Common Reed's Methane Potential Through Anerobic Digestion – Cost Analysis from Harvesting Biomass to Biogas Production

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Abstract

This thesis investigates the potential of common reed (Phragmites Australis) for biogas production through anaerobic digestion, focusing on the journey from biomass harvesting to biogas production. Addressing the dual challenge of managing common reed's overgrowth and meeting the demand for renewable energy sources, this research aims to evaluate the feasibility and efficiency of converting this invasive species into a sustainable energy source. A key objective is to identify the optimal season for harvesting common reed to maximize biogas yield.

The methodology combines theoretical and practical examinations, utilizing the Automatic Methane Potential Test System II (AMPTS II) laboratory instrument. The instrument is designed to measure various substrates' Biochemical Methane Potential (BMP) under anaerobic conditions. This enables precise measurements of methane yield from common reeds across different seasons. Alongside BMP assessments the research includes an economic analysis, including a detailed case study, to document the biomass-to-biogas conversion process, revealing the financial feasibility and identifying the optimal harvesting season for common reed.

The results indicate seasonal influence on the BMP of Common Reed, with the highest BMP identified in winter-harvested biomass. Economic analysis highlighted the challenge of balancing production costs with efficiency, pointing to winter as the most cost-effective season for harvesting.

Language: English

Keywords: Anaerobic Digestion, Common Reed, Biochemical Methane Potential, AMPTS II, Biogas Production

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EXAMENSARBETE

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Abstrakt

Denna avhandling undersöker potentialen hos vass (Phragmites Australis) för biogasproduktion genom rötning, med fokus på processen från biomassans skörd till biogasproduktion. Genom att ta sig an den dubbla utmaningen att hantera vassens igenväxning och möta efterfrågan på förnybara energikällor fokuserar denna forskning till att utvärdera genomförbarheten och effektiviteten i att omvandla denna invasiv art till en hållbar energikälla. Ett viktigt mål är att identifiera den optimala säsongen för att skörda vass för att maximera biogasutbytet.

Metodiken kombinerar teoretiska och praktiska undersökningar, där laboratorieinstrumentet Automatic Methane Potential Test System II (AMPTS II) har använts. Instrumentet är gjord för att mäta biokemisk metanpotential (BMP) hos olika substrat under anaeroba förhållanden. Detta möjliggör exakta mätningar av metanutbyte från vass över olika säsonger. Vid sidan av BMP-värderingar inkluderar forskningen en ekonomisk analys, inklusive en detaljerad fallstudie, för att dokumentera processen från biomassa till biogas, vilket avslöjar den ekonomiska genomförbarheten och identifierar den optimala skördesäsongen för vass.

Resultaten indikerar en betydande säsongsinfluens på BMP för vass, med det högsta metanutbytet identifierat i biomassan som skördats under vintern. Den ekonomiska analysen belyste utmaningen att balansera produktionskostnader med effektivitet, vilket pekar på vintern som den mest kostnadseffektiva säsongen för skörd.

Språk: engelska

Nyckelord: rötning, vass, metanpotential, AMPTS II, biogasproduktion

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Table of contents

List of Appendices

Appendix 1	Analysis of TS and VS in Winter Test Sample
Appendix 2	Analysis of TS and VS in Summer Test Sample
Appendix 3	Analysis of TS and VS in Autumn Test Sample

Abbreviations and definitions

AD – Anaerobic digestion.

Phragmites Australis – Latin name of the Common Reed.

TS – Total solids. Substrates remaining after the water evaporates in a drying chamber.

VS – Volatile solids. Percentage of TS available of the substrate after being burned in an oven at 550°C.

BMP – Biochemical Methane Potential. Describes the methane yield that can be produced from the given organic material.

Substrate – Organic material that can be used for biogas production.

Digestate – Biological remaining after completed biogas process.

HRT – Hydraulic retention time.

Nml – Normalized milliliters.

Nl – Normalized liters.

Ab Stormossen Oy – Company's legal name, will be written as Stormossen.

Lekatie – Selected storage site for the biomass, owned by City of Vaasa.

Inoculum – Digesting material inside an operating reactor containing established biogas-producing microorganisms.

1 Introduction

This thesis work is conducted within the 'Järviruosta biokaasuksi' (Reed to Biogas) project, a collaboration between Ab Stormossen Oy and the City of Vaasa. The project aims to explore the potential of utilizing common reed (Phragmites Australis) for anaerobic digestion (AD), aligning with Stormossen's commitment to circular solutions for enhanced biogas production and City of Vaasa’s demand for more biogas production for local transportation buses.

1.1 Background

The biogas laboratory tests were done in cooperation with the Interreg Aurora-funded project Boost Nordic Biogas, which will disseminate the results to the target group.

Financial support for the project is provided by two main sources: the Centre of Economic Development, Transport, and the Environment (ELY-Centre), and the City of Vaasa. Both entities equally contribute to cover the project's expenses. Meanwhile, Boost Nordic Biogas has covered all the laboratory expenses.

The background also encompasses the notable surge in demand for biogas production, driven by the expansion of locally operated gas-driven buses in Vaasa, reaching a total of 22 buses in 2022. (Hällilä 2023) Additionally, Stormossen's sales of BIG biogas saw a remarkable 47% increase compared to the previous year. (Ab Stormossen Oy 2022) This increased demand highlights the necessity for expanded biogas production.

Given the threat of eutrophication and overgrowth of common reed in the Southern City Bay of Vaasa, seasonal harvesting and processing into biogas offer a potential solution to improve both water quality and biogas production.

1.2 Purpose and Goal

The purpose of this thesis work is to analyze the possibility of biogas production through anaerobic digestion of common reed (Phragmites Australis) and assess its Biochemical Methane Potential (BMP). Additionally, the study aims to determine the optimal mixture of substrate to biowaste and sludge ratio. It will also evaluate which crop season - winter, summer, or autumn - yields the highest methane output.

The second segment of this thesis will involve cost calculations and an analysis of expenses associated with the entire process, from the shoreline to the biogas facility. This examination will account for all essential phases, providing a thorough understanding of the financial implications throughout the entire journey.

Furthermore, the goal is to evaluate if the common reed is a suitable substrate to increase biogas production at Stormossen, identifying the most effective season for this purpose. The intention is to make the City of Vaasa self-sufficient and less reliant on third-party gas producers.

1.3 Methods

To successfully achieve the objectives outlined earlier, a comprehensive approach combining both theoretical and practical methodologies was employed. The theoretical component includes crucial information on anaerobic digestion, covering various process steps and key parameters that influence the fermentation process. Furthermore, the theoretical dimension extends to include practical aspects regarding harvesting, transportation, pre-treatment, and storage methodologies.

The practical segment primarily involves hands-on laboratory work conducted at Novia University of Applied Sciences. This phase heavily relies on two specialized instruments known as Automatic Methane Potential Test System II (AMPTS II), designed specifically for measuring the Biochemical Methane Potential (BMP) derived from anaerobic digestion processes. This practical phase is instrumental in providing empirical data to complement and validate the theoretical framework established in this study.

2 Boost Nordic Biogas

Boost Nordic Biogas project is a cross-border project with the objective of improving the economic viability and efficiency of biogas production in the northern part of Finland, Sweden, and Norway. (BioFuel Region 2024)

Funding for the Boost Nordic Biogas project comes from the Interreg Aurora Programme, which is an initiative of the European Union Interreg community aimed at supporting cross-border cooperation during 2021-2027. In Finland, the project collaborators include Novia UAS and Ab Stormossen Oy, while in Sweden, the partners are BioFuel Region and the Swedish University of Agricultural Sciences (SLU), and in Norway, the participant is SINTEF Narvik.

Boost Nordic Biogas has financed this project for Novia, taking care of the expenses for laboratory equipment and all associated laboratory costs. Additionally, the joint project named "Järviruosta biokaasuksi" between Stormossen and the City of Vaasa receives partial funding from the ELY-centre and the City of Vaasa.

The Biogas system plays a crucial role in society by offering numerous societal benefits and contributing to all of the UN's global sustainability goals. It provides solutions for sustainable waste management, circular economy, and resource efficiency. After the extraction of biogas from the waste, digestion of the remaining product contains valuable nutrients that can be transformed into a locally sourced and renewable fertilizer.

2.1 City of Vaasa

Located on the west coast in the northern reaches of Finland, the City of Vaasa, boasts a population of 67,988 as of December 2022 (Tilastokeskus 2023), holds a key vital in the region. One of its key assets is Stormossen, an entity closely tied to the city's interests. A prominent concern for Vaasa has been the presence of reed in the Southern City Bay, a significant contributor to eutrophication due to its capacity to release plant nutrients in the likes of phosphorus and nitrogen into the water system.

Recognizing the urgency of the matter, Vaasa and Stormossen forged a partnership. They share a twofold objective, to effectively mitigate the reed overgrowth while concurrently bolstering biogas production. This comprehensive strategy places a significant emphasis on meeting Vaasa’s increased demand for biogas, a crucial resource for powering their fleet of 22 natural gas buses that form the public transportation network.

Additionally, the City of Vaasa is committed to preserving recreational activities in Southern City Bay and managing the environmental effects of its extensive reed bed area, which covers 3.5 square kilometers, as well as supporting the biogas needs of its public transportation fleet of gas-driven buses.

2.2 Ab Stormossen Oy

Ab Stormossen Oy, located in Mustasaari, Finland, has been in operation since 1985. It is collectively owned by six municipalities and primarily handles waste management for an approximate population of 107,000 within their jurisdiction. (Ab Stormossen Oy 2023)

In addition to waste management, the company operates two anaerobic biogas reactors that play a pivotal role in extracting valuable biogas from the waste materials processed by the facility. This process occurs in the absence of oxygen, creating anaerobic conditions that facilitate the efficient decomposition of organic matter and yield biogas as a valuable product. (Holmström 2023)

The biogas extracted from this process serves as a renewable energy source, contributing to the reduction of greenhouse gas emissions and promoting sustainable energy practices. The remnants of this anaerobic digestion process, referred to as digestate, undergo further processing and are transformed into nutrient-rich compost soil by Stormossen, thereby completing the cycle of waste management and resource recovery. (Holmström 2023)

2.2.1 Biogas Reactor 1

Biogas reactor 1 manages sludge from wastewater treatment plant in Vaasa, maintaining a consistent heating temperature within the thermophilic range, approximately 55°C. Sustaining this temperature is essential for fostering the growth of thermophilic microorganisms. Early in the process warm water (50°C-60°C) is added and works as a preheat after the screw press stage to simplify the further transportation into the system. Maintaining these bacteria at the optimal temperature is critical for maximizing biogas production. Not keeping the desired temperature can potentially kill the bacteria, thereby compromising biogas yield. (Holmström 2023)

2.2.2 Biogas Reactor 2

Biogas Reactor 2, unlike the previous one, manages biowaste sourced from ordinary households, food stores, and food processing industries. This reactor requires more pre-processing steps due to the frequent impurities and mixture with plastic and other non-biological materials. This reactor is populated with mesophilic bacteria, which are central to biogas production. Mesophiles thrive in slightly lower temperatures just around 45 ℃ so this reactor will optimally operate at that temperature. (Holmström 2023)

3 Theory

In this chapter, you will find theoretical information relevant to common reeds, anaerobic digestion, and the factors influencing biogas production in anaerobic environments. Starting from Chapter 3.5 and extending beyond, a thorough examination of the theoretical foundations of crucial stages in the process is revealed. This includes discussions on harvesting methodologies, logistical planning, storage techniques, and pre-treatment strategies.

