **1.2 Thesis structure**

This thesis begins with Section 1 providing an introductory overview of the thesis topic, outlining the aims and objectives in alignment with the requirements of the Rå Biopark project.

Following this, a study background is presented in Section 2, introducing Rå Biopark project, which has served as both an inspiration and a focal point for the thesis. Additionally, an overview of biogas production is provided to contextualize the project's scope. This includes an examination of biogas production levels in Europe, with a specific focus on the Nordic countries and Norway, where Rå Bioparc plans to establish its plant. This approach offers a comprehensive understanding of the current state of biogas plants across Europe.

Continuing into Section 3, situated within the theoretical framework of the thesis, alongside Section 2, which delves into digestate and its treatments. Besides, it introduces basic traits of digestate, explaining the technologies used by Rå Biopark, and includes examples of other methods in use. Ending the theoretical section, Section 4 introduces flowcharts and key data about the Rå Biopark project before transitioning to the practical part.

The practical section begins with Section 5, where the methodology used for all thesis calculations is outlined. The emphasis is making the calculations in an Excel template where values can be adjusted to obtain wanted results.

In Section 6, mass balance calculations for the Rå Biopark process are presented, with a particular focus on digestate treatment and valorization.

Section 7 delves into calculating the energy demands of various steps in digestate handling after anaerobic digestion, following the steps planned by Rå Biopark.

The practical part concludes with Section 8, the assessment of biochar and biogas yield rates is conducted, aligning with the tasks suggested and requested by the project.

Moving forward, Section 9 discusses results and important aspects of these practical sections, leading into a discussion in Section 10 and concluding with final thesis conclusions in Section 11.

## 2 Study background

The development of this thesis has been made within a project called Rå Biopark (<https://www.raa.bio/>) which aims to build a biogas plant in Northern Norway. Building on a previous project that explored using recycled materials for fertilizer in biogas production, Boost Nordic Biogas, financed by Interreg Aurora, aims to improve the economic viability and efficiency of biogas production in the Nordic region. This cross-border collaboration brings together researchers, producers, and entrepreneurs to identify challenges and develop solutions through knowledge sharing and new technologies (Boost Nordic Biogas, 2024).

### 2.1 Rå Biopark

Rå Biopark is a project that describes how a large-scale biogas plant can be realised in Northern Norway. The planned biogas plant is to be located on the site of the existing composting plant in Skibotn located in the north of Norway (see Figure 1), owned by Origo Skibotn AS.



Figure 1. Location on the map of Rå Biopark biogas plant.

(Author's own, adapted with Google maps)

Annually, it is expected to transform more than 63,000 tons of organic waste into biogas, a renewable energy source equivalent to 6 million liters of diesel or 60 GWh of power, serving the needs of 41 municipalities. This initiative underscores a commitment to mitigating environmental impact while meeting the energy demands of local communities on a significant scale (er, 2014).



Figure 2. Sketch of the Rå Biopark plant. (er, 2014).

Nonetheless, in Northern Norway regions agricultural capacity to utilize digestate (a byproduct of the biogas process) from a large biogas plant is restricted compared to areas further south, where there are higher concentrations of farmers and longer growing seasons. As a result, composting has been continued instead of biogas production in Northern Norway, a natural process turning organic waste into nutrient-rich soil improver. Unfortunately, the compost product's low profitability stems from quality issues and logistical challenges. Operators in the region face challenges: either continue composting or invest in small biogas plants lacking economies of scale, leading to unacceptably high waste delivery costs compared to areas with denser farming populations (Eu-Supply.com, 2024).

Therefore, the primary concern addressed in the Rå Biopark project is the limited capacity of agriculture in Northern Norway to absorb digestate, being impractical the traditional spreading of digestate slurry on nearby farmland.

## **2.2 Biogas production**

Biogas is a gas mixture that forms when organic waste decomposes in oxygen-free environments, a process known as anaerobic digestion. Biogas production can occur naturally in anaerobic environments such as wetlands or landfills, as well as through controlled processes in biogas plants (Biovoima, 2024).

AD is a microbial-driven process of organic matter breakdown in the absence of oxygen. This process is extensively utilized today for biogas production within sealed reactor vessels known as digesters, which requires ideal reactor conditions that can be influenced by the right feed composition. Moreover, a diverse array of microorganisms participate in anaerobic digestion, facilitating the conversion of organic matter into two primary outputs: biogas and digestate (Lemvigbiogas, 2024).

### **2.2.1 Purposes of Anaerobic Digestion**

By harnessing the natural decomposition process of organic waste, biogas systems generate this methane-rich gas that provides environmental and socio-economic benefits, making it a versatile and valuable resource. The primary purpose of producing biogas is to harness renewable energy from those organic waste materials. In other words, biogas can be used as a renewable energy source for heating, electricity generation, and cooking. It provides a sustainable alternative to fossil fuels, reducing dependency on non-renewable resources and contributing to the reduction of greenhouse gas emissions and mitigating global warming (IEA, 2024).

The basic form of raw biogas obtained from anaerobic digestion typically consists of 50-70% methane ( $\text{CH}_4$ ), 30-50% carbon dioxide ( $\text{CO}_2$ ), and minor gas constituents, including trace elements like hydrogen ( $\text{H}_2$ ), nitrogen ( $\text{N}_2$ ), and others. However, because of the presence of impurities, this raw biogas typically undergoes treatment afterward. Removing carbon dioxide, hydrogen sulfide, and other impurities through a process called upgrading purifies the biogas and creates biomethane. With a very high methane content biomethane

is the base for both Bio-LNG (Liquefied Natural Gas for long-distance transport) and Bio-CNG (Compressed Natural Gas for cars and trucks), offers a cleaner alternative to fossil fuels. (Rinfi Home, 2023).

Its production also aids in waste reduction. By converting these wastes into biogas, the process mitigates environmental pollution and reduces the volume of waste sent to landfills, thereby addressing waste management challenges. Also, the development of national biogas sector contributes to establishment of new enterprises, providing an additional income source for farmers in rural areas, and create new jobs.

Moreover, the byproduct of anaerobic digestion, known as digestate, is the nutrient-rich residue left behind after biogas production. This digestate is a valuable source of nutrients, such as nitrogen, phosphorus, and potassium, which are essential for plant growth. After the biogas production process, the organic material is broken down, making these nutrients more readily available for uptake by plants compared to the original feedstock. This digested material can then be applied to land as a fertilizer, reducing reliance on chemical fertilizers and promoting a more sustainable agricultural cycle. Furthermore, it can also serve as an excellent soil amendment, enhancing soil fertility and crop productivity (Lemvigbiogas, 2024). Therefore, Anaerobic Digestion offers a sustainable solution by closing the nutrient loop in food production. This circular approach ensures nutrients are returned to the soil, promoting a more environmentally friendly agricultural system.

All companies follow the mentioned process as a general guideline for the production of biogas through anaerobic biowaste digestion and the subsequent production of biogas and digestate. This dual benefit not only addresses the pressing need for renewable energy sources but also contributes to promoting soil health and sustainable agricultural practices. The following Figure 3 illustrates the schematic production process of Rå Biopark.

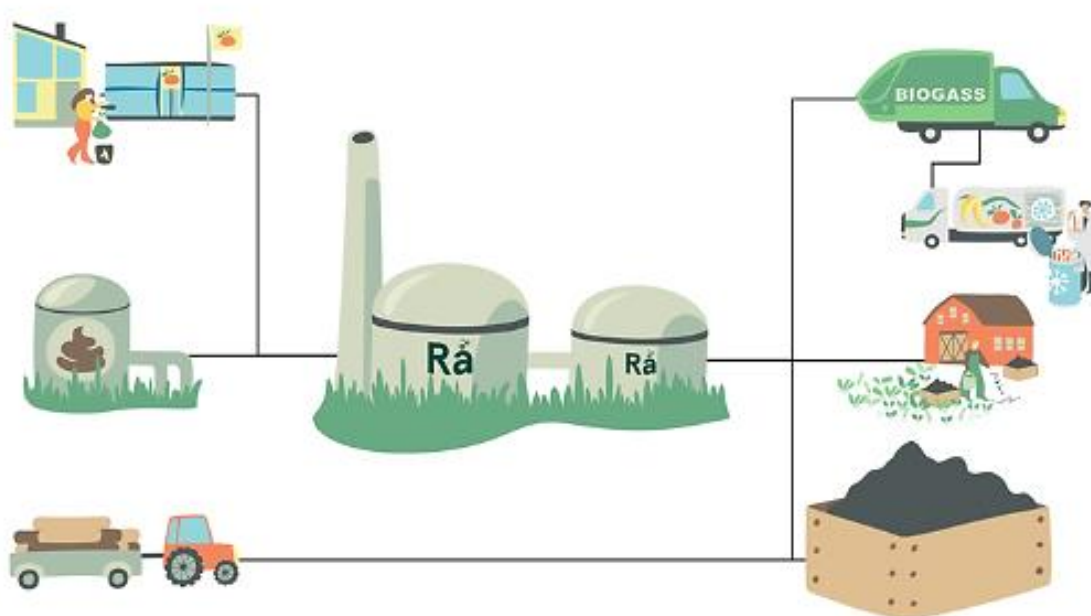


Figure 3. Rå Biopark biogas production process. (er, 2014).

### 2.3 Biogas production in Europe

In 2020, according to the European Biogas Association (EBA), Europe experienced a substantial increase in biogas production, reaching a total of 71 TWh. Germany, as the leading producer, significantly contributed to this production, with United Kingdom, Denmark, France and Italy also playing key roles in the European biogas landscape.

Figure 4 sets out the top 10 European countries with the highest biomethane production in 2020.

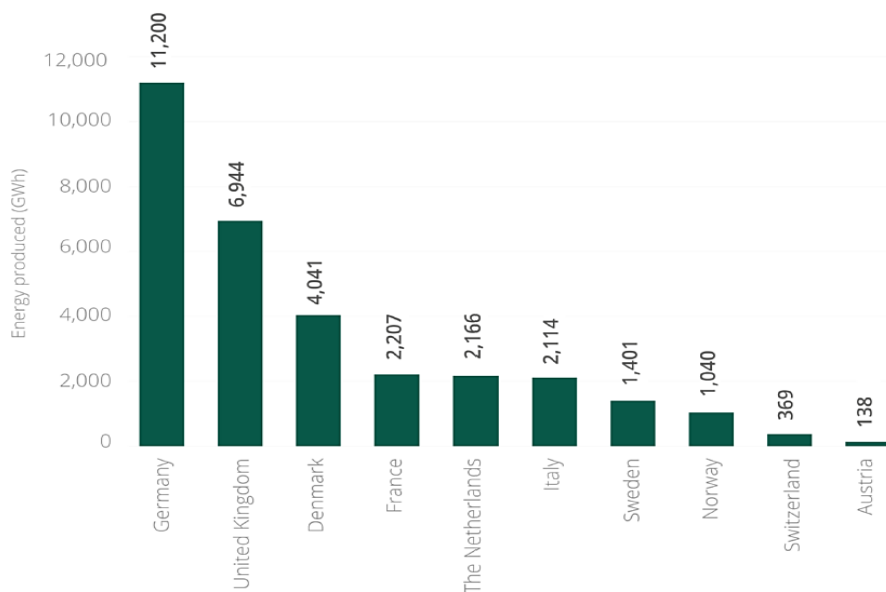


Figure 4. Top 10 European countries biomethane production. (EBA, 2023).

Furthermore, according to EBA (2020) Norway's emergence as a pioneering country in Bio-LNG production has added to the overall biogas and biomethane production in Europe, with the country's combined production exceeding 1 TWh. This growth underscores the evolving significance of Norway in the European biogas production sector, highlighting the country's potential to further contribute to the renewable energy landscape in the region.

As of April 2023, Europe boasts 1,322 biomethane-producing facilities, representing a significant 30% increase compared to 2021 (EBA, 2023). These plants play a crucial role in achieving Europe's ambitious renewable energy goals and contributing to a more sustainable future. So, considering the decreasing of gas demand, renewable gases can cover 30 – 40% of the gas demand by 2050.

### 2.3.1 Biogas production in Nordic countries

The Nordic countries, including Denmark, Finland, Iceland, Norway, and Sweden, are actively involved in the development and utilization of biogas plants. However, some of them such as Sweden, Finland and Norway have smaller and less developed natural gas networks compared to some other European countries. These countries lack extensive pipelines and associated infrastructure for transporting natural gas across their territories,

which hinders the widespread distribution of biomethane through the grid and favours on-site production of Bio-CNG for local use. This is partly due to their historical reliance on other energy sources like hydropower and nuclear power, and partly due to their lower population densities compared to other European regions (EBA, 2023).

Moreover, the cold climate of the Nordic countries significantly limits agricultural land, restricting the availability of crops and manure for biogas production. Current land use for agriculture in the Nordic countries varies, with Norway dedicating around 3.5% of its land area, Sweden utilizing approximately 7.6%, and Finland using roughly 7.2%. While Norway has seen a slight increase in agricultural land use, Sweden and Finland have maintained similar levels compared to past data (KTH, 2024). Therefore, the limited availability of nearby agricultural crops for digestate utilization can indeed be a challenge for spreading digestate from biogas plants in the Nordic countries.

### **2.3.2 Biogas production in Norway**

Norway's waste management system differs from countries with traditional MSW management companies. Instead, all 356 municipalities in Norway hold direct responsibility for collecting, treating, and disposing of the municipal solid waste generated within their borders (Wikiwand, 2020). While private companies might be involved in specific aspects like collection or treatment, the overall burden and decision-making authority lie with the individual municipalities. This system fosters local control and tailored waste management strategies for each region.

Considering the biogas sector, Norway has multiple existing plants and several new projects in the pipeline. Although official figures for 2023 are not readily available, data indicates the presence of at least 56 biogas plants operating in Norway as of 2022 (Biogass Norge, 2024).

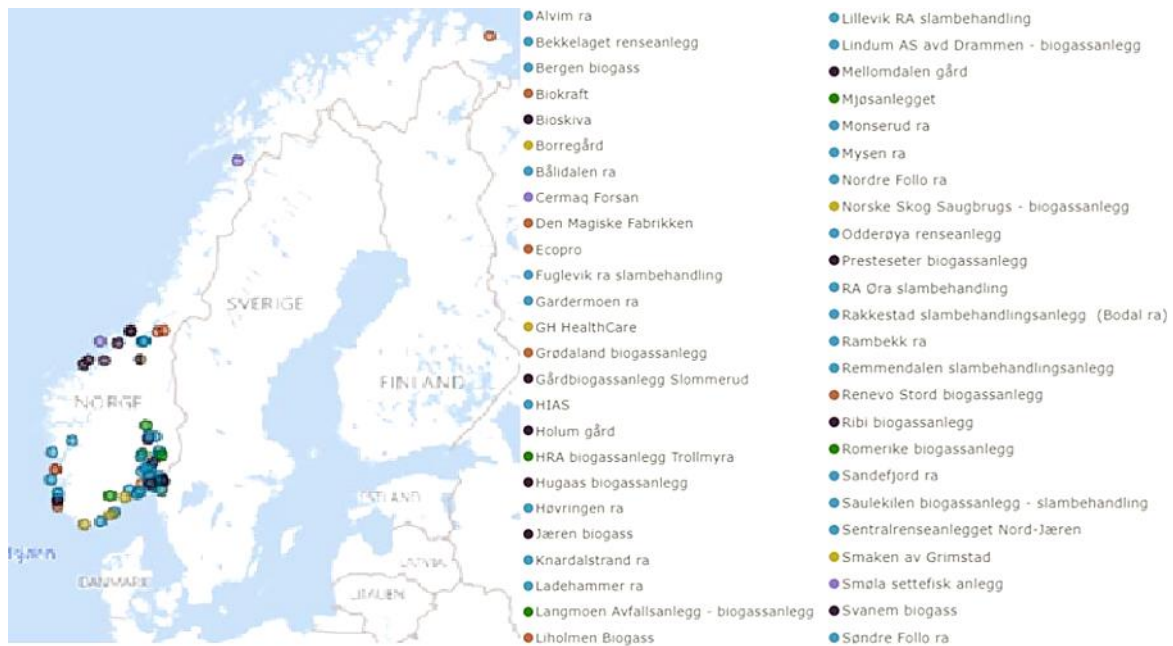


Figure 5. Biogas plants in Norway as of December 2022 (Biogass Norge, 2022).

### 3 Digestate from biogas plants

From the anaerobic digestion process, biogas and digestate are the two valuable products obtained. Biogas can be directly combusted to generate heat and electricity, or it can be upgraded and compressed for use as a transportation fuel. Hence, the digestate is a two-in-one solution for sustainable agriculture. Its content of essential plant nutrients allows it to directly act as a bio-fertilizer, reducing reliance on chemicals. Additionally, digestate improves soil structure, water retention, and microbial activity, functioning as a valuable soil amendment (Makádi et al., 2012).

While promising, a significant challenge arises after anaerobic digestion – digestate contains a high percentage of water. This excess water increases transportation costs, makes spreading across fields more difficult, and dilutes the readily available nutrients, reducing immediate fertilizing value. The majority of nutrients are present in the digestate in dissolved or suspended forms. So, processing the digestate to concentrate these nutrients offers a promising approach to enhance its fertilizing value and transform it into a more commercially viable bio-fertilizer product (Karunanithi, 2014). This means that biogas digestate as a substitute to manufactured mineral fertilizers closes the loop by allowing nutrient recycling. According to the Anaerobic Digestion and Bioresources

Association (ADBA), 1 ton of artificial fertilizer replaced with digestate saves 1 ton of oil, 108 tons of water and 7 tons of CO<sub>2</sub> emissions (EBA, n.d.).

### **3.1 Composition of digestate**

The raw digestate obtained from the digester will be either in solid form or liquid form, which are distinguished on the bases of their dry matter (DM) content. The liquid digestate contains less than 15% DM content, while the solid digestate contains more than 15% DM. Furthermore, the value of biogas digestate as an alternative to the mineral fertilizer is highly based on the effectiveness of AD on nitrogen availability and also the effect on nutrient content. The micro and macro nutrients present in the feedstock are also available in the digestate after the digestion. During the AD process, certain bio-chemical reactions occur which modifies the nutrient structure in the feedstock and make it available for crops (Lukehurst, 2012).

The composition and quality of the digestate is determined by the composition and quality of the feedstock combined with the effectiveness of the AD process, including manure from livestock farms, leftover food scraps from homes and restaurants, sewage sludge from treatment facilities, and even agricultural leftovers like straw and cornstalks (Gasum, 2024).

#### **3.1.1 Digestate macronutrients content**

Biogas digestate is rich in mineral nitrogen (N) find it usually in the form of ammonium denoted as  $\text{NH}_4^+ \text{-N}$  (Yang et al., 2022). The  $\text{NH}_4\text{-N}$  concentration tends to be higher when protein-rich feedstocks, like dairy by-products and slaughterhouse waste, are utilized. This conversion of organic nitrogen into  $\text{NH}_4\text{-N}$  enables crops to promptly access and utilize the nutrient as plant growth (Makádi et al., 2012).

