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BIOGAS PRODUCTION FROM PRESORTED BIOWASTE AND MUNICIPAL SOLID WASTE FROM SWEDEN

SUBSTRATE CHARACTERIZATION, WET FERMENTATION, AND CASH FLOW ANALYSIS

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With this signature, I declare on oath, that the present work was written by my own and no other than the specified source was used.

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ABSTRACT

Ostfalia University of Applied Sciences
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BIOGAS PRODUCTION FROM PRESORTED BIOWASTE AND MUNICIPAL SOLID WASTE FROM SWEDEN:
Substrate characterization, wet fermentation, and cash flow analysis

Bachelor's thesis pages 114, appendices pages 8
August 2014

Due to the great demand of methane as car fuel by the local population in the state of Västmanland, Sweden, a Swedish company called *Svensk Växtkraft AB* needs to the triple the biogas production until year 2016. A problem is the availability of biowaste, which is nearly completed utilized in the biogas plant already. To solve this problem, the utilization of pre-sorted municipal solid waste (MSW) is an option.

This thesis is aiming at characterization of pre-sorted biowaste and municipal solid waste regarding their utilization for biogas production by continuous mesospheric wet digester as well as mesophilic and thermophilic batch reactors. Biogas production for pre-sorted biowaste and municipal solid waste was investigating in the laboratory via self-constructed continuous reactors and at the same time, batch tests were carrying through for measuring the biogas potential of the wastes mentioned above, as well as the reject waste sorted out from existing biogas plant, at 40ºC and 55ºC. The biogas production results of municipal solid waste by mesophilic wet digester should be compared with the results of the same waste by mesophilic wet digester with enzyme addition, thermophilic dry garage fermenter and thermophilic plug flow fermenter. Besides, cash flow analysis for the company *Svensk Växtkraft AB* is also investigated in this thesis to find out the factors that affects the cash flow of the company.

The results indicated that biowaste and municipal solid waste are able to produce biogas consists of high methane concentration values, which is perfect for biogas quality. High reinvestment cost is the main factor that affects the cash flow of *Svensk Växtkraft AB.*

Keywords: biogas, methane, biowaste, municipal solid waste, cash flow analysis.

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Lishan Wu

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GLOSSARY

€	Euro
CH_4	Methane
CO_2	Carbon Dioxide
D	Day
DM	Dry Matter Content
FOS	Volatile Organic Acids
g	Gram
h	Hour
kg	Kilo
L	Liter
MSW	Municipal Solid Waste
N	Nitrogen
N	Prefix: Norm
NH_3	Ammonia
NH_4-N	Ammonium
ºC	Celsius Degree
oDM	Organic Dry Matter Content
OLR	Organic Loading Rate
ppm	Parts Per Million
t	Ton
TAC	Total Inorganic Carbon
TOC	Total Organic Carbon

1. INTRODUCTION

1.1 Aim of the thesis

This thesis is aiming at characterization of pre- sorted biowaste and municipal solid waste for a Swedish company called *Svensk Växtkraft AB* regarding their utilization for biogas production by continuous mesophilic wet digester as well as mesophilic and thermophilic batch reactors. Biogas production for pre-sorted biowaste and municipal solid waste is investigated in the laboratory via self-constructed continuous reactors and at the same time, batch tests are carried through for measuring the biogas potential of the wastes mentioned above, as well as the reject waste sorted out from existing biogas plant, at temperature of 40ºC and 55ºC. The biogas production results of municipal solid waste should be compared with my team mate Patrick Niekamp's thesis results and Matthäus Barasinski's thesis results. Patrick Niekamp's was doing similar continuous tests using the same sorted municipal solid waste from Sweden, with enzyme (*T.reesei*) addition to see the influence of cellulases on the biogas potential. His thesis topic is "Einfluss von cellulasen von t. Reesei auf das biogaspotential von kommunalen haushaltsabfällen". Another team mate Matthäus Barasinski used thermophilic dry garage fermenter for the investigation of biogas potential from unsorted municipal solid waste, and his thesis topic is "Etablierung einer Garagenfermentation zur Produktion von Biogas aus Abfällen". Also results should be compared with the pilot B with the thermophilic plug flow fermenter in Sweden, which uses the same sorted waste. [1] [2] Cash flow analysis for the company *Svensk Växtkraft AB* is also investigated in this thesis by using the company's historical data from the start-up year to the year 2013 to compare with the hypothetic data created from the excel tool with estimated values.

1.2 Introduction of Vafabmiljö and Svensk Växtkraft AB

VafabMiljö AB is a waste treatment company with ISO 14001 Environmental Certification which is located in the southeast of Sweden and is owned by 12 municipalities in the state of Västmanland together with the municipalities in Heby and

Enköping. The main task of *VafabMiljö* is to reduce the total amount of waste environmental friendly and economically via recycling and using it as a resource for materials and energy recovery. [3]

Svensk Växtkraft AB is a wholly owned subsidiary company of *VafabMiljö AB* in Gryta for waste treatment. A biogas plant owned by *Svensk Växtkraft AB* was built in the summer 2005 and since 2006 the plant has been in full operation. The biogas plant processes pre-sorted biowaste from households and restaurants, sludge from grease separators and ley crops as substrates and extracts energy from them by producing biogas via anaerobic digestion process. During the anaerobic digestion process, it creates a residue called digestate (biogödsel in Swedish), and it can be separated to liquid digestate and solid digestate. The liquid digestate is very rich in nitrogen and can be placed on farmland in the spring. The solid digestate is rich in phosphorus and laid out mainly in the fall as a soil conditioner. A plant for upgrading the biogas to vehicle grade fuel was also built, which is estimated to produce vehicle fuel from biogas to the equivalent of 2.3 million gallons of gasoline per year. There are also refueling stations for buses and cars and storage rooms for ley crops and the residual digested sludge for farming. [4] FIGURE 1 is the visualization of the biogas cycle in *Svensk Växtkraft AB.*

FIGURE 1: Visualization of the biogas cycle in Svensk Växtkraft AB [5]

Due to the great demand by the local population, the biogas production needs to be tripled until year 2016. A problem is the availability of biowaste, which is nearly completed utilized in the biogas plant already. To solve this problem, the utilization of pre-sorted municipal solid waste (MSW) is an option.

2. LITERATURE REVIEWS

2.1 Anaerobic digestion

Anaerobic digestion means in the absence of oxygen, organic matter is consumed by the microorganisms and it is broken down to form biogas for energy recovery. Anaerobic digestion occurs in nature, for example, at the bottom of lakes, in slurry and in the rumen of ruminants. [6] Anaerobic digestion includes four key biochemical stages, which are hydrolysis, acidogenesis, acetogenesis and methanation (FIGURE 2). The individual stages are carried out by different groups of microorganisms, which have syntrophic interrelation and have different requirements (for example, pH, and temperature) on the environment for their growths. [7] FIGURE 2 shows anaerobic digestion biochemical conversion pathways.

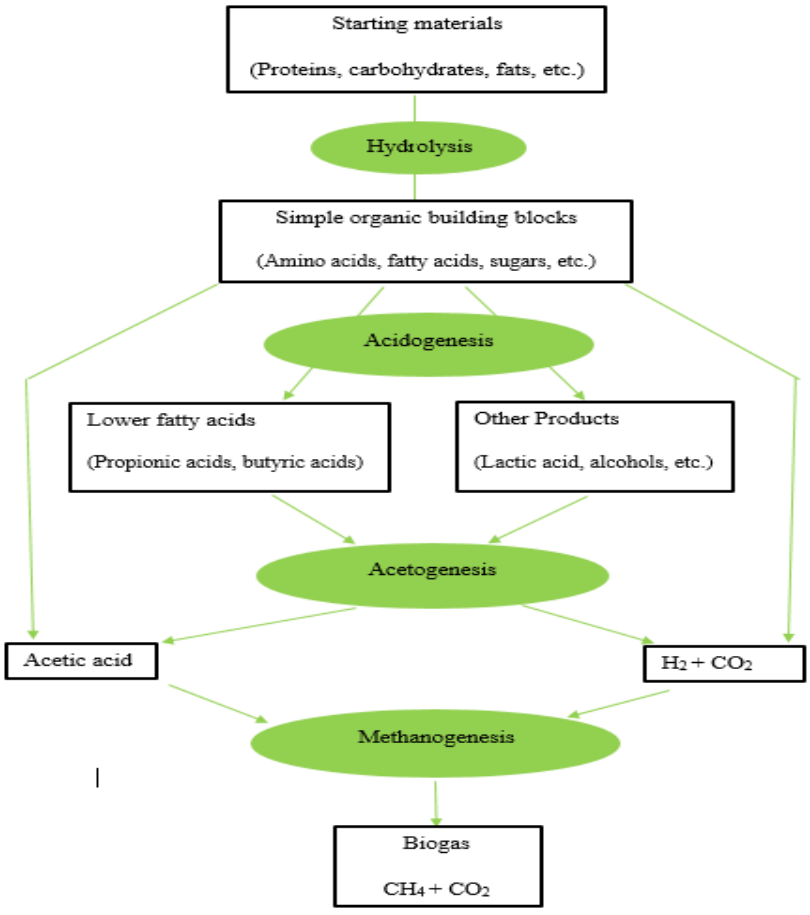

FIGURE 2. Anaerobic digestion biochemical conversion pathways [6]

2.1.1 Hydrolysis Phase

In the first phase, hydrolysis, the complex high-molecular substances of the starting materials (such as carbohydrates, proteins and fats) are broken down into simpler low-molecular organic compounds (such as amino acids, sugars and fatty acids) by means of enzymes released from the hydrolytic bacteria. [6]

Long-chain carbohydrates, such as cellulose, hemicellulose and starch, are water-insoluble compounds. They are broken down into short-chain sugars by hydrolases within few hours. Proteases break down proteins into amino acids and lipases break down fats into fatty acids and glycerin within few days. Lignocellulose and lignin can't be degraded completely and longer time is needed. [7]

2.1.2 Acidogenic Phase

Acid-forming bacteria break down the intermediate products (monomers) formed from hydrolysis further more to form lower fatty acids (acetic, propionic and butyric acids), H_2, CO_2 and small quantities of lactic acid, alcohol, NO and H_2S. At this stage, the concentration of the intermediate hydrogen can affect the nature of fermentation products. [7] The lower the partial pressure of the H_2 is, the more acetic acid, H_2 and CO_2 are produced. The higher partial pressure of H_2 is, the more organic acids, lactic acid and ethanol are formed. [8]

2.1.3 Acetogenic Phase

Lower fatty acids (acetic, propionic and butyric acids), alcohols and lactic acids from the previous phase (acidogenesis) are served as substrates for the acetogenic phase. The hydrogen partial pressure is of great importance at this phase. When the partial pressure of H_2 is low, acetogenic bacteria form predominantly H_2, CO_2 and acetate, which are the recourses for the methane formation. [7] When the partial pressure of H_2 is high, it prevents the conversion of the intermediate products of acidogenesis, more and more

organic acids such as propionic acid, isobutyric acid form and accumulate, which leads to inhibition of the methane formation. [6] According to the "interspecies hydrogen transfer", hydrogen is able to move directly from the acetogenic bacteria to the methanogens without being dissolved into the substrates. [7] The acetogenic bacteria (hydrogen-forming bacteria) and the hydrogen-consuming methanogenic archaea (interspecies hydrogen transfer) must exist in a close biotic community for providing proper environment for the acetogenic bacteria, which does not have too high partial pressure of hydrogen. [6]

2.1.4 Methanogenic Phase

Methanogenic phase takes place under strictly anaerobic condition. In this phase, all above acetic acid is converted into methane via acetic acid cleavage by acetoclastic the methane-forming bacteria, whereas H_2 and CO_2 are converted into methane by the hydrogenotrophic methanogens. [6] Methanogenic bacteria have very low growth rate and are very sensitive regarding to disturbances. When the methane formation works smoothly, the acetogenic phase is also running well. However, when the methane formation is disturbed, over acidification occurs. Furthermore, H_2S affects the methanogens toxically. [7]

2.2 Biogas Composition

Biogas is formed from methanogenic phase in the anaerobic digestion. The composition of biogas is a parameter for analyzing the circumstances in the digester. Methane and carbon dioxide are the main compositions of the biogas, there are also small amount of hydrogen sulfide, nitrogen, ammonia, oxygen and hydrogen. TABLE 1 shows the general composition of biogas. [6] The biogas generally contains 50-75% CH_4, 25-45% CO_2, 10 to 10000 ppm H_2S and small amounts of N_2, O_2, H_2 and NH_3. [9] [10]

TABLE 1: General composition of biogas [9] [10]

Compound	Chemical symbol	Content % (volume/volume)
Methane	CH_4	50- 75
Carbon Dioxide	CO_2	25-45
Hydrogen Sulfide	H_2S	10-10,000 ppm
Nitrogen	N_2	<2
Oxygen	O_2	<2
Hydrogen	H_2	<1
Ammonia	NH_3	<1

Biogas production and composition during continuous fermentation process should be relatively stable. If the biogas production drops vastly below the average value, or the biogas composition changes dramatically, it is most likely that there is inhibitor upsetting the fermentation process or gas leaks occurring. [11]

2.2.1 Methane

Methane content is an important parameter for evaluating the biocoenosis of the methanogenic phase. The general methane concentration is about 50% to 70% in the form of biogas. If the methane content reduces significantly despite constant feeding rate, it can be assumed that there is inhibition for the methanogenic bacteria. For operation of the combined heat and power (CHP) unit, it is important to ensure the content of the methane in the biogas is not below 40-45%, due to the fact that the engine of the CHP unit cannot utilize the biogas with too low methane content. [6]

2.2.2 Carbon dioxide

In the course of hydrolysis phase, acidogenesis phase and methanogenic phase, CO_2 is formed. It dissolves in water and forms the hydrogen carbonate buffer. If the substrate composition is stable, but the methane/carbon dioxide ratio in the biogas falls, it is a sign of a higher rate of acid formation compared with methane formation, which means the equilibrium of mass flows in the degradation process is disrupted. A fall in

methane/carbon dioxide ratio may be caused by the variation of the input quantities or the inhibition of the methanogenic population. [6]

2.2.3 Hydrogen sulfide

Hydrogen sulfide is formed by the sulfate reducing bacteria which are able to reduce sulfate present in the digester to hydrogen sulfide. Sulfate reducing bacteria are competitors with methane-forming bacteria, because they utilize the same substrate, however, instead of forming methane, sulfate reducing bacteria form hydrogen sulfide. It is difficult to cripple the simultaneous development of these sulfate reducing bacteria, but even if the biogas contains relatively high amount of hydrogen sulfide, the total methane production rate is not directly affected. [12]

This does not mean the high content of hydrogen sulfide in the biogas is accepted, actually, for achieving the high-quality of biogas, the hydrogen sulfide should be removed. [12] Due to the fact that hydrogen sulfide is the main cause of corrosion of the structures and materials in a biogas facility. During combustion, the hydrogen sulfide component is oxidized, resulting in the formation of acidic sulfur dioxide [13], equation 1 shows the formation of acidic sulfur dioxide:

$$2\,H_2S\ +\ 3\,O_2 - 2SO_2 +\ 2\,H_2O \qquad (1)$$

Sulfur dioxide has highly corrosive properties and causes rapid over acidification of the engine oils during combustion in the gas engine, thus there is limitation of the hydrogen sulfide concentration in biogas for protecting the CHP-unit. [13] [6] However, high concentrations of hydrogen sulfide do not affect the methanogenic bacteria until the concentration reach 20,000 ppm. [6]

2.2.4 Ammonia

Ammonia is produced by the biological degradation of the nitrogenous matters. For anaerobic digestion, protein is the main source of ammonia. Ammonia is an important nutrient, acting as a precursor to foodstuffs and fertilizers. Ammonia is generally encountered as a gas with the pungent smell. Too high ammonia concentration inside the digester, especially free ammonia, is regarded as an inhibitor for the anaerobic process. [10]

2.3 Biogas potential and inhibiting effects of selected substrates

Generally speaking, all types of biomass can be used as substrates as long as they contain carbohydrates, proteins, fats, cellulose and hemicellulose as main components. The biogas yield of a given substrate is not a fixed value, in fact, the variance is very high. The biogas yield is up to many factors, such as the variety, the weather conditions, the loading rate of the fermenter and the retention time in the fermenter. [7] TABLE 2 presents three different kinds of wastes from Sweden used as substrates. SVReject is the reject fraction from wet sieve in the pretreatment, and in the thesis there is no other research for it except batch tests. FIGURE 3 is the picture of SVReject waste. SVHH is the presorted biowaste which were separated by the locals before it arrived to *Växtkraft* plant. Nonename is the municipal solid waste, which is the feedstock to the dry digester (Pilot B) at Gryta. In this thesis, the Nonename waste (MSW) is sorted, because the continuous wet digester should avoid the impurities, such as plastic, metal and glass. Sorted municipal solid waste and presorted biowaste were investigated by using mesophilic continuous wet digester, mesophilic and thermophilic batch reactors.

TABLE 2: Sample labels and descriptions

Label	***Fraction***
SVReject	Reject fraction from the wet sieve in the pretreatment at Växtkraft(Reject waste)
SVHH	Source separated organic waste (presorted biowaste) as it arrived to Växtkraft
NoneName	Organic fraction from MBT(municipal solid waste (the feedstock to the dry digestor at Gryta)

FIGURE 3: SVReject waste from wet sieve

2.3.1 Municipal solid waste

Municipal solid waste (MSW) can be used as substrate for the biogas production, however, not so many plants are utilizing it, due to the problems with the sorting of impurities or due to the problems with the smell. Impurities should be picked away before the waste is entered in to the continuous reactor, in order to protect the reactor from physical harm. Great efforts are spent on minimizing the impurities from the municipal solid waste, such as plastic, metal and glass. For municipal solid waste, substrate properties can widely vary depending on its origin of production. [14] Climate, extent of recycling, collection frequency and cultural practices are also the factors that influence the production and composition of MSW. [15] As an example, FIGURE 4 is the proportion analysis of 251 million tons MSW in USA in the year 2012. As is showed, about 65% of MSW is biodegradable (paper, yard trimmings, food scarps, wood) and about 35% is non-biodegradable (plastic, metals, rubber, glass, etc.).

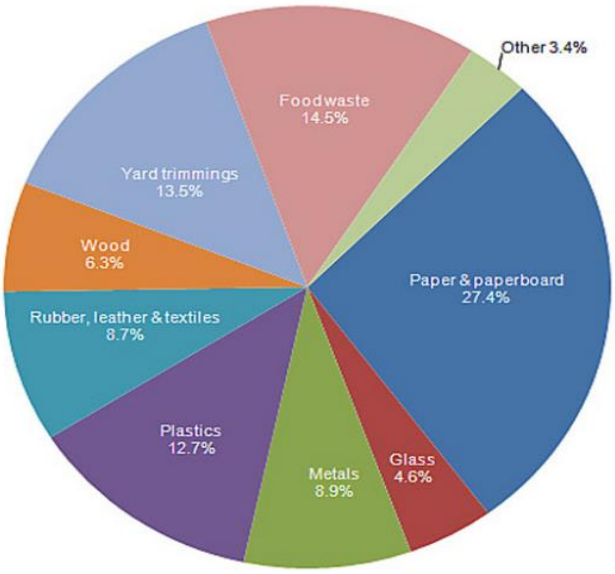

FIGURE 4: Total MSW Generation (by Material) in USA, 2012, 215 Million Tons (before recycling) [16]

The municipal solid waste investigated in the lab was from the region of Västerås, Sweden. As is showed in FIGURE 5, the waste on the left side is the original MSW sample from Sweden, it contains glass, wood, paper, plastic and other biodegradable and non-biodegradable materials. The waste on the right side of the picture is the sorted out impurities, such as plastic, metals, glass, which are not suitable for the anaerobic digester.

FIGURE 5: Municipal solid waste and its impurities

2.3.2 Source separated biowaste from households

Biowaste is mainly the separated kitchen and garden waste from private households. There are differences between biowaste quantities produced within a municipality and the quantities assumed to be collected, due to the fact that the quantities of biowaste are depending on the participation rate of citizens and the capture rate. Some of the organic waste is not suitable for anaerobic digestion, such as wood and other lignin containing waste materials. The biowaste composition varies depending on the geographic area and the income level. Generally speaking, it can contain vegetables, fruits, gardening residues, organic materials from animals or the entire kitchen waste and garden waste. [17] FIGURE 6 is the biowaste sample from the region of Västerås, Sweden. As is shown, thebiowaste contains paper, leaves and some kitchen waste, such as carrots, potatoes, bones and teabags.