3.1 Common Reed

Common reed, scientifically known as Phragmites australis seen in Figure 1, is a perennial grass that thrives in moist environments worldwide, including beaches, shallow waters, and ditches. Typically, these plants measure between 1 to 3 meters in height, although in optimal conditions, they can reach heights of up to 4 meters. Several factors influence the growth of common reeds, such as nutrient availability in the environment, temperature, humidity levels, and the quality of the ground. Interestingly, this species has demonstrated a positive response to climate change, which has promoted its expansion. (ELY-keskus 2023)

In recent years, Finland’s lakes and coastal bays have experienced significant eutrophication, leading to a rapid expansion of reed growth. Modern advancements in livestock management have eliminated the necessity of grazing areas on beaches, resulting in a drastic reduction of coastal meadows from 60,000 hectares to 6,000 hectares. This reduction poses a critical threat of eutrophication and contributes to excessive overgrowth, representing an environmental concern. (ELY-keskus 2022)

Several conditions are affecting the characterization of this semi-aquatic grass amongst those are temperature, nutrients, climate, and weather. So, the composition of the material has variations. (Van Tran, Unpaprom, and Ramaraj 2020)

Figure 1. Common Reed Scientifically Known as Phragmites Australis

3.2 Anaerobic Digestion

Anaerobic digestion is a well-established complex series of processes that utilizes microbial activity to decompose substrate in the absence of oxygen. The process can be segmented into four stages of degradation, starting with hydrolysis, and then proceeding through acidogenesis, acetogenesis, and methanogenesis, although these phases occur in near-simultaneous succession. (Bochmann and Montgomery 2013, p 89; Deublein and Steinhauser 2010, p 93)

In the initial phase of the process, hydrolysis, undissolved compounds, and complex organic matter like cellulose, proteins, and fats are disassembled into monomers, including amino acids and carbohydrates, through the action of hydrolytic bacteria. (Deublein and Steinhauser 2010, p 94) (Kumar 2012, p 38)

During the following stage, which is also referred to as the acidogenic phase, the monomers generated in the prior stage are further decomposed and transformed into organic acids, such as volatile fatty acids. Primarily, acetic acid, hydrogen, and carbon dioxide are the predominant end products during this phase. (Kumar 2012, p 38) (Deublein and Steinhauser 2010, p 94)

In the acetogenesis stage of anaerobic digestion, acetogenic bacteria are key in oxidizing organic acids to produce hydrogen, carbon dioxide, and acetic acid. This transformation is critical for preparing volatile fatty acids for conversion into methanogenic substrates. (Wellinger, Murphy, and Baxter 2013, p 107) (Deublein and Steinhauser 2010, p 97)

Lastly, in the fourth and final phase of the process, both acetic and hydrogen work as resources for the growth of methanogenic bacteria. The process occurs under strictly anaerobic conditions and is also very sensitive. (Deublein and Steinhauser 2010, p 98)

3.3 Total Solid and Volatile Solid

Every substrate contains a certain amount of water. When measured without any drying process, we refer to this as the wet weight or total weight. (House 1981, p 21)

Total solid (TS) analysis involves a drying process of the substrate slightly above boiling point, specifically at 105°C (Standards EN 12880) performed in a designated drying oven (in our case a heating cabinet) until the residue appears dry, usually overnight, or a minimum of 16 hours.(Characterization of sludges - Determination of dry residue and water content 2000) By doing so the water content of the substrate is presented and described in units of percent or grams per liter. (Drosg et al. 2013)

The formula provided below illustrates how the percentage of total solids (TS) is determined.

$$TS\% = \left(\frac{Mass\ of\ dried\ sample}{Mass\ of\ wet\ weigth\ sample}\right) * 100$$

Volatile solids (VS) describe the organic matter in the substrate that is biologically available for the bacteria. The remaining TS is burned in a designated furnace at 550°C for at least 60 minutes by the standard EN 12879. (Characterization of sludges - Determination of the loss on ignition of dry mass. 2000) Following this process, the resultant residue includes non-organic material, while the volatile solids (VS) comprise the burnt components.

The following equation is used to calculate the percentage of volatile solids (VS):

$$VS\% = \left(\frac{Dried\ sample - Burnt\ sample}{Mass\ of\ wet\ weigth\ sample}\right) * 100$$

3.4 Important Parameters

In this section, we will investigate and analyze the most significant parameters and conditions that influence biogas production. This examination will encompass an analysis of elements like fluctuations in temperature, hydraulic retention time, and pH levels.

3.4.1 Temperature

Anaerobic digestion can primarily be carried out by two distinct types of bacterial cultures: mesophilic bacteria and thermophilic bacteria, each thriving in different temperature environments. Mesophilic conditions allow for digestion to occur within a range of 32-42°C. However, thermophilic conditions occur between 48-55°C. Since mesophilic and thermophilic bacteria function optimally within their respective temperature ranges, it is crucial to maintain a stable process temperature in the reactor. (Deublein and Steinhauser 2010, p 113)

The ideal digestion temperature may vary based on factors such as substrate composition and digester type. However, it is essential to keep the temperature relatively consistent throughout the digestion process to ensure a steady rate of biogas production. Variations outside the optimal temperature range of more than +/- 2°C have the potential to result in a reduction of up to 30% in biogas production. (Deublein and Steinhauser 2010, p 113)

3.4.2 Hydraulic Retention Time

HRT, or Hydraulic Retention Time, refers to the average duration in days that a unit volume of slurry remains in the reactor. In small-scale reactors, the variation in cost between different hydraulic retention times is relatively modest. However, in large-scale reactors, expenses escalate rapidly, as every aspect - from tank size to heating equipment and agitation systems - must be proportionally increased. For large-scale systems, striking a balance among multiple factors becomes essential. (House 1981, p 42)

3.4.3 pH levels

Biogas fermentation necessitates a neutral pH environment. When the pH falls below 6 or rises above 8, it can hinder or even halt gas production due to its toxic effects on the methanogen population. The ideal conditions for biogas production occur when the pH of the input into the digester falls within the range of 6 to 7. (Kumar 2012, p 9)

The pH level in a digester is dependent on the balance between acidity, alkalinity, and the presence of carbon dioxide. (Kumar 2012, p 9)

3.5 Harvesting

Reed has been harvested over extended periods in numerous countries. It is frequently collected during the summer near cottage piers and bathing beaches, often for purposes of control or eradication. (Fredriksson 2002, p 10)

When selecting a harvesting system, it is crucial to consider several criteria. The design of the harvesting machine should prioritize the protection of the rhizome to avoid hindering regrowth. While a floating machine preserves the rhizome, it may pose challenges for harvesting reed in terrestrial areas, and machines with low-pressure tires may struggle with maneuvering in deeper water. Reed can be harvested in various forms: loose bulk, chopped into chips and bundled into sheaves, or compressed into bales. The chosen method significantly influences the capacity of the harvesting machine and the subsequent efficiency of transportation and processing. (Fredriksson 2002, p 10)

Finding aquatic harvesters capable of handling the volume required for this project is challenging. Given the need for efficient harvesting to accommodate the brief summer season in our Nordic region and considering that the early part of this period overlaps with the NATURA-2000 protected area regulations, the harvesting timeframe is particularly constrained.

The investigation identified RS Planering's aquatic harvester as the most appropriate choice. However, another aquatic harvester with a similar capacity was examined during a study visit to RH Harvesting Ab. A few concerns about the size of this vessel were raised, specifically regarding its maneuverability and depth requirements, which have some limitations in the desired cutting area, Southern City Bay of Vaasa.

The winter harvesting methods provide more flexibility, as there are more techniques for constructing vehicles that can operate on ice and harvest reed. One of the techniques, which was demonstrated to us, uses low-pressure tires on a modified harvester and is functionally straightforward. Therefore, the technique will be presented in the research.

3.5.1 RS-Series Weed Harvesters

The RS-Series Weed Harvesters are manufactured in Finland by RS-Planering Ab. The company provides two models: the RS 2000 and the RS 5000. The smaller model RS 5000 is a versatile amphibious harvester that excels not only in reed harvesting but also in removing light, low-floating algae. In contrast, the RS 2000 is specifically designed for aquatic reed harvesting and effectively manages issues caused by aquatic vegetation. Its design is optimized for the efficient harvesting and transportation of dense and heavy vegetation masses. (RS-Planering Ab 2023)

Figure 2. RS-2000 by RS-Planering Ab

The machine is powered by a paddle wheel which can be seen in Figure 2, which necessitates a water depth of at least 0.5 meters. Each wheel operates on its own hydraulic circuit, ensuring precise course changes and steering. Additionally, the machine has the capability to rotate around its own axis, facilitating smoother maneuvers. (RS-Planering Ab 2023)

The RS 2000 features a cutting board equipped with a horizontal cutter that spans 2.5 meters in width. This cutter is capable of trimming reed stems beneath the water surface at depths of up to 2 meters. As the machine progresses, it systematically trims the reed, with the cut portions conveyed to the rear of the machine. The maximum storage capacity of this part is 2500 kilograms until it requires unloading for further transportation on land. (RS-Planering Ab 2023)

The machine's harvesting efficiency relies on factors such as the density of the reed population and the distance to the unloading area. According to Rainer Salin of RS-Planering Ab, the harvesting capacity in a typical reed bed is approximately 1 hectare, not accounting for the transportation to the unloading site and the unloading process itself. (Fredriksson 2002, p 11)

3.5.2 Harvesting Machine with Low-Pressure Tires

During our visit to the ELY-centre’s hired contractor, two machines were observed, each of which resembled the size of a combine harvester. These two machines featured a sturdy cutting board capable of effectively managing dense and woody reeds, which is characteristic of reeds in winter conditions. Both machines were modified to be propelled by car engines and were steered via the rear axle to simplify maneuverability while ensuring the desired cutting area at the front remained intact.

Operational procedures were also observed during the visit, which always required at least two workers during the harvesting process. While one person operates the vehicle, the other handles the gathering of reed sheaves, tossing them onto the machine’s flatbed. This stands in contrast to a typical combine harvester, which can be operated by a single driver. Such a setup could potentially double the operational costs every operating hour.

3.5.3 Summary of Harvesting Machinery

For harvesting during summertime or any other season that would require an aquatic machine, the recommended choice is RS-Planering Ab's aquatic reed harvester. This is a proven and effective machine, produced by local professionals in Finland, and has been sold for many years. The company offers customization options to tailor the product to the buyer's specific needs and usage area. However, acquiring this harvester, with a price tag of 220,000€, could pose some financial difficulties.

Opting to harvest in the summer can potentially have a more positive environmental impact by removing reeds that contain higher nutrient levels, which is the factor contributing to the overgrowth issue Southern City Bay in Vaasa is facing.

For wintertime harvesting, the project may need to consider constructing a large, snow, and ice-capable machine that can harvest efficiently. However, it's worth noting that there are more harvestable days in the winter since it is a non-breeding season for the birds, which are NATURA-2000 protected. Additionally, the environmental impact during winter is somewhat reduced because the nutrient content of the reed is lower, and by cutting above the water level results in less of the plant being removed. This reduced impact must be noted even though harvesting during winter may seem like a more convenient option.

Table 1. Theoretical kg VS Harvested per Hour

Method	Amount	Season
RS-2000	7327	Summer
Winter machine	2666	Winter
Service KE-Trading	459	Summer

Table 1 outlines the estimated theoretical kilogram of volatile solids (VS) that can be harvested per hour by each machine or service provider listed.

The capacity of the Winter harvester is estimated based on information found in section 3.5.2 of the document, and these figures may vary depending on the specific growth area values provided by the contractor. Service KE-Trading, a local contractor, operates two Truxor brand aquatic harvesters. This company's method, which is currently in use, calculates productivity based on true collected data. This involves assessing the ratio of harvested mass to the hours billed.

In addition to the RS-2000 as an aquatic harvesting machine, we conducted a field study in September 2023 in Turku, where we visited Markku Järvinen at RH Harvesting Oy and his designed aquatic harvester seen in Figures 3 and 4. This machine features a large floating work platform with a modified cutting board at the front. It can cover approximately one hectare per hour, though a demonstration was not provided. The gathered material is fed into a baler, which produces finished bales. Concerns were raised regarding the depth required for the sizable floating platform and the maneuverability challenges posed by operating such equipment.

Figure 3. RH Harvesting Oy's Aquatic Harvester, Front Part

Figure 4. RH Harvesting Oy's Aquatic Harvester, Back Part

3.6 Pre-Treatment

Mechanical pre-treatment represents a straightforward approach for pre-treatment, seeking to enhance biomass surface area and availability. The act of reducing particle size can yield favorable outcomes, not only by boosting biogas production but also by influencing reactor viscosity. Additionally, this reduction prevents the formation of layers composed of floating particles, which could otherwise lead to reactor issues like outlet blockages and gas escape interference. Furthermore, this process prevents the substrate from being accessible for digestion due to its non-submerged state. (Bochmann and Montgomery 2013, p 91 - 92)(Kamarad *et* al., 2010)

The harvested reed should be shredded to ease the continuing handling. It also reduces the volume, which makes transportation more efficient and facilitates potential storage. (Fredriksson 2002, p 17)

This prompted the project to explore mechanical pre-treatment machines. Given the limited availability of machines suitable for this scale with the required processing capacity, the options I considered include horizontal grinders and tub grinders. These types of machines appear to be the most suitable for this project. While there may be other options available, none were identified during the research.

A challenge encountered with this pre-treatment method is that enhancing the surface of the biomass can accelerate degradation, as observed in this project. This issue will be further discussed in Chapter 5.3.