Digestate is rich not only in mineral nitrogen but also in phosphorus (P) and potassium (K), two other vital macronutrients for plant growth (Tambone et al., 2010). The phosphorus-potassium ratio in digestates averages around 1:3, which is particularly advantageous for crops such as grains and rapeseed (Makádi et al., 2012).

The averaged biogas digestate macronutrients composition obtained from wet AD process is shown in Table 1 which is gathered from different studies.

Table 1. Averaged macronutrient composition of biogas digestate (Karunanithi, 2014)

| <b>Nutrient</b> | <b>Amount</b>                   |
|-----------------|---------------------------------|
| Nitrogen (N)    | 2.3 – 4.2 kg/tonne of digestate |
| Phosphorous (P) | 0.2 - 1.5 kg/tonne of digestate |
| Potassium (K)   | 1.3 - 5.2 kg/tonne of digestate |
| Dry Matter      | 2 – 7%                          |

### 3.1.2 Digestate micronutrients content

In addition to the nutrients listed previously, small amounts of trace elements are also present in digestate. Some of these elements, such as copper (Cu) and zinc (Zn), are essential for various biological functions, while others like cadmium (Cd), chromium (Cr), mercury (Hg), and lead (Pb) can be toxic to living organisms. The primary sources of these heavy metals include animal feed additives, the food processing industry, flotation sludge, fat residues, and domestic sewage (Makádi et al., 2012).

## 3.2 Digestate management technologies

Several established technologies are currently employed to treat biogas digestate, aiming to increase its dry matter content through water removal. These advancements have transformed digestate into a manageable, valuable resource, and successful implementations of digestate-derived bio-fertilizers within large-scale agriculture have demonstrably proven the potential of this approach.

Indeed, a multitude of methods are available for processing digestate to enhance its safety for use. However, the specific processing required depends on the physicochemical characteristics of the digestate, which will determine its final use as well (Lamolinara et al., 2022). Below, the technologies that Rå Biopark aims to employ for reducing moisture content of the digestate are outlined and described. Additionally, through research, other potential alternatives to these technologies are mentioned.

### 3.2.1 Dewatering

After the anaerobic digestion process a digestate with a low percentage of dry matter content is obtained, meaning that its water content is significantly higher compared to solid matter. Therefore, the process proceeds with dewatering as the initial step to remove excess water and elevate the dry matter content.

The primary aim of this process is to divide the digestate into two distinct fractions: the Liquid Fraction Digestate (LFD) and the Solid Fraction Digestate (SFD). This process involves a combination of chemical and mechanical techniques like filtration (using belt filter presses, chamber filter presses, or vacuum filtration) and centrifugation (separating solids through high-speed spinning) (Lamolinara et al., 2022). This separation results in a solid cake, commonly referred to as biosolids, and a dewatering liquor (Svennevik, 2019). Additionally, both fractions are typically subjected to further treatment to increase their dry matter content until they reach the desired final products. This solid fraction can achieve a concentration of 20-30% or even higher (Lamolinara et al., 2022). Thus, the solid cake can be directly used as fertilizer without any further processing but also further treated to concentrate more the dry matter content. Meanwhile, the separated liquid, rich in nutrients, is often subjected to further processing for nutrient recovery (Svennevik, 2019). A basic diagram outlining this process is provided in Figure 6.

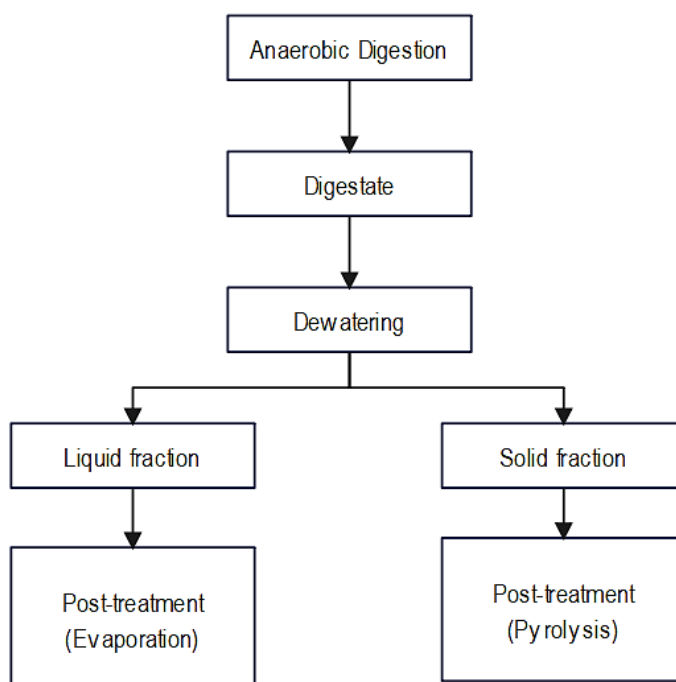


Figure 6. Dewatering process flowchart. (Author's own, adapted from Eu-Supply.com, 2024).

### 3.2.2 Pyrolysis

Following the dewatering step, as mentioned earlier, the solid portion of the bioresidue is further processed to convert it into a fertilizer product. There are various technologies available for this purpose, and one of the options considered in this project is the utilization of pyrolysis.

Pyrolysis is known as a thermochemical process which involves subjecting the biomass to high temperatures in an oxygen-free environment. Figure 7 shows the process which leads to the generation of valuable products including biochar, bio-oil, and gas(syngas) (Ghimire, 2020). There are six major types of pyrolysis technologies: fast pyrolysis, flash pyrolysis, slow pyrolysis, vacuum pyrolysis, hydro-pyrolysis, and microwave pyrolysis (MWP). These technologies are differed by their heating rate, pyrolysis temperature, residence time, reaction environments, and heating methods. In general, the proportions of value-added products generated by pyrolysis technologies are different (Li et al., 2023).

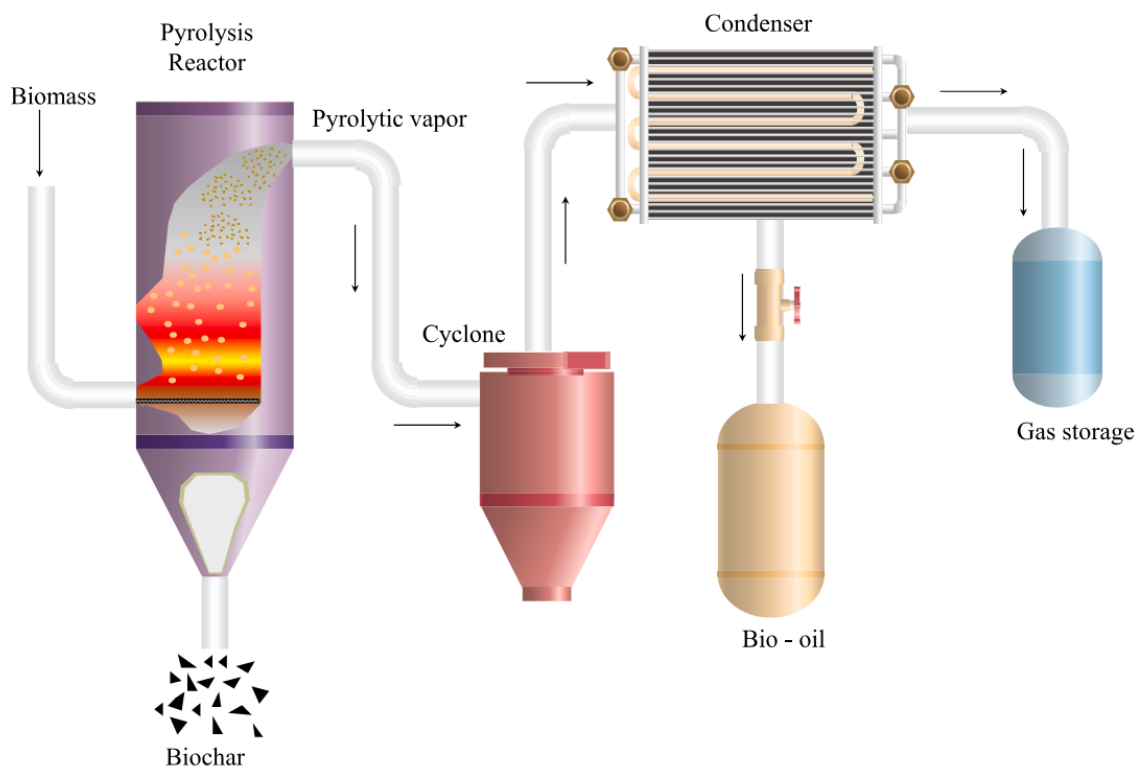


Figure 7. Schematic diagram of pyrolysis (N et al., 2022)

Biochar offers a range of advantages due to its properties, such as rich carbon content, high cation exchange capacity, large surface area and stable structure. These properties make it

a valuable resource in various environmental applications like soil and water remediation, carbon sequestration, and wastewater treatment. In comparison to activated carbon typically used in wastewater treatment, biochar exhibits superior adsorption capacity, especially at high initial concentrations of total chemical oxygen demand (Wang & Wang, 2019).

The liquid product, also known as bio-oil, holds significant commercial potential, serving as an alternative to fuel oil and as a valuable source of bioenergy and precursor materials for bio-based chemical production (Sharma et al., 2024). Hence, enhancing the quality of bio-oil through upgrading processes is essential to meet the standards required for its utilization as a chemical component and to match the quality of conventional petroleum-based liquid fuels (Lachos-Perez et al., 2023). Besides, the non-condensable gas byproduct of pyrolysis, known as syngas, can be a valuable source of both heat and electricity through a process known as combined heat and power (CHP) (Sharma et al., 2024).

Furthermore, numerous factors affect the production of these products through pyrolysis, including temperature, residence time, biomass composition, and heating rate. However, it is important first to identify the key parameters for our focus. The yield of biochar can be greatly impacted by the composition of different components in the biomass, especially hemicellulose, cellulose, and lignin. By focusing on these essential parameters, it can not only be increased biochar yield but also enhance its quality and characteristics for various applications. Hence, a comprehensive analysis of biomass composition is vital for maximizing the efficiency and efficacy of the pyrolysis process in biochar production (Mukherjee et al., 2022).

Temperature is also an important parameter to consider which plays a crucial role in determining the properties of biochar products. Generally, as the pyrolysis temperature increases, the yield of biochar tends to decrease. This is because higher temperatures (600°C) promote the breakdown of biomass components, such as cellulose and hemicellulose, into volatile gases like bio-oil and synthetic gas (Sharma et al., 2024). As a result, less solid biochar residue is formed, leading to lower biochar yields. However, with higher temperatures during pyrolysis result in a more stable biochar with a higher carbon

content. This increased stability is attributed to the higher carbon content and the removal of volatile components, which reduces the likelihood of further decomposition over time.

Nevertheless, lower pyrolysis temperatures (300°C) often result in higher biochar yields. At lower temperatures, there is less thermal decomposition of biomass components, leading to more solid biochar being produced. However, this biochar may have a lower carbon content and stability compared to biochar produced at higher temperatures (Mukherjee et al., 2022).

The impact of how long the biomass stays in the pyrolysis reactor, known as residence time, varies depending on the temperature used. At lower temperatures around 300°C, keeping the biomass in the reactor for longer periods significantly reduces the amount of biochar produced. However, at higher temperatures like 600°C, the residence time does not have much of an effect on the amount of biochar generated. This is because, at higher temperatures, the residence time mainly affects the surface and internal structure of the biochar, rather than the overall yield (Zhang et al., 2014).

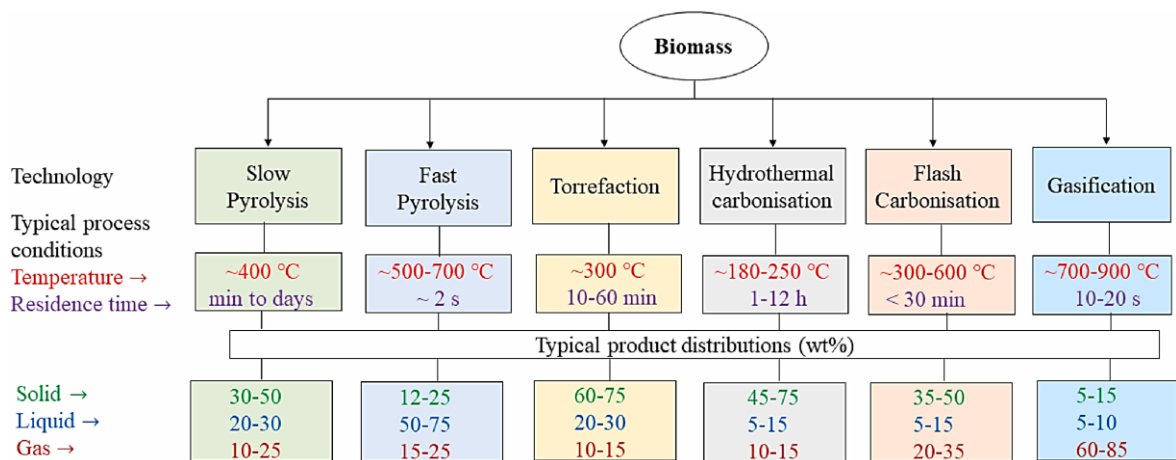


Figure 8. Biomass thermochemical conversion technologies, and product distribution depending on temperature and residence time conditions. (Sharma et al., 2024)

### 3.2.3 Evaporation

The liquid fraction, or the rejected water from the dewatering process, can be subjected to additional processing using various techniques, such as evaporation. This method can utilize excess heat generated from the Combined Heat and Power (CHP) unit in the biogas plant (Drosg et al., 2015). The purpose of evaporation is to significantly reduce the volume of the digestate fraction, obtaining two main output streams: concentrate and ammonia

water. The volume reduction of the liquid fraction digestate depends on its input parameters and the efficiency of the evaporator. The concentrate retains most of the original nutrients, with the loss primarily attributed to ammonia volatilization. This loss can be mitigated through pH modification using sulphuric or nitric acid. In the evaporation system, ammonia and water leave the evaporator as gas and enter a scrubber where the ammonia reacts with sulphuric acid to form ammonium sulphate (Vondra et al., 2019). In Figure 9 can be observed an example of a multistage evaporation system.

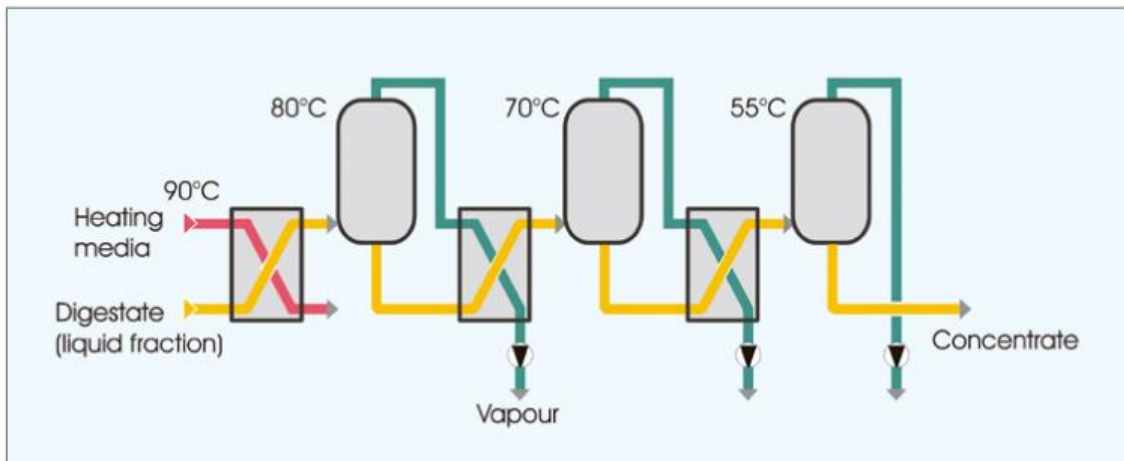


Figure 9. Multistage evaporation system (Drosg et al., 2015)

### 3.2.4 Alternative technologies

The design of digestate treatment system is technically challenging and requires multiple dimensions of considerations. A recent review (Monfet et al., 2018) concluded that there are 14 possible categories of processes for digestate treatment, including thickening, dewatering, membrane filtration, ammonia stripping, thermal drying, combustion, pyrolysis, gasification, among others (Vondra et al., 2019).

Additionally, Table 2 summarizes several alternative technologies utilized; however, pyrolysis and evaporation were chosen for further analysis due to their specific relevance to the project's interests.

Table 2. Alternative technologies for handling the digestate (Addapted from Lamolinara et al., 2022)

| <b>Process</b>   | <b>Application</b>   | <b>Main characteristics</b>   |
|--|--|---|
| <b>Thickening.</b> Including: gravity settling, filtration, air flotation and centrifugation   | Separation of the liquid and solid fractions of the digestate  | Digestate is concentrated up to 5–10% of suspended solids   |
| <b>Membrane filtration.</b> Including: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and forward osmosis (FO) | Removal of suspended solids, microorganisms, macromolecules, and small organic molecules and ions from liquid fraction<br>Permeates are rich in K and N and can be used as green fertilizers | Simple physical process that does not require addition of chemicals. Particles can be separated depending on their sizes. Operation and maintenance costs are lower than for other separation processes |
| <b>Ammonia stripping:</b> air and steam stripping  | Removal of ammonia from liquid fraction. The stripping can be applied directly to digesters, decreasing costs of removal and recovery of ammonia   | The stripped ammonia can be recovered and transformed into an ammonium salt which can be valorized in agriculture or chemical industries  |
| <b>Thermal drying</b>  | Elimination of water from dewatered solid fraction using forced convection of heated air   | Dried solid fraction can be pelletized to improve its management with the aim to valorize it by thermochemical processes or as a source of animal litter  |
| <b>Combustion</b>  | Energetic valorization of dried solid fraction to produce heat   | Dried solid fraction presents a heating value of 14 MJ/kg or highest which, is attractive to produce heat.  |
| <b>Gasification</b>  | Production of syngas which can be valorized as hydrogen for energetic or chemical purposes or to produce chemical block molecules  | Gas heating power is 23 MJ/Nm <sup>3</sup> , like natural gas. High potential to produce hydrogen from renewable sources  |

#### 4 Rå Biopark digestate handling

Rå Biopark plans to implement a comprehensive digestate treatment technologies to increase the value of the digestate and reduce the amount to be handled by 70-90%. This involves drying and concentrating the digestate to manufacture fertilizer products, aiming to improve efficiency and sustainability by enhancing the value of by-products and minimizing waste management.

## 4.1 Rå Biopark feedstock

Waste inputs of Rå Biopark encompass household, commercial, and food production waste, along with supermarket products and fats, oils, and grease. Brewery byproducts, factory residues, and animal manure contribute to the mix, while aquaculture waste, fish processing byproducts, wash water, and municipal sewage sludge offer additional feedstock, each necessitating specific treatment due to their diverse compositions and potential contaminants (Eu-Supply.com, 2024).

Figure 10 illustrates the breakdown of available feedstocks utilized in the project, delineating their respective percentages by weight (%).