Figure 6: SVReject waste from Sweden

2.3.3 Biogas potential

Due to the fact that the volume of gas is dependent on the temperature and the atmosphere pressure (ideal gas law), therefore normalization of the gas volume is necessary for making comparisons between different operating conditions. The biogas yield and methane yield are stated in units of normal cubic meters (Nm^3). [6] TABLE 3 presents the information about biogas potential from different literatures. The values may vary a lot, due to the different investigating methods. Biowaste and municipal solid waste are

able to produce biogas that has 58- 65% methane. The biogas yield from the biowaste varies from 0,3 to 1,0 m^3/kg oDM. The values of organic dry content from dry matter contents has big variations.

TABLE 3: Biogas potential from source-separated biowaste and Municipal solid waste

Substrate	DM	oDM per DM	Biogas yield	Biogas yield	Biogas yield	Methane content	Methane yield	Reference
Unit	%	%	m^3 /kg oDM	m^3/ton wet substrate	Nm^3/ton oDM	%	Nm^3/ton Substrate	
Biowaste	40-75	30-70	0.3-1.0					[7]
Biowaste	35	31.7			450	65		[18]
Biowaste	40	50			615	60	74	[10]
Food waste			0.695	140		59		[19]
Source-separated household waste(MSW)		80	0.35			65		[14]
Organic material recovered from MSW		70-89	0,533-0,676			58- 60		[20]

2.3.4 Inhibiting effects of selected substrates during the anaerobic process

Biowaste has a high nitrogen content as a result of the high protein component. During anaerobic digestion, nitrogen is converted to ammonia, causing toxicity to the acetoclastic methanogens. At the same time, the other methanogens, hydrogenotrophic methanogens has been indicated to be lacking the sufficient key trace elements to support the process to continue efficiently. The interaction is complex, however, it is observed that lacking certain trace elements leads to an increase in volatile fatty acids (VFA), which could give rise to the inhibition of the hydrogenotrophic methanogens and consequently lead to the failure of the digestion process. There is also exception, under high VFA, the digester can still continue its process, but at a very low loading rate, which is unlikely to be cost effective. [21]

The organic fraction of municipal solid waste has a high solid content (~50%) and limiting nitrogen content (C/N> 30). The main organic components are cellulose and hemicellulose. High concentration of municipal solid waste can inhibit the microbial growth due to the growth of methanogenic bacteria is inhibited by high concentrations of volatile organic acids. (10, 000mg/L). [15] Low pH also inhibits the methanogenic growth. Costello et al. (1991) concluded the pH inhibition factors (pH value and the inhibitors' concentration) as the TABLE 4 presented. [15]

TABLE 4: Concentrations of inhibitors of anaerobic digestion using Municipal solid waste [15]

Inhibitor	***Concentrations(mg/L)***
Phenol	2400
Heavy metals	
Zn^{+2}	160
Fe^{+3}	1750
Cd^{+2}	180
Cu^{+2}	170
Cr^{+3}	450
Cr^{+6}	530
Nickel	250
NH_4^+-N	6000
Calcium	2500-8000
Magnesium	1000-3000
Potassium	2500-12000
Sodium	3500-8000
Sulphide(S-)	600

2.4 Process and operating parameters

2.4.1 Temperature

The anaerobic digestion process can happen at different temperatures, which are divided generally into three ranges: psychrophilic (below 25ºC), mesophilic (25ºC – 45ºC), and thermophilic (45ºC –70ºC). [10] Generally speaking, the rate of chemical reaction increases along with the increase of the surrounding temperature. However, this is only partially applicable to biological decomposition and conversion processes, due to the fact that there are different optical temperatures for the metabolic processes of the

microorganisms. It is important to keep the constant temperature during the digestion process, because inhibitions occurs to the relevant microorganisms when the temperature is above or below its optical range. [6] Mesophilic bacteria are able to tolerate ±3ºC differences without significant reductions of the methane production. Thermophilic bacteria are more sensitive to the temperature fluctuation, ±1ºC differences already affect the methane production negatively. [10] Under thermophilic condition, temperature should be maintained precisely, because there would be gas loss of up to 30% if the temperature is not within the range of ± 2ºC. [7]

In practice, biogas plants operating in the mesophilic range (37- 42 ºC) are the most widespread, because its relatively high gas yields and good process stability. [6] Nowadays, there are also many modern biogas plants operating at thermophilic condition, because thermophilic process offers many advantages compared with mesophilic and psychrophilic ones. [10] Optimum temperature for thermophiles is in a range of 50- 60ºC, and such high temperature is able to kill off the pathogens effectively, this enhances the rate of decomposition and cuts down the viscosity of the substrate in anaerobic digestion. [6] [10] Methanogenic bacteria have higher growth rate in higher temperatures. As is shown in FIGURE 7, thermophiles has about 50% higher growth rate than mesophiles.

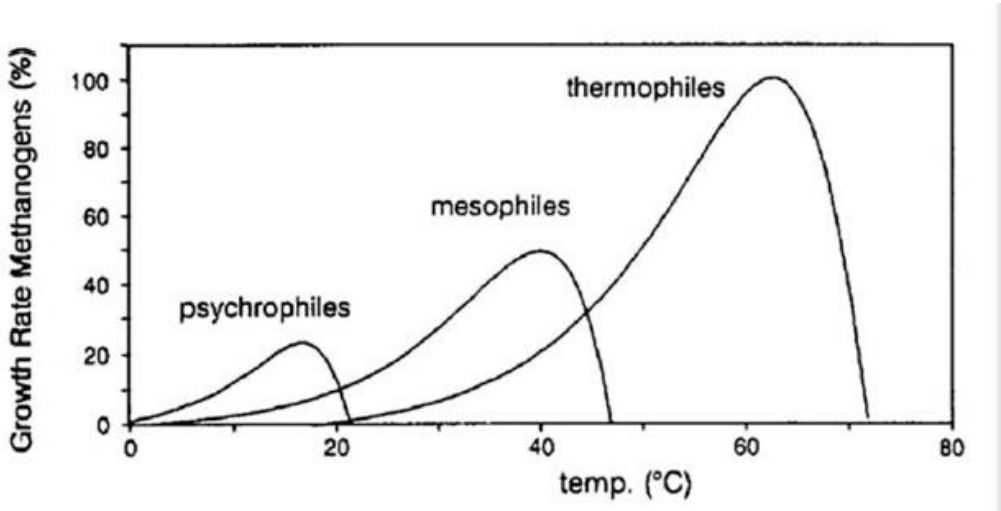

FIGURE 7: Relative growth rates of methanogens [22]

Despite of the advantages mentioned above, thermophilic process could cause some drawbacks, such as more energy is needed for heating up the process, larger degree of

imbalance would occur and higher risk of the ammonium inhibition would take place. As temperature increases, the ammonium toxicity increases. [10]

2.4.2 Organic acids

Generally speaking, organic acids are present in the substrates and decomposed during the methanation. Depending on the pH value, organic acids present in two forms, partly in undissociated and partly in dissociated. [7] Equation (2) shows calculation of the dissociation factor according to pH value.

$$f = \frac{10^{pK_S - pH}}{1 + 10^{pK_S - pH}} \qquad (2)$$

Where:

- *f* is dissociation factor
- *pKs* is the negative common logarithm of the acidity content
- *pH* is the pH value

In the steady state of anaerobic digestion, the concentration of organic acids is constant, because the rate of acid formation and transformation are identical. However, acid will accumulate and lead to the rise of its concentration if there is either a higher rate of acid formation or the degradation is inhibited. According to the principles described by Monod, bacterial growth is dependent on substrate concentration, which means an increase in acid concentration generates more bacteria, and within certain limits, the process stabilizes itself. However, if the rate of acid formation is too high that it exceeds the capacity of the acid-degradation microorganisms for a certain period of time, the acids concentration continues to rise. If there is no intervention carried out, the acids will accumulate to the point at which the buffer capacity of the system is exhausted and the pH value decreases. [6]

As an intermediate product during the formation of biogas, the organic acids is an important parameter for process monitor and control. Not only can the sum parameter of the acids but also the concentration of individual acids provide information for evaluating the fermentation process. Volatile fatty acids (VFA) concentration is probably the most sensitive parameter to monitor as a process performance indicator, due to the fact that they can be inhibitory of digestion process, causing system failure. VFA includes a group of six compounds, as is shown in TABLE 5. [11]

TABLE 5: Individual Volatile fatty acids (VFA) [11] [23]

VFA	Concentration mg/L	Interpretation
Acetic acid	<1000	stable process
	1000-4000	stable process, possible unstable process
	>4000	high probability of unstable process
Propionic acid	<250	stable process
	250-1000	stable process, possible unstable process
	>1000	high probability of unstable
Butyric acid Valeric acid Caproic acid Enanthic acid	<50	stable process
	>50	if longer chained VFA (and especially branched isomers) accumulate, severe process problems occur
Ration acetic/propionic acid	>2	stable process
	1-2	stable process, possible unstable process
	<1	high probability of unstable

In a well-operated fermenter, the concentration of total volatile fatty acids is typically below 1000 mg/L as acetic acid. When the total VFA concentration is over 4000 mg/L, fermentation might be inhibited and biogas production is limited. [11] [23] If the result shows that the longer-chain acids are increasing faster than the acetic acid, the transformation of these acids to acetic acids is being inhibited. When the ratio of acetic/propionic acid is less than 1, it is a sign of unstable process in the fermenter. Nowadays, there are many methods for determining the concentration of organic acids, using gas chromatography as a spectrum is one of them. [6]

2.4.3 Buffer capacity

In recent years, a titration test called FOS/TAC is commonly used for defining the buffer capacity and monitoring the fermentation process in biogas reactor. FOS stands for volatile organic acids content and is measured in mg HSceq/L while TAC means total inorganic carbonate (alkaline buffer capacity) and is measured in mg/$CaCO_3$/L. Acid concentration is an indicator for the production of produced biogas, while at the same time, the acids must be compensated by the buffer capacity of the sample in order to avoid acidification in the fermenter. [24] The value of FOS-TAC represents the quantity of volatile organic acids in relation to the buffer capacity of carbonate. [25] [7] Nowadays, the FOS/TAC value has become a critical parameter for the fast evaluation of the digester. [6] Based on the experience, a FOS/TAC value of 0.3 means well utilization of substrates in the digester. However, FOS/TAC value is a limiting value, which can vary depending on the specific plant. Therefore, the analytical results from different processes are not comparable. It is recommended to measure the FOS/TAC value regularly to observe the process changes in the fermenter in order to detect the problems in time, for example, in case of acidification. [6] [7]

2.4.4 pH value

In anaerobic digestion, each groups of microorganisms have specific optimum pH range. For example, the optimal pH for hydrolyzing bacteria and acidogenic bacteria is in a range of 5.2- 6.3 while for methanogenic bacteria and acetogenesis bacteria is in a range of 6.5-8 and the preferred level is pH 7.2. Hydrolysing and acid-forming bacteria are not totally reliant on this optimum pH, which means that they are still able to convert substrates at a slightly higher pH value despite that their activity is slightly reduced. Conversely, the pH value in the neutral range from 6.5 to 8 is of great importance for acetogenesis bacteria and methanogenic archaea. Therefore, in a mixed culture anaerobic digester, the optimal pH value is 6.5 to 8. [26] [6] [14]

During the anaerobic digestion, the pH value is held automatically within the system by the alkaline and acid metabolic products. However, acid metabolic products of acidogenesis will accumulate if the methanogens is inhibited or too much organic matters are inputted to the process within too short period of time. [6] Buffer capacity is an important parameter for process stability, which can resist pH changes in the system. There is a carbonate and ammonia buffer in the system. When the buffer capacity is exhausted, for example, if too many organic acids have built up, it would lead to a decrease of pH value. Drop of pH value is a sign of acidification, it results in the further inhibitory effect of hydrogen sulphide and propionic acid, to the extent that the anaerobic digestion process will stop in a very short period of time. [6] [7] For prevention of excessive acidification, the organic loading rate should be reduced or the substrate supply should be terminated so that the methanogenic bacteria are able to degrade the acid. Continuous removal of the acids and addition of dilution water are also ways to prevent the excessive acidification. [7]

On the other hand, the breakdown of organic nitrogen compounds would lead to the rise of the pH value because of the release of ammonia. The ammonia reacts with water to form ammonium and consequently the inhibitory of ammonia increases. [6] There will be irreversible loss of the activity of the bacteria in the fermenter if value of pH is more than 10. [7] Regarding to the process control, it is important to measure the pH value of the fermenter to ensure the better control of the system. [6]

2.4.5 Dry matter and organic dry matter

In order to obtain a mass balance, it is necessary to know the quantity, concentration and composition of the substrate. In practice, dry matter content (DM) and organic dry matter content (oDM) are the parameters commonly used to determine the concentration of substrates. Dry matter content means the total solid content after removing its water content. To determine DM, sample is dried to constant weight at 105ºC in the laboratory. Organic dry matter content is a sum parameter for assessing degradability of substrates, however, it does not tell the degradability of substrate under test nor the amount of biogas

expected to be produced. For determining the oDM, dried sample is burned away at 550ºC. The mass loss refers to the amount of organic dry matter. [6]

2.4.6 Organic loading rate

Economically, the biogas plants would like to get the maximum methane production within a shorter period of time, instead of getting the maximum amount of methane from complete decomposition of the organic constituents which needs a very long retention time in the digester. The aim of running anaerobic digestion in biogas plant is therefore to obtain optimum degradation performance at acceptable economic cost, referring mainly the retention time of the digester and the input of the substrates. [6]

Regarding to the aim mentioned above, the organic loading rate (OLR) is a crucial operating parameter. OLR provides information about nutrients supply of microorganisms and tells whether the plant is over or undercharging by comparing it with process parameters. OLR also indicates how many kilograms of organic dry matter (oDM) is fed into the digester per m^3 of working volume per unit of time. The equation 3 is calculating the OLR, expressed as kg/ oDM/ (m3•d). [6]

$$B_R = \frac{m \cdot c}{V_R \cdot 100} \; [kg\ oDM\ m^{-3} d^{-1}] \qquad (3)$$

From the equation 3, B_R is the organic loading rate (OLR), m is the amount of substrate added per unit of time [kg/d], c is the concentration of organic dry matter [% oDM] and V_R is the reactor volume [m^3]. [6]

2.4.7 Mixing

Mixing in the reactor can avoid the formation of layers, because there is density difference between bacterial mass and substrates and also up thrust from the gas formation. Due to

its higher density, most of the bacterial mass stays in the lower layer, whereas the substrates, which are supposed to be decomposed by the bacteria, are collecting in the upper layers. Furthermore, a scum, formed by some solids floating to the top, would increase the difficulty for gas to get away from the mixture. [6]

For purpose of reaching the high levels of biogas production, the bacteria and substrate must be in contact intensively. Therefore, sufficient mixing is necessary. Actually, sufficient mixing of the content in the digester not only can keep good contact of bacteria and substrate, but also can ensure uniform distribution of heat and nutrients inside the digester. [6]

2.4.8 Ammonium and Ammonia

During anaerobic biological degradation, organic substrates that contain nitrogen are broken down and the nitrogen is converted into ammonia (NH_3). Ammonia is dissociated with water and forms ammonium (NH_4-N), which is partly depending on the pH value. [7] [6] Ammonia (NH_3) has inhibiting effect on methanogens, and at high concentrations, it can even be toxic, while ammonium (NH_4-N), which is in equilibrium with ammonia, is rather innocuous. [7] [27] The reason for ammonia inhibition is not fully known, but it has been suggested that it is due to the uncharged ammonia entering the cell, converting ammonia to ammonium and consuming hydrogen ions, leads to the pH changes in the cell. In order to keep the pH constant, the methanogens have to be pumped in the hydrogen ions (H^+) from the environment, and at the same time, potassium ions (K^+) are pumped out. That is to say, ammonia/ammonium lead to potassium loss of methanogens. [27] [28] FIGURE 8 shows how ammonia affect the methanogens. As is shown, there is the pathway of potassium loss from the cell.

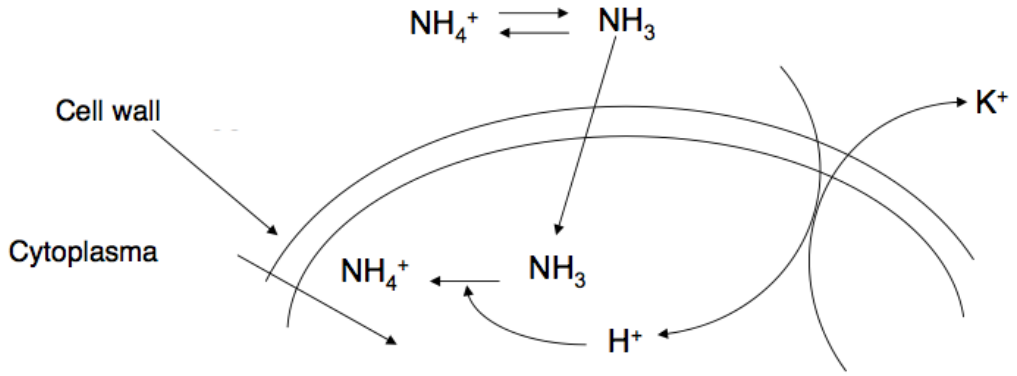

FIGURE 8: Effect of ammonia on methanogens [28]

There is much to suggest that the pH and temperature influence the inhibitory of methanogens. As temperature increases, more ammonium is shifted to ammonia, that is to say, inhibition increase with rising temperature. TABLE 6 shows the limit values of ammonia and ammonium.

TABLE 6: Limit values of ammonium and ammonia [7]

Substance	Concentration at which inhibition starts	Toxicity (mg/L adapted microorganisms
Ammonium	1500- 10000	30000
Ammonia	80	150

The inhibition by ammonia increases with the increase of pH value. As pH rises, more dissociated ammonium shifts into not dissociated ammonia. As is shown in FIGURE 9, at pH 7.3, the ammonium: ammonia ratio is 99:1 while at pH 8.0, the ratio is 94:6. [7]

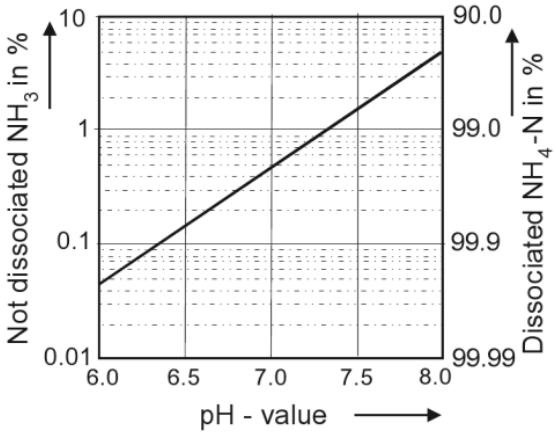

FIGURE 9: Dissociation equilibrium NH_3/NH_4-N [7]

According to FIGURE 9, when pH value is over 8, ammonia (NH_3) concentration increases, which can inhibit the methanogens. Although high NH_4-N concentrations can lead to inhibitory NH_3 concentrations, it can result in an increase in buffer capacity, which means under high NH_4-N concentrations, the anaerobic process can run in a stable way. However, under high NH_4-N concentrations, the anaerobic process is less robust against additional process problems, such as a change in pH, therefore an imbalance may be more drastic than at a low NH_4-N concentrations. [23]

2.4.9 Degree of degradation

The degree of degradation provides information about the efficiency of the substrate converted by biological and chemical degradation of organic compounds. The degradation rate is mainly based on metabolic processes. There are many ways to define the degradation rate, either as single component or as sum parameter, e.g. COD (chemical pxygen demany) and oDM (organic dry matter content). The commonly used analysis method is to determine the degree of degradation of the organic dry matter content. [6] [25] Equation 4 is for calculating the degree of degradation.

$$degradation\ rate(\%) = \frac{oDM\ of\ substrate\ fed(g) - leftover\ oDM\ of\ substrate(g)}{oDM\ of\ substrate\ fed(g)} \cdot 100\% \qquad (4)$$

A low value of degradation rate means there is metabolic process inhibitory or high amount of non-digestible ingredients in the substrate. [25]

3. MATERIALS AND METHODS

3.1 Batch tests

3.1.1 Layout and test operation

Batch tests are used to determine the potential biogas production rate and degradability of substrates. 5L Erlenmeyer flasks, rubber plugs, valves, pipes and Thesseraux® gas bags are the devices for batch tests. All the Erlenmeyer flasks should be cleaned before using them as bioreactors, toxic or aggressive cleaning agents shouldn't be used for the cleaning because they can cause process troubles. An overall amount of 3500 g mixture of substrates and inoculum is filled into 5L Erlenmeyer flasks for 35 days fermentation time until all the biodegradable ingredients are digested. Sewage sludge is used as inoculum. The ratio of inoculum and substrates is calculated according to the equation 5 [25]:

$$\frac{m(oDM,substrate)}{m(oDM,inoculum)} \leq 0{,}5 \qquad (5)$$

After calculation, the determined amount of substrate and inoculum is filled into the flasks. For comparisons, mesophilic (42°C) and thermophilic (55°C) batch tests are performed. In mesophilic batch tests, wastes are sanitized at 70°C for 1 hour before filling them with sewage sludge into flasks. In thermophilic batch tests, wastes don't require pre sanitation, because substrates that are under 55 ºC for more than 10 hours have had sanitation effect already. TABLE 7 lists the batch tests performed in the lab. The weights of all the empty Erlenmeyer flasks, inoculum, substrates, and the full flask with inoculum and substrates are written down.