3.6.1 Horizontal Grinder

The CBI Magnum Force 6400C Horizontal Grinder is a heavy-duty machine designed for processing a wide range of tough materials. The design allows for quick rotor swaps, making it convenient. The grinder is powered by a CAT C27 1050hp T4 engine or CAT C32 1200hp T4 engine, providing superior performance. The offset of the rotor minimizes energy loss and ensures even material distribution. The user interface allows for the customization of feed speeds and control systems. (Continental Biomass Industries 2019)

This machine is built to withstand the most demanding tasks, demonstrating exceptional in fragment entire trees, logs, stumps, and even the remnants of demolition debris. Its robust design and remarkable capabilities make it a stalwart companion for tackling the toughest challenges with ease. (Continental Biomass Industries 2019)

3.6.2 Tub Grinder

Agricultural tub grinders are purpose-built for handling baled and bulk agricultural feedstocks, serving as a valuable resource for animal feed and bedding. These machines, comparatively smaller and lighter than their industrial counterparts, are commonly powered by a tractor's Power Take-Off (PTO) or an integrated diesel engine. On the other hand, industrial tub grinders are specifically engineered to process wood waste, green waste, and various other feedstocks, ensuring they are appropriately sized for applications like compost, mulch, and other related products. (Rotochopper Inc. 2023)

Tub grinders rely on gravity and tub rotation to regulate the rate of material feed. Therefore, their efficiency is dependent on the consistency of the feedstocks. Lighter materials, such as tree limbs, slabs, and corn cobs, may pose a challenge as they tend to "float" above the rotor, lacking the necessary weight to be drawn into the rotor teeth. Conversely, denser feedstocks like bark, compact round bales, and compost may feed too rapidly, potentially leading to rotor lugging or even blockages. Consequently, tub grinders may undergo significant fluctuations in horsepower efficiency, as the feed material oscillates between hovering above the rotor and being drawn into the grinding chamber. (Rotochopper Inc. 2023)

Figure 5. Haybuster H-835. Picture taken from Nordfarm.se.

3.6.3 Summary of Pre-Treatment Machineries

The pre-treatment process in these quantities of this biomass type significantly narrows our machinery options. As outlined in Chapter 3.6, the two most common machinery types that were examined are tub and horizontal grinders. The horizontal grinder is designed for more heavy-duty tasks, such as grinding stumps and trees. Meanwhile, the tub grinder is commonly used for processing hay for bedding and feed for livestock. Hay shares a similarity as a material to common reed, which influenced its selection as suitable for this project.

Table 2. Comparative Analysis of Reed Shredding Machine

Option	Capacity (ton/hour)	Purchase Price	Operating Cost (per hour)	Lifespan (years	Depreciation (per year)	Additional Costs
Magnum force 6400	30	N/A	900,00 €	N/A	N/A	4 900 €
Farmcrusher 940HD	3,6	70 000 €	77,40 €	10	7 000 €	N/A
Haybuster H-835	4,5	64 763 €	77,40 €	10	6 476 €	N/A
Haybuster H-1000	10	119 918 €	82,50 €	10	11 992 €	N/A
Haybuster H-1030	16,5	160 556 €	87,60 €	10	16 056 €	N/A

Table 2 presents the various shredding machine purchase options currently on the market. The Haybuster models listed are supplied by the Swedish company Nordfarm Maskin AB, with the prices converted to local currency (date of conversion 8.3.23), which may introduce some inaccuracy. The Haybuster H-835 model can be seen in Figure 5.

The Farmcrusher 940HD, manufactured by NY-TEK Oy in Reisjärvi, Finland, appears to be a practical choice as locally manufactured equipment. All the machines featured are designed for agricultural purposes, such as processing feed and bedding for livestock. Ny-TEK Oy also provides the option to customize their machines according to the customer’s needs. However, H. Kiljala at NY-TEK Oy advises against using a sieve smaller than 20mm to prevent the material from turning into a paste. This situation is likely to occur with wet materials, such as those in summer and autumn.

The Magnum Force 6400, employed by Keskis Group Oy based in Vöyri, Finland, is built for heavy-duty tasks like grinding stumps and trees. It has been shown to be effective in shredding reed, but the cost can escalate quickly since it is charged by the ton of material processed. This service also entails an extra expense due to the necessity of transporting their equipment to the reed processing site, as detailed in Table 2.

In addition to the purchase price and capacity, Table 2 also includes operating costs. For the Magnum Force machine, which is displayed in Figure 6, these costs were computed at 30€ per ton since it operates as a service provider.

However, for the other machines, the operating costs were based on diesel consumption for the tractor's power take-off, which powers all these machines. The diesel consumption of the tractor was estimated based on the power recommended for each machine by their respective sellers, and labor costs were also factored into this calculation. Depreciation is calculated as the purchase price divided by the lifespan, which was assumed to be the same as a regular combine harvester.

Opting to purchase a smaller machine could be advantageous as it is less expensive and allows all the processed material to be directly transported and fed into the biogas reactor at Stormossen, potentially eliminating the need for storage. Essentially, it allows for processing only as needed. Keeping material fresh and unprocessed could mitigate the rate of the material's decomposition and reduce the biogas availability of the biomass.

Figure 6. Magnum Force 6400 by Keskis Group

3.7 Logistics

After the harvesting and shredding stages, the material must be transported to a storage or treatment facility, which can be done using either a tractor or a truck. Notably, loading a reed is most effectively accomplished with a gripper, especially during the summer and autumn when the reed is collected in the water at the docks. Therefore, it is ideal for the transport vehicle to be equipped with a gripper, allowing it to reach down to the floating reed piles in the water and eliminating the requirement for an additional machine solely for loading. Even in the winter, when reaching into the water is not necessary, the gripper remains effective as the reed is typically collected in bulk.

Truck transportation may encounter difficulties due to the challenging accessibility of the reed extraction site. The isolated or difficult-to-reach nature of these locations can impede the smooth flow of truck transport operations. (Fredriksson 2002, p 18)

In this project a contractor was used for the first segment from the Munsmo harbor cutting site to the selected storage area Lekatie, chosen because of its geographical location and owned by the City of Vaasa, reducing the project's overall cost. The contractor utilized a tractor equipped with a gripper feature.

3.7.1 Summary of the Logistics

Given the road conditions between the cutting site in Munsmo harbor and Lekatie the storage area—which was chosen for its geographical location and because it is owned by the City of Vaasa, thus marginally reducing storage costs, selecting the appropriate transport method for the harvested reed is crucial.

Wet weather could make truck transport difficult on the soft and wet terrain, suggesting that tractors may be a more practical option. However, if road conditions permit, truck transportation should be considered due to its ability to carry larger quantities of the load. This is particularly advantageous during winter harvesting when the ground is hard and frozen, allowing trucks to maneuver effectively.

Despite this, tractors are limited by their capacity, with the largest trailer accommodation only up to 25m^3, in contrast to truck trailers or container trucks that can hold up to 40m^3, in some cases, 50m^3. Additionally, trucks offer the advantage of quicker transportation and the ability to use the highway leading to the biogas production facility, Stormossen.

Table 3. Cost Breakdown for Reed Transportation from Cutting Site in Munsmo Harbor to Stormossen via Lekatie as Storage and Processing Area.

Route Segment	Transport Method	Distance (km)	Total weight (ton)	Cost per ton(€/ton)	Total cost (€)
Munsmo to Lekatie	Tractor (Contractor)	18,2	180	40,33 €	7 260 €
Lekatie to Stormossen	Tractor (City of Vaasa)	12,5	33,5	19,70 €	660 €

Table 3 outlines the current method of transporting reed, with the initial path handled by a local transport company using a tractor equipped with a gripper enabling the loading from the water onto the trailer. The expense calculation was based on figures provided by the Project Coordinator, S. Marttila. The tractor’s overall speed was also slightly low, taking 45 minutes for a one-way trip from the cutting site in Munsmo to Lekatie, the storage area.

The second segment of the journey involved using a tractor from the City of Vaasa's Green Area Unit, which is responsible for various environmental tasks throughout the city. This unit was assigned to manage the practical operations for this project. The transportation of approximately 33,5 tons of reed to Stormossen incurred a total expense of 660 euros, covering equipment, fuel, and labor costs.

These transportation costs could be reduced marginally if the project had the option to utilize its own equipment and workforce for the entire segment.

3.8 Storage

Harvested material may need to be stored when immediate processing is not possible, with the aim of extending its durability. Ensilage, a common agricultural method, involves preserving moist material through lactic acid fermentation. The ensilation properties of reed remain unknown. Factors like buffering capacity, availability of easily digestible nutrients, and the presence of lactic acid bacteria influence the ensilation process. In some cases, an additive may be necessary to make the material suitable for storage, potentially leading to increased storage costs. (Fredriksson 2002, p 20)

Several methods exist for producing silage, ranging from high cost with efficient techniques to more affordable, though less reliable. Concrete tower, while costly, excels in excluding oxygen effectively. Alternatively, walled bunker silos are a more affordable option but still viable for the same task. (Bochmann and Montgomery 2013, p 87)

The City of Vaasa, serving as the second funding source alongside the ELY-centre, must consider the storage space to minimize the costs at this stage. Therefore, the chosen storage area is a property owned by the City located in Lekatie. However, this space still requires some storage techniques to be functional.

The techniques explored are commonly used in agriculture, including bunker silo storage and ensilation through baling. These methods were considered due to their ability to preserve storage contents and slow down degradation, which is essential for storing biomass effectively.

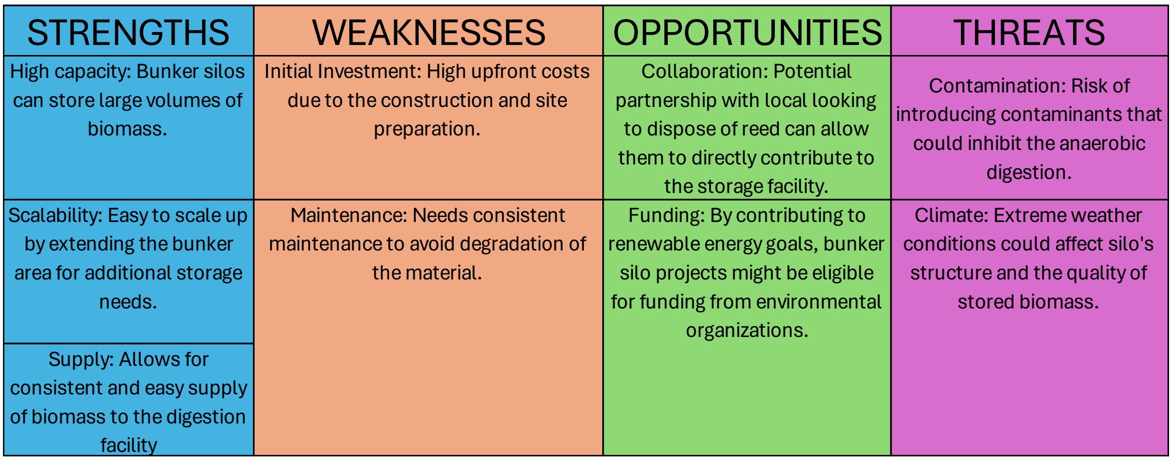
In this storage research, another possibility suggests that asphalt paving might be a viable choice from both a storage quality and economic standpoint. This option emerged when Stormossen received a test batch stored at Lekatie, which was found to contain stones and rocks causing a disturbance in the biogas production process, especially the pumps. Consequently, some form of groundwork, such as asphalt paving, was deemed necessary.

3.8.1 Bunker Silo

Bunker silos are a common agricultural storage method for silage. They usually consist of a space enclosed by three walls where the ensilage material is deposited. Loading is accomplished using a front-end loader, and the material is compacted to reduce air content. Plastic covering is employed to prevent air and rainwater from entering. The front-end loader is also utilized for extracting the ensiled material. Ideally, storage in a bunker silo is located near the site of intended use, but satellite storage facilities can also be utilized for transporting the material as required. (Fredriksson 2002, p 20)

SWOT analysis which stands for Strengths, Weaknesses, Opportunities, and Threats is presented in Figure 7.

Bunker Silo



STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
High capacity: Bunker silos can store large volumes of biomass.	Initial Investment: High upfront costs due to the construction and site preparation.	Collaboration: Potential partnership with local looking to dispose of reed can allow them to directly contribute to the storage facility.	Contamination: Risk of introducing contaminants that could inhibit the anaerobic digestion.
Scalability: Easy to scale up by extending the bunker area for additional storage needs.	Maintenance: Needs consistent maintenance to avoid degradation of the material.	Funding: By contributing to renewable energy goals, bunker silo projects might be eligible for funding from environmental organizations.	Climate: Extreme weather conditions could affect silo's structure and the quality of stored biomass.
Supply: Allows for consistent and easy supply of biomass to the digestion facility			

Figure 7. SWOT-Analysis for Bunker Silo

Figure 8. "Bunker Walls". Picture taken from Hanson Silo Company

Table 4. Construction Costs for Bunker Silo

Category	**Description**	**Cost per m^2**	**Total Costs**
Site preparation	Groundwork for 150m^2 area	21 €	3 105 €
Foundation	Concrete flooring for 150 m^2	49 €	7 395 €
Wall Construction	Concrete walls for 3 sides 1,5m height	123 €	8 303 €
Total Construction Costs			18 803 €

Table 4 presents a detailed summary of the costs involved in constructing a bunker silo, as retrieved from the Agriwise.org database. (Agriwise 2006) The original cost estimates were provided in Swedish Krona and were converted to Euros on April 4, 2024. These calculations consist of groundwork, flooring, and wall construction. It provides a financial projection for the establishment of a bunker silo with a floor space of 150m^2 which converts to a near volume of 150m^3, designed to accommodate an estimated 10 hectares of reed.