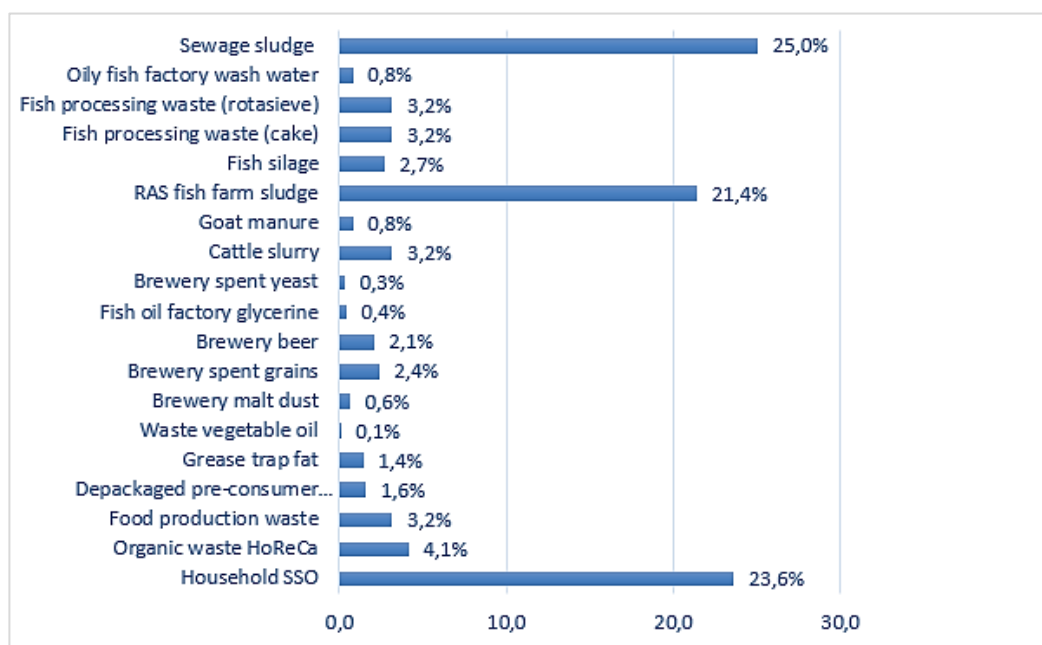


Figure 10. Rå Biopark available feedstock (Author's own, adapted from Eu-Supply.com, 2024)

It is also important to consider that the feedstock is received in two separate lines undergoing to the anaerobic digestion process. Line 1 primarily processes a variety of organic waste materials, while Line 2 is specifically designated for sewage sludge. This separation ensures that each type of feedstock receives tailored treatment suited to its unique characteristics.

The division into two lines at Rå Biopark ensures regulatory compliance, particularly for feedstocks like sewage sludge with elevated levels of contaminants, by segregating them into Line 2. This separation also optimizes processing for high-quality end products,

ensuring compliance with market standards and enhancing marketability. Additionally, dedicated lines enhance operational efficiency, minimize cross-contamination risks, and enable targeted treatment approaches for diverse feedstock compositions, ultimately ensuring consistent and reliable production outcomes (Eu-Supply.com, 2024).

## 4.2 Rå Biopark process flowcharts

The flowcharts for each of the lines have been created using the Wondershare EdrawMax tool ([www.edrawsoft.com](http://www.edrawsoft.com)). EdrawMax is a widely-used flowchart software known for its ease of use and compatibility with Mac OS X, Windows, and Linux systems.

The scope of work focuses only on the production process and does not include aspects such as waste acceptance or other external factors like transportation and subsequent product distribution. The incoming feedstock is separated into two distinct lines, ensuring that all the biowaste in line 1 remains untouched by the sewage sludge. Subsequently, the waste undergoes pre-treatment to remove contaminants, ensuring ease of pumping and digestion. However, the sewage sludge requires a mechanical separation first so as to remove its content of water.

The waste is subjected to wet anaerobic digestion technology to produce biogas and digestate. The digestate is then pasteurized to eliminate harmful bacteria and subsequently dewatered to remove some of the water content. This dewatering process increases the dry matter content of the digestate, resulting in two products: a Liquid Fraction (LFD) and Solid Fraction (SFD).

It is needed mentioning that Rå Biopark offers two options for handling the solid fraction: establishing a pyrolysis plant to treat the entire solid fraction of the biowaste, or implementing a drying process to further process the bioresidue until its dry matter content reaches 85%, ultimately forming fertilizer pellets. These are the two project options. However, the thesis has been developed with a focus on the pyrolysis process, given its ongoing evaluation and development, along with significant interest in producing biochar.

Therefore, the subsequent process presents a biochar product with a 70% content. This is illustrated in Figure 11 and Figure 12.

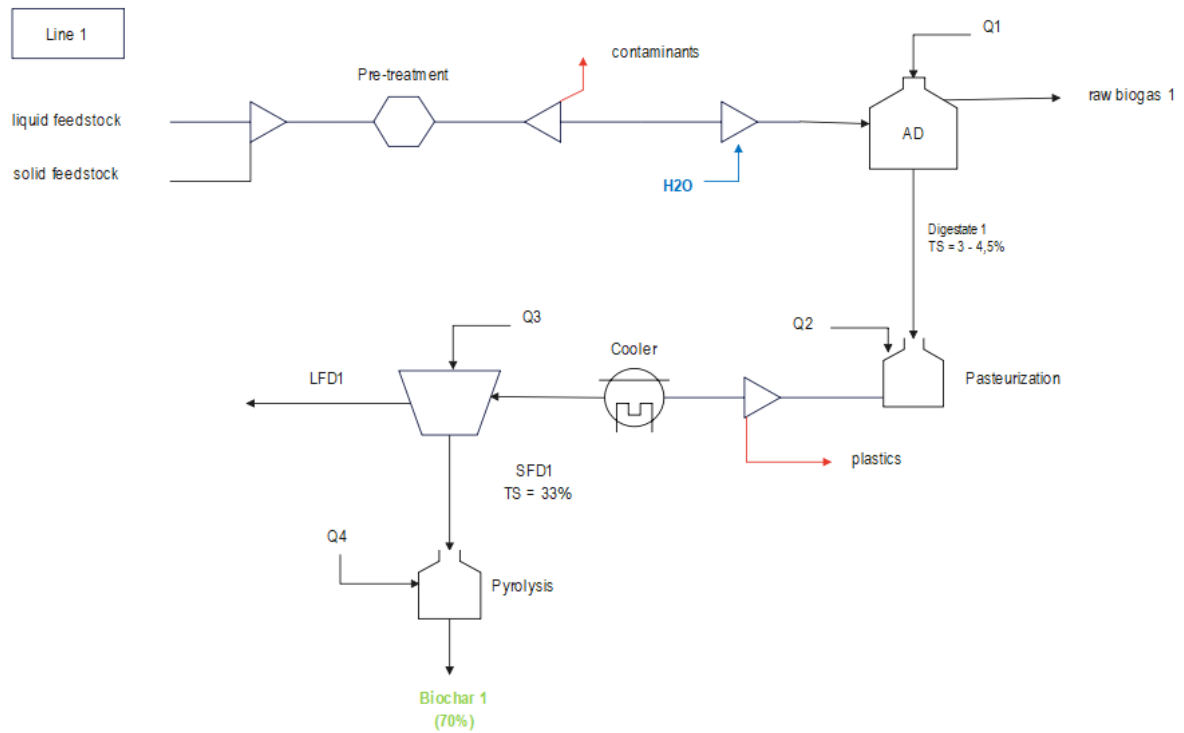


Figure 11. Treatment process of line 1 Solid Fraction Digestate (Author's own)

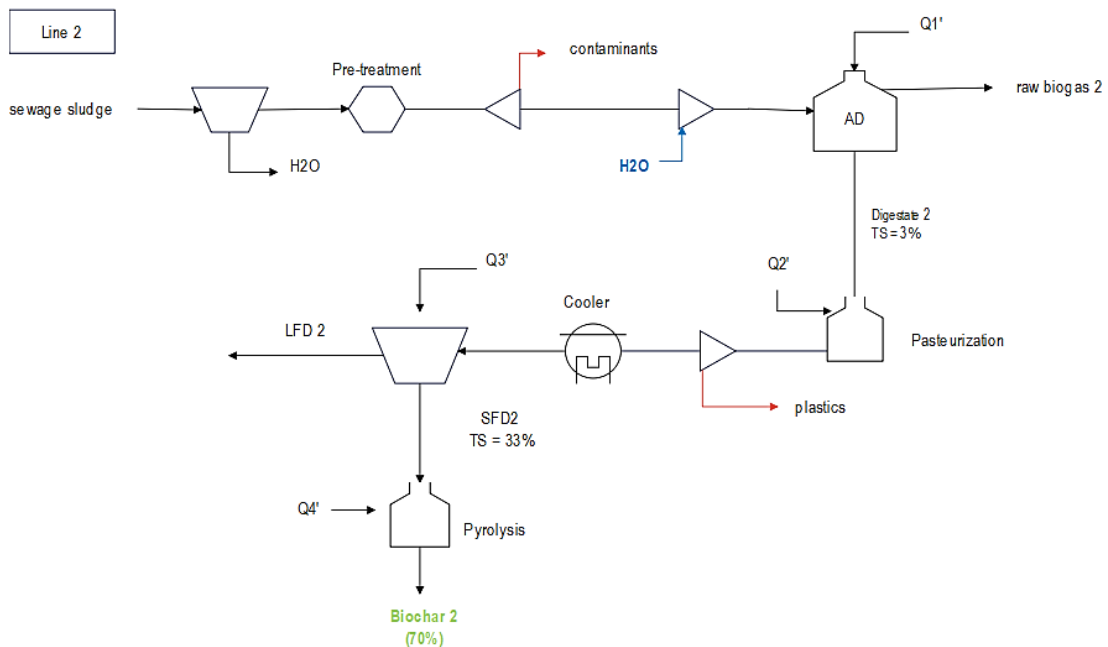


Figure 12. Treatment process of line 2 Solid Fraction Digestate (Author's own)

Additionally, as shown in Figure 13 and Figure 14, the Liquid Fraction Digestate from each line undergoes separate further processing using Mechanical Vapor Recompression (MVR) technology, a form of evaporation utilized to concentrate liquids in separation processes. This process yields several components: Nutrient liquor, containing concentrated nutrients suitable for additional processing; clean water; and an ammonium solution. The clean water serves a dual purpose: it can dilute incoming waste feedstock before entering the anaerobic digestion process, enhancing efficiency, and it can be collected as a usable byproduct.

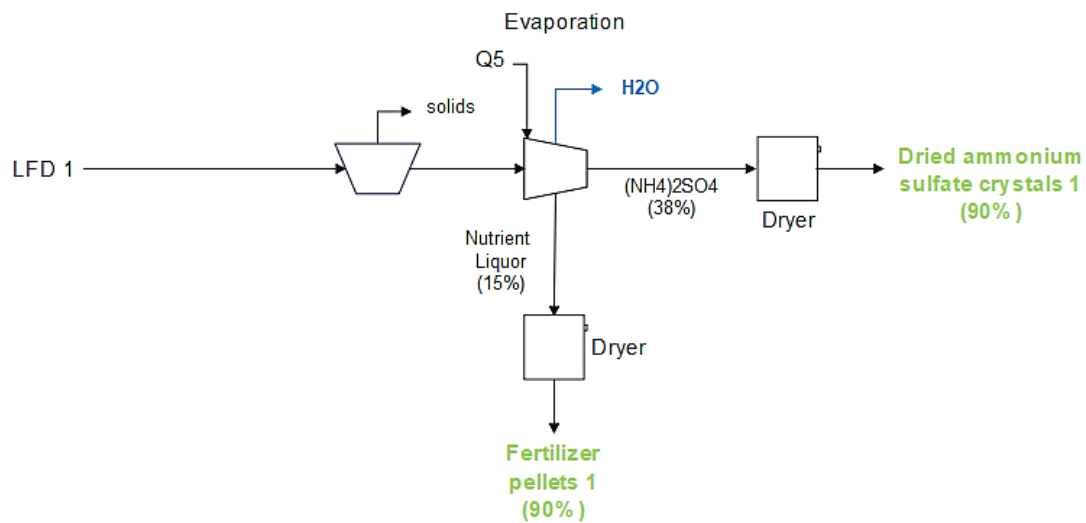


Figure 13: Treatment process of line 1 Liquid Fraction Digestate (Author's own)

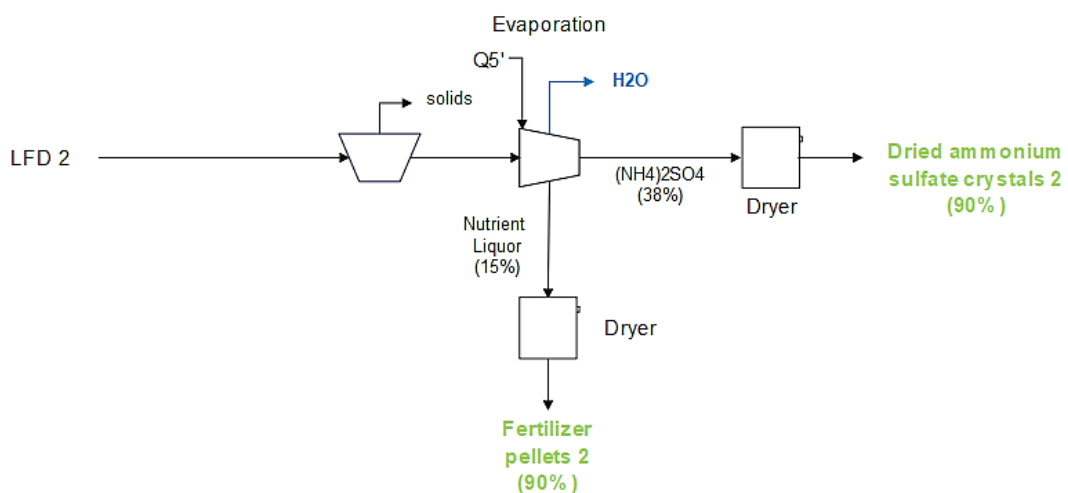


Figure 14: Treatment process of line 2 Liquid Fraction Digestate (Author's own)

## 5 Methodology

This chapter introduces the subsequent sections of the thesis that have been developed based on the specific needs of the Rå Biopark project. As mentioned throughout the study, the lack of agricultural fields in the vicinity of Rå Biopark makes the management and treatment of digestate of paramount importance.

One of the main objectives of this thesis is to determine the energy demands at each stage of the Rå Biopark process until the production of final products derived from digestate, including fertilizers. To achieve this, the analysis begins with an examination of potential mass balances, followed by a thorough exploration of various key parameters.

In addition, an assessment was done of some yields that are an interest point to know for the project. It has been calculated how much biogas different materials from the project can produce. This method will help Rå Biopark to understand how much biogas they can make from their raw materials, which can be useful to make better decisions and run their operations more efficiently. Furthermore, the biochar yield was calculated by considering the composition of lignocellulosic components in the biowaste. This is because the composition significantly impacts biochar yield. By understanding this relationship, this method can be explored as a potential strategy to improve not only the quantity of biochar produced, but also its quality and properties.

It is important to highlight that during the completion of this thesis, certain limitations in accessing data for the calculations were encountered due to the confidentiality of the project. Consequently, many of the important parameters have been obtained from different bibliographic sources, such as scientific articles and other studies and projects. Therefore, the importance of this work lies mainly in the process developed, rather than in the results obtained.

To achieve this objective, the Microsoft Excel tool ([www.microsoft.com](http://www.microsoft.com)) has been used, with which all the necessary balances and calculations have been developed. In this way, the project itself can modify the data for its own and automatically obtain the results wanted. Microsoft Excel is a spreadsheet software program developed by Microsoft that is used for a variety of purposes, including data analysis, calculations, graphing tools, and

information visualization. Excel allows users to create, edit, and format spreadsheets that contain rows and columns of data.

## **6 Mass Balances**

Following the Rå Biopark project, mass balances have been conducted, taking into account the quantity of product, as well as the dry matter and moisture content. While some of this data was provided by the project, additional calculations were necessary for certain parameters. The mass balances were performed using Excel, and the detailed balances are presented in Appendix I.

These balances have been conducted considering both lines of the process together, with a primary focus on digestate treatment. The main objective is to determine the final product amount, wherein the combined output of biochar, fertilizer pellets, and ammonium crystals equals the quantity of digestate produced during anaerobic digestion, which serves as a bioresidue.

To ensure clarity and completeness, the mass balances are presented in terms of total tons per year, along with their respective dry matter and moisture content for each product of the process. The moisture content, represents the variance between the total percentage (100%) and the dry matter content, which is also provided in both tons per year and percentage. The dry matter content at each stage of the digestate processing, along with specific quantities, has been extracted from the Rå Biopark document.

It is worth noting that the anaerobic digestion process requires a certain amount of water, while the dewatering step utilizes a diluted flocculant to aid in the process. Both masses have been sourced from the Norwegian document of Rå Biopark (Skibotn, 2024)

Additionally, it is ensured that the amount of digestate produced, along with the raw biogas, matches the quantity of feedstock used in both lines and the water consumed. In the digestate handling process, the global mass balance focuses solely on the digestate, ensuring input quantities match output ones. To facilitate this process, the diluted flocculant used in dewatering has been accounted for in the balances to prevent any discrepancies. Therefore, the combined weight of the digestate and the diluted flocculant

must be equivalent to the total weight of the products obtained, including biochar, ammonium crystals, fertilizer pellets, water, and the water removed during the process.

## **7 Energy demand of the process stages**

This section provides a detailed overview of the methodology utilized to assess the energy requirements across the stages of the Rå Biopark handling digestate process. The primary focus exists on the calculations of alternative technologies used to increase the dry matter content of the digestate, with particular emphasis on utilizing pyrolysis for the solid fraction and evaporation and drying for the liquid fraction. Additionally, other energy needs in various steps, including anaerobic digestion, pasteurization, and dewatering, are either mentioned or computed to discern the energy requirements throughout the entirety of the digestate handling process. These calculations take into account the volume of water to be removed to enhance the dry matter content, which aligns with the primary objective of the project.

The calculations have been carried out in an Excel spreadsheet, which will be provided to the project team in case they want to make any potential modifications with updated data and exact reactor temperatures, volumes, and percentages are determined. The calculated energy corresponds to the consumption over one year, as the project quantities are expressed in tons per year.

Figure 15 illustrates the system boundaries that are taken into account in the energy calculations. Moreover, in Appendix II, a detailed flowchart delineates the parameters included in the analysis and those excluded, providing clear boundaries for the scope of the study.