TABLE 7: Batch test setup

Batch tests	Wastes 75g		
Thermophilic batch tests 55°C, no presanitation sanitation	SVReject 1	SVHH1	NoneName1
	SVReject 2	SVHH2	NoneName2
Mesophilic batch tests 42° C, sanitation at 70°C for 1 hour	SVReject 1	SVHH1	NoneName1
	SVReject 2	SVHH2	NoneName2

After filling the flasks with an overall 3500g of substrate and sewage sludge mixture, pure nitrogen is injected into the flasks for providing anaerobic conditions for methanogenic bacteria (FIGURE 10). Valves and gas bags are attached to the rubber plugs, which are fitted with flasks for ensuring gas-tight condition (FIGURE 11). [25] As is seen in FIGURE 12, batch reactors are placed under mesophilic conditions (42 °C heating cabinet) and the other 6 batch reactors are placed under thermophilic conditions (55°C heating cabinet) for 35 days.

FIGURE 10: Injecting pure Nitrogen to the batch reactor

FIGURE 11: Batch reactor with gas bag, value and rubber plug attached

FIGURE 12: Batch tests in heating cabinet

There aren't continuous stirring devices available, thus the batch reactors must be shaken everyday manually to ensure sufficient mixing. While shaking the reactors, the rubber plugs should be controlled and the gas bags should be closed for avoiding gas leakage. If there is certain amount of gas, the gas bags should be measured at a gas measuring station. After the gas measurement, the gas bags are connected again to the batch reactors and valves are opened. After 35 days fermentation time, almost all of the biodegradable materials are digested and the batch tests can be stopped. The weight of the flask with the leftover from inoculum and substrates are measured for calculating the mass loss. [25]

3.1.2 Correction of Headspace in Batch tests

During batch tests, nitrogen is replaced by "plug flow" from the head space; thus a higher gas concentration is present in the headspace after separation of the bag in comparison to the gas concentration in the bag. This is noticeable especially in the first measurements. [29] Equation (6) is the method of getting the right gas concentration.

$$C_{(korr)} = C_{(t2)} + \{(C_{(t2)} - C_{(t1)}) \cdot (\frac{V_{(K)}}{V_{(B)}} \quad (6)$$

Where:

- $C_{(t2)}$ = gas concentration in actual measurement
- $C_{(t1)}$ = gas concentration in previous measurement
- $V_{(K)}$ = headspace volume of batch test
- $V_{(B)}$ = biogas volume being formed since last measurement

During the first measurement $C\ (t_1)$ is set to zero, since there is no CH_4 concentration (biogas) in the bag present. For small volumes this thereby gives indeed a mistake, which, however, it is taken into account, as it leads to a lower amount of gas in comparison to the real gas amount being formed; thus no higher biogas yield is suggested. [29] Once the measurement gives a sum of methane and carbon dioxide concentrations of 90% or more, the headspace correction is not applied anymore and the concentrations from the device are being used without headspace correction. [29]

3.2 Continuous tests

Continuous tests are carried out by using continuous reactors. Due to the fact that the reactors are not fed and the produced biogas is not measured during the weekend, this continuous test is not the exact description of the behavior of a continuous digester. [25]

3.2.1 Layout and devices

There are self-constructed continuous reactors made from acryl glass for the continuous tests (FIGURE 13). The rectors have a volume of 15 liters and normally are filled up to 12 liters of mixture of substrate and inoculum. As is shown in FIGURE 14, a modified drill machine is connected with agitating blade used for the reactor as a stirring device with a revolution of 100 rpm. The drill machine is fixed and connected with the socket with timer for providing regular and stable mixing. FIGURE 15 shows the timer for controlling the stirring devices. During sampling and feeding for the reactors, the timer should be turned off for stopping the mixing and avoiding the possible spatters. FIGURE

16 introduces the detail layout of the reactor with labels. Nr.1 shows the connection between drill machine and the acryl glass reactor. Nr.2 is the water seal; it can ensure a stirring without inserting air into the anaerobic process and prevent damages from overpressure inside the reactor. Therefore, the water level in the water seal should be kept in a range. Nr.3 is one of the two small gas collection holes, and it is for collecting the produced gas from reactor to Thesseraux® gas bag. Nr. 4 shows the double walled heating coat for providing optimal temperature of 42°C for digestion. Nr.5 shows the one of the water pipes connected between two reactors for water circulation.Nr.6 is the sampling port, which is for daily feeding and sampling.

FIGURE 13.Continuous reactors machine

FIGURE 14: Stirring device made from drill

FIGURE 15: Timer for stirring devices

FIGURE 16: Continuous reactor with labels

FIGURE 17 is the water bath set for constant 42°C heating. The heated water is pumped into reactors heating coat. FIGURE 18 is the sampling port is open for feeding and sampling.

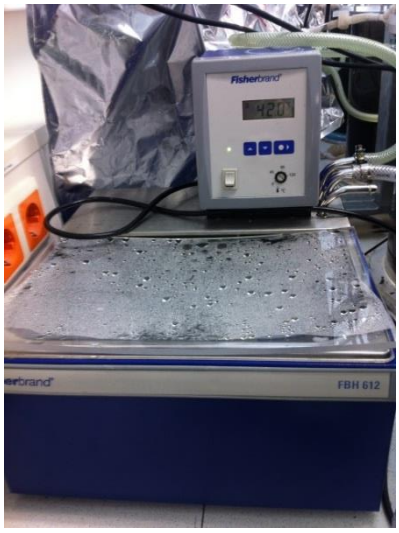

FIGURE 17: Water bath

FIGURE 18: Sampling and feeding connection

3.2.2 Test operation

After the reactors are set up, the reactors are filled with sewage sludge (inoculum) and heated at 42 °C for one day. Later on, cow dung and small amount of substrates are added to the reactors for the adaptation of methane bacteria. During this starting period, it is important to observe the process malfunctions, such as leaks and sufficient mixing. FOS/TAC value should be determined daily during this starting period for monitoring the environment in the reactors. There are important inspections shown in TABLE 8 that needs to be done daily for ensuring the stable running of the continuous reactors.

TABLE 8: Daily inspections and instructions

Daily inspections	***Instructions***
Level of water seals	Fill to the line with distilled water
Level of water bath	Fill with distilled water when the level of water is low
Leak tightness of heating coat	Use gas measurement device
Leak tightness of gas devices	Use gas measurement device
Stirring devices	Check the stirring speed when it is plugged in

When there is a missing gas production (empty gas-bags), it is an obvious indication for a problematic process, for example, there could be gas leaks or acidity in the process. System performance is determined based on collection of bioreactor process data: pH, FOS/TAC value, ammonium value, produced biogas yield and composition. In order to monitor the biogas process in the continuous reactors as good as possible, the analyses should be done daily or in certain period (TABLE 9).

TABLE 9: Analyses and instruction for continuous reactors

Analyses	*Instructions*
pH-Value	Daily
Determination of FOS/TAC Value	Daily
Ammonium	Once per week
Organic acids	Once per week
Amount of produced biogas	Daily
Composition of produced biogas	Daily

Besides the analyses, the continuous reactors should be fed every weekday and the wastes should be sanitized before the feeding.

3.2.3 Sample taking

The reactor is opened for a short time for taking a sample out of the digester. The sampling connection guarantees a minimal gas exchange and does not inhibit the anaerobic process. FIGURE 19 below is a device constructed for taking a sample.

FIGURE 19: Sample taking device

On every weekday, certain amount of mixture should be taken out from the reactor for ensuring the mixture volume in the reactor is constant. The amount of sampling material is chosen according to the amount of feeding. For daily analysis, about 50 g of sample should be taken out and for weekly analysis a bigger sample should be taken, about 200 g.

3.3 Chemical parameters

3.3.1 Ammonium

Samples are taken out from the four continuous reactors and centrifuged with 11,150 rpm for 20 minutes. The liquid phase of the sample after centrifugation is diluted for *Dr.Lange* cuvette tests, usually the dilution is 1:10 or 1:20. [25] The spectral photometer can analyze the sample only when the NH_4-N is between 47- 130 mg/L. FIGURE 20 shows the pictures from the Lange cuvette test package showing work steps at a glance.

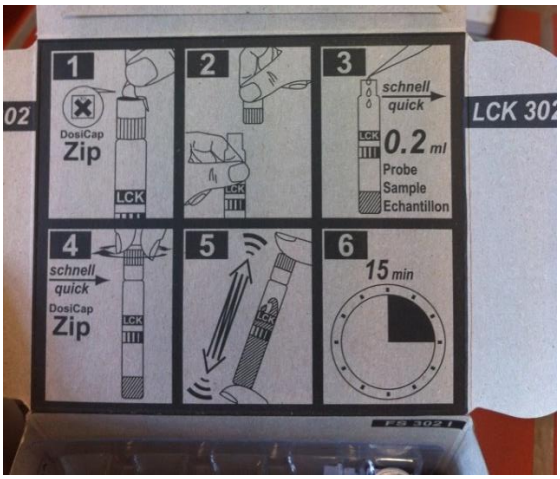

FIGURE 20: picture from the Lange cuvette test package showing work steps

Firstly, the metallized shield is removed from the cap and then the cap is removed as well. When the test tube is opened, it is important to keep the cap vertical, because there is dry reagent inside the cap. 0.2 ml of diluted sample is placed into the test tube quickly, and the cap is turned upside down while attaching to the test tube again so that the reagent

can drop to the test tube. After the cap is tightened, shake the test tube well and wait 15 minutes before placing it to the spectral photometer for analysis.

3.3.2 pH-value

pH-value should be measured every weekday for monitoring the digester process. The sample is taken out from the reactor and measured with pH meter. It is suggested to move the electrode of the measuring device to get representative result, or get stirring with a magnetic stirrer for sufficient mixing of the sample.

3.4 Physical parameters

3.4.1 Dry matter and organic dry matter content

The instructions of defining dry matter and organic dry matter content of samples are *EN 12880(2001-02)* and *EN 12879(2001-02).* The determination of dry matters is by weighting the fluid loss of samples. The first step is to weight the ceramic crucibles and record their mark numbers. Then the ceramic crucibles are filled with samples and weighted again. After recording the weight of each sample, the crucibles are placed in the heating cabinet for 48 hours at 105ºC temperature (FIGURE 21). [25]

FIGURE 21: Samples in the heating cabinet

After 48 hours, the samples are dried. Ceramic crucibles are taken out from the heating cabinet and placed in a desiccator for cooling down. When the crucibles are at room

temperature, they can be weighted again for defining the dry matter of samples. Equation (7) is the calculation of defining the dry matter content of samples. [25]

$$DM = \frac{(W3-W1)}{W2} \times 100[\%] \quad (7)$$

Where:

- W1= tare weight of crucible in grams
- W2= weight of original sample as received in grams
- W3= weight of dried sample and crucible in grams

For defining the organic dry matter content of samples, the dried samples from heating cabinet should be placed in a muffle kiln (see FIGURE 22) and burned at 550ºC for 360 minutes. After the reduction to ashes, the crucibles should stay inside the muffle kiln until they reach a lower temperature, before cooling down in a desiccator and afterwards weighted. The organic matters are burned away in the muffle kiln, and only the inorganic compounds remain as ashes. The equation 7 is for calculating the organic dry matter content relating to the original fresh mass. [25]

$$oDM = \frac{W3-W4}{W2} \times 100[\%] \quad (8)$$

Where:

- W2= weight of original sample as received in grams
- W3= weight of dried sample and crucible in grams
- W4= weight of the ash and crucible in grams

FIGURE 22: Muffle klin

3.4.2 Sanitation

Although the present of pathogens or pathogenic microorganisms in the substrate does not usually affect the outcome of the biogas process, but it can influence the quality. If there is epidemiological and pathogenic risks in the substance groups, thermal pretreatment is obligatory. [6] Terms of sanitation are regulated by *EG-sanitary* regulations. According to the guideline *1774/2002*, substances which underlie the sanitation regulation have to be heated at 70 °C for an hour. Particles of the substrate may not be larger than 12 mm for ensuring safe pasteurization. Sanitizing the substances at 55ºC is also feasible, but a period of not less than 10 hours is required. FIGURE 23 shows that the water bath is used for sanitizing the substances at 70ºC, while heating chamber is used for sanitizing at 55ºC, because the temperature is easier to hold for ten hours. [25]

Figure 23: Water batch for 70 Celsius degree sanitation

3.5 Parameters for process monitoring

3.5.1 FOS/TAC

The buffer capacity is defined by a titration test called FOS/TAC, according to the instruction from the *Federal agricultural research center of Germany (Johann Heinrich von Thünen Institue(vTI)*. [25]

For the determination of FOS/TAC, samples are taken from reactors and filled into special centrifugal tubes. The total weight of each sample and tube should be similar for the correct operation of the centrifuge. The tubes are then placed in the centrifuge and centrifuged with 11150 rpm for 20 minutes. After centrifuging, beaker is labeled and placed on a scale for resetting the zero. 5g of the liquid phase from each centrifugal tube is transferred into the beaker and afterwards filled to 20g with miller pore water for getting the sample with dilution rate 1: 4. It is of great importance to work accurate and get the exact weight to avoid variability in FOS/TAC values. Next step is to add a magnetic stir bar to the beaker, which would be placed on the magnetic stirrer for creating a stable speed to get a homogenized sample. In the laboratory the pH meter and the titrator is placed next to each other, and the titrator includes a magnetic stirrer (FIGURE 25).

FIGURE 24: Titrator with magnetic stirrer *FIGURE 25: pH meter is placed next to titrator*

As is seen in FIGURE 24, the probe and the pipette are placing in the sample, and the beaker is on the magnetic stirrer. Now the pH value of the sample has to be adjusted with 0.1N H_2SO_4 with the titrator to pH 5.0. The amount of used acid is displayed on the titrator and has to be written down for the calculation of TAC value. Afterwards the titrator is

reset to zero for the second titration from pH 5.0 to pH 4.4. The amount of acid should be also written down for the calculation of FOS value. It is important to keep in mind that the second titration only needs small amount of acid to reach pH 4.4, therefore the second titration should be operated carefully and slowly to avoid the over fall of pH. [25] The calculation of FOS/TAC is shown in equation (9).

vTI guidelines:

Amount of substrate: 20 mL
H_2SO_4: 0.1N (=0.05mol/L)
TAC= H_2SO_4- usage till pH 5.0 in mL x 1000
FOS= (H_2SO_4-usage till pH 4.4 in mL x 1.66 x 4-0.15) x500

$$FOS/_{TAC} = \frac{FOS(((amount\ H_2SO_4\ from\ pH\ 5.0\ till\ pH\ 4.4 \times 1.66 \times 4) - 0.15) \times 500)}{TAC(amount\ of H_2SO_4\ from\ pH\ X.X\ till\ pH\ 5.0 \times 100)} \quad (9)$$

The FOS/TAC ratio from 0.3 to 0.4 is common, however, every individual biogas plant has its own optimal value. Due to the fact that the optimum FOS/TAC value is determined through long term monitoring and continuous measuring, as the value is depending on the substrate composition. At the starting phase of anaerobic digestion, the FOS/TAC value can vary a lot, but it is still important to keep measuring because every increase of FOS/TAC can cause a process inhibition. TABLE 10 shows the FOS/TAC value meanings. [25]

TABLE 10: Referable meanings of FOS/TAC values [25]

VALUE	Background	Procedure
>0,6	plant heavily overfed	stop feeding
0,5-0,6	plant overfed	reduce feeding
0,4-0,5	plant heavily loaded	increase measuring
0,3-0,4	plant well-utiliyed	hold feeding
0,2-0,3	plant hungry	increase feeding slowly
<0,2	plant very hungry	increse feeding quick

3.5.2 Volatile fatty acids

For better monitoring of the continuous reactors, organic acids is determined. The samples from the digester must be pretreated before measuring the amount of acids with gas chromatograph and mass spectrometer. The samples must have a pH-value between 1 and 2 by adjusting with 10% sulfuric acid. In the laboratory, 20 g of sample from the continuous reactor is weighted in a beaker, then 10% sulfuric acid is titrated into the sample while at the same time pH meter is used for measuring the pH changes in the sample. It is suggested to shake the probe gently to provide a well mix of sample and acid. After the pH value reaches between 1 and 2, the mixture of acid and sample is filled with miller pore water for dilution to a mass factor of three. Afterwards, the adjusted and diluted sample is input to the special centrifugal tube for centrifuging at 11150 rpm for 20 minutes. After centrifugation, the liquid phase is filtered using 10ml Syringe and 25mm Syringe filter with 0.2 µm Polypropylene membrane and filled into the 1.5 ml sampling vial for gas chromatography for measurement of acids. [25] FIGURES 26, 27 and 28 are the pictures of syringe, filter and vial used for the measurement.

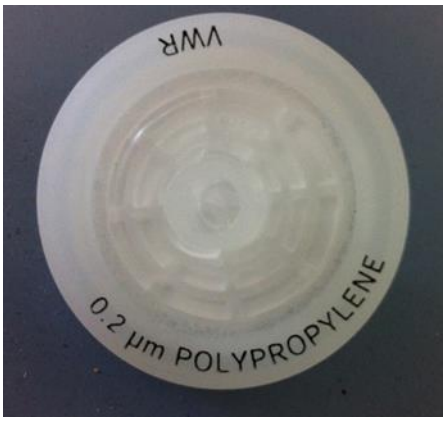

FIGURE 26: 0.2 µm Polypropylene filter

FIGURE 27: Sample in the 1.5ml sampling vial

FIGURE 28: 10ml Syrine

3.5.3 Biogas yield and measurement

Produced gas from continuous reactors as well as batch reactors is measured by gas measuring device called *SEWERIN SR2-DO* (FIGURE 32), which can measure the volume of CH_4 and CO_2 of gas in percentage(% vol) and H_2S in parts per millions(ppm). After measuring the composition of gas, gas pump (FIGURE 31) can be used to pump out the gas from the gas bag while at the same time, the total gas volume through the pump as well as the gas measuring device is recorded by the gas meter called *Ritter*. (FIGURE 29) FIGURE 30 is the overall picture of the layout of gas measurement setup.