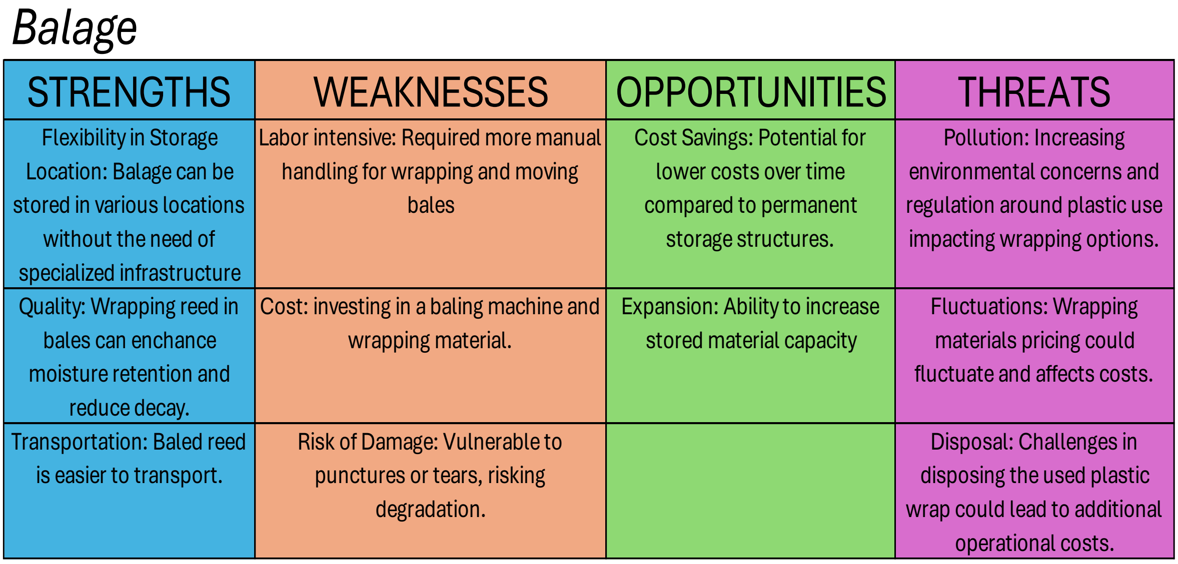
3.8.2 Balers

Balers are mechanized devices designed to gather harvested materials, such as swaths from the field, and compress them into compact units known as bales. These bales, consisting of biomass, can be easily transported to a designated storage area or directly to a bioenergy facility. Key considerations for bales and the baling process encompass factors like shape, size, stacking convenience, compactness, density, and the material used for wrapping. The primary categories of balers are round and large rectangular, each with its own set of merits and drawbacks in terms of baling methodology. (Wang 2014, p 172)

Round bales are popular for smaller farms due to their cost-effectiveness and well-matched equipment size. Smaller bioenergy producers may opt for round balers for the lower initial investment, or they may hire custom harvesting services with larger rectangular balers. However, for biomass supply to bioenergy facilities, large square bales weighing a ton are preferred. (Wang 2014, p 173)

Square bales stack efficiently, minimizing void spaces in fields, storage, and trucks. They are easier to handle and load for transport without road width constraints. Loading round bales onto semitrailers takes twice as long as loading rectangular bales. (Hess et al, 2009, as cited in Wang, 2014).

SWOT analysis for the baling of the biomass is presented in Figure 9.



Balage

STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
Flexibility in Storage Location: Balage can be stored in various locations without the need of specialized infrastructure	Labor intensive: Required more manual handling for wrapping and moving bales	Cost Savings: Potential for lower costs over time compared to permanent storage structures.	Pollution: Increasing environmental concerns and regulation around plastic use impacting wrapping options.
Quality: Wrapping reed in bales can enchance moisture retention and reduce decay.	Cost: investing in a baling machine and wrapping material.	Expansion: Ability to increase stored material capacity	Fluctuations: Wrapping materials pricing could fluctuate and affects costs.
Transportation: Baled reed is easier to transport.	Risk of Damage: Vulnerable to punctures or tears, risking degradation.		Disposal: Challenges in disposing the used plastic wrap could lead to additional operational costs.

Figure 9. SWOT-Analysis for Balage

Table 5. Cost Breakdown per Hectare for Purchase and Operational Use of a Baling Machine

Expense Category	Description	Cost per hectare
Fixed Cost	Purchase price of baling machine	9 800 €
Variable Cost	Materials per hectare	178 €
	Operational per hectare	188 €
Total Variable Costs per Hectare		366 €

Table 5 covers the expenses of purchasing a baling machine, also including variable expenses like materials and labor. The machine's purchase price is taken from Nettikone.fi and was one of the more affordable options that could be found. Material costs are based on baling plastic film prices from Hankkija.fi, also selected for its affordability. Labor expenses were estimated by considering the time needed to bale a hectare of reed, alongside tractor operating costs.

Table 5 details the choice of a Claas 250 CCT baling machine for producing round bales with a diameter of 1.25 meters, assuming an average weight of 250kg per bale. Consequently, it's estimated that 40 bales are needed per hectare, requiring approximately 2 rolls of plastic for wrapping.

3.8.3 Summary of Storage

The selected storage area, located at Lekatie and owned by the City of Vaasa, does not necessitate extra permission for biomass storage. Its geographical position is among the closest available to the City of Vaasa near the cutting area at Munsmo harbor, the reason it was chosen.

There are numerous viable options for storage solutions, with cost being a significant determinant in selecting the most suitable one. However, the total volume of reeds to be stored also plays a crucial role in determining the most practical storage solution. Therefore, I presented a SWOT analysis for the two most common storage solutions in each of their respective chapters Figure 7 for bunker silo and Figure 9 for baling. Implementing storage methods would also improve the conditions of the biomass by reducing impurities from it such as rocks and sand.

Figure 10 presents an overhead perspective of the storage site, utilizing a mapping tool available to the City of Vaasa. The site covers a total area of 3284 m^2. A conversation with the project coordinator has determined an estimation that a minimum of 1000 m^2 is required for the site to adequately accommodate the mass storage of the reed. Shifting some of our focus to asphalt paving could be a better option.

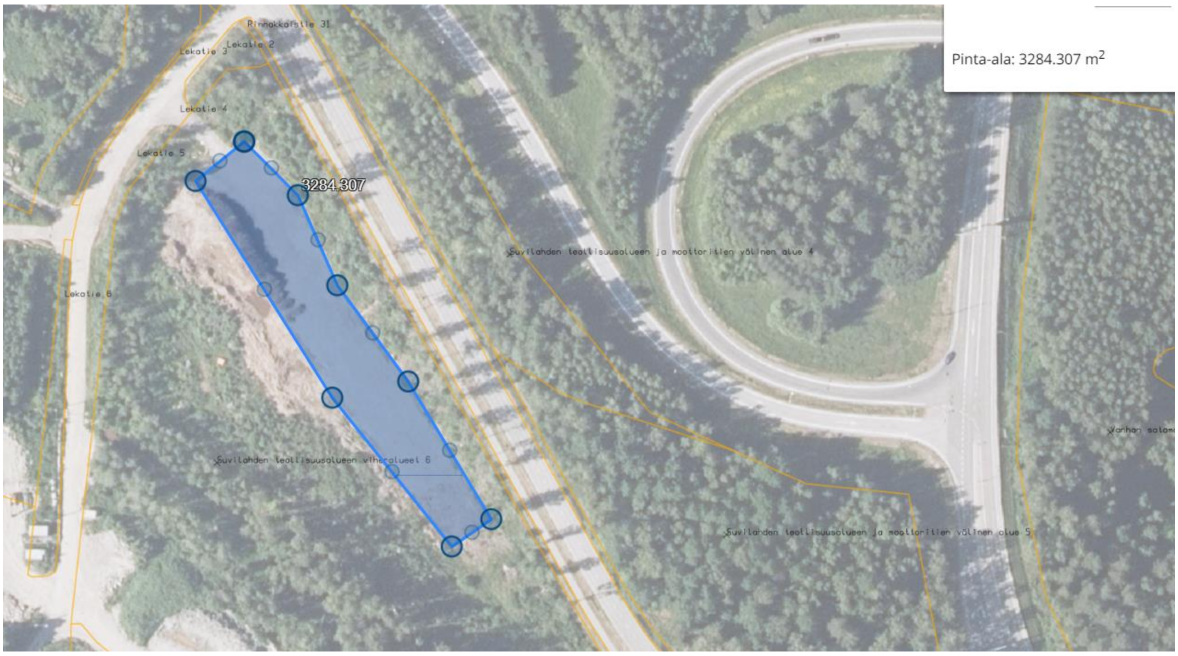


Figure 10. Area of the Storage Site at Lekatie

It was also determined that a large plastic film is necessary to fully cover the stored biomass to protect it from environmental elements such as weather and wind.

Table 6. Asphalt Sample Prices according to Object Size, graph taken from asfalttitieto.fi.

Item size	**Price per square meter of asphalt**	**The price of asphalt**
100 m^2	€25/m^2	2 500 €
650 m^2	€17/m^2	11 050 €
1800 m^2	10/m^2	18 000 €

The cost of asphalt is determined by several factors including the groundwork, the cost of the asphalt material itself, and the labor involved in laying it. For smaller areas, the cost is typically between 20-30 €/m^2. For areas of medium size, the expense ranges from 15-20 €/m^2, while larger projects can expect costs between 7-15€/m^2. The variation in asphalt pricing is influenced by the project's dimensions, configuration, geographical setting, and the extent of foundational preparation needed. (Koskinen 2021) Table 6 describes the cost of asphalt paving in 2021 with the information and prices taken from asfalttitieto.fi.

4 Laboratory Work

This chapter provides a detailed explanation of the procedures involved in the practical laboratory tests. The content will contain the entire segment, beginning with the initial substrate pre-treatment, followed by the determination of total solids and volatile solids, and finally, involving the setup, activation, and monitoring of the biogas measurement instrument, AMPTS II. The device is displayed in Figure 11.

4.1 AMPTS II (Automatic Methane Potential Test System II)

Figure 11. AMPTS II

AMPTS II is a device that enables users to analyze the Biochemical Methane Potential of various biomass substrates. It consists of three main components:

1. *Sample Incubation Unit*: The adjustable thermostatic water bath incubates a total of 15 glass bottles (500ml) which function as reactors. This water bath also maintains the desired temperature of these 15 reactors consistently throughout the process. (Bioprocess Control Sweden AB 2016, p 10) In our case, we operated a dual setup with temperatures set at 42℃ for the biowaste test and 53℃ for the sludge test. Each individual rotating agitator within the reactor ensures proper mixing of the sample.

2. *CO_2-absorbing Unit*: The biogas generated within each reactor is directed through a tube into their individual vial filled with Sodium hydroxide and a pH indicator solution called Thymolphthalein. As the biogas flows through it, carbon oxide (CO_2) and hydrogen sulfide(H_2S) become trapped. (Bioprocess Control Sweden AB 2016, p 10) The solution is initially blue in color but transitions to colorless as it fills with unwanted gas. This color change serves as a signal that the solution's capacity to bind unwanted gas has been reached, indicating the need to replace the solution to continue effective gas absorption.

3. *Gas Volume Measuring Device*: Following the CO_2-absorbing unit, the remaining component in the stream is methane (CH_4), which is then directed to the wet gas flow measuring unit with a multi-flow cell arrangement for continuous monitoring and measurement. This device operates based on the principles of liquid displacement and buoyancy, allowing it to monitor even extremely low gas flows. (Bioprocess Control Sweden AB 2016, p 10)

The entire AMPTS II unit is linked to the devices previously mentioned, and in addition to this, it is connected via an Ethernet cable to a computer, enabling the display, recording, and analysis of the result.

4.2 Preparation

In this subsection, comprehensive information, along with the necessary steps and processes that must be completed before the initiation of the practical test, will be presented. This pre-test phase is designed to ensure a well-prepared and organized approach to the experimentation process, covering various crucial aspects and preparation that set the foundation of the practical tests. It includes everything from pre-treatment to setup, equipment calibration, safety protocols, and initial measurements, ensuring and enhancing the reliability and validity of the experimental outcomes.

4.2.1 Pre-Treatment

Mechanical pre-treatment emerged as the primary method under consideration, primarily due to its straightforward nature. This choice aimed to maximize substrate surface area, streamline the digestion process, and reduce the reed’s floating characteristics.

During a meeting between Stormossen and Novia’s RDI-unit staff, a consensus was reached that the smaller particles were preferable, with the optimal target being just under 5mm. This choice primarily aimed to enhance the properties of the pump used in the process.

Based on Latvian research (Dubrovski and Kazulis 2012), it was determined that the particle size between 1-2mm yielded the highest biogas output. However, achieving this specific size range is challenging as it demands more advanced machines with extensive shredding capabilities. Our objective aligns with replicating the industrial-scale process, which involves shredding the substrate to a size that accurately reflects real-world conditions.