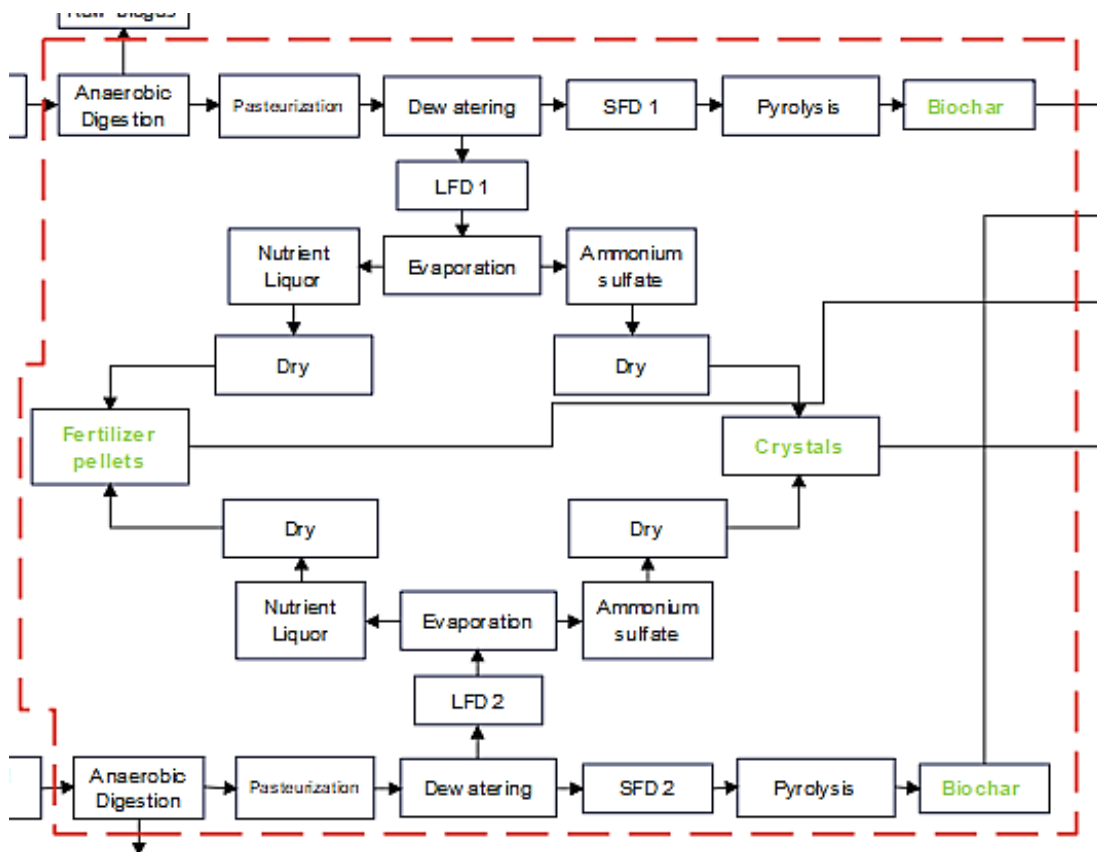


Figure 15. Boundaries of process stages considered in calculations. (Author's own)

## 7.1 Anaerobic digestion demand

The energy demand in anaerobic digestion includes both direct and indirect energy. Direct energy refers to the energy consumed as fuel, such as electricity and heat used in the production process. For example, electricity is needed for pumps, mixers, and heaters in the anaerobic digestion system. Indirect energy refers to the energy required to produce equipment, construction materials, and tools used in the process. Also, parasitic energy needed to operate the system must be considered, such as the electricity used for the operation of auxiliary equipment and the heat required for certain processes (Zhang, 2013).

Rå Biopark expects to generate 59 GWh, which means that the consumption of heat and electricity in this process should be significantly lower to ensure that it does not exceed the energy produced finally. This balance between production and energy consumption is crucial to ensure the efficiency and economic viability of the system. By minimizing energy

consumption relative to the expected production, the overall performance of the process is optimized, and dependence on external energy sources is reduced.

## **7.2 Pasteurization energy demand**

Pasteurization is typically attained by thermal treatment of the material at a minimum of 70 °C for at least 1 h prior or after the anaerobic digestion. This thermal treatment could be viewed as a pre-treatment of the feedstock since it may affect the biodegradability of ingoing organic material (Nordell et al., 2022). For instance, in this project, a post-pasteurization step is planned after the anaerobic digestion process. This decision stems from the intention to operate the digestion tanks with a notably high incoming TS content, making it challenging to utilize standard pre-pasteurization units relying on heat exchange (Eu-Supply.com, 2024).

Due to a lack of available information specific to the context, the energy requirement for pasteurization has been estimated based on standard quantifications observed in other biogas plants.

This process requires significant energy, particularly when considering the heating of materials to achieve the necessary temperature levels. The energy needed to pasteurize a material to 70°C for 1 hour varies based on the initial temperature. Generally, treating post-digester products requires approximately 41 kW of energy per ton to elevate the digestate's temperature (Hale, 2021).

## **7.3 Dewatering energy demand**

As mentioned previously, digestate typically contains a significant amount of water, which must be reduced to enhance its handling, transportation, and storage properties. In the Rå Biopark process, an initial dewatering step is employed to remove excess moisture from the residual organic matter remaining after anaerobic digestion.

In order to determine the energy needed for dewatering digestate during a year—separating it into liquid and solid fractions to increase dry matter content of the solid one—it is first needed to be quantified the amount of water to be removed. Subsequently, the energy consumption required for drying is calculated.

The solid fraction, with an initial dry matter content of 3.5%, undergoes a drying process to achieve the desired 33% dry matter content. This involves removing a significant amount of water from the solid material. In this case, the water content of the solid fraction needs to be reduced from 96.5% to 67%. To determine the amount of water that has to be removed, the following equations (1) and (2) are followed (Equi-Analytical, 2020):

$$WM(t) = TM(t) \cdot (1 - (DM (\%)/100)) \quad (1)$$

$$WM_r(t) = WM_d(t) - WM_s(t) \quad (2)$$

Next, the energy consumption for drying is computed, assuming 100% efficiency for both heat transfer and energy source. This is determined by multiplying the amount of water to be removed by the heat of vaporization of water, the constant amount of energy needed to convert 1 kg of liquid water at its boiling point into 1 kg of water vapor. Since the specific conditions of temperature and pressure are unknown, an average value is utilized for this calculation with a constant value of 2265 kJ/kg.

$$E = WM_r \cdot \Delta H \quad (3)$$

Next, to convert the energy values into kWh, the formula is modified as follows (Reynaga, 2020):

$$E (kWh) = \frac{WM_r \cdot 10^3(kg) \cdot \Delta H (kJ/kg)}{3600 (kJ/kWh)} \quad (4)$$

This is a simplified calculation assuming no heat losses or inefficiencies. In reality, the actual energy consumption will be higher due to these factors.

#### 7.4 Pyrolysis energy demand

Following the dewatering process, which enhances the digestate's dry matter content, two products are obtained: a Liquid Fraction Digestate (LFD) and a Solid Fraction Digestate (SFD). The SFD, with a 33% dry matter content, is selected for pyrolysis to produce biochar, thereby increasing its dry matter content to 70%.

Pyrolysis involves the thermochemical transformation of dry organic materials to achieve the production of biochar. Biochar is advocated for its ability to enhance soil properties, fertility, and carbon sequestration (CSANR, 2021).

In this section, the energy consumption of this stage of the process is calculated, taking into account the amount of water ultimately removed to increase the dry matter content to the expected level in biochar, as well as the temperature difference.

The total energy balance for this section is represented by equation (5) (U.D.S,2020) where the required energy corresponds to the total heat absorbed by the water, assuming a 100% of efficiency. This includes the sensible heat needed to raise the water temperature ( $Q_s$ ) along with the heat required to vaporize the water ( $Q\lambda$ ):

$$E = Q_s + Q\lambda \quad (5)$$

According to the equation X, it can be represented as the following:

$$E = WM_r \cdot \bar{C}_p \cdot \Delta T + WM_r \cdot \Delta H \quad (6)$$

Then, in order to express the energy values in kWh, the formula transforms into the following:

$$E (kWh) = \frac{WM_r \cdot 10^3 (kg) \cdot \bar{C}_p (kJ/kg^\circ C) \cdot \Delta T (^\circ C)}{1000 (J/kJ) \cdot (3600 kJ/kWh)} + \frac{WM_r \cdot 10^3 (kg) \cdot \Delta H (kJ/kg)}{(3600 kJ/kWh)} \quad (7)$$

In the context of that formula about water heating, a specific heat capacity of water ( $C_p$ ) of approximately 4.18 kJ/kg $\cdot$ °C (Calor Y Calorimetría, 2021) could be used along with the mass of water removed ( $WM_r$ ) and the desired temperature increase ( $\Delta T$ ) to calculate the sensible heat ( $Q_s$ ) required to raise the water temperature before vaporization.

As previously mentioned, the heat of vaporization remains constant at 2265 kJ/kg. Due to the unspecified conditions of temperature and pressure, an average value is employed for this computation.

## 7.5 Evaporation and drying energy demand

The rejected water from the dewatering of the biowaste after decomposition in both lines (Liquid Fraction Digestate) is directed to an evaporation plant that will produce a concentrate and a condensate.

The dry matter content of the LFD is not explicitly known. However, given that it comprises the rejected water from the solid fraction, it is assumed to have a negligible dry matter content, likely close to 0%. This assumption is considered in the calculations.

The concentrate, named Nutrient Liquor, will initially have a dry matter content of 15-20% (in liquid form), but by complementing it with a drying/crystallization process in the planned drying plant, the TS content can be increased to over 80%. The concentrate is high in nitrogen, phosphorus, and potassium, making it an excellent fertilizer product that can be utilized locally.

On the other hand, it is also feasible to develop a method for removing ammonia from the rejected water through steam extraction or equivalent means, resulting in a solution with a dry matter content of 38%. Moreover, it can be also dried further to produce Ammonium crystals with a dry matter content of 90%. These salts might find utility as agricultural fertilizers or for industrial purposes (such as NO<sub>x</sub> removal in industrial processes) (Eu-Supply.com, 2024).

After the evaporation process, as previously mentioned, the subsequent step involves drying. This step is aimed at preparing the wet fractions for conversion into pellets, which serve as a fertilizer product.

To calculate the energy required for these steps, the procedure conducted earlier with the pyrolysis can be relied upon. They are techniques employed to manipulate the water content of a material, ultimately aiming to increase the dry matter content for a final product with a high concentration of solids.

Evaporation, operates at a much lower temperature than pyrolysis, approximately 100°C, focusing solely on the removal of water from the material through vaporization. In the context of digestate treatment, evaporation serves as a crucial step after separation

processes to achieve a drier solid fraction with a higher concentration of organic matter and nutrients, potentially enhancing its usability as a fertilizer or soil amendment.

Therefore, the calculation of heat required for evaporation and drying in this context utilizes the same principles as in pyrolysis (U.D.S,2020) . Initially, the total mass of water that needs to be evaporated is calculated, and then applying the equation mentioned earlier, the energy consumed in this stage of the process is obtained. Moreover, the calculation needs to be done for both the nutrient liquor and the ammonium solution.

## **8 Assessment of yield rates for the Rå Biopark project**

This section of the thesis presents independent assessments of two key performance indicators for our biogas plant: biochar yield and biogas potential.

Firstly, biogas potential is analyzed which is indeed related to the methane yield and volatile solids of the feedstock used in the anaerobic digestion process. Secondly, the yield of biochar is calculated based on the lignocellulosic composition of the feedstock used in the process.

### **8.1 Methane potential assessment of Rå Biopark feedstocks**

This section is focused on assessing the methane potential of the Rå Biopark feedstocks. This evaluation is crucial for determining the biogas production capabilities of the project, by considering the methane yield of each feedstock and their volatile solids content. Additionally, it allows us to estimate the biogas yield per unit of processed organic material.

As the project document solely provides the quantities of each substrate used in tons per year, without specifying additional characteristics, an extensive search through literature was undertaken to uncover crucial data. Specifically, the percentage of total solids (TS), percentage of volatile solids (VS) and methane yield for each substrate, measured in millilitres per gram of VS as needed for each substrate. This investigation was imperative to accurately predict the theoretical biogas yield of the plant, factoring in the diverse range of feedstocks. Table 3 provides a comprehensive inventory of the feedstocks utilized within the operations of Rå Biopark's project.

Nevertheless, certain substrates posed challenges in sourcing relevant information from the literature. Consequently, estimations were made, drawing upon similarities with comparable substrates. Estimates were formulated for the methane yield of brewery malt dust, brewery beer, brewery spent yeast, and oily fish factory wash water, as well as the percentage of TS and VS of the last one. It also has to be considered that most of the literature findings were found in more than one value. Therefore, an average was calculated to derive a representative value for the purpose of making the necessary calculations.

Table 3. Inventory of Rå Biopark feedstock (Author's own)

| Feedstocks  | Lines | Amount (t/year) | TS (%) | VS (% of TS) | Methane yield (mL/gVS) | References  |
|---|-------|-----------------|--------|--------------|------------------------|---|
| Household SSO   | 1     | 14.900          | 21     | 91,9         | 350                    | (Lukitawesa, 2020; Razaq et al., 2016)                  |
| Organic waste of Hotels Restaurants and Catering (HoReCa) | 1     | 2.600           | 29     | 95           | 350                    | (Ahlberg-Eliasson et al., 2021; Razaq et al., 2016)     |
| Food production waste                                     | 1     | 2.000           | 29     | 95           | 396                    | (Ahlberg-Eliasson et al., 2021; Razaq et al., 2016)     |
| Depackaged pre-consumer supermarket organics              | 1     | 1.000           | 29     | 95           | 350                    | (Ahlberg-Eliasson et al., 2021; Razaq et al., 2016)     |
| Grease trap fat   | 1     | 900             | 2,25   | 90           | 307                    | (Lukitawesa, 2020; Davidsson et al., 2008)              |
| Waste vegetable oil                                       | 1     | 50              | 2,25   | 90           | 875                    | (Lukitawesa, 2020)                                      |
| Brewery malt dust   | 1     | 400             | 26,1   | 89,3         | 650                    | (Lukitawesa, 2020; Collin et al., 2021)                 |
| Brewery spent grains                                      | 1     | 1.500           | 26     | 89,3         | 461                    | (Lukitawesa, 2020; Głowacki et al., 2022)               |
| Brewery beer  | 1     | 1.300           | 26     | 89,3         | 350                    | (Lukitawesa, 2020)                                      |
| Fish oil factory glycerine                                | 1     | 250             | 3,01   | 82,6         | 598                    | (Ásgeirsson, n.d.)                                      |
| Brewery spent yeast                                       | 1     | 200             | 26,1   | 89,3         | 450                    | (Lukitawesa, 2020)                                      |
| Cattle slurry   | 1     | 2.000           | 19     | 25           | 108                    | (Comino et al., 2012; Jeppu et al., 2021)               |
| Goat manure   | 1     | 500             | 33,65  | 82           | 159                    | (Zhang et al., 2013; Fernández-Rodríguez et al., 2021)  |
| RAS fish farm sludge                                      | 1     | 13.500          | 2      | 66           | 785                    | (Libonatti et al., 2023; Matías Del Campo et al., 2010) |

|                                   |   |       |    |    |     |   |
|-----------------------------------|---|-------|----|----|-----|---|
| Fish silage                       | 1 | 1.700 | 38 | 93 | 785 | (Hortence et al., 2023; Libonatti et al., 2023) |
| Fish processing waste (cake)      | 1 | 2.000 | 38 | 93 | 390 | (Hortence et al., 2023; Libonatti et al., 2023) |
| Fish processing waste (rotasieve) | 1 | 2.000 | 38 | 93 | 390 | (Hortence et al., 2023; Raposo et al., 2012)    |
| Oily fish factory wash water      | 1 | 500   | 2  | 5  | 75  | (Raposo et al., 2012)                           |
| Sewage sludge                     | 2 | 15800 | 28 | 57 | 376 | (Havukainen et al., 2022)                       |

To calculate the theoretical methane yield of the biogas from this plant, an initial step involves assessing the methane production potential of each substrate, followed by the summation of these individual quantities.

The methane production in cubic meters (m<sup>3</sup>) from each substrate can be calculated by first determining the number of VS present in each substrate, as methane yields are measured in millilitres per gram of VS. This calculation can be performed as follows:

$$m_{VS} (g/year) = m_f (t/year) \cdot \frac{10^6 g}{1t} (VS (\%)/100) \cdot (TS(\%)/100) \quad (8)$$

After determining the quantity of VS in each substrate, the methane production of each feedstock in mL/year can be calculated by multiplying the VS (g/year) by the methane yield (mL/g of VS). This result needs to be converted to cubic meters per year. The formula used for this conversion is as follows (Ben, 2023):

$$V_{CH4} (m^3/year) = m_{VS} (g/year) \cdot MSY (mL/gVS) \cdot \frac{1m^3}{10^6mL} \quad (9)$$

Moreover, in order to determine the theoretical methane yield of each substrate, it is essential to convert cubic meters into tons using the methane gas density, which was assumed to be 0.72 kg/m<sup>3</sup> (Biogas, 2024).

To ascertain the methane yield of each feedstock, it is imperative to aggregate the methane produced by each substrate (in tons per year). Subsequently, the methane production of each feedstock is divided by the total methane production to determine its methane yield.

This process allows for a detailed understanding of the relative methane production contributions of each feedstock within the overall biogas production system.

Ultimately, the total theoretical methane yield (Equation 10) (wikiHow, 2012) of the plant can be determined by dividing the total amount of methane produced in tons by the total tons of feedstock utilized, providing a comprehensive measure of the plant's overall methane production efficiency.

$$Y_{CH4} (\%) = \frac{TM_{CH4} (t/year)}{TM_f (t/year)} \cdot 100 \quad (10)$$

### 8.1.1 Biogas production

Upon completing all calculations about methane yield, it becomes feasible to compute the biogas production of the plant. Utilizing the methane fraction of the obtained biogas, the annual tons of raw biogas can be determined. As per the project document provided by Rå Biopark, the methane fraction of the raw biogas falls within the range of 63% to 66%. Therefore, an average of these values has been utilized for the calculations, being used a methane fraction of 64,5%.

The calculation for the biogas produced in tons per year by each individual feedstock is as follows:

$$V_b (m^3/year) = \frac{V_{CH4} (m^3/year)}{0,645} \quad (11)$$

Subsequently, the total amount of biogas produced is obtained by summing the contributions from each individual feedstock.

### 8.1.2 Energy production

With the total amount of biogas produced determined, it is now possible to approximate the energy production that can be generated. Typically, the energy content of biogas falls within the range of 6.0 to 6.5 kWh per  $m^3$  (DSpace, 2024). For the purposes of this thesis, a value of 6.25 kWh per cubic meter was selected as the defined biogas energy content.

Furthermore, by multiplying the total amount of biogas produced by its energy content, the energy production of the plant can be ascertained, as illustrated in the following equation:

$$E_p (GWh) = V_b (m^3/year) \cdot 6,25kWh/m^3 \cdot \frac{10^6 GWh}{1 kWh} \quad (12)$$

All calculations were conducted using an Excel spreadsheet since the values for %TS, %VS, and methane yield (mL/gVS) were not provided by Rå Biopark. This approach allows for easy modifications in Excel should the company wish to input its own data. The calculations are automated, providing the final results directly within the Excel spreadsheet in case of making any changes. Appendix IV presents the results obtained utilizing data sourced from literature.

Note that these estimates have been derived from data gathered from various scientific articles and considering 100% efficiency of the reactor, which may not precisely align with the data from Rå Biopark itself. The primary goal is to establish a process through which the company can adjust the content of the Excel spreadsheet to obtain automated results.