FIGURE 29: Ritter gas meter

FIGURE 30: Overall setup for gas measurement

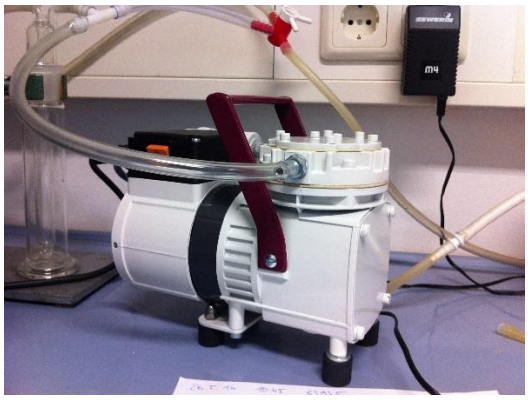

FIGURE 31: Pump for pumping the gas

FIGURE 32: SEWERIN SR2-DO

Gas volume varies depending on the surrounding conditions: pressure, temperature, water content and composition. Therefore, gas volumes must be standardized. According to *DIN 1343*, gas is in standard conditions when the temperature is normed temperature T_n= 273.15K (or t_n= 0°C) and the pressure is normed pressure P_n= 101325 Pa (or 1013.25 mbar). V_n is the normed gas volume when it is under normed conditions. Another important thing is the amount of moisture of biogas. With increasing amounts of moisture the heating value decreases. Therefore, for better comparability, it is advisable to declare the normed gas volume on anhydrous gas, which means the relative humidity is equal to 0%. There are many ways of calculating the saturated vapor pressure. Using the using the *August-Roche-Magnus* formula can made a good approximation of saturated vapor pressure and therefore it is used here. [25] [30]

$$P(H_2O) = 6.1094\exp\left(\frac{17.625T}{T+243.04}\right) \quad (10)$$

Where:

$P(H_2O)$ is the saturated vapor pressure in hPa, T is the room temperature on Celsius scale. [30]

Now the gas volume can be normalized according to the ideal gas law with the value of saturated vapor pressure. Equation is introduced below:

$$V_n = V \times \frac{(P - P(H_2O) \times 273.15)}{1013.25 \times (273.15 + T)} \quad (11)$$

Where:

- V_n is the normed volume of gas on cubic meter
- V is the measured gas volume in the laboratory on cubic meter
- T is the room temperature on Celsius scale
- $P(H_2O)$ is the saturated vapor pressure in Pa
- P is the atmosphere pressure recorded during gas measurement in Pa

3.5.4 Organic loading rate

The organic loading rate is one of the most important and significant parameters for a biogas plant. For an ideal operating of lab scale fermenter, a steady feeding is necessary with the organic loading rate between 1 to 5 kg oDM/(m^3 *d). To define the amount of feeding an organic loading rate should be chosen first. It is suggested to start the feeding with low organic loading rate so that the reactor does not have overcharging and also it is good for the increase of methanogens amount. [25]

3.5.5 Degree of degradation

On the last day of batch tests and on the 7^{th} day after substrate fed stopped in continuous reactors, DM and oDM tests were carried through in order to determine the degree of degradation of substrates. The basic principle of defining degradation rate is mentioned in chapter 2.4.8, however, there are different practical equations for the calculation of degradation rate of substrate in batch test and continuous test.

3.5.5.1 Determination of degree of degradation of substrate in continuous reactors

On every weekday, certain amount of substrate is fed in the continuous reactors and certain amount of digestate is taken out from the reactor for ensuring the mixture volume in the reactor is constant. That is so to say, the mass of digestate in continuous reactor is always constant. The equation below can be used for defining the degradation rate of substrate in continuous reactors. [6] On the 7th day after substrate fed stopped in continuous reactors, the DM and oDM tests were done to get the information about the efficiency of substrates conversions. Equation (12) shows the method of calculating the degree of degradation for substrate in continuous reactor.

$$Degree\ rate = \frac{oDM_{sub} \cdot m_{sub} - (oDM_{dig} \cdot m_{dig})}{oDM_{sub} \cdot m_{sub}} \cdot 100[\%] \qquad (12)$$

Where:

- oDM_{sub}= organic dry matter content of substrate in %
- m_{sub}= total substrate fed to the reactor in g
- oDM_{dig}= organic dry matter content of digestate from reactors
- m_{dig}= the mass of total digestate in continuous reactor in g

3.5.5.2 Determination of degree of degradation of substrates in batch reactor test

On the first day, total amount of 3500 g mixture of inoculum and substrate is inputted in the batch reactor for 35 days. That is to say, there is no further more substrate added in the batch reactors. After 35 days, there is mass lost in the reactors but it is not easy to tell the exact amount of mass lost from inoculum and substrate. Therefore the equation 11 is not suiTABLE to define the degree of degradation of substrate in batch reactors. There are zero batch tests with only 3500g of inoculum for determination of DM and oDM of wastewater after 35 days batch test. In order to get the exact organic dry matter left from

leftover substrate, the equation below is used. [31] Equation (13) shows the method of calculating oDM of leftover substrate in batch reactor.

$$oDM_{leftover} = (m_{dig} * oDM_{dig)} - (m_{dig} * oDM_{zero}) \quad (13)$$

Where:

- $oDM_{leftover}$ = organic dry matter of leftover substrate after 35 days in g
- m_{dig}= mass of leftover digestate(mixture) after 35 days in g
- oDM_{dig}= organic dry matter content of leftover digestate(mixture) after 35 days
- oDM_{zero}= organic dry matter content of zero batch test after 35 days

As long as the oDM of leftover substrate is known, the degradation rate of it can be calculated by using the equation (14). [31]

$$degree\ rate = \frac{oDM_{begining} - oDM_{leftover}}{oDM_{begining}} * 100[\%] \quad (14)$$

Where:

- $oDM_{begining}$= organic dry matter of original substrate in g
- $oDM_{leftover}$ = organic dry matter of leftover substrate after 35 days in g

4 RESULTS

In this chapter, results from mesophilic continuous wet reactors tests and batch tests are introduced in detail, as well as the operating parameters. My team mate Patrick Niekamp was doing similar continuous tests using the same municipal solid waste from Sweden, with adding enzyme for increasing the methane yield. His thesis topic is "Einfluss von cellulasen von t. Reesei auf das biogaspotential von kommunalen haushaltsabfällen". [1] Another team mate Matthäus Barasinski's thesis topic is "Etablierung einer Garagenfermentation zur Produktion von Biogas aus Abfällen", he was doing thermopilic dry garage digester tests using same municipal solid waste. [2] In Sweden, there is a pilot plant using also the same municipal solid waste to produce biogas by plug flow reactor. Therefore, results of total methane production per kg fresh mass (municipal solid waste) inputted from wet digesters, dry digester and plug flow reactor are compared here. There are also results of cash flow analysis using actual data from *Svensk Växtkraft AB* and theoretical data, which will be introduced in this chapter.

4.1 Dry matter and organic dry matter content

TABLE 11 is the information about the average dry matter and organic dry matter content of the substrates SVHH (Presorted biowaste), SV Reject and NN (municipal solid waste). DM and oDM percentages are referred to the original sample, which means the fresh mass. NN samples were sorted before measurements, it had relatively high dry matter content but lower organic dry matter content compared with other wastes. There were three batches of municipal solid waste received from Sweden. The first batch municipal solid waste contained quite much glass, and small amount of metals, but not much plastic. The second batch municipal solid waste contained quite much plastic but much less glass. The third batch municipal solid waste had similar properties with the first batch. The organic dry matter test showed that the second batch municipal solid waste had most dry matter and organic dry matter.

TABLE 11: Dry matter and organic dry matter content of substrate

Name	DM%	oDM%
SVHH (Presorted biowaste)	31,01	28,11
SV Reject	34,64	30,83
NN on day 1st (municipal solid waste)	48,11	27,26
New NN on day 36th	59,76	44,22
New NN on day 51st	50,77	33,01

On the last day of batch tests and on the 7th day after substrate fed stopped in continuous reactors, DM and oDM tests were carried through in order to determine the degree of degradation of substrates. TABLE 12 below is the results of DM and oDM of leftover digestate.

TABLE 12: oDM results of leftover digestate

	Name	Average oDM [%]
Continuous Test	Reactor 1	2,06
	Reactor 2	2,10
	Reactor 3	3,84
	Reactor 4	3,65
Mesophilic Batch Test	Reject 1	0,35
	Reject 2	0,29
	NN1	0,41
	NN2	0,38
	HH1	0,35
	HH2	0,35
	Zero Batch Test(Only Inoculum)	0,25
Thermophilic Batch Test	Reject 1	0,36
	Reject 2	0,32
	NN1	0,30
	NN2	0,43
	HH1	0,32
	HH2	0,29
	Zero Batch Test(Only Inoculum)	0,17

As is shown in TABLE 12 above, the oDM% of leftover digestate in continuous reactors had about 10 times bigger values than the ones in batch reactors. Zero batch tests had the smallest value of oDM%, continues reactor 3 and 4 had the biggest value of oDM%.

4.2 Presorted Biowaste

4.2.1 Continuous Mesophilic Wet Digester Tests of Presorted Biowaste

There were two reactors (reactor 1 and reactor 2) running with presorted biowaste, as parallel tests. Both reactors ran for 65 days, over the weekends there were no substrates fed nor gas production measurements. Both of the reactors had an average organic loading rate of 2 kg oDM/ (m3*d) on the first 28 days, 1, 34 kg oDM/(m3*d) from day 29th to day 56th , on day 59th substrate fed stopped, the last gas measurement was on day 65th. Below the results of each reactor test would be introduced separately.

4.2.1.1 Reactor 1

FIGURE 33 is the cumulative methane amount compared with fresh mass input from reactor 1, as is shown. Total methane amount is 0,28Nm^3, and in total 3502 g of fresh mass (presorted biowaste) was used. The line of total CH_4 has similar trend with the line of total substrate input. On day 31st, the heating bath stopped for 20 hours, the reactor's temperature dropped from 42 ºC to 21 ºC. Feeding stopped for 4 days after noticing the FOS/TAC value increased. On day 36th, feeding started again, but the feeding amount reduced from 119, 5 g to 80 g. There was gas leaks from gas bag on day 25th, 43rd and 44th. From day 59th to 62nd, the stirrer stopped, mixing was not sufficient. The specific methane yield in reactor 1 was 79,95 [(Vn) L/kg] CH_4/fresh mass.

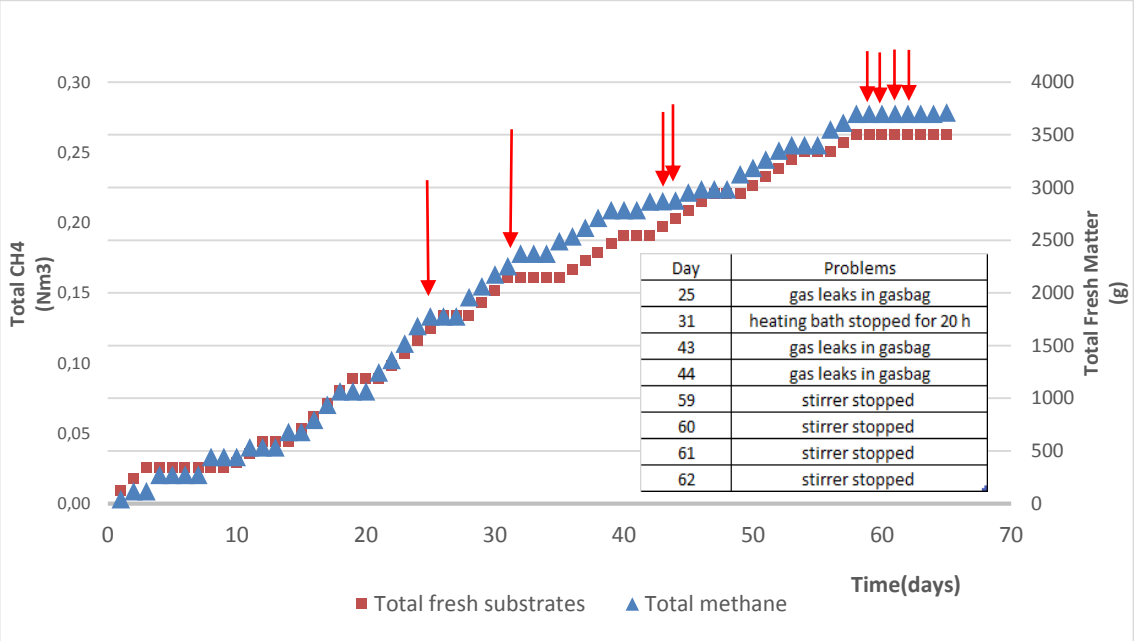

FIGURE 33: Cumulative methane amount compared with fresh mass (presorted biowaste) input- reactor 1

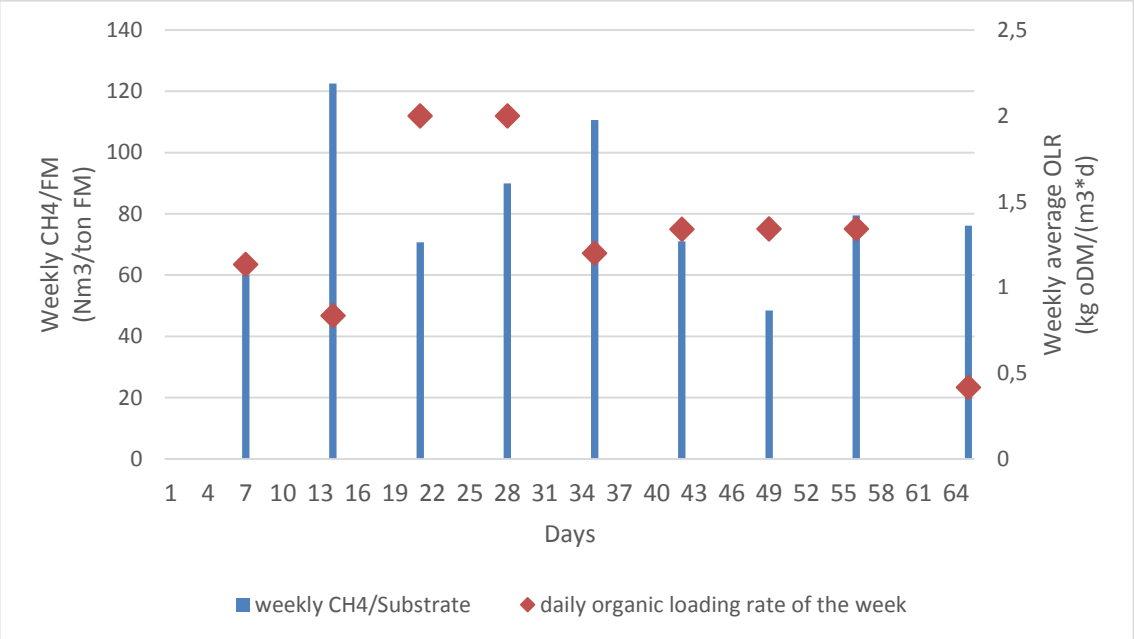

FIGURE 34: Weekly methane production with weekly average organic loading rate- reactor 1

In FIGURE 34, the blue column is the average weekly methane production per fresh substrate input, which is calculated by dividing the sum fresh mass used of the week with the sum methane production of the week. The red point is the average daily organic loading within the same week. As is show, between days 44 to 49, the weekly CH_4/fresh mass is 50 Nm^3/ton, much lower than the other weeks, it is mainly due to gas leaks for two days during this week. In the last week, only 160g of substrate was input to the reactor, and the gas production was collected from day 57th to day 65th, in total 9 days instead of 7 days.

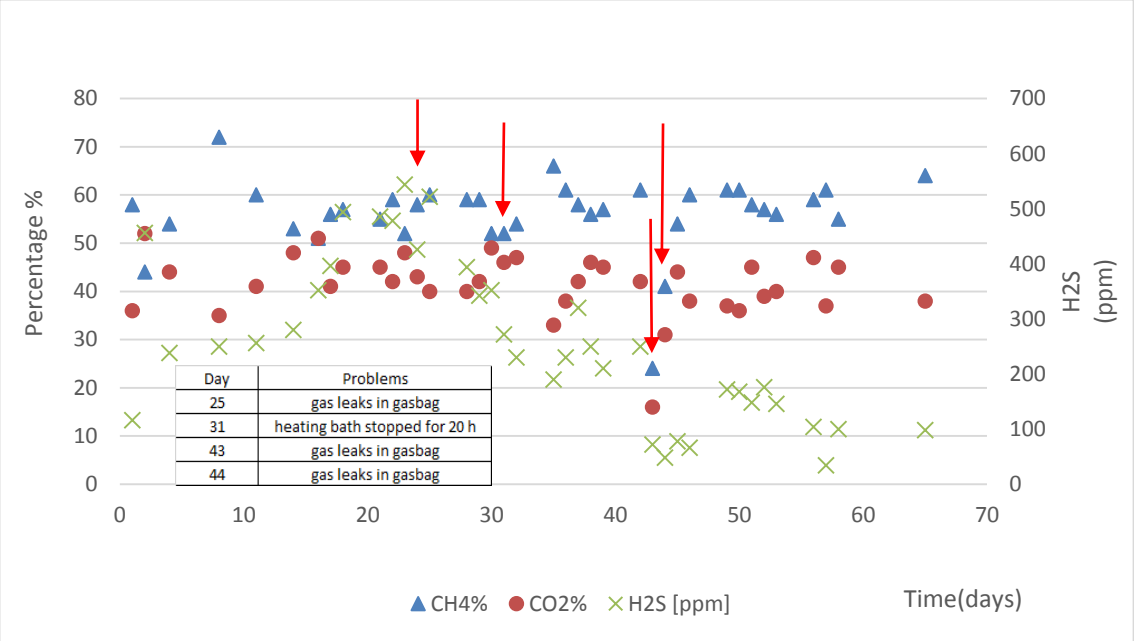

FIGURE 35: Biogas composition from reactor 1

FIGURE 35 is the detail information about produced biogas composition during the 65 days from reactor 1. H_2S concentration first increased from 130 ppm to 520 ppm and decreased after day 25th. On day 31st, the heat batch stopped working for 20hours, the methane concentration dropped a bit, and since this day, H_2S concentration started to decrease gradually. On day 43rd and 44th, there was gas leaks from gas bag, leading to the drop of CH_4 % and CO_2 %. In the last week, due to the insufficient mixing in the reactor, there wasn't much gas production. The average methane percentage in produced biogas is 56, 5%.

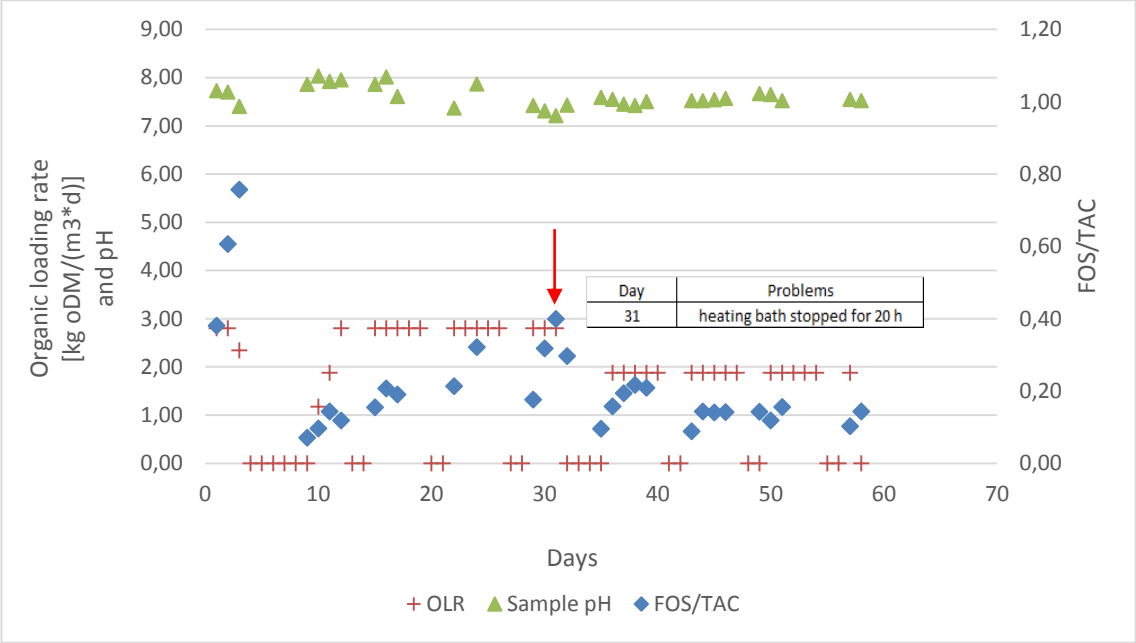

FIGURE 36: Operational parameters (Organic Loading Rate, pH, FOS/TAC) in reactor 1

FIGURE 36 above is the operational parameters in reactor 1. As is shown in the graph, the pH value of the samples from reactor 1 was relatively stable, only on day 31st when the heat bath stopped and the temperature inside the reactor dropped from 42ºC to 21º C, the pH decreased a bit. On the same day, the FOS/TAC value of the sample reached to 0, 4. Substrate fed stopped for four days after this issue, and the daily organic loading rate during weekdays decreased from 2,8 kg oDM/ (m^3*d) to 1,87 kg oDM/ (m^3*d) from that on (day 36th).