For this purpose, SM 100 mill by Retch was used, which was provided by the Novia RDI unit within their laboratory and seen in Figure 12. The mill was selected because of its ability to shred material down to the desired particle size of approximately 2mm. The machine is a 2002-year model and is equipped with three cutting blades. Inside the shredding area, there is a metal sieve that prevents the material from falling into the end-product container until it reaches a specific size through shredding. Still, this was not optimal due to the reed's slim properties it could slip through vertically and some long fragments could be found in the container.

Figure 12. Laboratory Shredding Machine by Retch

Figure 13 displays the winter reed processed by the laboratory shredder. The shredding produced a modest amount of dust due to the dry inflorescences of the plant. However, the overall outcome was satisfactory.

Figure 13. Shredded Winter Reed with a Scale as a Comparison Tool

Figure 14. Shredded Summer Reed with a Scale as a Comparison Tool

Like the previous figure, Figure 14 shows the summer reed shredded by the laboratory equipment, yielding a satisfactory outcome despite some challenges. A significant challenge in processing the summer crushed reed was the material's moisture, leading to frequent clogging of the shredder's bottom sieve and cutting blades. This required multiple cleanings and unplugging to fully shred the desired batch for testing.

Contrary to the material from other seasons, Figure 15 showcases reed shredded by Keskis Group using the Magnum Force, a powerful shredder designed for trees and stumps. This equipment was previously discussed in section 3.6.3 and displayed in Figure 6. The operation was carried out to evaluate the mechanical pre-treatment in a large scaler and to conduct a test batch at the biogas production facility, Stormossen, as part of the project's objectives.

The shredded particle size was significantly larger compared to the other samples that were processed with a laboratory mill. This necessitated the removal of the largest pieces to fit the size of laboratory reactors, which cannot process such large particles. However, Stormossen’s biogas reactor has no issues running these sizes. The test run was successful with only minor disturbances for the facility’s pumps caused by the rocks and stones in this biomass batch, which had been stored in Lekatie, the designated storage area without any storage technique.

Figure 15. Shredded Autumn Reed by Keskis Group.

4.2.2 Determination of Total Solids

The Total Solids (TS) determination test is conducted to evaluate the water content of substrates. The results are expressed as a percentage; for instance, if a certain season's reed is reported as 80% TS, this indicates that it contains 20% water. The test involves weighing the sample before and after placing it in the drying chamber, to determine the amount of water that has evaporated.

The substrates selected for testing are determined by the types of material processed in the Stormossen reactors: one reactor digests biowaste from ordinary households, while the other processes sludge from wastewater treatment plant in Vaasa. In addition to these raw substrates, inoculum was also tested. Inoculum refers to the material inside a biogas reactor that already contains established biogas-producing microorganisms, which are essential for biogas production.

The inoculum and raw biomass, including biowaste and sludge, were all collected in 5-liter plastic containers from Stormossen's biogas facility usually a few days prior to testing.

Additionally, prior to the weighting procedure, we ensured that the doors were securely closed, preventing any airflow from interfering with the scale's measurements. This precaution was taken to ensure more precise and accurate results possible. Handling these substrates involves a vital safety measure: laboratory coat, gloves, and protective eyewear. This layered approach to safety is crucial for ensuring the well-being of individuals working with these materials.

During the total solid testing, each substrate was placed in an aluminum tray. These trays were additionally labeled with individual numbers, primarily aimed at simplifying recognition and mitigating the possibility of unintentional mixing due to human error.

Each substrate was carefully poured into its designated container in a triplicate setup allowing calculation of the averages between the three of them. Figure 16 displays the pouring process onto the aluminum tray on a scale for weighting measurements.

Figure 16. Substrate Weighting Procedure: Adding Substrate to an Aluminum Tray Placed on a Scale

Following the weighting process, all the trays were placed inside the drying chamber displayed in Figure 17. These samples were left there for a minimum duration of 16 hours, in accordance with the requirement outlined in the SFS-EN 12880 standard. After the drying process, all the substrates were once again weighed.

Figure 17. Drying Chamber

4.2.3 Determination of Volatile Solids

The analysis of volatile solids is conducted by burning the substrate in a furnace at 550°C for 2 hours. This test is performed to determine the percentage of the substrate that is biodegradable. The test involves weighing the substrate before and after it is placed in the furnace. The ash that remains after the furnace represents the non-biodegradable organic matter, while the material that has burned off is identified as volatile solids (VS) which is available for biogas production. The results are expressed as a percentage; for example, if the reed is recorded at 90% VS, this means it contains 10% of non-biodegradable organic matter.

To evaluate the volatile solids, it is necessary to pre-burn the ceramic crucibles at least a day prior, to remove unwanted particles and ensure the crucibles have been cooled off. Pre-burning involves placing the crucibles inside a furnace at 550°C for either one hour or a minimum of 30 minutes. (Characterization of sludges - Determination of the loss on ignition of dry mass. 2000)

Following the drying process, numerous substrates have assumed various shapes and forms, as illustrated in Figure 18 which shows biowaste after the drying process. That transformation occurs as the water content evaporates, leaving behind dry residue. The subsequent step involves crushing this residue into finely sized pieces and transferring it into the designated crucibles. These crucibles are used as containers for the substrates that underwent testing in the previous total solids test. Subsequently, the crucibles are transferred into a desiccator to gradually cool down to the ambient temperature. The desiccator not only facilitates cooling but also safeguards the crucibles from moisture present in the air.

Figure 18. Biowaste Substrate after Drying Process.

It's worth noting that the inoculums tend to dry out and adhere to the sides of the aluminum tray. This necessitates gently scraping off the dried material using a laboratory spoon. This step holds particular importance as it aims to recover as much of the remaining material from the trays as possible, ensuring an accurate measurement when transferring it to the crucible.

Once transferring the crucibles into the furnace, one should map out the placement, to be certain where the specific crucible is. The crucibles inside the furnace are displayed in Figure 19.

Figure 19. Crucibles Inside the Furnace.

Table 7. Summary of TS and VS for All Respective Seasons.

Season	**Reed$_{winter}$**	**Reed$_{summer}$**	**Reed$_{autumn}$**
TS%	89,48 %	39,06 %	17,23 %
VS%	88,07 %	36,87 %	9,98 %

Table 7 presents the Total Solids (TS) and Volatile Solids (VS) content of reed, categorized based on the season of harvest. As seen in the table, winter-harvested reed contains more total solids and volatile solids compared to reed harvested in summer and autumn. Volatile solids refer to the organic matter in the substrate that is available for the biogas-producing bacteria. Theoretically, a higher volatile solids percentage indicates better biogas production potential.

The tests on winter-harvested reeds were carried out using reeds that had been harvested the previous winter and left to dry naturally until the laboratory tests were conducted in the autumn. This process likely reduced the water content of the reed to some extent.

4.2.4 Mixing into Laboratory Reactors

The optimal testing ratios for the mixtures were established through discussions between two of the three project partners, Stormossen and Novia UAS. The agreed-upon ratios for testing include 90% of either sludge from the wastewater treatment plant or biowaste from waste disposal from ordinary households mixed with 10% common reed, and an equal split of 50% for each component. These ratios, determined to be the most logical amounts for feeding into the Stormossen's reactors, received united approval from all three partners involved in the project.

This was the most sensitive step that can prove to be quite challenging is combining the substrates together inoculum into the reactors. Given the necessity to maintain the proper mixing ratio, any extra added component cannot be extracted without a complete restart of the mixing step for that specific reactor mixture. The main reason is, if extracting in the mixture process it could potentially disrupt the ratio. To achieve the correct amount during the mixing process a pipette was used for the final portion to allow for more accurate regulation.

Another thing that can be challenging in the procedure of determining the weight is the characteristic of some substrate that holds particles. These particles can lead to sudden shifts in weight, resulting in rapid fluctuations. Like earlier, a pipette was used for the final portion for more accurate regulation. The particles could sometimes get trapped within the pipette, necessitating a switch to a new pipette if removal of the particle is not possible.

All test samples were conducted in triplicates, as shown in Table 8 for sludge and Table 9 for biowaste. The first set of three samples contains raw materials, either sludge or biowaste. This is followed by three samples each with a 50:50 mix of reed and sludge, and reed with biowaste. Another triplet features a 90:10 mixture ratio of sludge and reed, and biowaste and reed.

The subsequent three samples are mixes of reed with the respective test inoculum, either sludge or biowaste inoculum. Specifically, the sludge inoculum mixed with reed, labeled as Reed 53°C, operates at its optimal temperature and was used to determine the methane potential of reed alone. A similar procedure was followed for the biowaste test, marked as Reed 42°C, also conducted at its optimal temperature. The last three reactors in each test series contain only inoculum, serving as a baseline measurement for the inoculum's BMP.

Table 8. Sludge Tests Configuration

Sludge (raw)	Sludge (raw)	Sludge (raw)
Sludge 50% + Reed 50%	Sludge 50% + Reed 50%	Sludge 50% + Reed 50%
Sludge 90% + Reed 10%	Sludge 90% + Reed 10%	Sludge 90% + Reed 10%
Reed 53°C	Reed 53°C	Reed 53°C
Sludge reactors inoculum	Sludge reactors inoculum	Sludge reactors inoculum

Table 9. Biowaste Tests Configuration

Biowaste (raw)	Biowaste (raw)	Biowaste (raw)
Biowaste 50% + Reed 50%	Biowaste 50% + Reed 50%	Biowaste 50% + Reed 50%
Biowaste 90% + Reed 10%	Biowaste 90% + Reed 10%	Biowaste 90% + Reed 10%
Reed 42°C	Reed 42°C	Reed 42°C
Biowaste reactors inoculum	Biowaste reactors inoculum	Biowaste reactors inoculum

It's important to highlight that the inoculum is added to all the tests with the inoculum-to-substrate ratio (I/S) at 2/1. Tests on the inoculum alone are conducted to analyze and then subtract its contribution from the mixture's BMP values to ascertain the BMP values solely attributed to the substrate. This explains why tests exclusively on the inoculum are always necessary. The inoculum is the digestate containing a pre-established microorganism culture, which initiates the digestion process. The inoculum was provided by Stormossen from their operating reactors.

The sludge tests reactors post-mixture phase and ready for operation can be seen below in Figure 20.

Figure 20. Reactors Post-Mixture Phase, Prepared for Operation

4.2.5 CO_2-absorbing Unit

Within this segment, an introduction to the preparation procedure of the CO_2 unit will be provided, the unit is displayed in Figure 21. This unit is designed to capture unwanted gases such as CO_2 and Hydrogen Sulfide (H_2S). The capture process uses a sodium hydroxide (NaOH) solution with Thymolphthalein, which is initially blue and turns colorless as it becomes saturated, indicating that the solution needs to be changed.

The CO_2-unit consists of 15 vials for each reactor, each with a capacity of 80 ml. The composition of the solution contained within the vials is sodium hydroxide (NaOH) and distilled water. After the NaOH dissolves in the distilled water, prepare 0,4% Thymolphthalein of the total mixture and let it dissolve into the solution, this is the color-changing pH indicator.

A minimum of 1200 ml of the NaOH solution is required to fill all 15 vials. It is recommended to prepare an extra batch of solutions complete with a pH indicator to be able to fill at least three additional vials as a quick replacement in case the absorption process gets impaired.