## 8.2 Biochar yield based on lignocellulosic composition

There are numerous factors influencing biochar production via pyrolysis, including temperature, residence time, composition of the biomass, heating rate, among others.

It is important first to identify the key parameters. The yield of biochar can be significantly influenced by the composition of various components in the feedstock, particularly hemicellulose, cellulose, and lignin. Among these components, lignin stands out as particularly important to consider if we aim to enhance biochar yield (Mukherjee et al., 2022).

Additionally, understanding the role of these components can provide valuable insights into optimizing the biochar production process. By targeting these key parameters, it can not only improve biochar yield but also enhance its quality and properties for various applications. Therefore, a thorough examination of the composition of the feedstock is essential for maximizing the efficiency and effectiveness of the pyrolysis process in biochar production.

### 8.2.1 Effects of lignocellulosic components

Biochar production through pyrolysis is a thermochemical process that converts organic materials into a carbon-rich solid product. The yield and quality of biochar are significantly influenced by the composition of the starting material, particularly its content of lignocellulosic components. Lignocellulose, the primary structural material in plants, is comprised of three main components: lignin, cellulose, and hemicellulose. Each component exhibits distinct thermal behaviors during pyrolysis, impacting the final biochar yield (Sharma et al., 2024).

Lignin is a complex aromatic polymer with a high carbon content and low volatility. Unlike cellulose and hemicellulose, it resists thermal decomposition at pyrolysis temperatures. This stability ensures its significant contribution to the final biochar yield. During pyrolysis, lignin undergoes a series of transformations, with a substantial portion remaining unconverted and forming the core structure of the biochar. Consequently, maximizing the lignin content in the feedstock offers a promising strategy for enhancing biochar yield (Behr et al., 2021).

On the other hand, cellulose and hemicellulose have simpler structures and higher oxygen content compared to lignin, making them more susceptible to breakdown at elevated temperatures due to their volatile nature. Their thermal decomposition during pyrolysis releases lighter volatile compounds such as organic vapors and gases. These compounds can either condense to form bio-oil or escape as pyrolysis gases. Consequently, cellulose and hemicellulose contribute less directly to biochar formation but instead play a significant role in the production of bio-oil and gases (Ganesapillai et al., 2023).

Furthermore, the biochar yield has been calculated, taking into account the individual contributions of each lignocellulosic component using an Excel spreadsheet so it can be easily changed with real values (Appendix V).

To perform these calculations accurately, it is essential to concentrate on the quantities of cellulose, hemicellulose, and lignin present in the Solid Digestate Fraction (SDF) of each line individually, both before initiating the pyrolysis process and after pasteurization. This approach aligns with the flowcharts prepared in advance, ensuring a systematic analysis of the biomass composition and its transformation during the process.

Table 4. Composition and pyrolysis yields of lignocellulosic components in line 1

| Components    | SDF 1 (in %)   | Biochar 1 (in %) | Pyrolysis yields of each individual component (in %) |
|---------------|----------------|------------------|--|
| Cellulose     | C <sub>1</sub> | C <sub>1b</sub>  | Y <sub>p,C<sub>1</sub></sub>                         |
| Hemicellulose | H <sub>1</sub> | H <sub>1b</sub>  | Y <sub>p,H<sub>1</sub></sub>                         |
| Lignin        | L <sub>1</sub> | L <sub>1b</sub>  | Y <sub>p,L<sub>1</sub></sub>                         |

Table 5. Composition and pyrolysis yields of lignocellulosic components in line 1

| Components    | SDF 2 (in %)   | Biochar 2 (in %) | Pyrolysis yields of each individual component (in %) |
|---------------|----------------|------------------|--|
| Cellulose     | C <sub>2</sub> | C <sub>2b</sub>  | Y <sub>p,C<sub>2</sub></sub>                         |
| Hemicellulose | H <sub>2</sub> | H <sub>2b</sub>  | Y <sub>p,H<sub>2</sub></sub>                         |
| Lignin        | L <sub>2</sub> | L <sub>2b</sub>  | Y <sub>p,L<sub>2</sub></sub>                         |

In the Excel spreadsheet, the pyrolysis yields of each individual component can be determined by dividing the weight percentage of the component in the final biochar product divided by the percentage of that component in the digestate before pyrolysis, as shown in (13). This calculation method provides a clear understanding of how each component contributes to the composition of the resulting biochar, providing insight into how much of each component is transformed during the pyrolysis process, thereby

influencing the overall composition and properties of the biochar. It has been followed the method according to Gul et al. (2021):

$$Y_{p, C_1} = \frac{C_1 b}{C_1} \cdot 100 \quad (13)$$

However, in experimental terms, this data can be obtained through a Thermogravimetric Analysis (TGA). This method measures the loss of mass of a sample as the temperature increases, relying on the thermal decomposition of lignocellulosic components of biochar at different temperatures. The result of the experiment is a graph called a TGA curve. This curve shows how much weight the sample loses at each temperature. The yield of each component is calculated by looking at the weight difference between two specific points on the TGA curve. These points represent the starting and ending temperatures of the component's decomposition stage (Oyedun et al., 2014).

Once all necessary data have been gathered, the following formula to calculate the yield of biochar is utilized, providing how much of the original biomass is converted to biochar during the pyrolysis process (Gul et al. 2021):

$$Y_{b_1} = 100 - (1 - x) \cdot 100 \quad (14)$$

Moreover,  $x$  is calculated as the weighted sum of the pyrolysis yields of the individual biomass components (15). To do this, the percentage of each component (hemicellulose, cellulose, and lignin) is multiplied by the corresponding pyrolysis yield for that component, and then add these products.

$$x = C_1 \cdot Y_{p, C_1} + H_1 \cdot Y_{p, H_1} + L_1 \cdot Y_{p, L_1} \quad (15)$$

It is also possible to calculate it directly with the weight % of each component in the final biochar product (16).

$$x = C_1 b + H_1 b + L_1 b \quad (16)$$

In addition, an specific formula is used to calculate how much of the final carbon comes from a specific component. It is based on the difference between the amount of carbon

produced by the total biomass and the amount of carbon that would have been produced if only the contribution of the component considered. This is expressed as a percentage of the total weight of the biomass. The equation shown below (17) uses the lignin of line 1 as an example.

$$L_b = \frac{x - (L_1 \cdot Yp, L_1)}{x} \cdot 100 \quad (17)$$

Where  $L_b$  is the carbon production from lignin in the sample after pyrolysis (expressed in wt %) and  $x$  is the mass of biochar calculated after the pyrolysis treatment.

As before, instead of considering the pyrolysis yield of each individual component, the weight % of each component in the final biochar product can be calculated (18).

$$L_b = 1 - \frac{x - L_1 b}{x} \cdot 100 \quad (18)$$

## 9 Results

This section provides an overview of all the calculations and tasks undertaken in this thesis. It is important to note that this thesis encompasses several objectives, including conducting mass balances, determining the energy demand for handling the digestate, calculating methane yield to estimate biogas production and determining biochar yield based on the lignocellulosic composition of the digestate.

It is worth mentioning that not all tasks yield numerical results due to a lack of project data. Instead of providing numerical outcomes, a template with the calculations has been developed in Excel to allow for the input of relevant data. Images of the Excel content provided alongside the thesis are included in Appendages.

### 9.1 Mass balances numerical results

As previously mentioned, the comprehensive mass balances are documented in Appendix I. Furthermore, the global mass balances have been meticulously conducted, ensuring that the final quantities align with the initial ones. This includes accounting for the water removed during the process.

Below, Table 6 and Table 7 show summarized versions of both the overall process and the digestate treatment mass balances provided, with detailed versions available in the mentioned appendices.

Table 6. Overall process mass balances

| <b>Before Anaerobic Digestion</b> |                | <b>After Anaerobic Digestion</b> |                 |
|-----------------------------------|----------------|----------------------------------|-----------------|
| Total feedstock                   | 63100 tons p.a | Raw biogas                       | 9825 tons p.a   |
| Water                             | 95000 tons p.a | Digestate                        | 148270 tons p.a |

$$GMB = 63100 + 9500 = 9825 + 148275 = 72600 \text{ tons p.a} \quad (19)$$

Table 7. Digestate treatment mass balances

| <b>Before treatment</b> |                 | <b>After treatment</b> |                 |
|-------------------------|-----------------|------------------------|-----------------|
| Digestate               | 148270 tons p.a | Biochar                | 8820 tons p.a   |
|                         |                 | Fertilizer pellets     | 1350 tons p.a   |
| Diluted Flocculant      | 6746 tons p.a   | Ammonium crystals      | 1344 tons p.a   |
|                         |                 | Water                  | 143507 tons p.a |

$$\begin{aligned} GMB_d &= 148275 + 6746 = 8820 + 1344 + 1350 + 143507 \\ &= 72600 \text{ tons p.a} \end{aligned} \quad (20)$$

## 9.2 Energy consumption

Appendix III provides the Excel spreadsheet where the calculations for energy demand can be seen.

While the overall energy demand for dewatering appears high in our results, it is important to consider the scope. This calculation assumes dewatering the entire digestate volume produced over a year. In contrast, the energy demand figures for the other technologies only account for treating the solid or liquid fraction. The energy demand for dewatering is lower than the energy demand for the other processes. This is because dewatering removes water from the suspension by filtration or centrifugation, while evaporation and drying remove water by evaporating water from the surface of the material. Evaporation requires more energy than dewatering because the water must be heated to its boiling point before it can evaporate. Drying requires even more energy than evaporation because the water must also be removed from the inside of the material (Lamolinara et al., 2022).

Pyrolysis is a thermochemical process where a material is heated in an oxygen-free environment. This process breaks down the material into gases, liquids, and solids. The energy demand for pyrolysis is directly tied to the chosen temperature and reaction time. Since pyrolysis typically operates at extremely high temperatures, it requires significant energy input. This explains why, compared to the other methods, pyrolysis has the highest overall energy demand (Ghimire, 2020).

## 9.3 Methane yield

The methane yield was determined using the methodology outlined in section (7.1). Due to the confidentiality of the project's data, information from literature sources was utilized. As a result, the obtained results may not align completely with those of the Rå Biopark project. This discrepancy can be attributed to the use of methane yield and total solids and VS data sourced from various literature references. The absence of specific data from the Rå Biopark project, owing to confidentiality constraints, hindered the attainment of precise results.

A comprehensive table presenting all the obtained results can be found in Annex IV, detailing both the methane and biogas produced from each feedstock as well as the total quantities. However, Table 8 provides a condensed version.

Table 8. Methane and biogas produced from each substrate

| <b>Feedstocks</b>                            | <b>m<sup>3</sup> CH<sub>4</sub>/year</b> | <b>Methane yield (%)</b> | <b>m<sup>3</sup> raw biogas/year</b> |
|--|--|--------------------------|--------------------------------------|
| Household SSO                                | 992.065,1                                | 24,40                    | 1538085,4                            |
| Organic waste HoReCa                         | 250.705,0                                | 6,17                     | 388689,9                             |
| Food production waste                        | 218.196,0                                | 5,37                     | 338288,4                             |
| Depackaged pre-consumer supermarket organics | 96.425,0                                 | 2,37                     | 149496,1                             |
| Grease trap fat                              | 5.595,1                                  | 0,14                     | 8674,5                               |
| Waste vegetable oil                          | 885,9                                    | 0,02                     | 1373,5                               |
| Brewery malt dust                            | 60.599,0                                 | 1,49                     | 93951,9                              |
| Brewery spent grains                         | 161.170,0                                | 3,96                     | 249875,9                             |
| Brewery beer                                 | 106.048,2                                | 2,61                     | 164415,8                             |
| Fish oil factory glycerine                   | 3.717,0                                  | 0,09                     | 5762,7                               |
| Brewery spent yeast                          | 20.976,6                                 | 0,52                     | 32521,8                              |
| Cattle slurry                                | 10.378,8                                 | 0,26                     | 16091,2                              |
| Goat manure                                  | 21.936,4                                 | 0,54                     | 34010,0                              |
| RAS fish farm sludge                         | 139.887,0                                | 3,44                     | 216879,1                             |
| Fish silage                                  | 474.218,6                                | 11,66                    | 735222,6                             |
| Fish processing waste (cake)                 | 277.175,3                                | 6,82                     | 429729,2                             |
| Fish processing waste (rotasieve)            | 277.175,3                                | 6,82                     | 429729,2                             |
| Oily fish factory wash water                 | 37,5                                     | 0,00                     | 58,1                                 |
| Sewage sludge                                | 948.151,7                                | 23,32                    | 1470002,6                            |

The Rå Biopark project has set an ambitious annual energy production target of 59 GWh. To achieve this goal, it is crucial to determine the corresponding biogas production volume. Typically, the energy content of biogas is estimated at 6.25 kWh per cubic meter. Thus, to produce 59 GWh annually, the project needs to generate approximately  $9.4 \times 10^6 \text{ m}^3$  of biogas.

Considering that biogas primarily consists of methane, the next step is to calculate the required annual production of methane. With the methane fraction of the Rå Biopark biogas estimated at 0.645, it is projected that approximately 6,088,800  $\text{m}^3$  of methane needs to be produced annually to meet the energy production target.

To provide a clearer picture, it is helpful to convert this volume of methane into a more tangible measure, such as tons. Using the methane density of  $0.72 \text{ kgCH}_4/\text{m}^3$ , the annual

production of methane amounts to approximately 4,383.94 tons. This calculation highlights the substantial amount of methane production necessary for the Rå Biopark project to achieve its energy production objectives.

#### **9.4 Biochar yield**

In this section, numerical results were not directly obtained. Instead, a customized Excel template was developed to facilitate the input of cellulose, hemicellulose, and lignin parameters as percentages. This template allows for the automated calculation of various outputs based on the entered data.

Appendix V provides a detailed illustration of how this Excel template was constructed to execute these calculations effectively.

#### **9.5 Sensitivity analysis**

Mass balances, though essential for process efficiency, are sensitive to factors like dry matter content and instrument precision. Inaccurate moisture measurements can skew results, highlighting the importance of proper sampling techniques as well.

This sensitivity extends to other calculations. For example, an accurate energy demand comparison requires consistent analysis across all stages (dewatering, evaporation, drying, pyrolysis). Additionally, process-specific factors like dewatering technology type, evaporation/drying temperature and equipment efficiency, and pyrolysis temperature/reaction time can significantly impact energy demand.

For methane yield, the source of data (project-specific vs. literature) and the assumed methane fraction of biogas can significantly impact the required annual methane production. Similarly, changes in Rå Biopark's annual energy target directly affect the needed methane yield. Finally, Biochar yield depends on the makeup of the feedstocks, especially lignin content. High-carbon lignin boosts yield, while cellulose and hemicellulose contribute less directly. Other factors like temperature also matter, so a comprehensive analysis is key for optimizing biochar production.

## **10 Discussion**

Section 10.1 discusses the results pertaining to the initial aims and objectives. The limitations of the work are also addressed, as discussed in Section 10.2, and highlights consistencies and inconsistencies identified in Section 10.3. Additionally, suggestions for project enhancements are provided in Section 10.4.

### **10.1 Initial aims and objectives**

To achieve the aim of the thesis, which, although not entirely concise, aimed to meet the requirements set by Rå Biopark, all of which were related to the interest in treating digestate to increase its dry matter content for easier transport and utilization in other agricultural areas. To achieve this, various objectives were pursued.

The first objective, which was more theoretically based, has been effectively accomplished through the explanation and exploration of technologies enabling digestate drying, particularly those that are supposed to be utilized by Rå Biopark, alongside mentioning alternative options. This understanding of technologies has set the stage for pursuing other objectives.

The second objective, centered on developing calculation processes for these different technologies, has also been met. Especially for dewatering, pyrolysis, and evaporation, calculation methods have been identified to determine the amount of heat required to remove the necessary water and increase the dry matter content.

Next, methodologies for determining the yields of different products in the Rå Biopark process have also been successfully developed. The Excel templates are structured to allow the project to adjust the values of interest.

Lastly, mass balances have been accurately conducted, taking into account the quantities specified by Rå Biopark to ensure the same amount of final products—biochar, fertilizer pellets, ammonium crystals, water, and biogas—as the initial feedstocks and water are obtained.

## **10.2 Limitations of the work**

Throughout the thesis development, several limitations were encountered, with the primary and overarching one being the lack of information necessary to arrive at final numerical results. The absence of real project data posed numerous challenges during the analysis phase. Initially, the intention was to calculate these values, but due to project confidentiality, many crucial data points could not be provided. Consequently, certain sections had to be condensed, and parameters were analyzed in a more simplified manner or sourced from literature to compensate for the lack of project data. However, it became evident that the process and methodology followed were of greater importance to the project than the final results. Hence, the idea of establishing an Excel template aimed to simplify result generation by taking advantage of the user-friendly features of Excel, enabling instant calculations.

Another limitation that may have caused some disorder in the completion of this thesis is the lack of a concise objective from the outset. Ultimately, the thesis has involved fulfilling tasks requested by the project, all aimed at mutual improvement, but without expecting specific results or a final hypothesis to confirm.

## **10.3 Consistencies and inconsistencies**

A comprehensive review of the project revealed both consistencies and inconsistencies in the methodology and results. The mass balances were conducted rigorously and aligned with the objectives of the project, producing accurate and reliable results. However, due to data limitations, the energy balances and product yield calculations could not be categorized as conclusive for Rå Biopark. Despite this constraint, the methodology employed for these calculations was sound, allowing for the extraction of valuable insights.

## **10.4 Suggestions for project enhancements**

While the current project offers valuable insights, several enhancements can unlock even more precise and Rå Biopark-specific conclusions. Firstly, a more rigorous sensitivity analysis can be conducted to pinpoint critical parameters and assess the overall robustness of the calculations.

Furthermore, by incorporating project-specific values for these parameters, the calculations can be tailored directly to Rå Biopark's unique conditions, leading to more accurate and relevant results. To further strengthen the foundation of the project, prioritizing data collection efforts can address any existing gaps and ensure more definitive calculations. Validating models used and quantifying calculation uncertainties would further enhance confidence and understanding of the limitations.

Finally, incorporating heat losses into the energy calculations would provide a more realistic picture of energy consumption. These losses, often occurring during various stages of the process, can impact overall energy consumption.

## **11 Conclusions**

The construction of biogas plants has emerged as a beacon of sustainability, offering a dual advantage: biogas production and digestate utilization, not merely as sources of renewable energy but also as hubs for nutrient recovery and sustainable food production. This thesis has delved into the realm of biogas digestate treatment, with a particular focus on the Ra Biopark project.

The outcome was the effective production of the expected products. Mass balances revealed quantities of 8820 tons per year of biochar, 1350 tons of fertilizer pellets, and 1344 tons of ammonium crystals, along with 143507 tons of water that can be reused within the same process or treated for other purposes. The sum of these outputs perfectly aligns with the initial inputs anticipated for the Ra Biopark process. Furthermore, to enhance the project's long-term value, Excel templates allow for future modifications once Ra Biopark acquires the necessary data for energy demand calculations and biogas and biochar yield calculations.