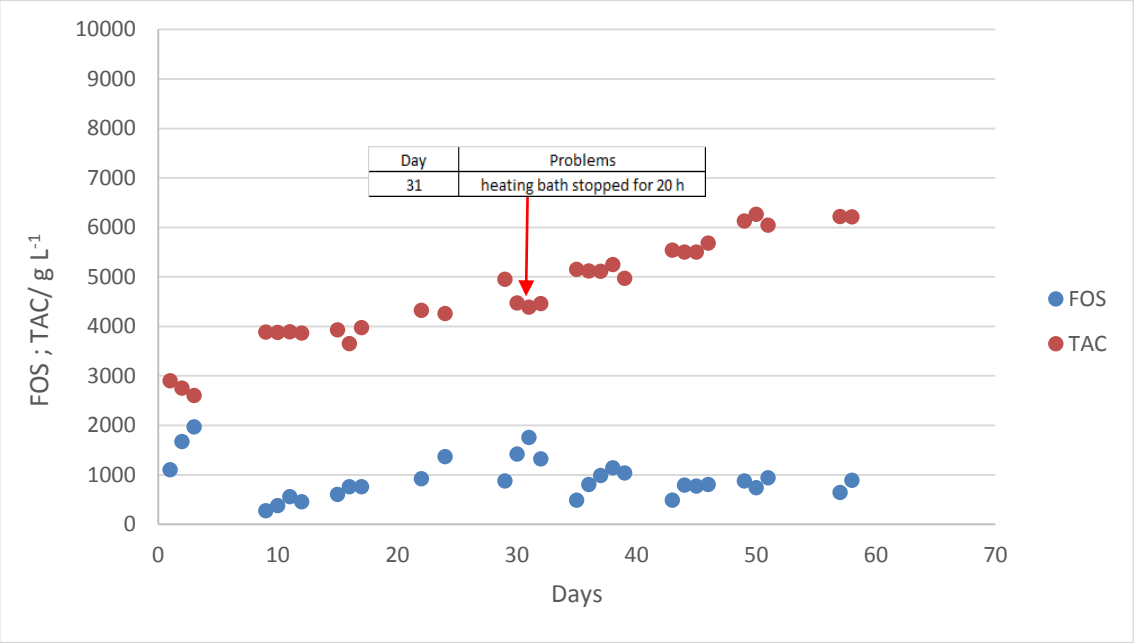

FIGURE 37: FOS and TAC value in Reactor 1 Samples

FIGURE 37 above is the FOS and TAC value in reactor 1 samples. On day 31st, heating bath stopped and reactor temperature dropped to 21 ºC, the FOS value increased. During these 65 days, the FOS value was quite constant, and the TAC value had a gradually increasing trend.

TABLE 13 is the organic acid test result of the samples from reactor 2. As is presented, there was only acetic acid in the samples, and the concentration was rather low.

TABLE 13: Organic acid test result of reactor 1

HH1	Acetic acid[mg/l]
Day 38	124,31
Day 46	78,01

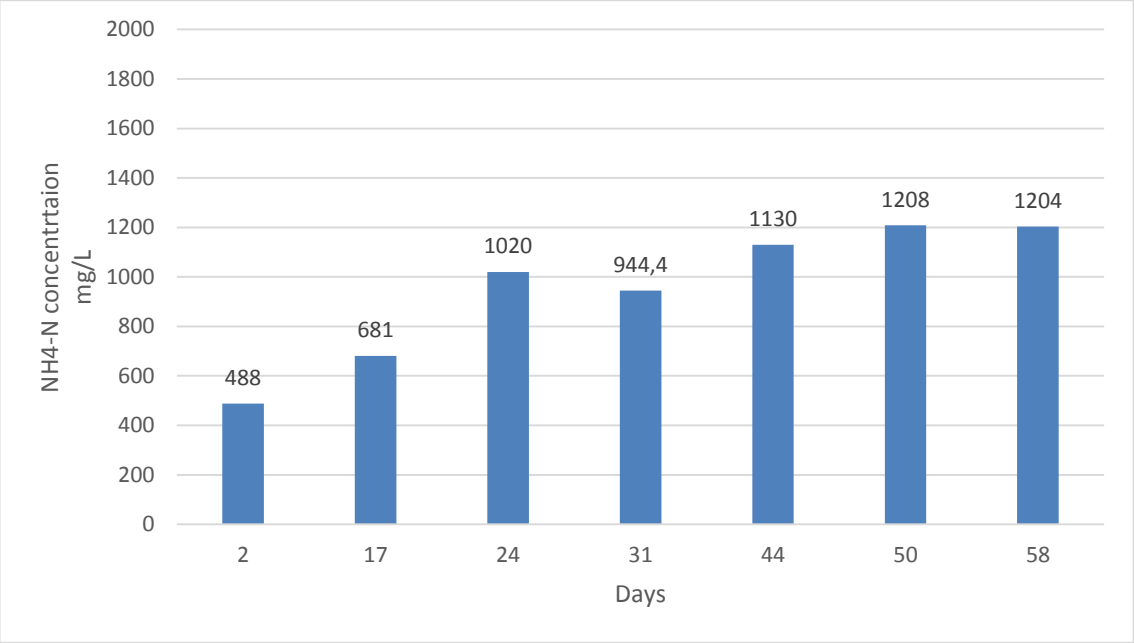

FIGURE 38: Ammonium concentration in reactor 1

FIGURE 38 is the ammonium concentration of the samples from reactor 1. As is shown below, the ammonium concentration was increasing gradually along the operational process, and the highest value of ammonium concentration was 1208 mg/L.

TABLE 14 below is the degradation rate of leftover substrate in reactor 1. The sample was taken from day 65th for the DM and oDM test, which was the 7th day after substrate fed stopped. The was 2,06% organic dry matters in the digestate from reactor 1, and the result of degradation rate of leftover substrate was 74,87%, which means that in continuous reactor 1, the bacteria were able to digest 74,87% of the inputted 3502 g substrate.

TABLE 14: Fermentation information

Name		Ø oDM [%]	Degree of Degradation	Added Substrate
Continuous test		average	%	g
Reactor 1		2,06	74,87	3502

4.2.1.2 Reactor 2

The total methane production from reactor 2 was 0, 22 Nm^3, and the total fed biowaste was 3502g, as the same as reactor 1's. The specific methane yield in reactor 2 was 63, 45 CH_4/fresh mass [(Vn) L/kg].

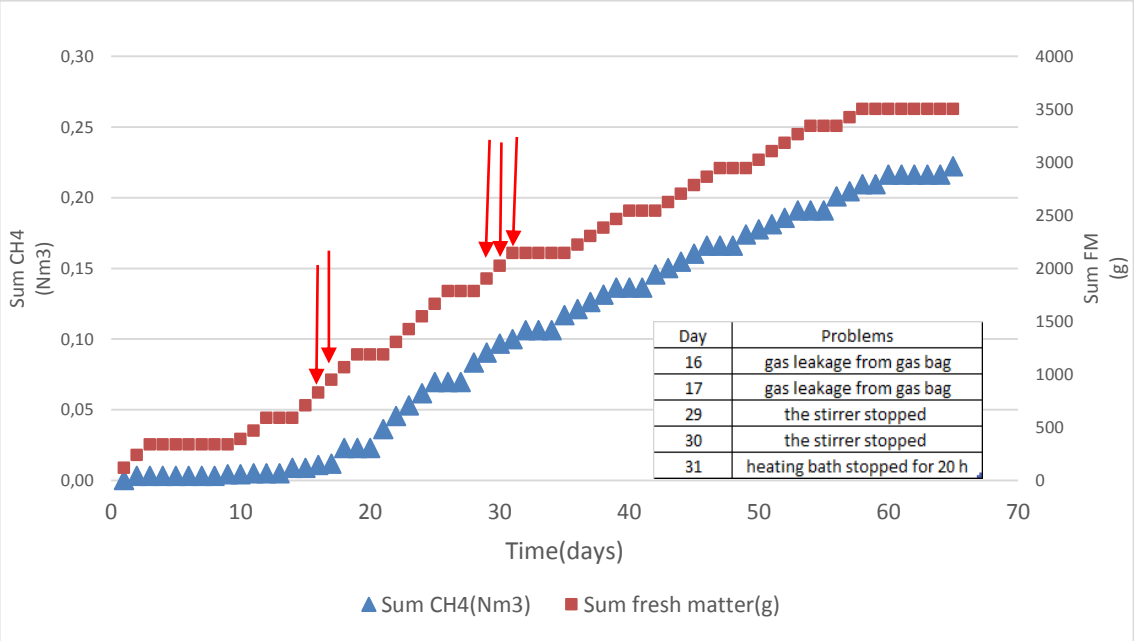

FIGURE 39: Cumulative methane amount compared with total biowaste fed in reactor 2

FIGURE 39 above is the total methane production during the process running compared with the amount of fed substrate. As is presented, the two lines are not close up to each other, the line of sum CH_4 is quite much under the line of sum substrate. There was gas leaks on day16th and 17th, the stirrer did not work for two days (29th and 30th), and on day 31st the heating bath stopped working, temperature inside the reactors dropped to 21ºC.

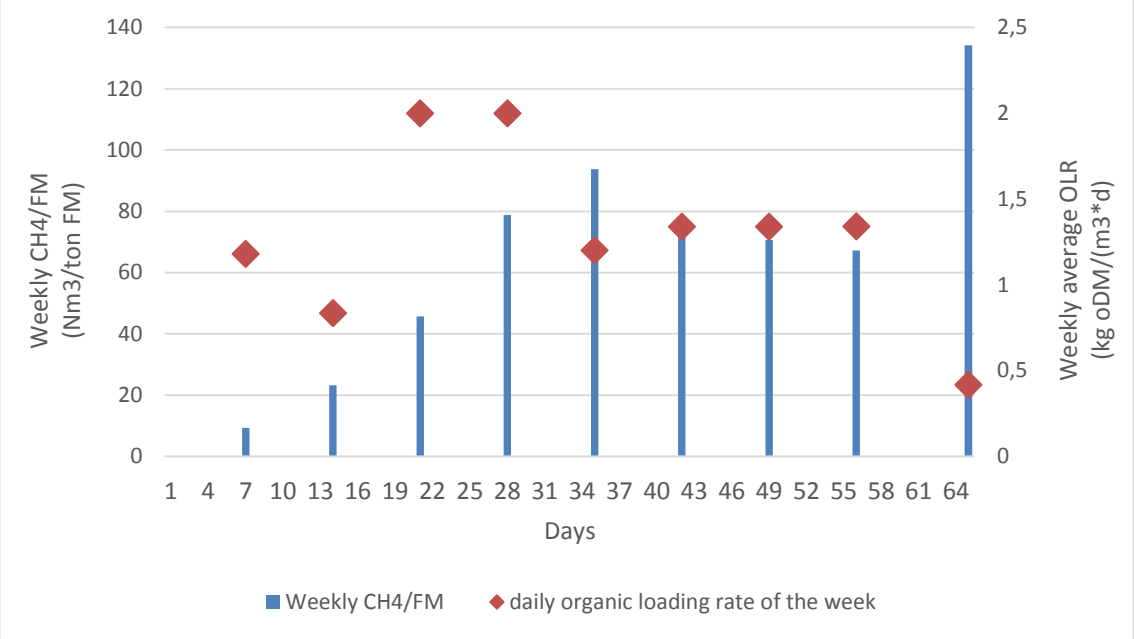

FIGURE 40: Weekly methane production per ton biowaste presented with daily organic loading rate of the week

FIGURE 40 above is the result of weekly CH_4/ton fresh mass input with average weekly organic loading rate presented. The blue column is the average weekly methane production per fresh substrate input, which is calculated by dividing the sum fresh mass used of the week with the sum methane production of the week. The red point is the average daily organic loading within the same week. In the first 4 weeks, the methane production was rather low, and from week 5th, the methane production level tended to be more stable. The last blue shows such high value is due to the fact that in the last week, there was only two days (day 57th and 58th) feeding with in total 160 g of biowaste, the gas production was collected from day 57th to day 65th, in total 9 days instead of 7 days. Particularly worth mentioning is the much less substrate fed in the last week, which leads to the smaller value as the divisor in the equation, resulting in the high value of CH_4/FM. In FIGURE 34, the last blue column shows a much smaller value, it is mainly due to the much less gas production in reactor 1 of the last week.

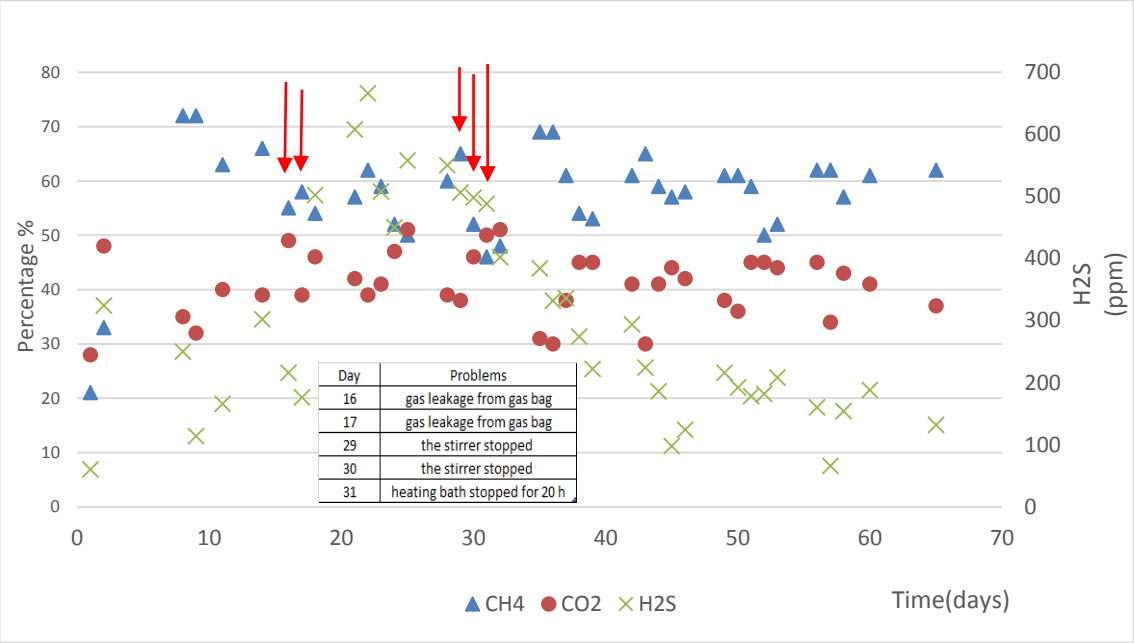

FIGURE 41: Biogas composition from reactor 2

FIGURE 41 shows the detail produced biogas composition in reactor 2. On day 16th and 17th, gas leaks from gas bag was noticed, the CH_4 content decreased a bit and CO_2 % was close to 50%. During day 16th to 32nd, the CH_4 % was quite low, especially when the stirrer stopped (day 29th and 30th) the CH_4% was less than 50%, and on day 31st, the temperature in the reactor dropped, the CH_4% reached to the lowest point compared with other stable days. Overall CH_4% in reactor 2 was changing between 72% and 47%, and the CO_2% had 3 record of exceeding 50%. The average methane percentage in produced biogas is 59%. H_2S concentration was increasing since day 1st till day 22nd, and the highest record was 666 ppm. From day 22nd, the concentration of H_2S decreased gradually.

As is showed in FIGURE 42 below, the FOS/TAC value of samples from reactor 2 was not so constantly stable. It was always higher than the one in reactor 1, although both of the reactors had the same feeding and used the same type of substrate. On day 29th and day 30th, the stirred stopped working, mixing in the reactor 2 stopped, the FOS/TAC value increased from 0, 45 to 0, 66. On day 31st, temperature dropped to 21 ºC, FOS/TAC reached 1, 04, pH dropped to 6, 96. Feeding stopped for four days after day 31st, on day

35th, organic loading rate changed from 2,8 to 1,87 kg oDM/(m3*d), FOS/TAC value of samples decreased.

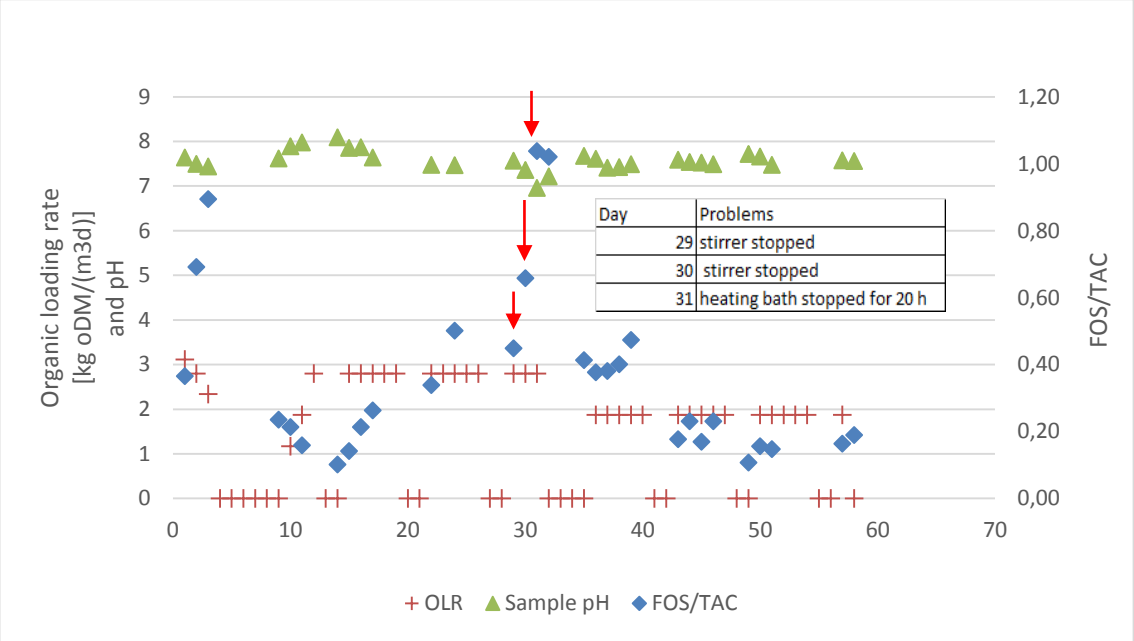

FIGURE 42: Operational Parameters (pH, OLR, FOS/TAC)) of Reactor 2

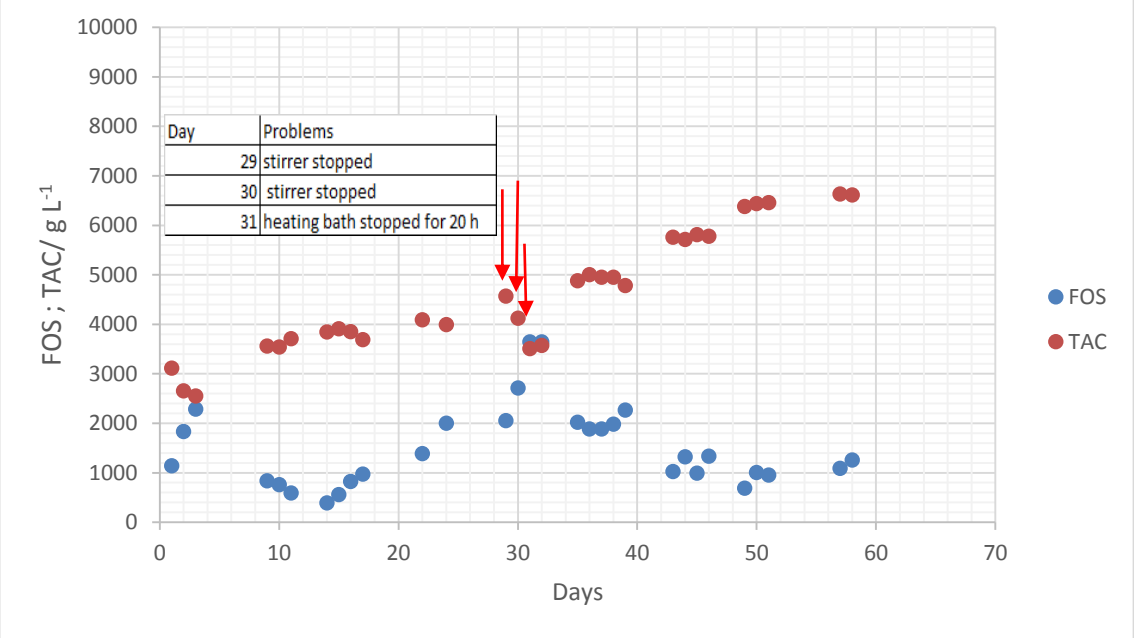

FIGURE 43: FOS and TAC value of samples from reactor 2

FIGURE 43 shows the TAC value tended to increased gradually, except on from day 29th to 31st, it dropped significantly. FOS value was not stable, it increased significantly from day 20th, and reached to highest value on day 31st. From day 35th, the FOS value tended to drop constantly and slowly.