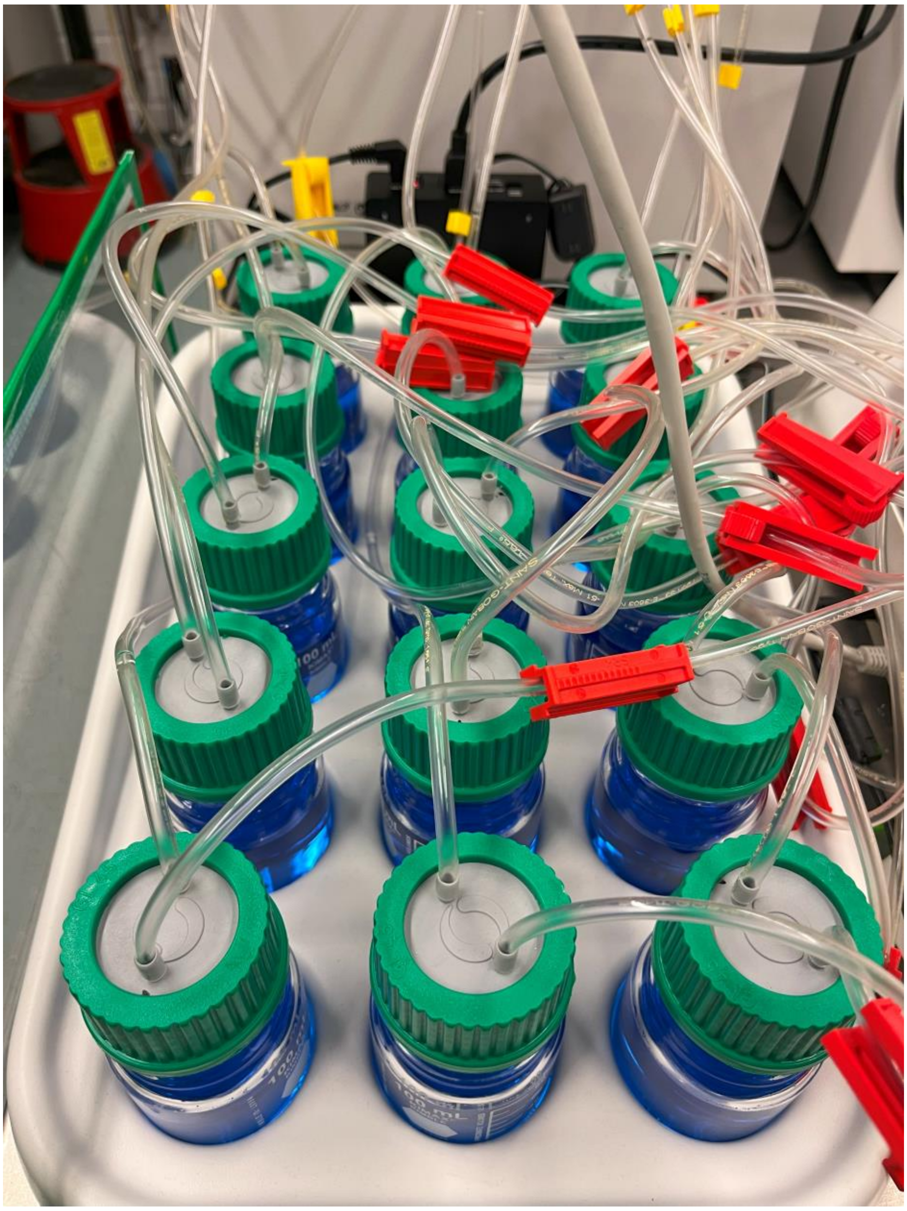


Figure 21. CO2-absorbing Unit with Tubing.

Figure 21 presents the CO_2-absorption unit, with the tubing equipped with red flow clamps serving as the outlet. This outlet is open during system flushing as described in the Start-Up section. The outlet remains closed until the tube is attached to the gas volume measuring unit. Once connected, the clamp is reopened to allow the gas flow. Additionally, for every individual absorption unit, an individual tube serves as an inlet from the reactors.

4.2.6 Gas Volume Measuring Unit

Figure 22. Gas volume measuring unit filled with distilled water.

Figure 22 presents the gas volume measuring unit which is a water bath containing distilled water. The gas measurements which operate are based on the principles of liquid displacement and buoyancy. The preparation demands relatively less effort compared to the preceding units. The importance of this apparatus lies in the tubing connections, which are labeled with numbers ranging from 1 to 15 for each connection to their respective reactor and CO_2-absorbing vial.

4.2.7 Motor Connection

Once all the reactors have been mixed and lowered into their respective water baths, which maintain the desired temperatures of 42°C for the biowaste test batch and 53°C for the sludge test batch, each reactor is fitted with an agitating motor that enables internal stirring. The agitator on reactor number 1 is powered directly by a power source, while the remaining agitators are powered sequentially through serial connections originating from it.

The agitator features three unique stirring modes: clockwise, anti-clockwise, and an automatic mode that switches the stirring direction as per the pre-set program. Mainly, the auto mode of the agitator was utilized.

4.3 Start-Up

Following the completion of the preparation phase and the proper placement of the last tube, the next step involves the flushing process. Nitrogen is utilized to flush the system, starting from each reactor, and passing through the tubes and CO_2-unit. A flushing duration of 60 seconds is assigned for each reactor, ensuring comprehensive purging of oxygen in the system, and thereby creating anaerobic condition. Subsequently, after flushing each reactor in numerical order, the tubes are connected to the gas volume measuring unit. The fully prepared configuration is showcased in Figure 23.

Every motor is equipped with a manual on/off switch that is activated sequentially to initiate the stirring process. Once all the switches have been turned on and the computer program configured to record gas measurements, the procedure is initiated and operational.

Figure 23. Reactor Setup with Agitator Fully Prepared for Initiation, Complete with All Necessary Tubing and Cable Connection.

4.4 Monitoring and Maintenance

After the test is running, regular maintenance is important. The system requires maintenance and recording of daily measurement results every alternate day. Specifically, the designated maintenance days were set as Monday, Wednesday, and Friday.

The maintenance protocol encompasses a series of steps aimed at ensuring the system's smooth operation. These steps include inspecting the tubing for potential damage or excessive bending that could interfere with the gas flow. Additionally, the thermostatic water bath and the gas measuring unit need to be refilled with distilled water as a part of the maintenance routine. This is necessary because the water is heated to 42°C for biowaste tests and 53°C for sludge tests which causes the water to evaporate at a quicker rate than normal.

Furthermore, a vital aspect of the maintenance process involves checking each CO_2-absorbing vial for any observable color changes. This alteration in color signifies the solution's capability to absorb CO_2 and is hence crucial for assessment.

Typically, the thermostatic water bath requires around 600ml of water for replenishment. In the case of the sludge tests, a slightly larger amount is needed due to increased evaporation, primarily because of elevated operating temperature.

4.5 End of Operation

To confirm the appropriate endpoint, a method involves dividing the daily flow by the accumulated volume. If the outcome is below 1% for each sample over a span of at least three days, it verifies that the process is complete and ready for conclusion.

Start off by checking all the generated and downloaded data for both the biowaste and sludge folders. Next, the manual switch for each agitator is individually turned off, followed by the ending of the gas measurement through the computer program.

The process of disconnecting agitator cables and tubing can now begin. Each reactor was individually emptied onto a sieve, allowing for a detailed examination of the digestion process and the reed's degradation capability in each mixture, which was further documented through photographs.

5 Results

This chapter will feature the presentation of results from the laboratory experiments, including the Biochemical Methane Potential (BMP) tests. The content is organized by seasons from winter to autumn, dividing each chapter accordingly. The gas measurement results are provided in normalized liters per kilogram of VS as a unit.

5.1 Winter

Figure 24 demonstrates that raw biowaste emerges as the most effective substrate in terms of biogas production per kilogram of VS, with mixtures of biowaste and reed generating significantly less methane. A potential reason for the underperformance of biowaste and reed mixtures may be attributed to the floating of the reed within the laboratory reactor, preventing it from fully submerging and thus, hindering optimal methane generation. Additionally, sludge mixtures have shown a slightly higher BMP over pure sludge this season, which is an encouraging indicator. This suggests that combining sludge with common reed can increase the total biomass and indeed enhance biogas production.

In Figure 24, the bars labeled Reed 42℃ and Reed 53℃ on the far right of the chart represent the BMP values for mixtures of reed with inoculum. Reed 42℃ includes biowaste inoculum mixed with reed, while Reed 53℃ contains sludge inoculum mixed with reed. Both mixtures were tested to establish the BMP values of the reed with the various inoculums.

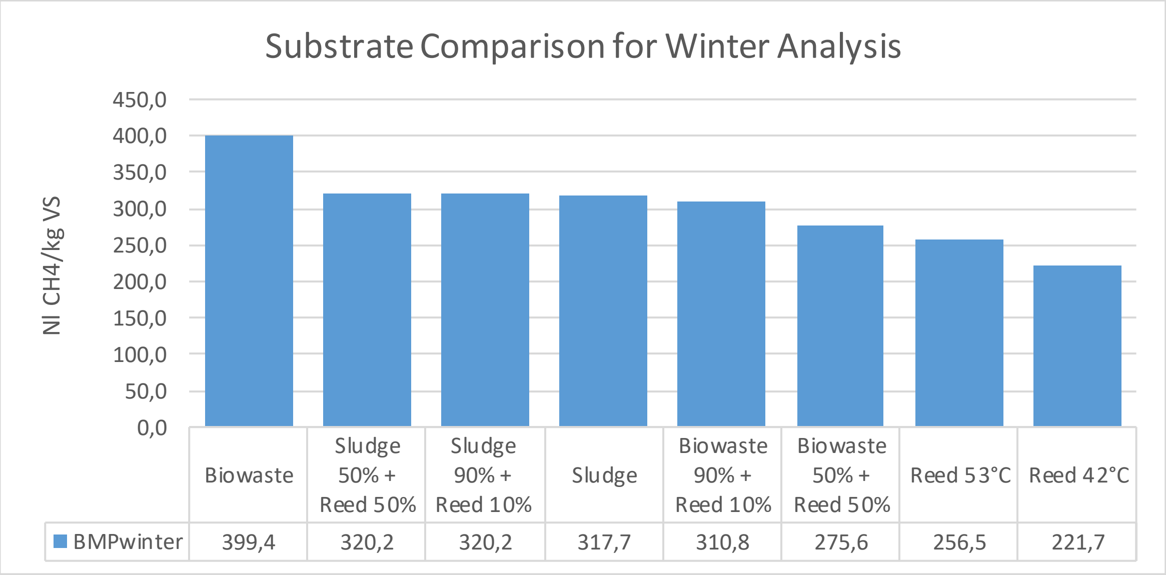


Figure 24. Substrate Comparison for Winter Analysis

5.2 Summer

Regarding Figure 25, which presents the analysis for the summer season, it’s noticeable that both the raw biowaste and its mixtures with reed achieve higher biogas yields than the sludge variants, even for biowaste inoculum mixed with reed surpassed raw sludge’s BMP. An explanation for this could be that the raw sludge generates less methane in the summer compared to the winter test, suggesting that the quality of the inoculum mixed into all the samples varied.

The gap in BMP value between the raw biowaste and its mixtures is narrower than in the winter seasons, especially for the mixture with a 90% biowaste to 10% reed ratio. A possible explanation for this could be the higher moisture content in the summer-harvested reed, which allows for better submersion within the reactor during mixing. However, these biowaste mixtures still don’t contribute positively to the BMP if compared to raw biowaste, and the biowaste mixtures still do not surpass the biogas production efficiency of the raw biowaste.

The summer BMP analysis graph shows that the sludge mixture, when compared to raw sludge, is very similar and demonstrates only a slight negative effect. This suggests that mixing might still be worthwhile due to the increase in biomass.