In conclusion, this thesis has demonstrably achieved its primary purpose and the defined objectives, encompassing the development of methodologies for digestate treatment technologies and the precise conduct of mass balances. While acknowledging limitations, suggestions for project improvement are underscored, particularly in incorporating more precise data into calculations and conducting a more rigorous sensitivity analysis. Nevertheless, the project stands as a contribution to the advancement of Ra Biopark project.

## 12 References

- Affald – Lemvig Biogas. (2024) *Lemvigbiogas.com*. [online] Retrieved from: <https://lemvigbiogas.com/>
- Ahlberg-Eliasson, K., Westerholm, M., Isaksson, S. and Schnürer, A. (2021) Anaerobic Digestion of Animal Manure and Influence of Organic Loading Rate and Temperature on Process Performance, Microbiology, and Methane Emission from Digestates. *Frontiers in Energy Research*, [online] 9, doi: 10.3389/fenrg.2021.740314.
- Ambarish, K. (2014) System Analysis of De-Watering Process for Treating Biogas Digestate. [online] ResearchGate. Retrieved from: <https://www.divaportal.org/smash/get/diva2:706175/FULLTEXT01.pdf>
- Ásgeirsson, H. (2015) *Methane Potential from Fish Oil Byproducts Anaerobic Digestion of Spent Bleaching Earth and Glycerin*. Faculty of Electrical and Computer Engineering. University of Iceland. Retrieved from: <https://skemman.is/bitstream/1946/21586/1/Methane%20potential%20from%20fishoil%20production.pdf>
- Behr, M., El Jaziri, M. and Baucher, M. (2021) Lignin: An Innovative, Complex, and Highly Flexible Plant Material/Component. *Elsevier EBooks*, [online], pp. 35–60, doi:10.1016/b978-0-12-820303-3.00002-3.
- Ben, S. (2022) *The Establishment of a Biogas Plant at Pajumaito Ltd Dairy Farm*. Information and Communication Technology. Häme University of Applied Sciences. Retrieved from: <https://www.theseus.fi/bitstream/handle/10024/788804/>
- Bhatia, S.C. (2014). Biogas. *Elsevier EBooks*, [online], pp. 426–472, doi: 10.1016/b978-1-78242-269-3.50017-6.
- Biogas. (2024) *Emison.com*. [online] Retrieved from: [www.emison.com/produccion%20biogas.htm](http://www.emison.com/produccion%20biogas.htm).
- Biogas Plant – from Organic Waste and Side Streams to Income - Biovoima. (2024) *Biovoima*, [online] Retrieved from: <https://biovoima.com/en/solutions/biogas-plant>
- Biogass Norge. (2024) *Biogassnorge.no*. [online] Retrieved from: <https://biogassnorge.no/>
- Boost Nordic Biogas. (2024,). *BioFuel Region*. [online] Retrieved from: <https://biofuelregion.se/projekt/boost-nordic-biogas/>
- Calor Y Calorimetría. (2021) *Tesla.us.es*. [online] Retrieved from: [http://tesla.us.es/wiki/index.php/Calor\\_y\\_calorimetr%C3%ADa#:~:text=l%C3%ADquidos%20y%20gases](http://tesla.us.es/wiki/index.php/Calor_y_calorimetr%C3%ADa#:~:text=l%C3%ADquidos%20y%20gases).
- Collin, T., Cunningham, R., Deb, M., Villa, R., MAcAdam, J. and Jefferson, B. (2021) Energy

Potential of Household Fats, Oils and Grease Waste. *WEJ/Water and Environment Journal*, [online] 36, 13 July 2021, pp. 132–141, doi:10.1111/wej.12744.

Comino, E., Riggio, V.A. and Eosso, M. (2012) Biogas Production by Anaerobic Co-Digestion of Cattle Slurry and Cheese Whey. *Bioresource Technology*, [online] 114, pp. 46–53, doi: 10.1016/j.biortech.2012.02.090.

CSANR Wsu.edu. (2021) *Biochar (pyrolysis)*. [online] Retrieved from: <https://csanr.wsu.edu/publications-library/energy/biochar/#:~:text=Pyrolysis%20is%20the%20thermo%2Dchemical,while%20also%20producing%20renewable%20energy.>

Davidsson, Å., Lövestedt, C., la Cour Jansen, J., Gruvberger, C. and Aspegren, H. (2008) Co-Digestion of Grease Trap Sludge and Sewage Sludge. *Waste Management*, [online] 28 pp. 986–992, doi:10.1016/j.wasman.2007.03.024.

Division of Energy Systems. (2024) *KTH*. [online] Retrieved from: <https://www.energy.kth.se/energy-systems>

Drosg, B., Fuchs, W., Al Seadi, T., Madsen, M. and Linke, B. (2015) Nutrient Recovery by Biogas Digestate Processing. *ieabioenergy*. [online] Retrieved from: [https://www.ieabioenergy.com/wp-content/uploads/2015/08/NUTRIENT\\_RECOVERY\\_RZ\\_web2.pdf](https://www.ieabioenergy.com/wp-content/uploads/2015/08/NUTRIENT_RECOVERY_RZ_web2.pdf)

EBA. (2023) *Europeanbiogas.eu*. [online] Retrieved from: [www.europeanbiogas.eu/](http://www.europeanbiogas.eu/)

Equi-Analytical | Profiling Feed for Better Nutrition. (2020). *Equi-Analytical*. [online] Retrieved from: <https://equi-analytical.com/resources/as-sampled-vs-dry-matter-results/>

er, Biopark. (2014) *Rå Biopark*. [online] Retrieved from:: [www.raa.bio/omraabiopark](http://www.raa.bio/omraabiopark)

Eu-Supply.com. (2024) *Eu-Supply.com* Retrieved from: [https://eu.eu-supply.com/app/rfq/publicpurchase\\_docs.asp?PID=380035&LID=445102&AllowPrint=1.](https://eu.eu-supply.com/app/rfq/publicpurchase_docs.asp?PID=380035&LID=445102&AllowPrint=1)

Fernández-Rodríguez, M.J., Puntano, N.F., Mancilla- Leytón, J.M. and Borja, R. (2021) Batch Mesophilic Anaerobic Co-Digestion of Spent Goat Batch Mesophilic Anaerobic Co-Digestion of Spent Goat Straw Bedding and Goat Cheese Whey: Comparison with the Mono-Digestion of the Two Sole Substrates. *Journal of Environmental Management*, [online] 280, pp. 111733–111733, doi:.1016/j.jenvman.2020.111733.

Gasum (2024) *Your Partner in the Energy Transition*. [online] Retrieved from: <https://www.gasum.com/en/gasum/products-and-services/biogas-and-liquefied-biogas/how-is-biogas-produced/>

- Ghimire, R. (2020) *Life cycle assessment of biochar in Norway*. Noregian University of Science and Technology. [online] Retrieved from: <https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2779661/no.ntnu:inspera:57317890:34576805.pdf?sequence=1>
- Gul, E., Bkoor, A., Masek, O., Øyvind Skreiberg, Corona, A., Zampilli, M., Wang, L., Samaras, P., Yang, Q., Zhou, H., Bartocci, P. and Fantozzi, F. (2021). Production and use of biochar from lignin and lignin-rich residues (such as digestate and olive stones) for wastewater treatment. *Journal of Analytical and Applied Pyrolysis*, [online] 158, 105263–105263. doi: 10.1016/j.jaap.2021.105263
- Gupta, A. and Abhishek, C. (2023). Municipal Solid Waste Management Market Size by Source (Residential, Commercial) *Global Market Insights*. [online] Retrieved from: <https://www.gminsights.com/industry-analysis/municipal-solid-waste-management>
- Głowacki, S., Salamon, A., Sojak, M., Tulej, W., Bryś, A., Hutsol, T., Salamon, M., Kukharets, S. and Janaszek-Mańkowska, M. (2022). The Use of Brewer's Spent Grain after Beer Production for Energy Purposes. *Materials*, [online] 15, pp. 3703–3703, doi:3390/ma15103703.
- Hale, M. (2021). Busting the Myths about AD Pasteurisation | HRS Heat Exchangers. *HRS Heat Exchangers*. [online] Retrieved from: [www.hrs-heatexchangers.com/news/busting-myths-ad-pasteurisation](http://www.hrs-heatexchangers.com/news/busting-myths-ad-pasteurisation)
- Havukainen, J., Saud, A., Astrup, T. F., Peltola, P. and Horttanainen, M. (2022) Environmental Performance of Dewatered Sewage Sludge Digestate Utilization Based on Life Cycle Assessment. *Waste Management*, [online] 137, pp. 210–221, doi: 10.1016/j.wasman.2021.11.005.
- Hortence, I., Ntambara, B. and Mazimpaka, E. (2023) Characterization and Analysis of Fish Waste as Feedstock for Biogas Production. *The International Journal of Low Carbon Technologies*, [online] 18, pp. 212–217, doi: 10.1093/ijlct/ctac135.
- Hvor Produseres Biogass - Biogass Norge. (2022) *Biogass Norge*. [online] Retrieved from: <https://biogassnorge.no/fakta-om-biogass/produksjon/>
- IEA – International Energy Agency - IEA. (2024) *IEA*. [online] Retrieved from: [www.iea.org/search?q=biogas](http://www.iea.org/search?q=biogas).
- Jeppu, G.P., Janardhan, J., Kaup S., Janardhanan, A., Mohammed, S. and Acharya, S. (2021). Effect of Feed Slurry Dilution and Total Solids on Specific Biogas Production by Anaerobic Digestion in Batch and Semi-Batch Reactors. *Journal of Material Cycles and Waste Management*, [online] 24, pp. 97–110, doi: 10.1007/s10163-021-01298-1.
- Lachos-Perez, D., Martins-Viera, J. C., Missau, J., Anshu, K., Siakpebru, O. K., Thengane, S. K., Morais, A.C., Hiromitsu, E. and Assumpção, D. (2023) Review on Biomass Pyrolysis with a Focus on Bio-Oil Upgrading Techniques. *Analytica*, [online] 4, pp. 182–205, doi: 10.3390/analytica4020015.

Lamolinará, B., Pérez-Martínez, A., Guardado-Yordi, E., Guillén, C., Diégez-Santana, K. and Ruiz-Mercado, G. (2022) . Anaerobic Digestate Management, Environmental Impacts, and Techno-Economic Challenges. *Waste Management*, [online] 140, pp. 14–30, doi:10.1016/j.wasman.2021.12.035.

Li, W. (2023) Advancements and Challenges in Municipal Solid Waste Management: A Comprehensive Analysis of Disposal Methods and Their Environmental Impacts. *E3S Web of Conferences*, [online] 424, pp. 01001–01001, doi:10.1016/j.e3sconf/202342401001.

Li, Y., Gupta, R., Zhang, Q. and You, S. (2023). Review of Biochar Production via Crop Residue Pyrolysis: Development and Perspectives. *Bioresour. Technol.* [online] 369, pp. 128423–128423, doi:10.1016/j.biortech.2022.128423.

Libonatti, C. C., Agüería, D. A. and Breccia, J. (2023). Fish Waste Silage, a Green Process for Low Feedstock Availability. A Review. *Agronomía Mesoamericana*, [online], p. 51077, doi:10.15517/am.v34i2.51077.

Lukitawesa. (2020) Methane and Volatile Fatty Acids Production from Toxic Substrate." *DIVA*, Höskolan i Borås. [online] Retrieved from: <https://hb.diva-portal.org/smash/record.jsf?pid=diva2%3A1415139&dswid=-9017>

Ganesapillai, M., Metha, R., Tiwari, A., Sinha, A., Singh, H., Chellappa, V. and Drewnowski, A. (2023) Waste to Energy: A Review of Biochar Production with Emphasis on Mathematical Modelling and Its Applications. *Heliyon*, [online] 9, pp. e14873–e14873, doi:10.1016/j.heliyon.2023.e14873.

Makádi, M., Tomócsik, A. and Orosz, V. (n.d) *Digestate: A New Nutrient Source -Review*. [online]. Retrieved from: <https://cdn.intechopen.com/pdfs/31331.pdf>

Matías Del Campo, L., Ibarra, P., Gutiérrez, X. and Takle, H. (2010). *Utilization of sludge from recirculation aquaculture systems*. [online] Retrieved from: <https://nofima.brage.unit.no/nofima-xmlui/bitstream/handle/11250/2559653/Rapport%2B09-2010.pdf?sequence=1&isAllowed=>

Moore, D. (2024) Report: Global Municipal Solid Waste Projected to Increase to 3.8 Billion Tonnes by 2050. *Circular Online*. [online] Retrieved from: [www.circularonline.co.uk/news/report-global-municipal-solid-waste-projected-to-increase-to-3-8-billion-tonnes-by-2050](http://www.circularonline.co.uk/news/report-global-municipal-solid-waste-projected-to-increase-to-3-8-billion-tonnes-by-2050)

Mukherjee, A., Patra, B. R., Podder, J. and Dalai, A. K. (2022). Synthesis of Biochar from Lignocellulosic Biomass for Diverse Industrial Applications and Energy Harvesting: Effects of Pyrolysis Conditions on the Physicochemical Properties of Biochar. *Frontiers in Materials*, [online] 9, doi:10.3389/fmats.2022.870184.

Yogalakshmi, K. N., Devi, P., Sivashanmugam, P., Kavitha, S., Yukesh, R., Varjani, S., Adishkumar, S., Kumar, G. and Banu, R. (2022). Lignocellulosic Biomass-Based Pyrolysis: A Comprehensive Review. *Chemosphere*, [online] 286, pp. 131824–131824, doi:10.1016/j.chemosphere.2021.131824.

Nordell, E., Bkörn, A., Waern, S., Shakeri, S., Sundgren, I. and Moestedt, J. (2022). Thermal Post-Treatment of Digestate in Order to Increase Biogas Production with Simultaneous Pasteurization. *Journal of Biotechnology*, [online] 344, pp. 32–39, doi:10.1016/j.jbiotec.2021.12.007.

Novak, J. T. (2006). Dewatering of Sewage Sludge. *ResearchGate* doi:10.1080/07373930600840419

Oyedun, A.O., Zhi Tee, C., Hanson, S. and Hui, C. W. (2014) Thermogravimetric Analysis of the Pyrolysis Characteristics and Kinetics of Plastics and Biomass Blends. *Fuel Processing Technology*, [online] 128, pp. 471–481, doi: 10.1016/j.fuproc.2014.08.010

Raposo, F., De la Rubia, M.A., Fernández-Cegrí, V. and Borja, R. (2012). Anaerobic Digestion of Solid Organic Substrates in Batch Mode: An Overview Relating to Methane Yields and Experimental Procedures. *Renewable & Sustainable Energy Reviews*, [online] 16, 861–877, doi:10.1016/j.rser.2011.09.008. Accessed 28 Apr. 2024.

Razaq, A., Tlaiaa, Z. and Khishala, Y. (2016). Methane Biogas Production from Mixing of Algae and Municipal Solid Waste by Anaerobic Digestion. *Int. J. Environ.* 10(4), 613–624.

Reynaga, D. (2020, July 9) *Calor Latente de Vaporización-Cálculo*. [video] Retrieved from: [www.youtube.com/watch?v=QS1\\_v46vijs](https://www.youtube.com/watch?v=QS1_v46vijs).

RINFI Home. (2023) *Mdp.edu.ar*. [online] Retrieved from: <https://rinfi.fi.mdp.edu.ar/>

Schmidt, C. (2024) EU States Recycled Less and Landfilled More Municipal Waste in 2022. *Euwid-Recycling.com*. [online] Retrieved from: <https://www.euwid-recycling.com/news/policy/eu-member-states-recycled-less-and-landfilled-more-municipal-solid-waste-in-2022-160224/>

Seadi, T (n.d.). *Quality Management of Digestate from Biogas Plants Used as Fertiliser*. [online] Retrieved from: [https://www.ieabioenergy.com/wp-content/uploads/2012/05/digestate\\_quality\\_web\\_new.pdf](https://www.ieabioenergy.com/wp-content/uploads/2012/05/digestate_quality_web_new.pdf)

Skibotn. (2024). Statsforvalteren I Troms Og Finnmark. [online] Retrieved from: <https://www.statsforvalteren.no/troms-finnmark/horinger/2024/02/ra-biopark-soker-om-a-etablere-biogassanlegg-i-skibotn/#:~:text=R%C3%A5%20Biopark%20AS%20s%C3%B8ker%20om,februar%202024.>

Sharma, T., Gbolahan, I., Bhushan, A., Joshi, J., Shah, K., Krishna, A. and Sharma, A. (2024). Parametric Influence of Process Conditions on Thermochemical Techniques for Biochar Production: A State-of-The-Art Review. *Journal of the Energy Institute*, [online] 113, pp. 101559–101559, doi:10.1016/j.joei.2024.101559.

Svennevik, O. (2019) *Dewatering of Digested Biomass*. Faculty of Chemistry, biotechnology and Food Science. Norwegian University of Life Science. [online] Retrieved from: <https://nmbu.brage.unit.no/nmbu-xmlui/bitstream/handle/11250/2740198/102844%20NMBU%20Svennevik%20finalshed.pdf?sequence=1&isAllowed=y>

Tambone, F., Scaglia, B., D'Imporzano, G., Schievano, A., Orzi, V., Salati, S. and Adani, F. (2010). Assessing Amendment and Fertilizing Properties of Digestates from Anaerobic Digestion through a Comparative Study with Digested Sludge and Compost. *Chemosphere*, [online] 81, pp. 577–583, doi:10.1016/j.chemosphere.2010.08.034.

Topics. (2018). *World Bank*. [online] Retrieved from: [https://www.worldbank.org/404\\_response.htm](https://www.worldbank.org/404_response.htm)

U. D. S. *Capítulo IV Sección de Pirólisis*. [online] Retrieved from: <http://tesis.uson.mx/digital/tesis/docs/628/Capitulo4.pdf>

Vondra, M., Tous, M., and Teng, S. (2019). Digestate Evaporation Treatment in Biogas Plants: A Techno-Economic Assessment by Monte Carlo, Neural Networks and Decision Trees. *Journal of Cleaner Production*, [online] 238, p. 117870, doi:10.1016/j.jclepro.2019.117870.

Wang, J. and Shizong, W. (2019). Preparation, Modification and Environmental Application of Biochar: A Review. *Journal of Cleaner Production*, [online] 227, pp. 1002–1022, doi:10.1016/j.jclepro.2019.04.282.

wikiHow. Cómo Calcular El Rendimiento Porcentual En Química. (2012) *WikiHow*. [online] Retrieved from: [https://es.wikihow.com/calcular-el-rendimiento-porcentual-en-qu%C3%ADmica#:~:text=Si%20quieres%20expresar%20la%20eficacia,%2Frendimiento%20te%20B3rico\)%20x%20100.](https://es.wikihow.com/calcular-el-rendimiento-porcentual-en-qu%C3%ADmica#:~:text=Si%20quieres%20expresar%20la%20eficacia,%2Frendimiento%20te%20B3rico)%20x%20100.)

Wikiwand - List of Municipalities of Norway. (2020) *Wikiwand*. [online] Retrieved from: [https://www.wikiwand.com/en/List\\_of\\_municipalities\\_of\\_Norway](https://www.wikiwand.com/en/List_of_municipalities_of_Norway).