Below is the organic acid test result. There was no other organic acids in the samples except acetic acid, the concentration was below 400 mg/L, and they were high compared with the organic acid test result from reactor 1.

TABLE 15: Organic acid test result from reactor 2

HH2	Acetic acid[mg/l]
Day 38	396,17
Day 46	202,68

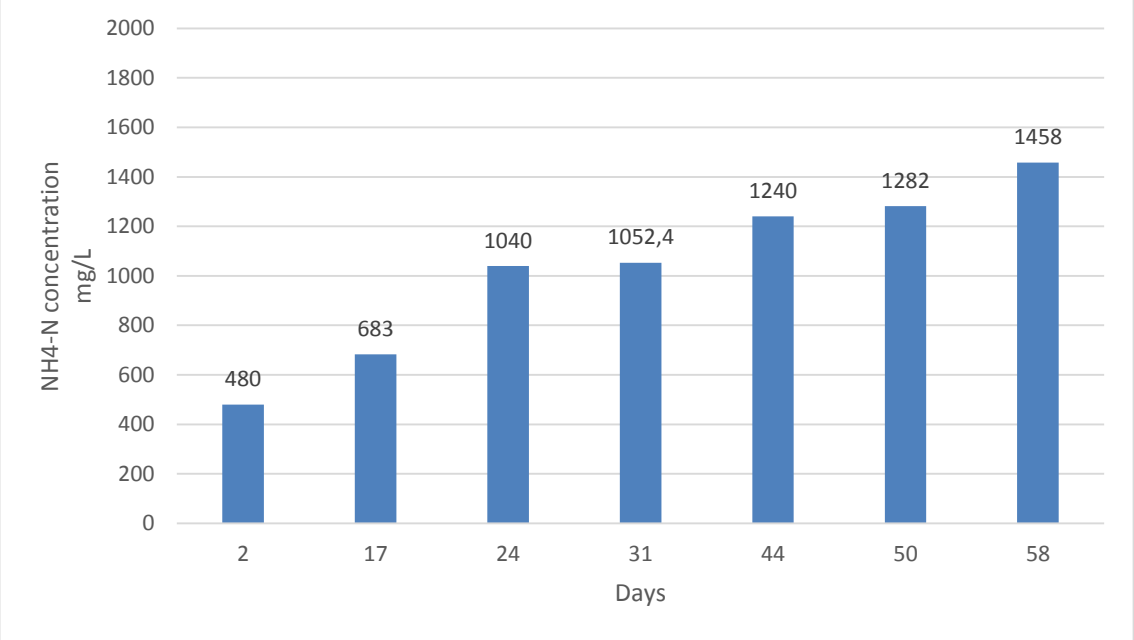

FIGURE 44: Ammonium concentration of reactor 2

FIGURE 44 is the ammonium concentration of the samples from reactor 2. As is shown above, the ammonium concentration was increasing gradually along the operational process, and the highest value of ammonium concentration was 1458 mg/L.

TABLE 16: Degradation rate of leftover substrate in reactor 2

Continuous test	oDM of digestate [%]	Added substrate [g]	Degree of degradation of leftover substrate [%]
Reactor 2	2,10	3502	74,36

TABLE 16 above is the degradation rate of leftover substrate in reactor 2. The sample was taken from day 65th for the DM and oDM test, which was the 7th day after substrate fed stopped. There was 2,10% organic dry matters in the digestate from reactor 2, and the result of degradation rate of leftover substrate was 74,36%, which means that in continuous reactor 2, the bacteria were able to digest 74,36% of the inputted 3502 g substrate. Leftover substrate in reactor 1 had a higher degradation rate (74, 87%).

4.2.2 Batch test of presorted biowaste

There were two parallel mesophilic batch tests and two parallel thermophilic batch tests for the investigation of presorted biowaste biogas potential. FIGURE 45 and 46 are the cumulative methane volume per ton fresh biowaste input.

In mesophilic batch test, there was quite big value difference between reactor 1 and 2, one was able to produce 81, 46 Nm^3 CH_4 per ton biowaste, while the other one only produced 55, 22 Nm^3 CH_4 per ton biowaste. The average CH_4/FM was 68 Nm^3/ ton in mesophilic batch test. In thermophilic batch test, the average CH_4/FM was 47, 10 Nm^3/ton, one produced 51, 77 Nm^3 methane per ton biowaste, another one produced 42, 43 Nm^3 methane per ton biowaste. The average methane percentage in mesophilic batch test was 55, 6%, and 53, 9% in thermophilic batch test.

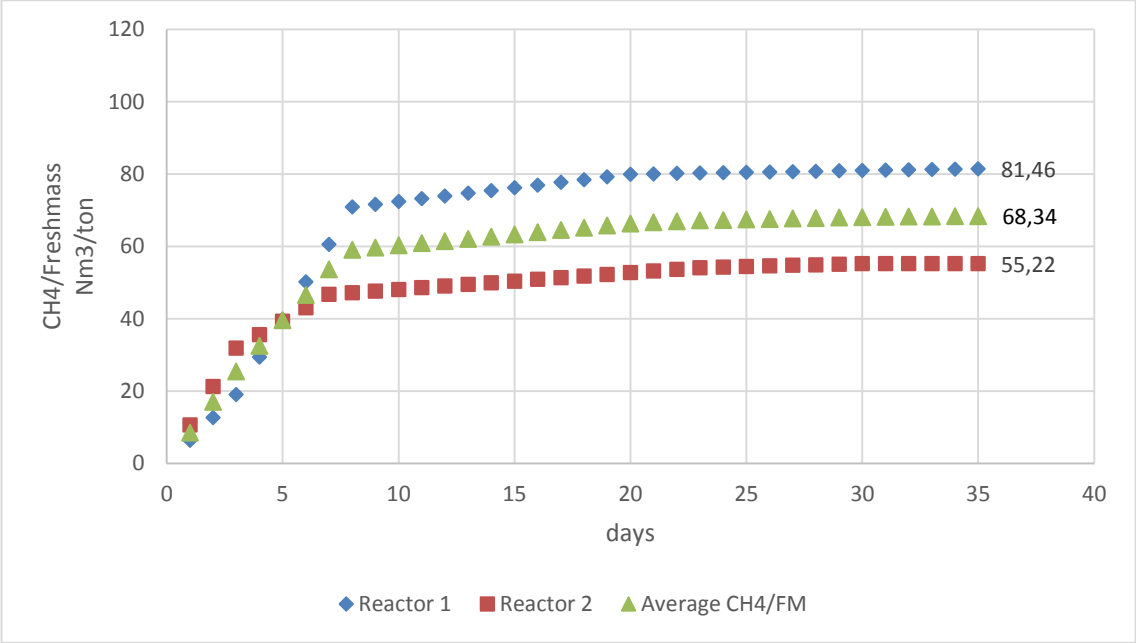

FIGURE 45: Mesophilic batch test results- Cumulative methane amount per ton Pre-sorted biowaste

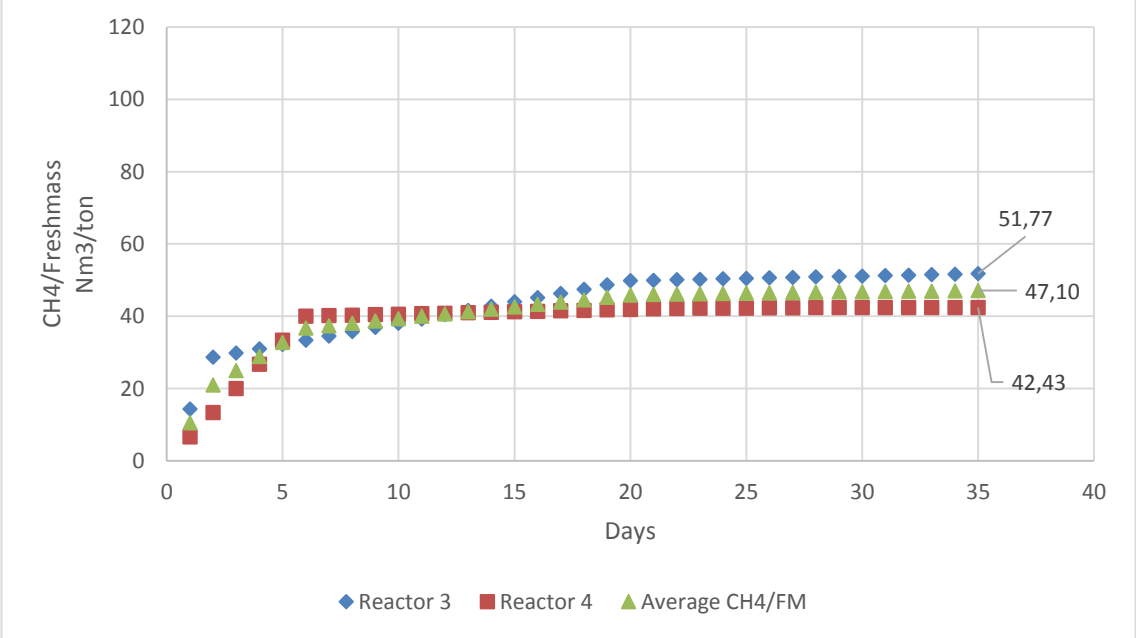

FIGURE 46: Thermophilic batch results- Cumulative methane amount per ton Pre-sorted biowaste

TABLE 17 below presents the fermentation data for pre-sorted biowaste batch tests. Mesophilic batch tests had higher degradation rate of substrate than thermophilic ones. Substrate in Reactor 2 had the highest degradation rate (83, 58%), while substrate in reactor 3 had the lowest degradation rate (75, 50%).

TABLE 17: Fermentation data for per sorted biowaste batch tests

		Fermentation test			abort	Mass different	Degradation rate of organic dry matter
Temperature condition	Sample	Empty flask (g)	Inoculum (g)	Substrate (g)	Full flask after 35d	(g)	(%)
Mesophilic	Reactor 1	1523,3	3424,3	74,2	4998,2	23,6	82,80
	Reactor 2	1488,5	3388,9	75	4938,8	13,6	83,58
Thermophilic	Reactor 3	1478,8	3424,2	74,6	4960	17,6	75,50
	Reactor 4	2240,8	3364	75	5662,3	17,5	80,20

4.3 Municipal solid waste

Municipal solid waste was roughly sorted before being used. Impurities such as big pieces of glass, plastic and iron were sorted out. Continues mesophilic wet reactors and batch reactors were fed with certain amount of municipal solid waste.

4.3.1 Continuous reactor results

There were two mesophilic wet reactors (reactor 3 and reactor 4) as parallel tests for the investigation of municipal solid waste biogas potential. Both reactors had the same substrate fed and same operations in the lab. Both reactors ran for 65 days, over the weekends there was no substrates fed nor gas production measurements. Both of the reactors had an average organic loading rate of 1, 74 kg oDM/ (m^3*d). On day 59^{th} substrate fed stopped, the last gas measurement was on day 65^{th}. The results of gas

production and the operational parameters of each reactor are introduced in different sub chapter as below.

4.3.1.1 Reactor 3

FIGURE 47 below is the results of cumulative methane yield and sum fresh municipal solid waste input for the reactor 3. The two lines have parallel growth trend, while on day 16th and 17th the two lines were not close to each other, due to gas leaks from reactor tap. On day 31st, temperature dropped in the reactor, causing the decrease in methane yield, and it is noticeable in the graph below. In total 3965g of sorted municipal solid waste was input to reactor 3, and the total methane production was 0, 27272 Nm^3. The specific methane yield in reactor 3 was 68, 78 [(Vn) L/kg] CH_4/fresh mass.

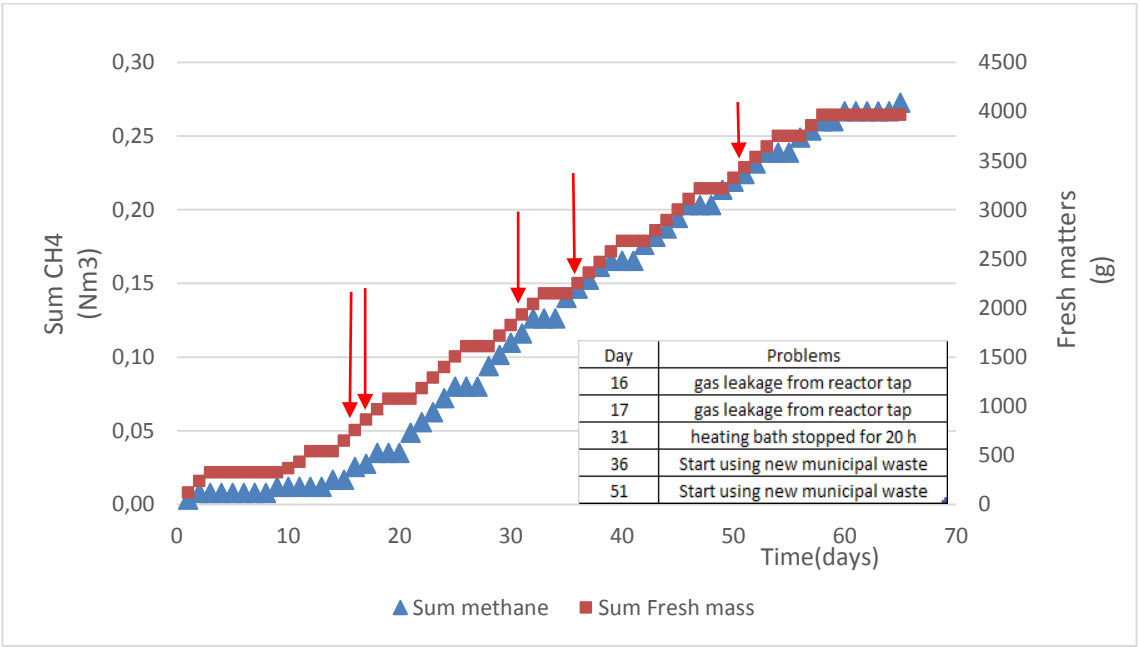

FIGURE 47: Cumulative methane yield in comparison with total fresh mass input in reactor 3

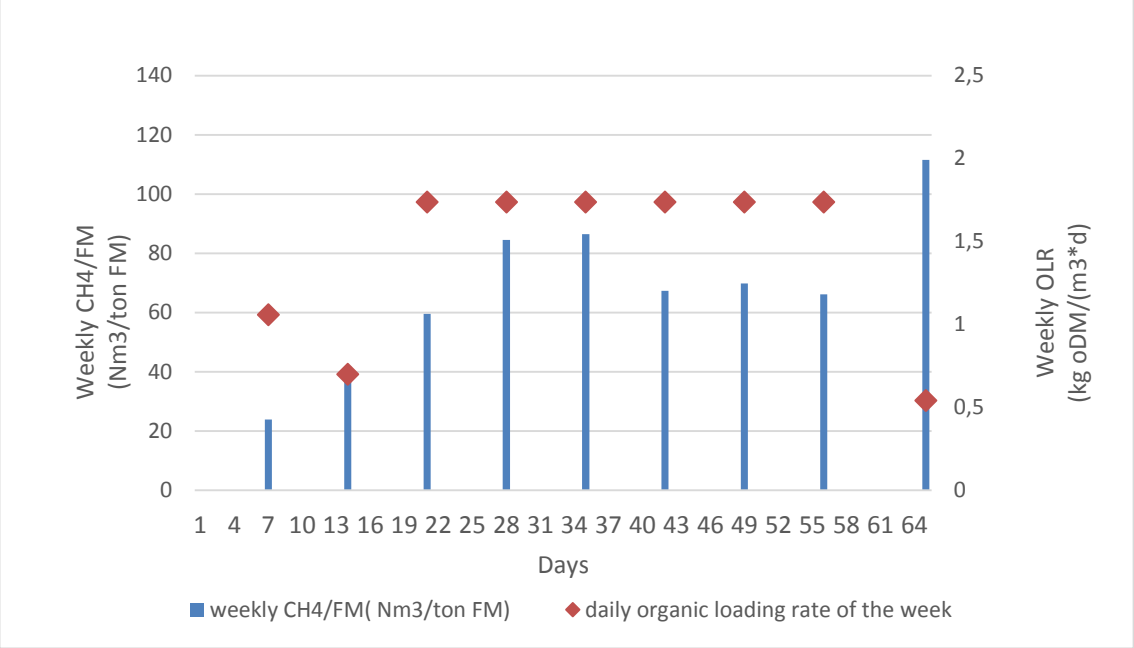

FIGURE 48: Weekly methane yield and organic loading rate in reactor 3

FIGURE 48 is the results of weekly methane yield per ton fresh mass as well as the reactor's daily average organic loading rate of the week. The blue column is the average weekly methane production per fresh substrate input, which is calculated by dividing the sum fresh mass used of the week with the sum methane production of the week. The red point is the average daily organic loading within the same week. The organic loading rate was constant for 6 weeks (week 3 to week 8), and during these six weeks, the methane yield was higher in the third and fourth week and in the last three weeks the methane yield was similar. In the last week, there were only two days of feeding, in total 214g of fresh mass, and the gas production was collected from day 57th to day 65th, in total 9 days instead of 7 days. Particularly worth mentioning is the much less substrate fed in the last week, which leads to the smaller value as the divisor in the equation, resulting in the high value of CH_4/FM.

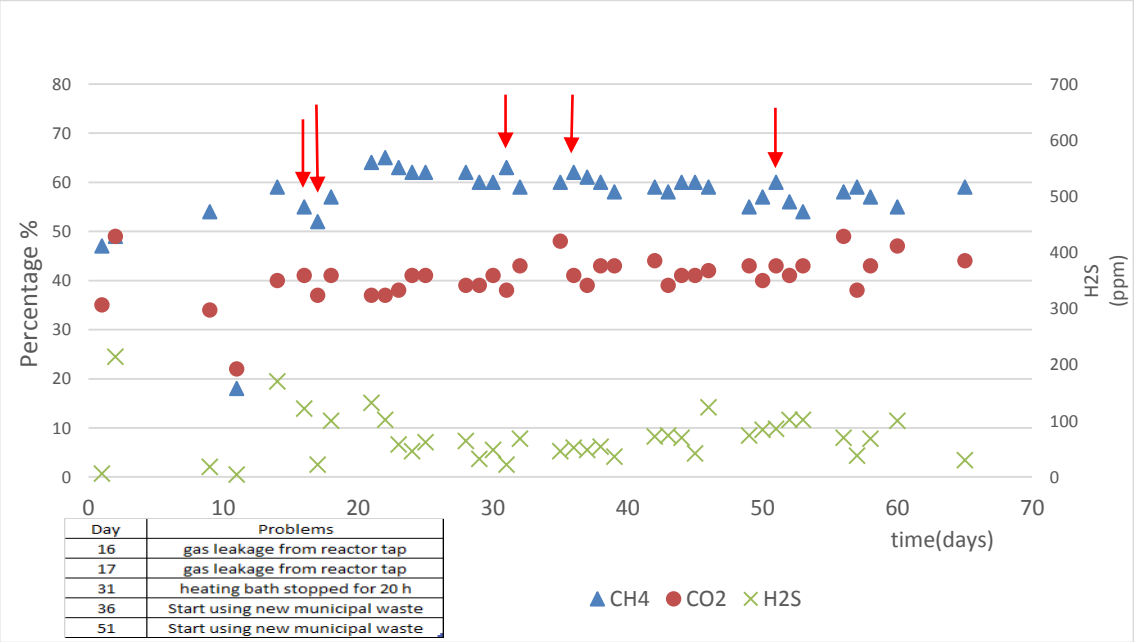

FIGURE 49: Biogas composition from reactor 3

FIGURE 49 contains the detail information of biogas composition. In the starting period, day 1st to day 11th, the biogas composition had big variations. On day 16th and 17th, there was gas leaks from reactor tap, the CH_4% in the collected biogas was lower. On day 31st the heating bath stopped working, temperature dropped to 21ºC, it seemed the methane content was not directly influenced by this dramatic temperature change. On day 36th and 51st, new municipal waste from Sweden was used. In general, the CH_4 and CO_2 concentration in produced biogas was quite constant, H_2S concentration was rather low. The average CH_4 concentration in produced biogas was 57, 32%.