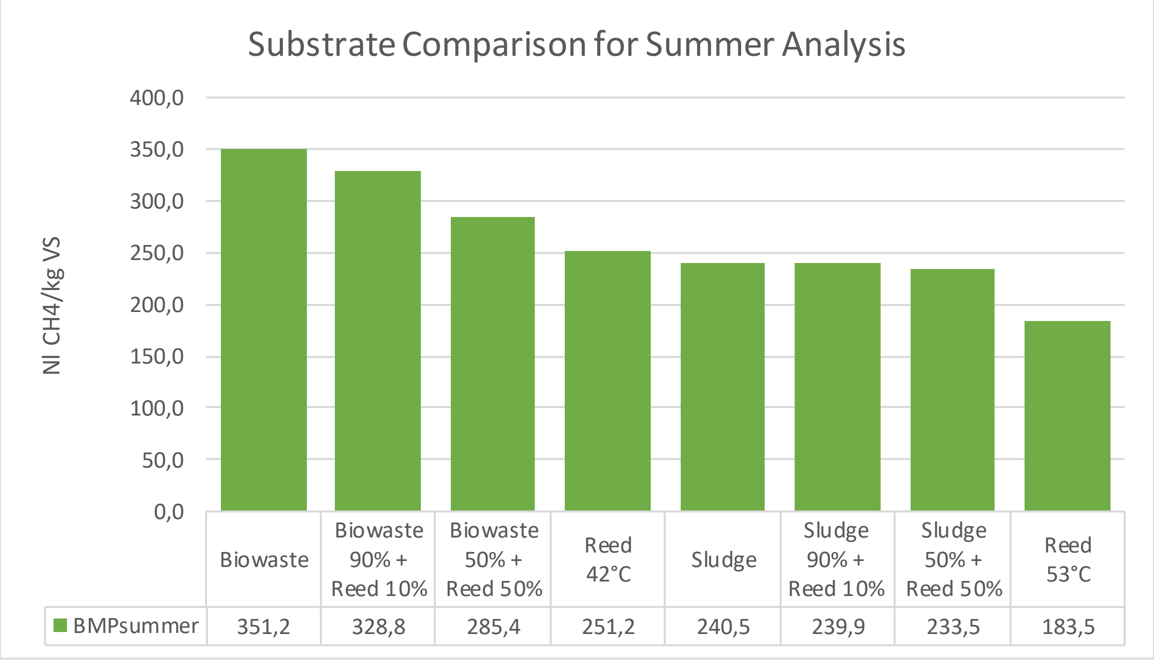


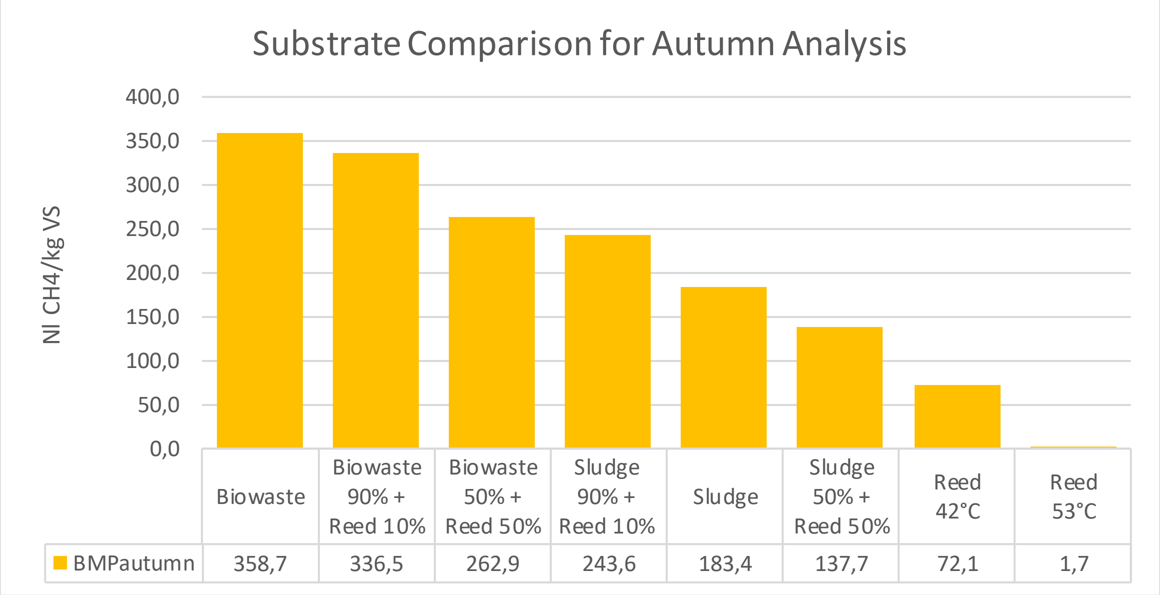
Figure 25. Substrate Comparison for Summer Analysis

5.3 Autumn

Figure 26 displays the results of the autumn analysis, where the results are notably subpar. The reed employed in this study had been pre-processed by an external contractor and stored at the designated storage area, Lekatie without any storage technique and was affected by the weather condition for an unknown amount of time. It is presumed that the reed had undergone some degree of decomposition during this time, and the material lost some of its digestion availability, rather than being used in its raw state and shredded by a laboratory mill displayed in Figure 12, for optimal particle sizes.

The highest-yielding substrate is raw biowaste, which is expected given its effectiveness in biogas production. The 90:10 mixture of biowaste and reed yields results close to the raw test of biowaste, but the 50:50 mixture reveals a significant decline in performance when it got exposed by mixing in a larger amount of reed to 50% of the mixture’s total VS, the BMP values indicates.

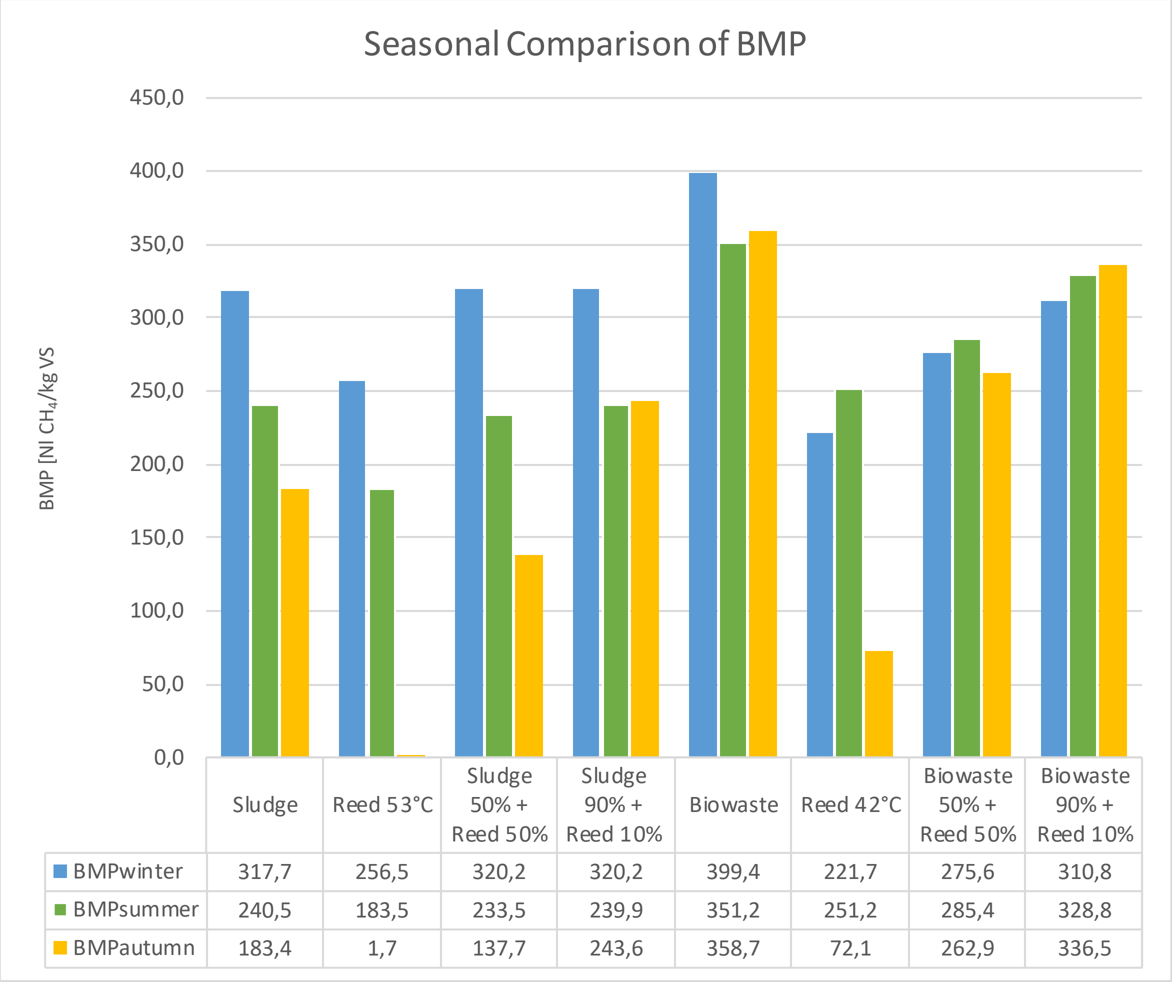
The graph demonstrates that the methane yield from the reed mixed with inoculum was insignificant. Additionally, the raw sludge’s performance in the autumn test was considerably lower when compared with the results from other seasons.



	Biowaste	Biowaste 90% + Reed 10%	Biowaste 50% + Reed 50%	Sludge 90% + Reed 10%	Sludge	Sludge 50% + Reed 50%	Reed 42°C	Reed 53°C
■ BMPautumn	358,7	336,5	262,9	243,6	183,4	137,7	72,1	1,7

Figure 26. Substrate Comparison for Autumn Analysis

5.4 Seasonal Comparison of BMP



	Sludge	Reed 53°C	Sludge 50% + Reed 50%	Sludge 90% + Reed 10%	Biowaste	Reed 42°C	Biowaste 50% + Reed 50%	Biowaste 90% + Reed 10%
🟦 BMPwinter	317,7	256,5	320,2	320,2	399,4	221,7	275,6	310,8
🟩 BMPsummer	240,5	183,5	233,5	239,9	351,2	251,2	285,4	328,8
🟨 BMPautumn	183,4	1,7	137,7	243,6	358,7	72,1	262,9	336,5

Figure 27. Chart of Seasonal Comparison of BMP

This chapter examines the seasonal comparison of the Biochemical Methane Potential (BMP) of common reed, drawing on the analysis conducted across different seasons, winter, summer, and autumn. By examining the BMP values across these seasons, we aim to identify variations and the optimal conditions for methane production from common reed, thereby contributing valuable insight for enhancing biogas production efficiency.

Figure 27 demonstrates a chart as an analysis and reveals distinct seasonal variations in Biochemical Methane Potential (BMP) values depending on the season.

Winter season BMP tests show that sludge mixtures, in both 90:10 and 50:50 ratios, achieved the highest methane production just slightly more than raw sludge, and only surpassed by raw biowaste. This suggests that winter could be most beneficial for utilizing reed as substrate in biogas production.

Summer tests showed promising results, especially for mixtures involving biowaste and reed. Although the BMP values for pure biowaste and sludge were higher, the mixtures still demonstrated considerable methane production potential. The higher moisture content of summer-harvested reed likely contributed to better substrate interaction within the reactors, leading to higher output compared to winter reed mixed with biowaste, where the reed tends to float and not submerge.

The autumn analysis presented the lowest BMP values among the seasons. The pre-processed and shredded autumn-harvested reed did not perform as well as expected, potentially due to decomposition and loss of optimal fermentable qualities during storage. Autumn material did not receive the same mechanical pre-treatment as the other two seasons, winter, and summer. This discrepancy also makes it unfair to compare the results of these tests.

The 90:10 mixtures of biowaste and reed show that the autumn mixture yields the highest BMP values. However, when comparing these results to the raw biowaste from the summer tests, it appears the summer tests perform worse. Essentially, the autumn mixture superiority is in correlation to the effectiveness of that season's raw biowaste. On the other hand, the winter mixture of 90:10 biowaste and reed performs significantly worse, primarily because the reed tends to float in the reactors.

Additionally, it’s noteworthy that raw sludge across these seasons has high BMP fluctuation, with autumn displaying considerably lower levels. This variation could negatively impact all the autumn mixtures. For instance, Reed 53°C and Reed 42°C which were reed mixed with inoculum, showed particularly poor results in the autumn season. This suggests that autumn-reed contains less organic material suitable for digestion, resulting in lower BMP values for this season.

To address the huge fluctuation of these raw materials BMP, control samples should be added to the test. These samples would consist of microcrystalline cellulose digested and tested like a regular sample. This will assess the quality of the inoculums and the functionality of the equipment. Unfortunately, our testing setup did not accommodate these control samples.

5.5 Case Study: Economic and Production Analysis of Biomass to Biogas Conversion

This study provides an economic and production analysis of converting biomass into biogas, focusing on a winter reed harvesting scenario solely because it has the highest Biochemical Methane Potential (BMP). The scenario includes detailed costs and biogas production per hectare, alongside one-time expenses.

Table 10 showcases the fixed costs associated with the project. I determined that purchasing a shredder for the pre-treatment method is the most cost-effective strategy, as it eliminates outsourcing. This will benefit the project in the long term financially as the equipment could later be sold, minimizing losses. The selected processing machine is Haybuster H-835 which I consider adequate for this project with its processing capacity of 4,5 tons per hour it takes roughly 2,25 hours to process one hectare of winter material.

Table 10. Fixed Costs of Biomass Harvesting during Wintertime

Expense Category	**Investment Items**	**Total Cost (EUR)**	**Comment**
Processing	Haybuster H-835	64 763 €	One-time purchase
Storage	Asphalt Storage Area	10 000 €	1000m^2
Total Fixed Costs		**74 763 €**	

Additionally, the chosen storage area at Lekatie, which was chosen for its location and economic standpoint, faces challenges due to impurities in earlier test batches suggesting implementing a bottom layer at this storage area is necessary.

Asphalt paving can be viewed as expensive as a one-time expense but becomes cost-effective compared to baling after just harvesting 27,3 hectares. Constructing a bunker silo cost nearly 9000€ more than asphalt paving, and the quality of storage achieved with a bunker silo can almost be matched by asphalt if the biomass is covered with a plastic film. Therefore, I identified asphalt paving as the most suitable solution. The determined paving area is set to 1000m^2 which is an assumption of the estimated area needed.

Table 11. Variable Costs of Biomass Harvesting during Wintertime

Expense Category	**Equipment/Operation**	**Unit Cost (EUR/ha)**	**Comment**
Harvesting	Contractor	2 150 €	Outsourcing
Processing	Operational Cost	174 €	Per hectare
	Biomass Transport	605,70 €	Per hectare
Total Variable Costs		**2 929,70 €**	

Table 11 focuses on variable costs and outlines each step involved. Currently, the chosen method for harvesting involves outsourcing to a contractor found through John Nurminen's foundation. This contractor uses a harvester equipped with caterpillar tracks, enabling it to operate on ice. Operations of this scale are uncommon, and it's even rarer to find a contractor engaged in this type of business, and only a handful were presented in John Nurminen's foundation article.