Yang, D., Chen, Q., Liu, R., Zhang, Y. and Dai, X. (2022). Ammonia Recovery from Anaerobic Digestate: State of the Art, Challenges and Prospects. *Bioresource Technology*, [online] 363, pp. 127957–127957, doi:10.1016/j.biortech.2022.127957.

Zhang, T., Liu, L., Song, Z., Feng, Y., Han, X. and Yang, G. (2012). Biogas Production by Co-Digestion of Goat Manure with Three Crop Residues. *PloS One*, [online] 8, pp. e66845–e66845, doi:10.1371/journal.pone.0066845.

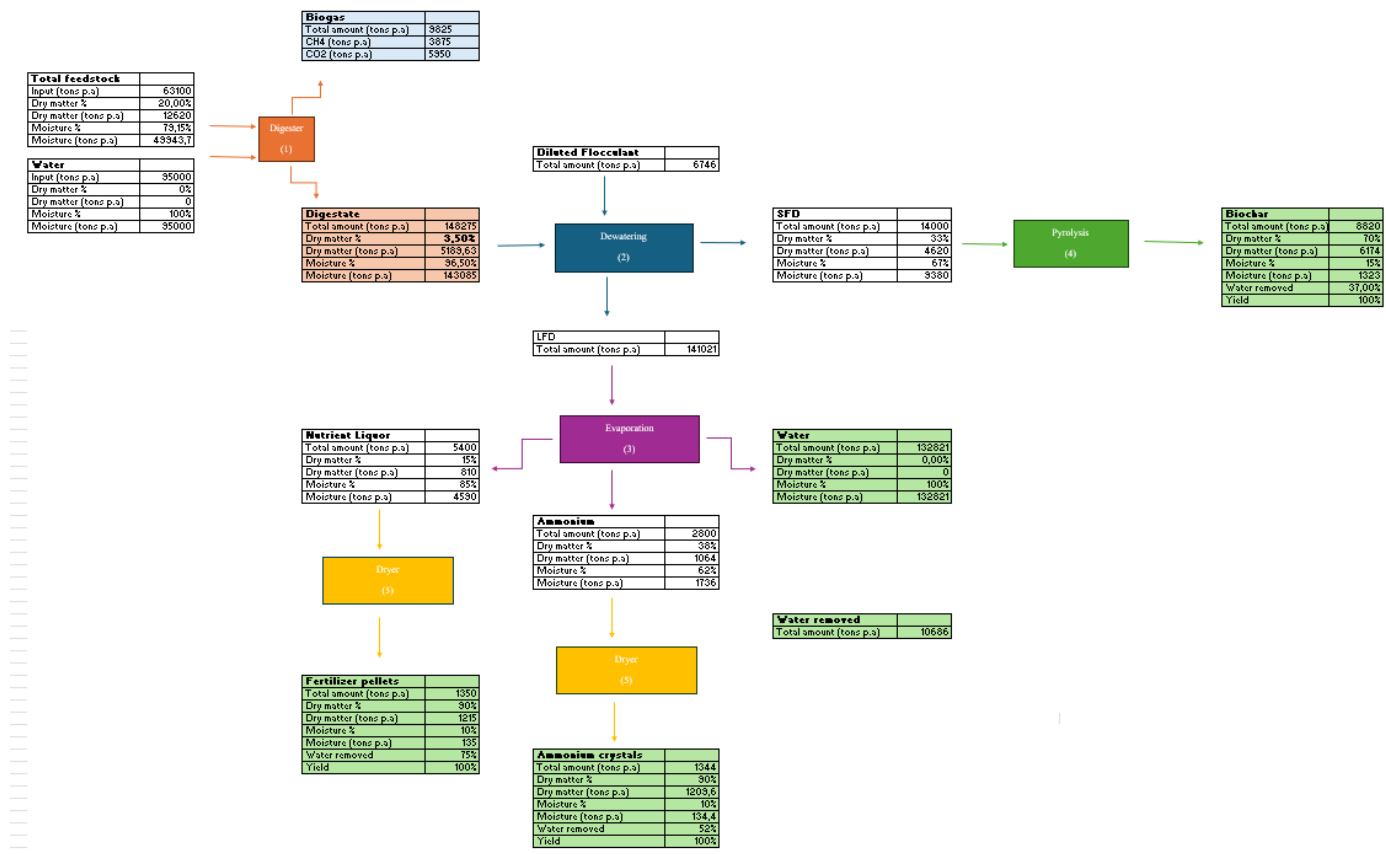
Zhang, Y. (2013). *Anaerobic Digestion System Energy Balance*. University of Southampton. [online]. Retrieved from: [https://www.valorgas.soton.ac.uk/Pub\\_docs/JyU%20SS%202013/VALORGAS\\_JyU\\_2013\\_Lecture%2013.pdf](https://www.valorgas.soton.ac.uk/Pub_docs/JyU%20SS%202013/VALORGAS_JyU_2013_Lecture%2013.pdf)

Zhang, Z., Sun, J., He, F. and Pan, Y. (2014). Effects of Pyrolysis Temperature and Residence Time on Physicochemical Properties of Different Biochar Types. *Acta Agriculturae Scandinavica*. [online] doi:10.1080//09064710.2016.1214745.

# Appendix I. Rå Biopark mass balances

Detailed mass balances conducted in Excel of Rå Biopark process.

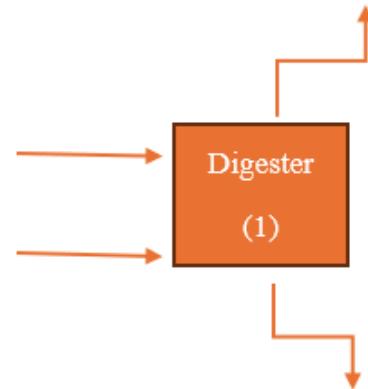
## 1. Global mass balances overview



## 2. Anaerobic Digestion mass balances

| Total feedstock       |          |
|-----------------------|----------|
| Input (tons p.a)      | 63100    |
| Dry matter %          | 20,00%   |
| Dry matter (tons p.a) | 12620    |
| Moisture %            | 79,15%   |
| Moisture (tons p.a)   | 49943,65 |

| Water                 |       |
|-----------------------|-------|
| Input (tons p.a)      | 95000 |
| Dry matter %          | 0%    |
| Dry matter (tons p.a) | 0     |
| Moisture %            | 100%  |
| Moisture (tons p.a)   | 95000 |

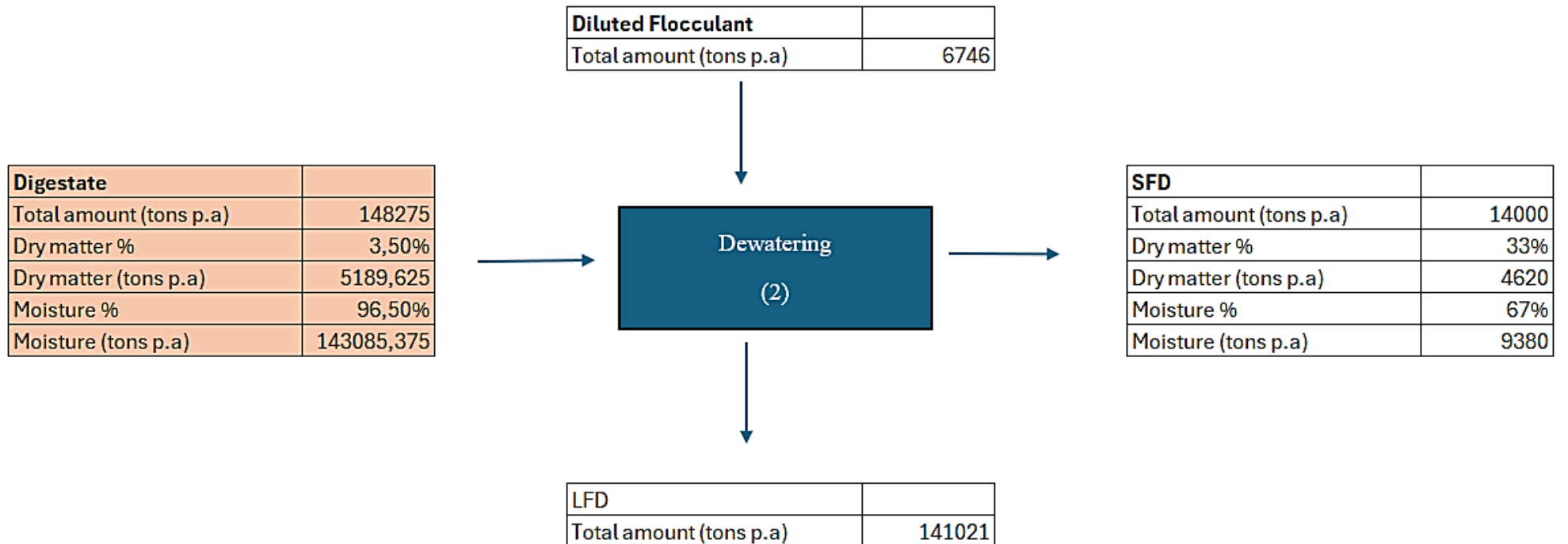


| Biogas                  |      |
|-------------------------|------|
| Total amount (tons p.a) | 9825 |
| CH4 (tons p.a)          | 3875 |
| CO2 (tons p.a)          | 5950 |

| Digestate               |           |
|-------------------------|-----------|
| Total amount (tons p.a) | 148275    |
| Dry matter %            | 3,50%     |
| Dry matter (tons p.a)   | 5189,625  |
| Moisture %              | 96,50%    |
| Moisture (tons p.a)     | 143085,38 |

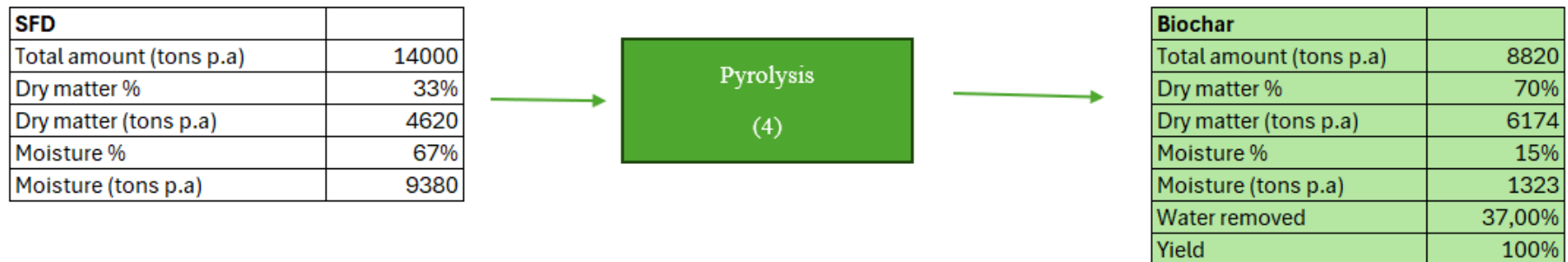
(Author's own, adapted from data facilitated by Rå Biopark)

### 3. Dewatering mass balances



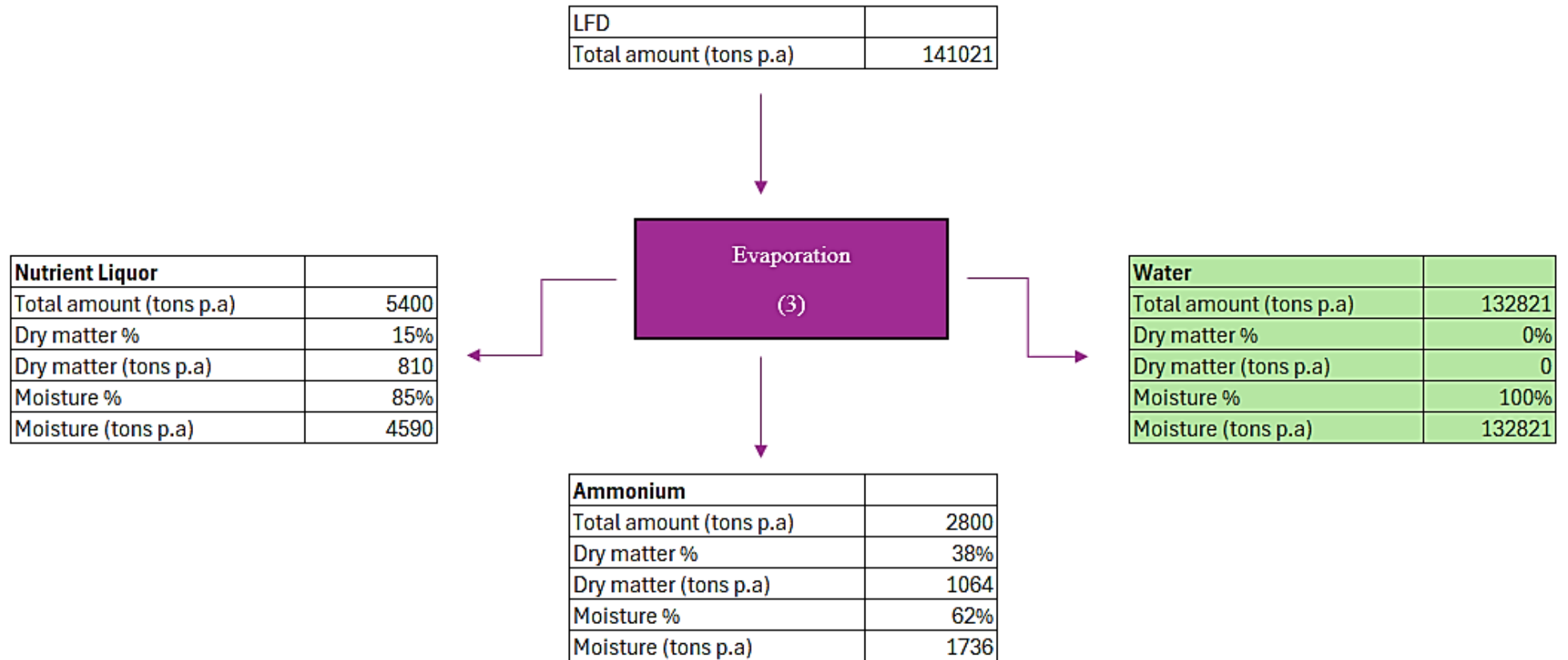
(Author's own, adapted from data facilitated by Rå Biopark)

#### 4. Pyrolysis mass balances



(Author's own, adapted from data facilitated by Rå Biopark)

## 5. Evaporation mass balances



(Author's own, adapted from data facilitated by Rå Biopark)

## 6. Drying mass balances

| Ammonium                |      |
|-------------------------|------|
| Total amount (tons p.a) | 2800 |
| Dry matter %            | 38%  |
| Dry matter (tons p.a)   | 1064 |
| Moisture %              | 62%  |
| Moisture (tons p.a)     | 1736 |



| Ammonium crystals       |        |
|-------------------------|--------|
| Total amount (tons p.a) | 1344   |
| Dry matter %            | 90%    |
| Dry matter (tons p.a)   | 1209,6 |
| Moisture %              | 10%    |
| Moisture (tons p.a)     | 134,4  |
| Water removed           | 52%    |
| Yield                   | 100%   |

| Nutrient Liquor         |      |
|-------------------------|------|
| Total amount (tons p.a) | 5400 |
| Dry matter %            | 15%  |
| Dry matter (tons p.a)   | 810  |
| Moisture %              | 85%  |
| Moisture (tons p.a)     | 4590 |



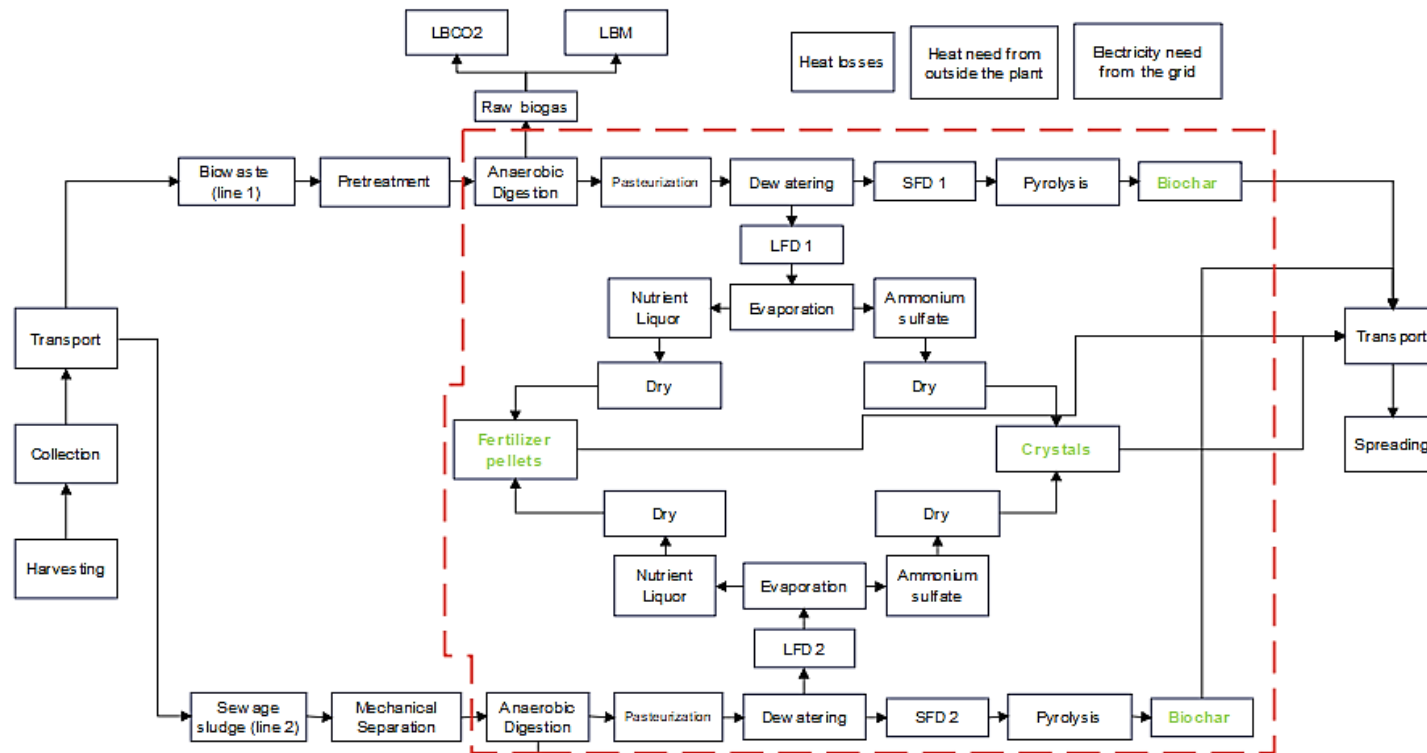
| Fertilizer pellets      |      |
|-------------------------|------|
| Total amount (tons p.a) | 1350 |
| Dry matter %            | 90%  |
| Dry matter (tons p.a)   | 1215 |
| Moisture %              | 10%  |
| Moisture (tons p.a)     | 135  |
| Water removed           | 75%  |
| Yield                   | 100% |

| Water removed           |       |
|-------------------------|-------|
| Total amount (tons p.a) | 10686 |

(Author's own, adapted from data facilitated by Rå Biopark)

## Appendix II. System boundaries

This appendix provides a comprehensive flowchart illustrating the parameters incorporated in the energy demand analysis alongside those omitted, establishing distinct boundaries for the study's scope.