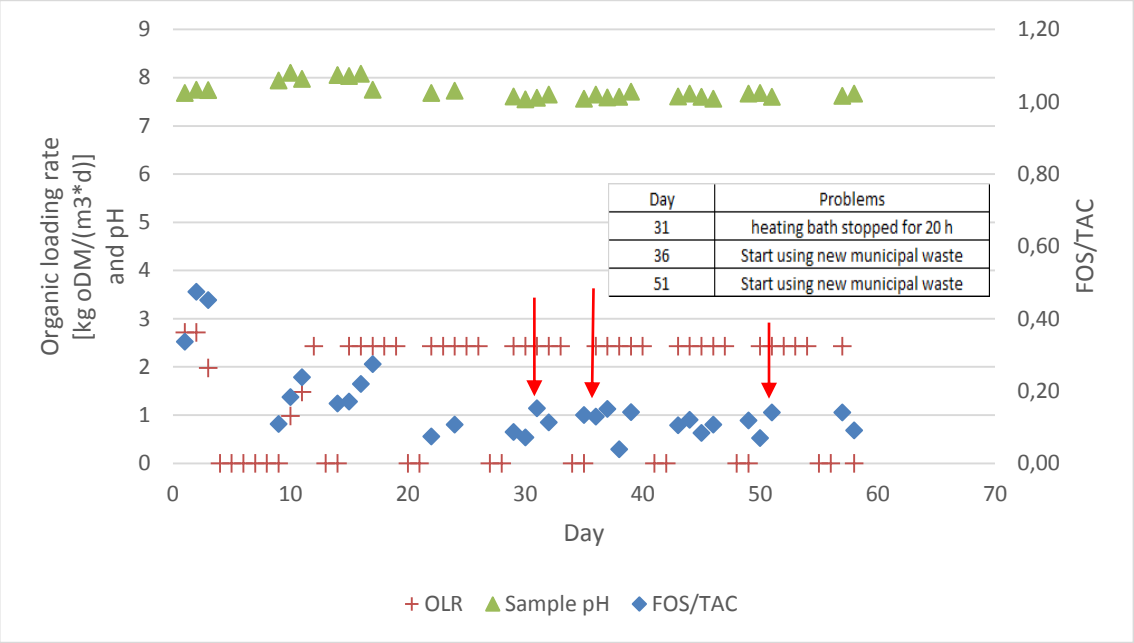

FIGURE 50: Operational parameters (pH, FOS/TAC, organic loading rate) of reactor 3

FIGURE 50 above is the operational parameters of reactor 3. In general, the FOS/TAC and pH value were quite stable, except in the starting period with small variations. The FOS/TAC value raised and felt within a range of 0 to 0, 2 after day 22nd. pH was also in a stable level, after day 17th, the pH value was in a range of 7,5 to 7,8. Organic loading rate was constant after day 12th. During the weekdays, the organic loading rate was 2, 43 kg oDM/(m^3*d), and in the weekends the organic loading rate is 0 kg oDM/(m^3*d), because of no substrates fed. In each week, the reactor 3 had an average daily organic loading rate of 1, 74 kg oDM/ (m^3*d) by dividing the 5 days substrate feeding amount to 7 days.

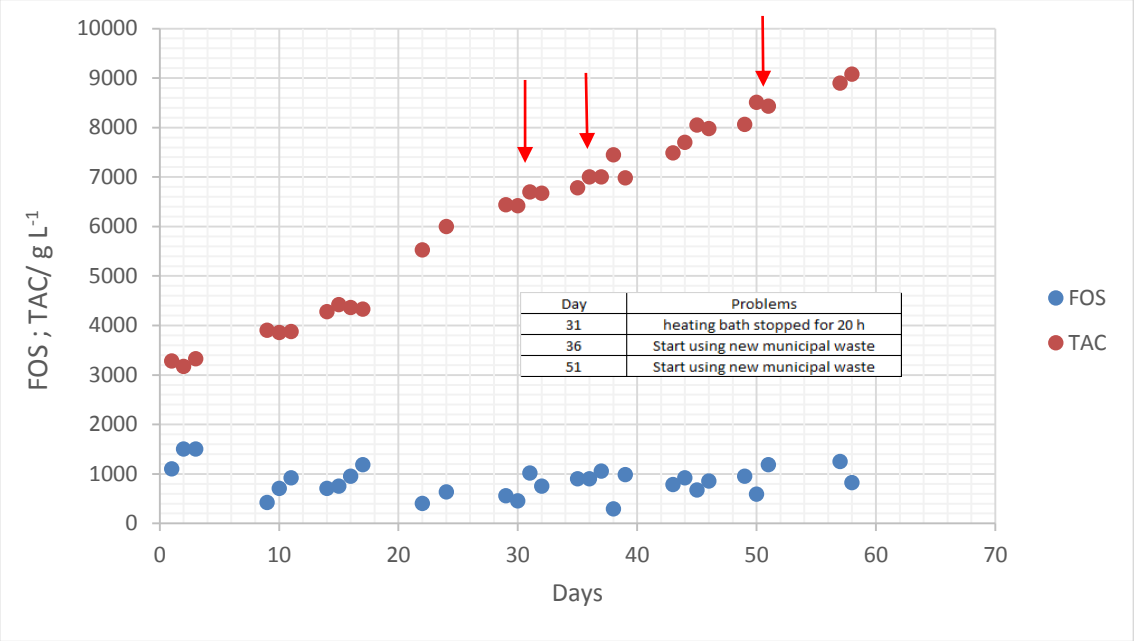

FIGURE 51: FOS and TAC value from reactor 3

In general, the FOS value had a steady rise and the TAC value stayed constant in reactor 3. The average FOS value was below 1500 g/L. The temperature change in reactor did not affect the FOS and TAC value greatly.

Table 18 is the organic acid test result. The organic acids concentrations were too low to show their values, even acetic acid had 0 mg/l concentration from the gas chromatograph and mass spectrometer.

TABLE 18: Organic acid result for reactor 3

NN1	Acetic acid [mg/l]
Day 38	0
Day 46	0

TABLE 19 is the degradation rate of leftover organic dry matter of the substrate in reactor 3. The sample was taken from day 65th for the DM and oDM test, which was the 7th day after substrate fed stopped. There was 3,84% organic dry matters in the digestate from reactor 3, and the result of degradation rate of leftover substrate was 57,39%, which

means that in continuous reactor 3, the bacteria were able to digest 57,39% of the inputted 3965 g substrates.

TABLE 19: Degradation rate of leftover substrate in reactor 3

Continuous test	oDM of digestate [%]	Added substrate [g]	Degree of degradation of leftover substrate [%]
Reactor 3	3,84	3965	57,39

FIGURE 52 is the ammonium concentration of samples from reactor 3. As is shown, the ammonium concentration of samples from reactor 3 had gradually increase trend, the highest concentration was measured on day 58th, and the value was 1788 mg/L.

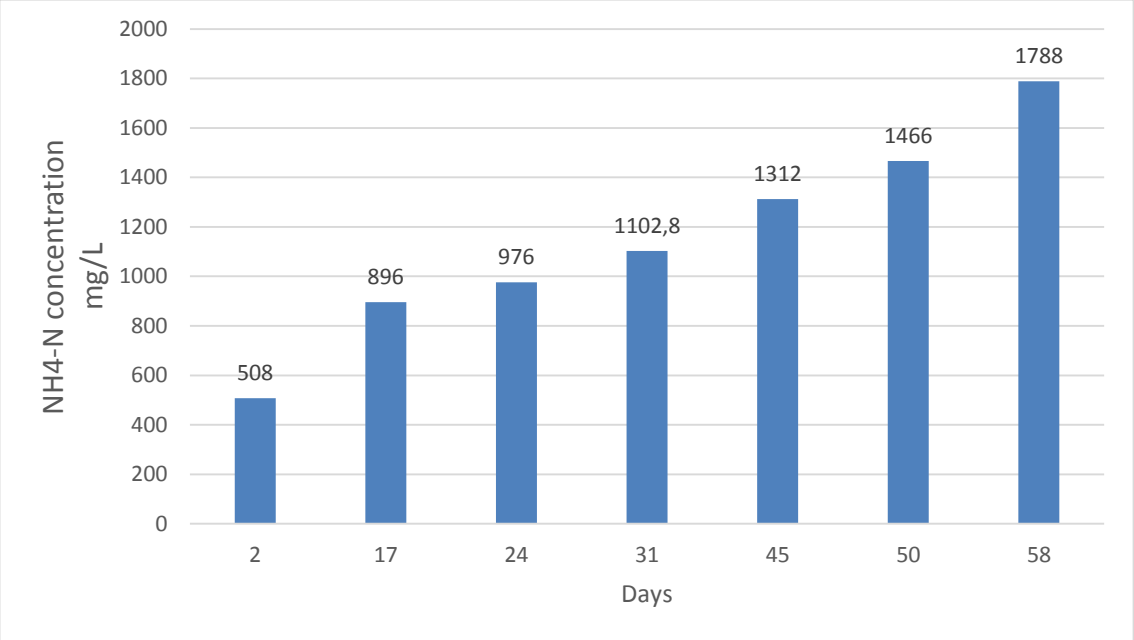

FIGURE 52: Ammonium concentration in reactor 3

4.3.1.2 Reactor 4

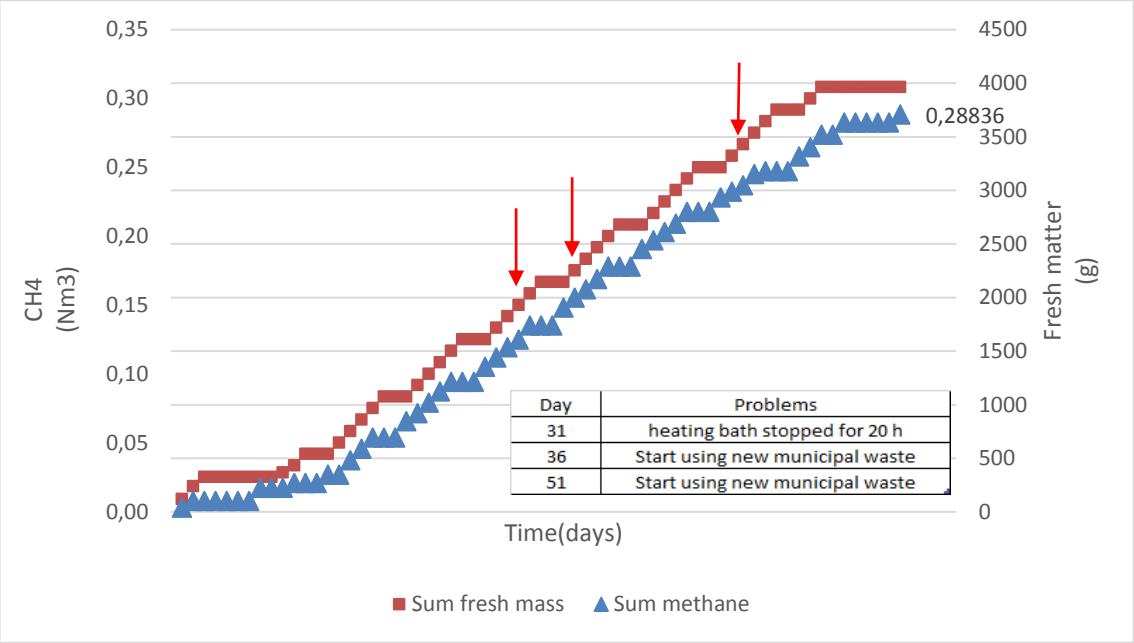

FIGURE 53: Cumulative methane yield in comparison with total fed substrate in reactor 4

FIGURE 53 is the cumulative methane production in reactor 4 compared with the total fed substrate. The line of total CH_4 has the same trend as the line of total fresh mass used in the reactor 4. Reactor 4 produced 0, 29 Nm^3 methane and received 3965 g sorted municipal solid waste. The specific methane yield in reactor 4 was 73, 14 [(Vn) L/kg] CH_4/fresh mass.

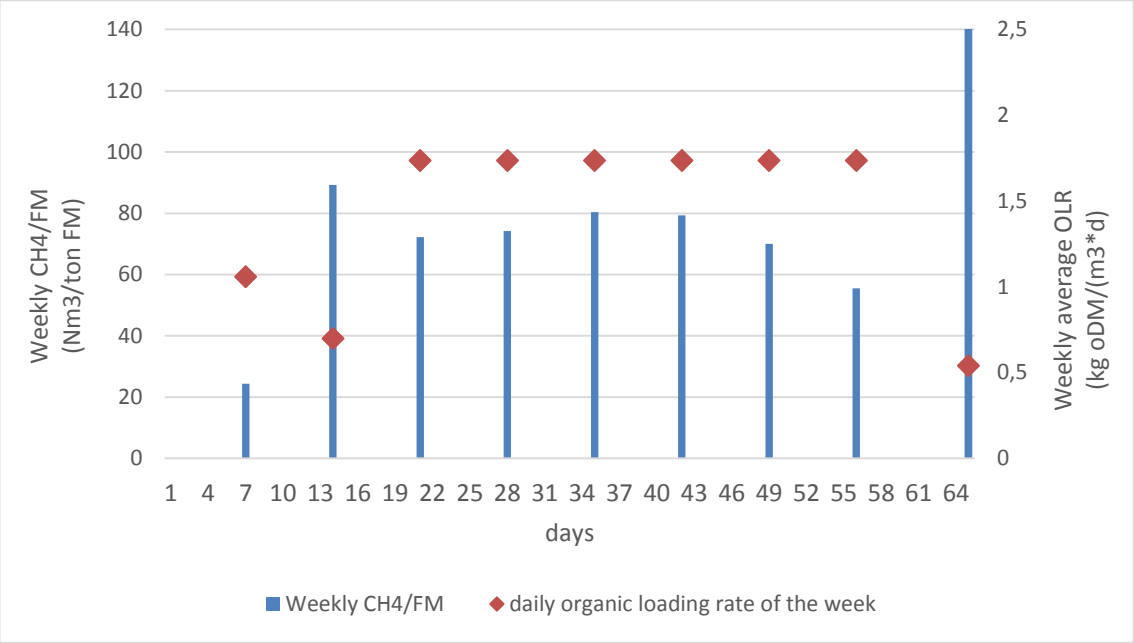

FIGURE 54: Weekly methane production and daily organic loading rate of the week in reactor 4

FIGURE 54 is the result of weekly methane production per ton fresh mass with the specific weekly average organic loading rate. The blue column is the average weekly methane production per fresh substrate input, which is calculated by dividing the sum fresh mass used of the week with the sum methane production of the week. The red point is the average daily organic loading within the same week. From week 3 to week 7, the value of CH_4/FM was similar, in week 8, the value was lower although the loading rate was the same as before. In week 9, only 214 g of substrate was input for the first two days of the week to the reactor, with an organic loading rate of 0,5 kg oDM/(m^3*d) and the gas production was collected from day 57th to day 65th, in total 9 days instead of 7 days. Particularly worth mentioning is the much less substrate fed in the last week, which leads to the smaller value as the divisor in the equation, resulting in the high value of CH_4/FM.

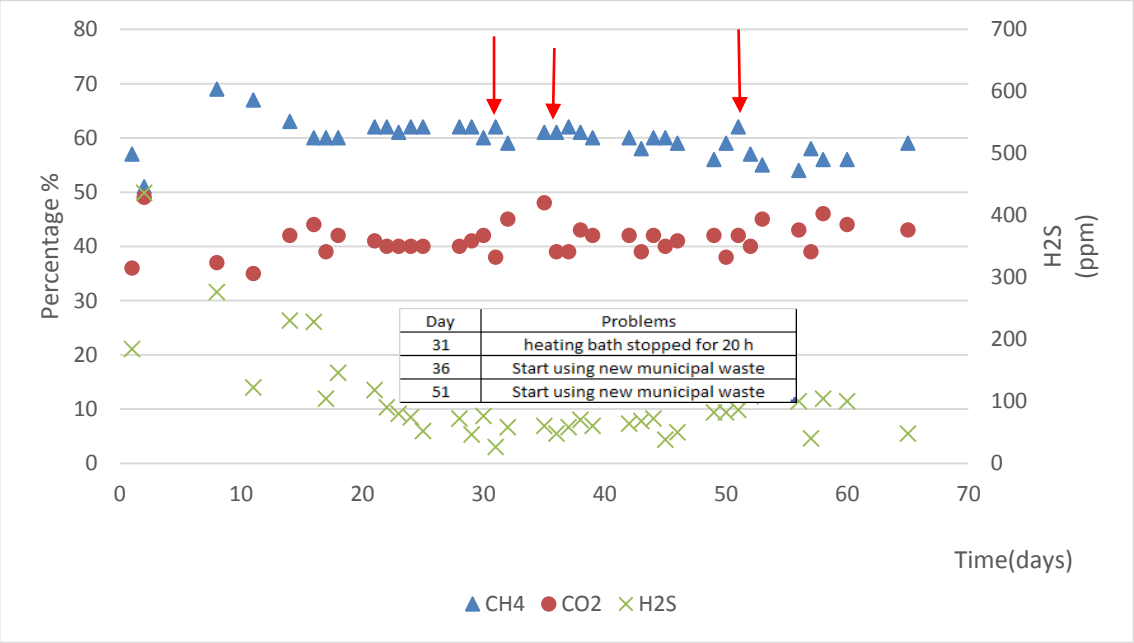

FIGURE 55: Biogas composition from reactor 4

FIGURE 55 shows the biogas composition from reactor 4. Methane concentration of produced biogas from reactor 4 was quite stable, data of CH_4% was generally above 50%. On day 32nd, after heating bath stopped working and temperature in the reactor dropped to 21ºC, the CH_4% of produced biogas was lower than the average value, at the same time, the CO_2 concentration increased a bit. H_2S concentration was around 300 ppm at the beginning of the fermentation process, and decreased gradually from day 8th to day 21st, since day 22nd, the H_2S concentration in produced biogas was in a steady level with small variations.