A drawback of this option is that up to this point, they were the only contractor to respond to my inquiry and provide an actual quote. The prices they offered ranged from 1800 to 2500 euros, leading me to base my calculations on the midpoint, which is 2150 euros per hectare. There are a few more contractors that should be considered when a quotation is received and analyzed.

The processing expenses include labor costs and the expenses associated with operating the Haybuster H-835, which includes a tractor for power. Transportation costs are based on the present method. This is because the transportation method requires a loading gripper, a feature that is relatively rare without requiring a separate machine with a grapple arm. Transportation expenses, covering two separate route segments, are combined into one overall cost per hectare.

The suggestion for transportation is exploring a truck transport contractor with vehicles equipped with grapple arms. This approach allows for easier decision-making by the funding sources, as obtaining various quotes enables direct cost comparison. Additionally, using trucks is more practical during winter harvesting, as the summer and autumn seasons may pose challenges due to soft terrain and wet road conditions.

Table 12. Output Overview: Biomass and Biogas

Category	Value	Units
Biomass Yield	10,09	tons/ha
Biogas-Substrate Yield	8,89	ton VS/ha
Biogas Production	2845	Nm^3/ha
Biogas Energy Content	28363	kWh
Marketable Biogas	2101	kg

Table 12 showcases the anticipated biomass and biogas production from winter-harvested reed, with a projected 8,89 tons per hectare of Volatile Solids (VS) yield. Utilizing the approved decision by all the partners and testing a 50:50 mixture of reed and sludge from the wastewater treatment plant which achieved the highest BMP, the yield is 2845 Nm^3 of biogas per hectare.

Based on data sourced from Stormossen's website, where 1 Nm^3 of biogas is valued at 9,97 kWh, the total energy content derived for biogas per hectare amounts to 28363 kWh. This energy is then translated into a commercially viable form, measured in kilograms, with each kilogram reflecting an energy content of 13,5 kWh, finalizing in a total of 2101 kg of energy-equivalent biogas ready for the market.

Table 13. Payback Period Analysis

Description	**15 hectares**	**30 hectares**	**Comment**
Total Fixed Costs (EUR)	74 763 €	74 763 €	Investment for equipment and infrastructure
Total Variable Costs (EUR)	43 946 €	87 891 €	Variable Costs/ha multiplied by hectares
Total Revenue (EUR)	56 410 €	112 820 €	Revenue from biogas sales
Net Cash Flow (EUR)	12 465 €	24 929 €	Total Revenue minus Total Variable Costs
Payback Period (Years)	**6,00**	**3,00**	Fixed Costs/Net Cash flow

Table 13 presents the payback period analysis. The table includes a comment in the far-right column as to how the values were determined. Revenue from biogas sales was calculated based on Stormossen's BIG Biogas sales price at 1,79€ per kilogram in April 2024, this price can vary every month. As indicated in Table 13, the estimated biogas production per hectare is 2101 kg.

Table 13 illustrates that harvesting 30 hectares, as opposed to 15 hectares per year, reduces the payback period by half to approximately 3 years.

A limitation of this calculation is that the revenue does not truly reflect the actual situation because, in this project, we are combining the harvested reed with sludge. The sludge is already generating biogas for Stormossen, and any gains from it do not directly benefit the project.

The expenses of generating biogas at Stormossen's facility, where the biogas reactor is owned by Stormossen, were not factored into the revenue and cash flow calculations. These two oversights are likely to extend the payback period.

6 Conclusion

This thesis has investigated the potential of common reed (Phragmites Australis) as a substrate for anaerobic digestion and its subsequent conversion into biogas. Through comprehensive laboratory work, seasonal analysis, and an economic and production case study focused on winter harvesting, this research provides insightful findings and recommendations for optimizing the biogas production process.

Key Findings

Seasonal Variability and BMP: The Biochemical methane potential (BMP) tests revealed variations in methane production from common reed across seasons, especially raw sludge indicating notable fluctuations. Winter-harvested reed, particularly when mixed with sludge at a 50:50 ratio and 90:10, showed the highest potential for biogas production, surpassing the raw sludge’s BMP.

Economic Feasibility: The cost analysis, including the detailed breakdown of fixed and variable costs associated with harvesting, processing, and storage, highlights the economic challenges and opportunities of utilizing common reed for biogas production. The investment in equipment like the Haybuster H-835 and the costs of asphalt storage area setup are substantial but crucial for the project's long-term sustainability.

Environmental Impact: Utilizing common reed for biogas production presents a dual environmental benefit. It offers a sustainable method for managing the overgrowth of this invasive species, contributing to eutrophication mitigation, and provides a renewable energy source that can help reduce greenhouse gas emissions. The environmental impact can vary depending on the season of harvest.

Recommendations

Optimal Harvesting Season: Based on the BMP results, winter is recommended as the most beneficial season for harvesting common reed for biogas production. Future projects should consider optimizing harvesting operations to capitalize on the higher methane yields during this season. Other seasons that have been tested also necessitate the use of aquatic harvesting machinery, which presents greater challenges and more expensive harvesting techniques.

Optimization of Variable Costs: A detailed examination of variable costs related to harvesting, processing, and transportation revealed potential areas for financial improvement. Optimizing these costs could significantly enhance the project's economic feasibility. Exploring cost-effective transportation options could reduce overall operational expenses. Additionally, selecting an economical harvesting contractor should be prioritized to further reduce expenses.

Investments: The findings suggest investing in efficient pre-treatment machinery and suitable storage solutions is essential. Asphalt paving of the storage area, despite its high initial cost, offers a viable solution to minimize biomass contamination and enhance the overall quality of the biomass.

Further Research and Development: Subsequent research and development efforts should concentrate on designing a custom-built winter harvesting machine to secure long-term economic advantages and eliminate outsourcing service fees.

The autumn test needs to be repeated to obtain more accurate results, using biomass that is in a better state and condition, ideally fresher material that has not undergone degradation during storage.

Since both the 90:10 and 50:50 ratios of the winter mixture yield the same results, it would be advantageous to conduct further research. This could help in fine-tuning the mix proportions to enhance biogas production. Overall, more ratios should be considered and tested.

The thesis demonstrates that common reed, particularly when harvested in winter, presents a promising substrate for biogas production through anaerobic digestion. While the process involves significant economic investment and technological challenges, the environmental benefits and potential for sustainable energy production make it a viable option worth further exploration. By implementing the outlined recommendations, stakeholders can enhance the efficiency and economic feasibility of biogas production from common reed, contributing to the transition towards a more sustainable and circular economy.

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Appendix 1 – Analysis of TS and VS in Winter Test Sample

Substrate	Sample#	Aluminiumtray [g] [g]	Sample Weight Wet [g]	Dried sample (105 degC) [g] + tray	TS [%]	Crucible [g]	Dried sample (105 degC)[g]	Burnt sample (550 degC) [g] + tray	VS_{tot} [%]	$VS_{TS\ [\%]}$
Common reed	1	2,98	3,09	5,74	89,32	71,06	2,79	71,13	88,03	97,49
	2	2,96	3,01	5,65	89,37	66,21	2,72	66,28	88,04	97,43
	3	2,97	3,12	5,77	89,74	72,36	2,82	72,43	88,14	97,52
	Average				**89,48**				**88,07**	**97,48**
Biowaste	1	2,99	31,13	6,51	11,31	64,30	3,50	64,65	10,12	90,00
	2	3,00	31,85	6,63	11,40	72,68	3,63	73,04	10,27	90,08
	3	3,00	31,34	6,59	11,46	71,60	3,56	71,97	10,18	89,61
	Average				**11,39**				**10,19**	**89,90**
Inoculum	1	3,01	49,35	4,82	3,67	73,94	1,83	74,52	2,53	68,31
Biowaste	2	2,99	50,60	4,86	3,70	65,24	1,89	65,83	2,57	68,78
42°C	3	2,97	50,49	4,85	3,72	66,69	1,88	67,26	2,59	69,68
	Average				**3,70**				**2,57**	**68,92**
Sludge	1	2,97	29,86	5,06	7,00	71,18	2,09	71,84	4,79	68,42
	2	3,02	31,34	5,17	6,86	70,22	2,18	70,91	4,75	68,35
	3	3,00	29,49	5,04	6,92	69,10	2,06	69,75	4,78	68,45
	Average				**6,93**				**4,77**	**68,41**
Inoculum	1	2,98	49,65	3,95	1,95	75,11	0,98	75,52	1,15	58,16
Sludge	2	2,98	49,92	3,97	1,98	66,79	0,99	67,21	1,14	57,58
53°C	3	3,01	52,52	4,06	2,00	73,37	1,05	73,81	1,16	58,10
	Average				**1,98**				**1,15**	**57,94**

Appendix 2 – Analysis of TS and VS in Summer Test Sample

Substrate	Sample#	Aluminiumtray [g] [	Sample Weight Wet [g]	Dried sample (105 degC) [g] + tray	TS [%]	Crucible [g]	Dried sample (105 degC)[g]	Burnt sample (550 degC) [g] + crucible	VS_{tot} [%]	$VS_{TS\ [\%]}$
Common reed	1	2,97	3,98	4,52	38,94	70,67	1,57	70,78	36,68	92,99
	2	2,96	4,27	4,63	39,11	65,40	1,69	65,51	37,00	93,49
	3	2,97	4,09	4,57	39,12	66,21	1,62	66,32	36,92	93,21
	Average				**39,06**				**36,87**	**93,23**
Biowaste	1	2,98	30,26	6,33	11,07	66,69	3,37	67,04	9,98	89,61
	2	3,00	32,02	6,60	11,24	73,94	3,62	74,31	10,15	89,78
	3	2,99	31,18	6,49	11,23	72,20	3,52	72,55	10,17	90,06
	Average				**11,18**				**10,10**	**89,82**
Inoculum	1	3,02	50,07	4,85	3,65	69,10	1,88	69,70	2,56	68,09
Biowaste	2	3,00	50,13	4,90	3,79	70,22	1,92	70,82	2,63	68,75
42°C	3	2,98	50,50	4,90	3,80	75,14	1,93	75,71	2,69	70,47
	Average				**3,75**				**2,63**	**69,10**
Sludge	1	2,99	31,77	5,50	7,90	72,36	2,53	73,19	5,35	67,19
	2	2,98	30,59	5,41	7,94	65,24	2,44	66,05	5,33	66,80
	3	2,99	30,36	5,38	7,87	73,36	2,40	74,16	5,27	66,67
	Average				**7,91**				**5,32**	**66,89**
Inoculum	1	2,99	51,66	4,22	2,38	61,03	1,25	61,57	1,37	56,80
Sludge	2	2,99	51,00	4,20	2,37	69,82	1,23	70,35	1,37	56,91
53°C	3	3,00	51,43	4,22	2,37	66,79	1,23	67,32	1,36	56,91
	Average				**2,38**				**1,37**	**56,87**

Appendix 3 – Analysis of TS and VS in Autumn Test Sample

Substrate	Sample#	Aluminiumtray [g] [	Sample Weight Wet [g]	Dried sample (105 degC) [g] + tray	TS [%]	Crucible [g]	Dried sample (105 degC)[g]	Burnt sample (550 degC) [g] + crucible	VS_{tot} [%]	$VS_{TS [\%]}$
Common reed	1	3,00	10,30	4,68	16,31	71,04	1,68	71,69	10,00	61,31
	2	2,99	10,05	4,86	18,61	72,67	1,89	73,55	10,05	53,44
	3	3,00	10,91	4,83	16,77	64,28	1,85	65,05	9,90	58,38
	Average				**17,23**				**9,98**	**57,71**
Biowaste	1	3,00	29,10	5,66	9,14	70,66	2,65	70,91	8,25	90,57
	2	3,02	30,11	5,74	9,03	71,60	2,73	71,83	8,30	91,58
	3	2,99	30,33	5,76	9,13	71,18	2,74	71,42	8,24	91,24
	Average				**9,10**				**8,26**	**91,13**
Inoculum	1	3,01	40,87	4,37	3,33	75,12	1,40	75,51	2,47	72,14
Biowaste	2	2,97	39,08	4,28	3,35	73,36	1,34	73,75	2,43	70,90
42°C	3	2,96	40,75	4,39	3,51	72,18	1,43	72,60	2,48	70,63
	Average				**3,40**				**2,46**	**71,22**
Sludge	1	2,95	35,42	5,56	7,37	69,10	2,61	69,85	5,25	71,26
	2	2,95	33,08	5,41	7,44	72,36	2,46	73,06	5,32	71,54
	3	2,98	38,11	5,75	7,27	66,78	2,80	67,57	5,27	71,79
	Average				**7,36**				**5,28**	**71,53**
Inoculum	1	2,98	42,44	4,13	2,71	61,02	1,17	61,53	1,56	56,41
Sludge	2	2,96	42,67	4,12	2,72	73,94	1,19	74,45	1,59	57,14
53°C	3	2,96	44,96	4,23	2,82	70,21	1,28	70,76	1,63	57,13
	Average				**2,75**				**1,59**	**56,89**