(Author's own, adapted from Rå Biopark)

(Author's own, adapted from Rå Biopark)

## Appendix III. Energy demand calculations Excel

This appendix presents examples of Excel templates showcasing energy demand calculations for each stage of the digestate treatment process.

### 1. Tables Solid Fraction Digestate lines 1 and 2

| <b>Digestate 1</b>                  |                |
|-------------------------------------|----------------|
| Total amount (m <sup>3</sup> /year) | <b>120.000</b> |
| Dry matter (%)                      | 4,0            |
| Moisture (%)                        | 96             |
| Temperature (°C)                    | 38             |
|                                     |                |
| <b>SFD 1</b>                        |                |
| Total amount (tons/year)            | <b>11.600</b>  |
| Dry matter (%)                      | 33,0           |
| Moisture (%)                        | 67             |
| Water removed (%)                   | 29             |
| Temperature (°C)                    | <b>30</b>      |
|                                     |                |
| <b>Biochar 1</b>                    |                |
| Total amount (tons/year)            | <b>5.568</b>   |
| Dry matter (%)                      | 85,0           |
| Moisture (%)                        | 15             |
| Water removed (%)                   | 52             |
| Temperature (°C)                    | <b>400</b>     |

| <b>Digestate 2</b>                  |               |
|-------------------------------------|---------------|
| Total amount (m <sup>3</sup> /year) | <b>30.000</b> |
| Dry matter (%)                      | 3,0           |
| Moisture (%)                        | 97            |
| Temperature (°C)                    | 38            |
|                                     |               |
| <b>SFD 2</b>                        |               |
| Total amount (tons/year)            | <b>2.400</b>  |
| Dry matter (%)                      | 33,0          |
| Moisture (%)                        | 67            |
| Water removed (%)                   | 30            |
| Temperature (°C)                    | <b>30</b>     |
|                                     |               |
| <b>Biochar 2</b>                    |               |
| Total amount (tons/year)            | <b>1.152</b>  |
| Dry matter (%)                      | 85,0          |
| Moisture (%)                        | 15            |
| Water removed (%)                   | 52            |
| Temperature (°C)                    | <b>400</b>    |

(Author's own, adapted from data facilitated by Rå Biopark)

## 2. Example of Water Mass calculation

| Dewatering Energy Demand      |                               |
|-------------------------------|-------------------------------|
| Water removed:                |                               |
| $WM_r(t) = WM_d(t) - WM_s(t)$ |                               |
| WM <sub>d</sub> (t)           | 115200                        |
| WM <sub>sfd</sub> (t)         | $=19 \cdot (1 - ((110)/100))$ |
| WM <sub>r</sub> (t)           | 107428                        |
| Energy consumption:           |                               |
| $E = WM_r \cdot \Delta H$     |                               |
| $\Delta H$ (kJ/kg)            | 2265                          |
| E (MWh/year)                  | 67590                         |

|                          |               |
|--------------------------|---------------|
| <b>SFD 1</b>             |               |
| Total amount (tons/year) | <b>11.600</b> |
| Dry matter (%)           | 33,0          |
| Moisture (%)             | 67            |
| Water removed (%)        | 29            |
| Temperature (°C)         | <b>30</b>     |

(Author's own, adapted from data facilitated by Rå Biopark)

### 3. Dewatering line 1 and line 2 separately

| Dewatering Energy Demand      |                                 |
|-------------------------------|---------------------------------|
| Water removed:                |                                 |
| $WM_r(t) = WM_d(t) - WM_s(t)$ |                                 |
| WM_d (t)                      | 115200                          |
| WM_sfd (t)                    | 7772                            |
| WM_r (t)                      | 107428                          |
| Energy consumption:           |                                 |
| $E = WM_r \cdot \Delta H$     |                                 |
| $\Delta H$ (kJ/kg)            | 2265                            |
| E (MWh/year)                  | $=(((C32*10^3)*C38)/3600)/1000$ |

| Dewatering Energy Demand      |                                 |
|-------------------------------|---------------------------------|
| Water removed:                |                                 |
| $WM_r(t) = WM_d(t) - WM_s(t)$ |                                 |
| WM_d (t)                      | 115200                          |
| WM_sfd (t)                    | 7772                            |
| WM_r (t)                      | 107428                          |
| Energy consumption:           |                                 |
| $E = WM_r \cdot \Delta H$     |                                 |
| $\Delta H$ (kJ/kg)            | 2265                            |
| E (MWh/year)                  | $=(((C32*10^3)*C38)/3600)/1000$ |

(Author's own, adapted from data facilitated by Rå Biopark)

#### 4. Pyrolysis line 1

##### Pyrolysis Energy Demand

$$E = Q_s + Q_\lambda$$

$$E = WM_r \cdot \bar{C}_p \cdot \Delta T + WM_r \cdot \Delta H$$

$$E \text{ (kWh)} = \frac{WM_r \cdot 10^3 \text{ (kg)} \cdot \bar{C}_p \text{ (J/kJ}^\circ\text{C)} \cdot \Delta T \text{ (}^\circ\text{C)}}{1000 \text{ (J/kJ)} \cdot (3600 \text{ kJ/kWh})} + \frac{WM_r \cdot 10^3 \text{ (kg)} \cdot \Delta H \text{ (kJ/kg)}}{(3600 \text{ kJ/kWh})}$$

WM\_sfd (t)                      7772

WM\_char (t)                    2895,36

WM\_r (t)                        4876,64

Cp (kJ/jg°C)                    4,18

|              |      |
|--------------|------|
| E (MWh/year) | 3070 |
|--------------|------|

(Author's own, adapted from data facilitated by Rå Biopark)

## 5. Pyrolysis line 2

### Pyrolysis Energy Demand

$$E = Q_s + Q_\lambda$$

$$E = WM_r \cdot \bar{C}_p \cdot \Delta T + WM_r \cdot \Delta H$$

$$E \text{ (kWh)} = \frac{WM_r \cdot 10^3 \text{ (kg)} \cdot \bar{C}_p \text{ (J/kJ}^\circ\text{C)} \cdot \Delta T \text{ (}^\circ\text{C)}}{1000 \text{ (J/kJ)} \cdot (3600 \text{ kJ/kWh})} + \frac{WM_r \cdot 10^3 \text{ (kg)} \cdot \Delta H \text{ (kJ/kg)}}{(3600 \text{ kJ/kWh})}$$

|                     |            |
|---------------------|------------|
| WM_sfd (t)          | 1608       |
| WM_char (t)         | 599,04     |
| WM_r (t)            | 1008,96    |
| Cp (kJ/jg°C)        | 4,18       |
| <b>E (MWh/year)</b> | <b>635</b> |

(Author's own, adapted from data facilitated by Rå Biopark)

## 6. Tables Liquid Fraction Digestate line 1 and line 2 together

|                          |                |                          |              |                           |              |
|--------------------------|----------------|--------------------------|--------------|---------------------------|--------------|
| <b>LFD</b>               |                | <b>Nutrient Liquor</b>   |              | <b>Fertilizer pellets</b> |              |
| Total amount (tons/year) | <b>141.021</b> | Total amount (tons/year) | <b>5.400</b> | Total amount (tons/year)  | <b>1.350</b> |
| Dry matter (%)           | 0,0            | Dry matter (%)           | 15,0         | Dry matter (%)            | 90,0         |
| Moisture (%)             | 100            | Moisture (%)             | 85           | Moisture (%)              | 10           |
| Water removed (%)        | 0              | Water removed (%)        | 15           | Water removed (%)         | 75           |
| Temperature (°C)         | <b>30</b>      | Temperature (°C)         | <b>100</b>   | Temperature (°C)          |              |
|                          |                |                          |              |                           |              |
|                          |                | <b>Ammonium</b>          |              | <b>Ammonium crystals</b>  |              |
|                          |                | Total amount (tons/year) | <b>2.800</b> | Total amount (tons/year)  | <b>1.344</b> |
|                          |                | Dry matter (%)           | 38,0         | Dry matter (%)            | 90,0         |
|                          |                | Moisture (%)             | 62           | Moisture (%)              | 10           |
|                          |                | Water removed (%)        | 38           | Water removed (%)         | 52           |
|                          |                | Temperature (°C)         | <b>100</b>   | Temperature (°C)          |              |

(Author's own, adapted from data facilitated by Rå Biopark)

## 1. Evaporation and Drying

| Evaporation Energy Demand |              | Dryer Energy Demand |             |
|---------------------------|--------------|---------------------|-------------|
| Nutrient Liquor           |              | Fertilizer pellets  |             |
| WM_lfd (t)                | 141021       | WM_nl (t)           | 4590        |
| WM_nl (t)                 | 810          | WM_fp (t)           | 1012,5      |
| WM_r (t)                  | 140211       | WM_r (t)            | 3577,5      |
| Cp (kJ/jg°C)              | 4,18         | ΔH (kJ/kg)          | 2265        |
| <b>E (MWh/year)</b>       | <b>1180</b>  | <b>E (MWh/year)</b> | <b>2251</b> |
| Ammonium                  |              | Ammonium crystals   |             |
| WM_lfd (t)                | 141021       | WM_a (t)            | 1736        |
| WM_a (t)                  | 1736         | WM_ac (t)           | 698,88      |
| WM_r (t)                  | 139285       | WM_r (t)            | 1037,12     |
| Cp (kJ/jg°C)              | 4,18         | ΔH (kJ/kg)          | 2265        |
| <b>E (MWh/year)</b>       | <b>11,32</b> | <b>E (MWh/year)</b> | <b>653</b>  |

(Author's own, adapted from data facilitated by Rå Biopark)

## Annex IV. Table results biogas yield

The table below facilitates understanding the contribution of each substrate to biogas yield.

| Feedstocks                                   | t/year          | TS (%) | VS (% of TS) | Methane yield (mL/gVS) | m <sup>3</sup> CH <sub>4</sub> /year | t CH <sub>4</sub> /year | VS (t)         | Methane yield | m <sup>3</sup> raw biogas/year | t raw biogas/year |  |
|--|-----------------|--------|--------------|------------------------|--------------------------------------|-------------------------|----------------|---------------|--------------------------------|-------------------|--|
| Household SSO                                | 14.900          | 20,7   | 91,9         | 350,0                  | 992.065,1                            | 714,3                   | 2834,5         | 24,4          | 1538085,4                      | 1107,4            |  |
| Organic waste                                | 2.600           | 29,0   | 95,0         | 350,0                  | 250.705,0                            | 180,5                   | 716,3          | 6,2           | 388689,9                       | 279,9             |  |
| HoReCa Food production waste                 | 2.000           | 29,0   | 95,0         | 396,0                  | 218.196,0                            | 157,1                   | 551,0          | 5,4           | 338288,4                       | 243,6             |  |
| Depeckaged pre-consumer supermarket organics | 1.000           | 29,0   | 95,0         | 350,0                  | 96.425,0                             | 69,4                    | 275,5          | 2,4           | 149496,1                       | 107,6             |  |
| Grease trap fat                              | 900             | 2,3    | 90,0         | 307,0                  | 5.595,1                              | 4,0                     | 18,2           | 0,1           | 8674,5                         | 6,2               |  |
| Waste vegetable oil                          | 50              | 2,3    | 90,0         | 875,0                  | 885,9                                | 0,6                     | 1,01           | 0,0           | 1373,5                         | 1,0               |  |
| Brewery malt dust                            | 400             | 26,1   | 89,3         | 650,0                  | 60.599,0                             | 43,6                    | 93,2           | 1,5           | 93951,9                        | 67,6              |  |
| Brewery spent grains                         | 1.500           | 26,1   | 89,3         | 461,0                  | 161.170,0                            | 116,0                   | 349,6          | 4,0           | 249875,9                       | 179,9             |  |
| Brewery beer                                 | 1.300           | 26,1   | 89,3         | 350,0                  | 106.048,2                            | 76,4                    | 303,0          | 2,6           | 164415,8                       | 118,4             |  |
| Fish oil factory glycerine                   | 250             | 3,0    | 82,6         | 598,0                  | 3.717,0                              | 2,7                     | 6,2            | 0,1           | 5762,7                         | 4,1               |  |
| Brewery spent yeast                          | 200             | 26,1   | 89,3         | 450,0                  | 20.976,6                             | 15,1                    | 46,6           | 0,5           | 32521,8                        | 23,4              |  |
| Cattle slurry                                | 2.000           | 19,2   | 25,0         | 108,0                  | 10.378,8                             | 7,5                     | 96,1           | 0,3           | 16091,2                        | 11,6              |  |
| Goat manure                                  | 500             | 33,7   | 82,0         | 159,0                  | 21.936,4                             | 15,8                    | 138,0          | 0,5           | 34010,0                        | 24,5              |  |
| RAS fish farm sludge                         | 13.500          | 2,0    | 66,0         | 785,0                  | 139.887,0                            | 100,7                   | 178,2          | 3,4           | 216879,1                       | 156,2             |  |
| Fish silage                                  | 1.700           | 38,2   | 93,0         | 785,0                  | 474.218,6                            | 341,4                   | 604,1          | 11,7          | 735222,6                       | 529,4             |  |
| Fish processing waste (cake)                 | 2.000           | 38,2   | 93,0         | 390,0                  | 277.175,3                            | 199,6                   | 710,7          | 6,8           | 429729,2                       | 309,4             |  |
| Fish processing waste (rotasieve)            | 2.000           | 38,2   | 93,0         | 390,0                  | 277.175,3                            | 199,6                   | 710,7          | 6,8           | 429729,2                       | 309,4             |  |
| Oily fish factory wash water                 | 500             | 2,0    | 5,0          | 75,0                   | 37,5                                 | 0,0                     | 0,5            | 0,0           | 58,1                           | 0,0               |  |
| Sewage sludge                                | 15.800          | 28,0   | 57,0         | 376,0                  | 948.151,7                            | 682,7                   | 2521,7         | 23,3          | 1470002,6                      | 1058,4            |  |
| <b>Total</b>                                 | <b>63.100,0</b> |        |              |                        | <b>4.065.343,5</b>                   | <b>2.927,0</b>          | <b>10155,1</b> | <b>100,0</b>  | <b>6302858,1</b>               | <b>4538,1</b>     |  |
| <b>Total Methane Yield</b>                   |                 |        |              |                        | <b>28,82</b>                         |                         | <b>%</b>       |               |                                |                   |  |
| <b>Energy production</b>                     |                 |        |              |                        | <b>39,39</b>                         |                         | <b>GWh</b>     |               |                                |                   |  |

(Author's own, adapted from data collected from different literature sources)

## Appendix V. Biochar yield Excel template

This appendix outlines the various sections in the Excel template for calculating biochar yield (Gul et al. 2021).

### 1. Data input tables.

| SFD 1         |   | m3/year |  | Biochar       |   | m3/year |
|---------------|---|---------|--|---------------|---|---------|
| Cellulose     | 0 | %       |  | Cellulose     | 0 | %       |
| Hemicellulose | 0 | %       |  | Hemicellulose | 0 | %       |
| Lignin        | 0 | %       |  | Lignin        | 0 | %       |

### 2. Calculation of the contribution of each component to the biochar yield (Y)

#### 2.1. Pyrolysis yields of each individual component (in %)

| SFD 1         |   | m3/year |  | Biochar       |   | m3/year |
|---------------|---|---------|--|---------------|---|---------|
| Cellulose     | 0 | %       |  | Cellulose     | 0 | %       |
| Hemicellulose | 0 | %       |  | Hemicellulose | 0 | %       |
| Lignin        | 0 | %       |  | Lignin        | 0 | %       |

Calculation of the contribution of each component to the biochar yield (Y):

| Pyrolysis yields of each individual component (in %) |                   | Mass of biochar produced by each component |            |
|--|-------------------|--|------------|
| Yc (cellulose)                                       | $= (G6/C6) * 100$ | cellulose                                  | ⚠️ #DIV/0! |
| Yh (hemicellulose)                                   | ⚠️ #DIV/0!        | hemicellulose                              | ⚠️ #DIV/0! |
| Yl (lignin)  | ⚠️ #DIV/0!        | lignin                                     | ⚠️ #DIV/0! |

2.2. Mass of biochar produced by each component.

| SFD 1         |   | m3/year | Biochar       |   | m3/year |
|---------------|---|---------|---------------|---|---------|
| Cellulose     | 0 | %       | Cellulose     | 0 | %       |
| Hemicellulose | 0 | %       | Hemicellulose | 0 | %       |
| Lignin        | 0 | %       | Lignin        | 0 | %       |

Calculation of the contribution of each component to the biochar yield (Y):

| Pyrolysis yields of each individual component (in %) |          | Mass of biochar produced by each component |            |
|--|----------|--|------------|
| Yc (cellulose)                                       | #;DIV/0! | cellulose                                  | =(C6/100)* |
| Yh (hemicellulose)                                   | #;DIV/0! | hemicellulose                              | C16/100)   |
| Yl (lignin)  | #;DIV/0! | lignin                                     | #;DIV/0!   |

2.3. Mass of biochar after pyrolysis

| Pyrolysis yields of each individual component (in %) |                | Mass of biochar produced by each component |          |
|--|----------------|--|----------|
| Yc (cellulose)                                       | #;DIV/0!       | cellulose                                  | #;DIV/0! |
| Yh (hemicellulose)                                   | #;DIV/0!       | hemicellulose                              | #;DIV/0! |
| Yl (lignin)  | #;DIV/0!       | lignin                                     | #;DIV/0! |
| x  | =SUMA(E16:E18) | (mass of biochar after pyrolysis)          |          |

2.4. Biochar yield calculation

|                      |                    |                                   |
|----------------------|--------------------|-----------------------------------|
| x                    | #;DIV/0!           | (mass of biochar after pyrolysis) |
| <b>Biochar Yield</b> | =100-((1-C21)*100) | %                                 |

## 2.5. Contribution of each component

| Pyrolysis yields of each individual component (in %)  |          | Mass of biochar produced by each component                     |          |
|---|----------|--|----------|
| Yc (cellulose)  | #;DIV/0! | cellulose  | #;DIV/0! |
| Yh (hemicellulose)                                    | #;DIV/0! | hemicellulose  | #;DIV/0! |
| Yl (lignin)   | #;DIV/0! | lignin   | #;DIV/0! |
| x   | #;DIV/0! | (mass of biochar after pyrolysis)                              |          |
| <b>Biochar Yield</b>                                  | #;DIV/0! | %  |          |
| <b>Contribution of each component</b>                 |          | (how much of the final carbon comes from a specific component) |          |
| $= (1 - (\text{C}_{21} - E16) / \text{C}_{21}) * 100$ |          |  |          |
| Hemicellulose   | #;DIV/0! |  |          |
| Lignin  | #;DIV/0! |  |          |