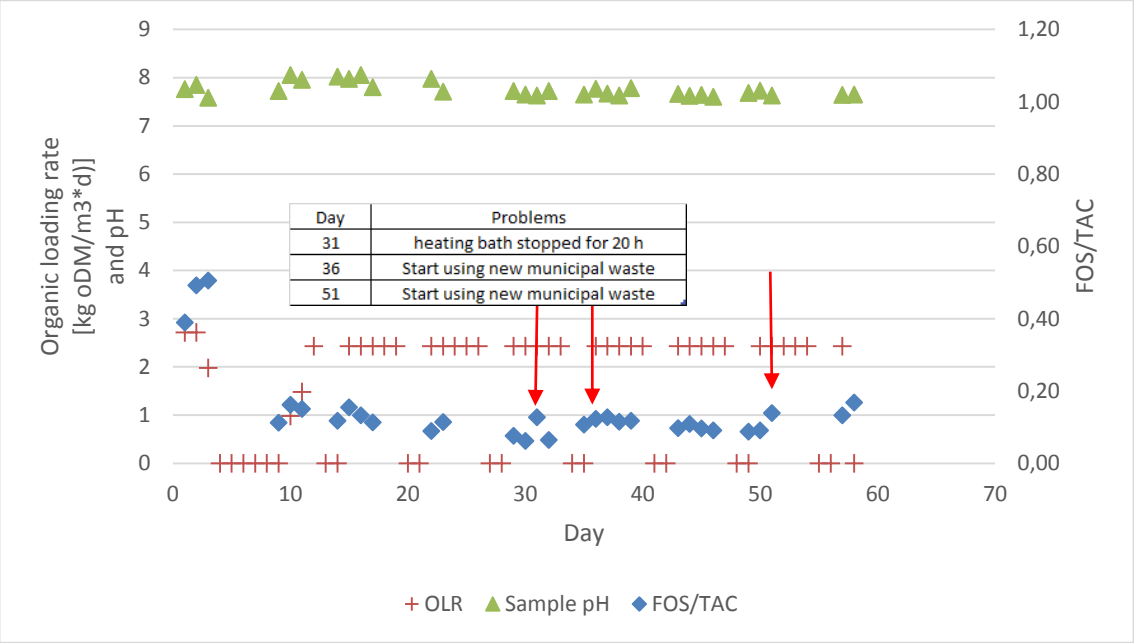

FIGURE 56: Operational parameters (pH, FOS/TAC, organic loading rate) of reactor 4

FIGURE 56 is the results of operational parameters measurements of reactor 4. The results of pH was quite constant, especially from day 23rd to day 58th, the value of pH was in a range of 7, 6 to 7, 8. The FOS/TAC value was low, in a range of 0, 06 to 0, 2 after day 9th. On day 9th, the heating bath stopped, temperature dropped and the FOS/TAC value increased to 0, 13. The average CH4 concentration in produced biogas was 59, 87%.

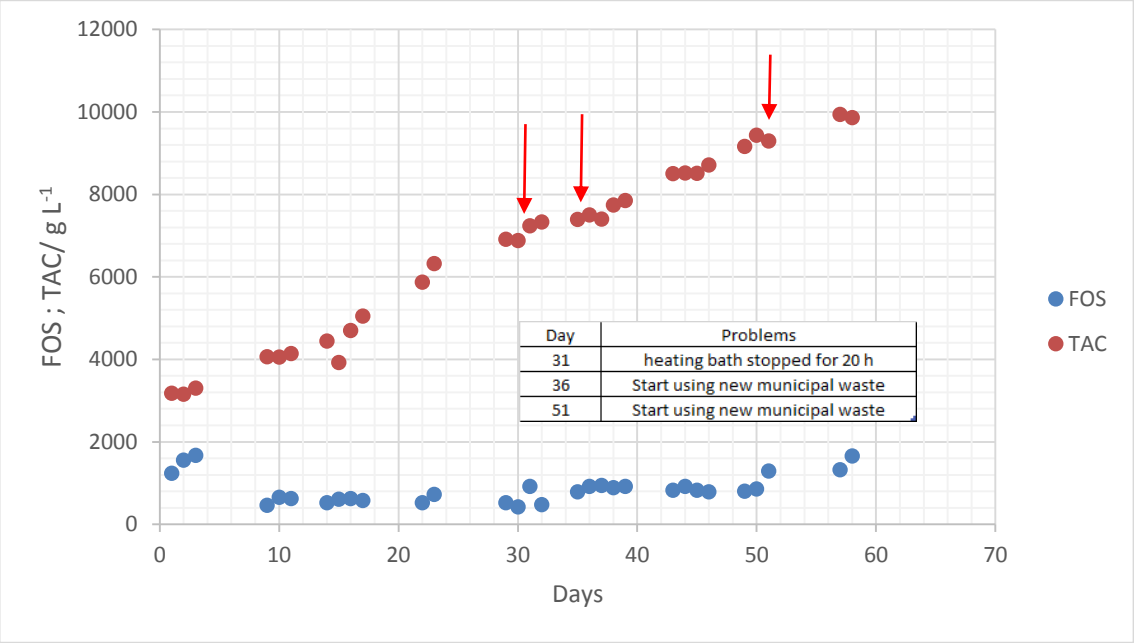

FIGURE 57: FOS and TAC value for reactor 4

FIGURE 57 is the FOS and TAC value of reactor 4. In general, the FOS value in the process stayed constantly with a low range between 400 to 1700 g/l, while TAC value was increasing gradually and reached to the highest value of 9940 g/l on day 57th.

TABLE 20 is the result of organic acid test for reactor 4. There was no other organic acid concentration record except acetic acid. On day 38th, the measured result of acetic acid was 0, 05 mg/l, and on day 46, the result was zero mg/l.

TABLE 20: Organic acid test result

NN2	Acetic acid [mg/l]
Day 38	0,05
Day 46	0

TABLE 21 is the degradation rate of leftover substrate in reactor 4. The sample was taken from day 65th for the DM and oDM test, which was the 7th day after substrate fed stopped. There was 3,65% organic dry matters in the digestate from reactor 4, and the result of

degradation rate of leftover substrate was 59,46%, which means that in continuous reactor 4, the bacteria were able to digest 59,46% of the inputted 3965 g substrates.

TABLE 21: Degradation rate of leftover substrate in reactor 4

Continuous test	oDM of digestate [%]	Added substrate [g]	Degree of degradation of leftover oDM in substrate [%]
Reactor 3	3,65	3965	59,46

FIGURE 58 is the results of ammonium concentration along the experiment period. The concentration of ammonium was increasing gradually and the highest record was on day 58th, and the value was 1960 mg/l.

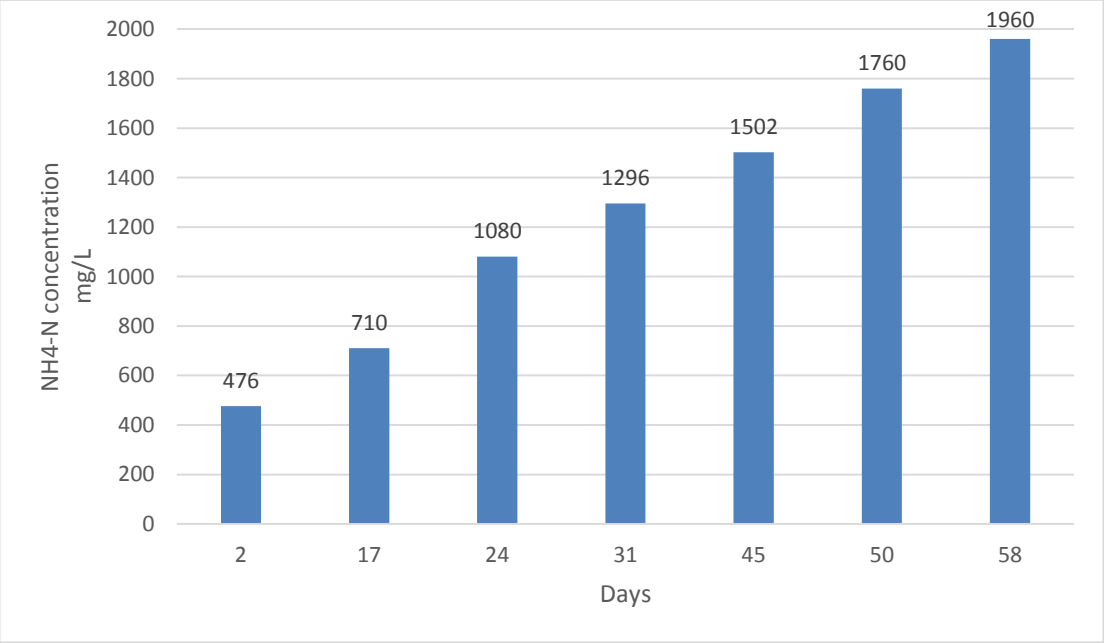

FIGURE 58: Ammonium concentration in reactor 4

4.3.2 Batch Tests of sorted Municipal Solid Waste

There were two parallel mesophilic batch tests and two parallel thermophilic batch tests for the investigation of municipal solid waste biogas potential. FIGURE 59 and 60 are the cumulative methane volume per ton municipal solid waste. The waste was sorted before use.

The production of methane per ton fresh mass varied in the parallel tests. In mesophilic batch test, sample 1 had a result of 94, 18 Nm^3/ton fresh mass, while sample 2 had only 42, 30 Nm^3/ton fresh mass. Similar situation happened in thermophilic batch test as well. However, the average methane production in mesophilic and thermophilic batch tests was close to the same, as the mesophilic batch test had a result of 68,24 Nm^3/ton fresh mass and thermophilic one had a result of 68,71 Nm^3/ton fresh mass.

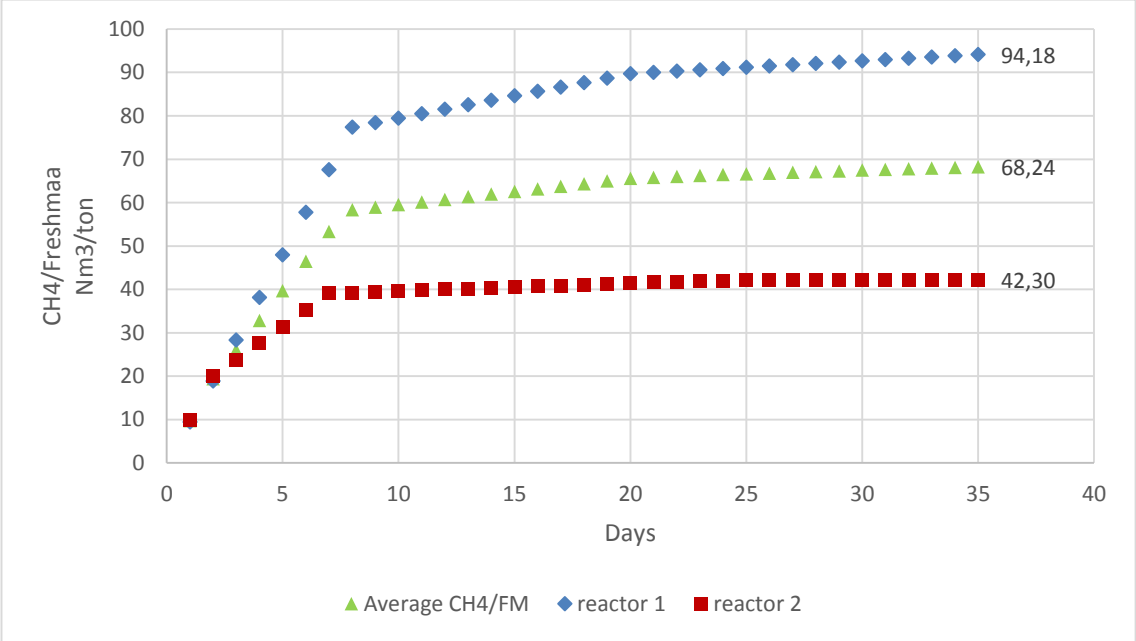

FIGURE 59: Results of Mesophilic batch test with sorted municipal solid waste

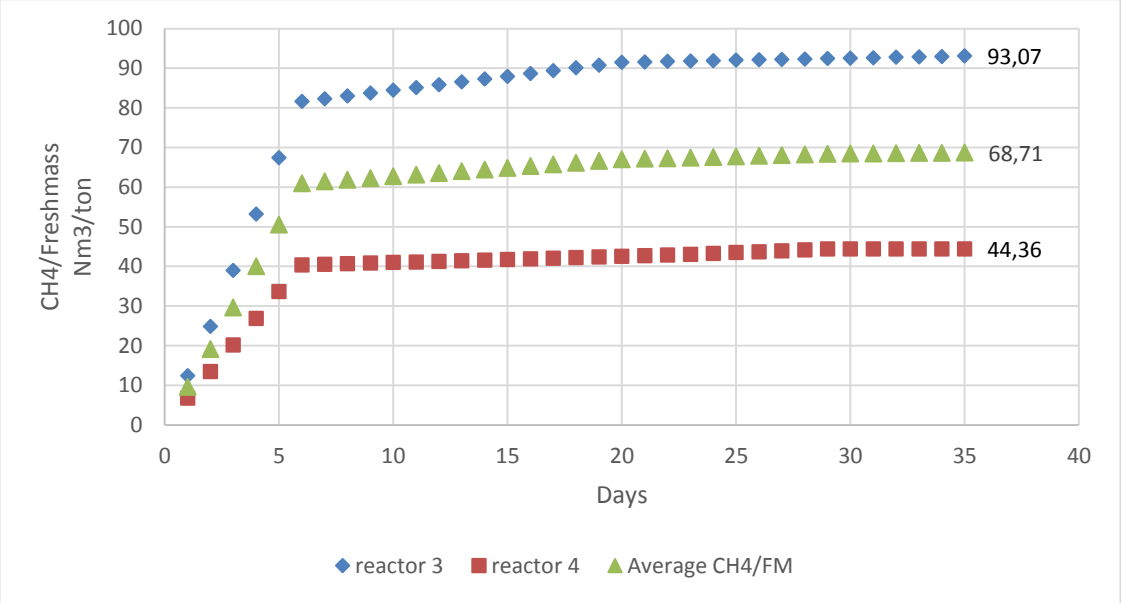

FIGURE 60: Results of Thermophilic batch test with sorted municipal solid waste

TABLE 22 presents the fermentation data for sorted municipal solid waste batch tests. Mesophilic batch tests had higher average degradation rate of substrate than thermophilic ones. Substrate in Reactor 2 had the highest degradation rate (78, 77%) with lowest mass lost after 35 days test, while substrate in reactor 4 had the much lowest degradation rate than the other three reactors (55, 96%).

TABLE 22: Fermentation data for sorted municipal solid waste batch tests

		Fermentation test			abort	Mass different	Degradation rate
Temperature condition	Sample	Empty flask (g)	Inoculum (g)	Substrate (g)	Full flask after 35d	(g)	(%)
Mesophilic	Reactor 1	1497,5	3417,5	74,8	4972,2	17,6	72,70
	Reactor 2	1488,2	3399,0	75,0	4953,2	9,0	78,77
Thermophilic	Reactor 3	1665,0	3429,2	74,2	5147,0	21,4	77,99
	Reactor 4	1495,0	3370,4	75,0	4926,8	13,6	55,96

4.4 Reject waste and inoculum gas potential by batch tests

In order to find out the gas production from inoculum, two zero batch tests with only 3500g of inoculum (waste water) were implemented under mesophilic and thermophilic conditions. From mesophilic zero batch test, there was 0, 27 L produced biogas, and from thermophilic zero batch test, there was only 0, 08 L produced biogas. However, the gas amounts were too small for the gas composition measurement. Therefore, in the calculations of produced methane in other batch tests with biowaste, municipal solid waste and reject waste, the gas potential of inoculum was neglected, which might have led to a bit higher gas production recorded than they supposed to have.

There were two parallel mesophilic batch tests and two parallel thermophilic batch tests for the investigation of reject waste biogas potential. FIGURE 61 and 62 are the cumulative methane volume per ton reject waste. Results from parallel tests were relatively similar. In mesophilic batch test, reject waste had an average methane potential of 65, 67 Nm^3/ton fresh mass and in thermophilic batch test, it had an average methane potential of 70, 41 Nm^3/ton fresh mass.

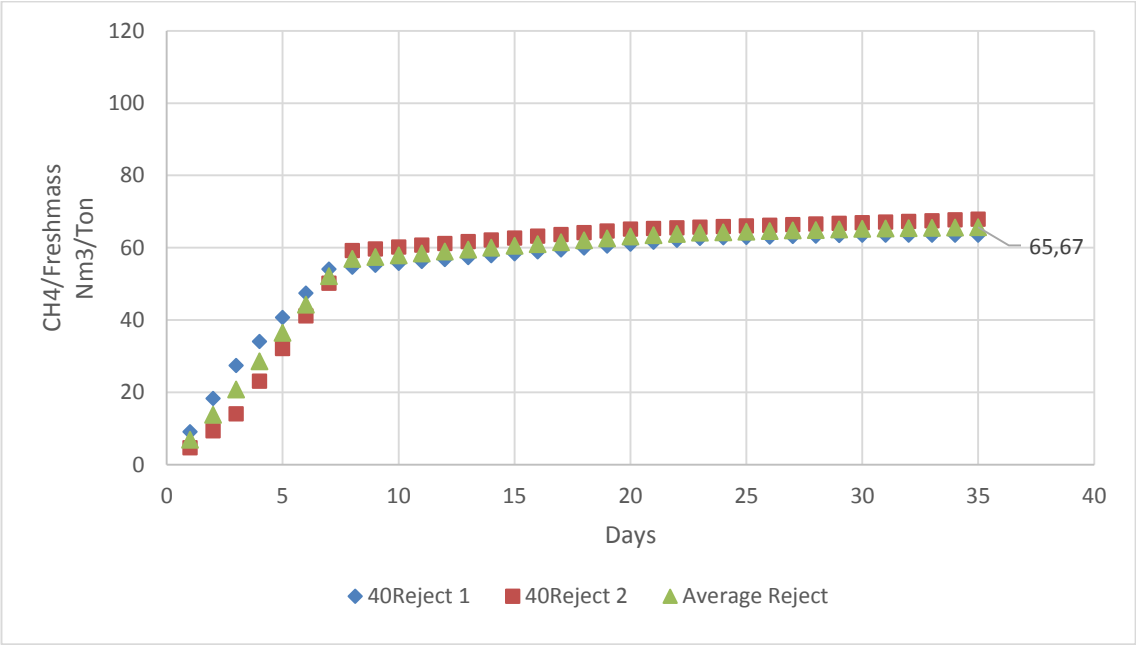

FIGURE 61: Mesophilic batch test of reject waste

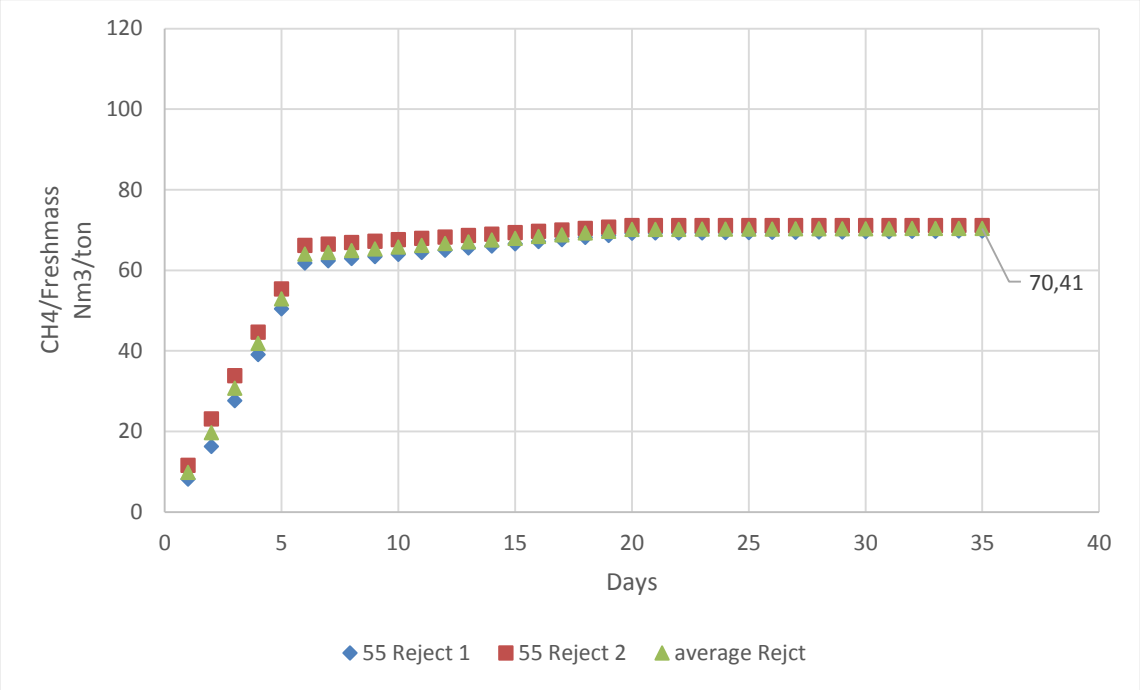

FIGURE 62: Thermophilic batch test of reject waste

TABLE 23 presents the fermentation data for reject waste batch tests. Mesophilic batch tests had higher average degradation rate of substrate than thermophilic ones. Substrate in Reactor 2 had the highest degradation rate (93, 72%), while substrate in reactor 3 had the lowest degradation rate than the other three reactors (70, 82%). Mass lost were larger in thermophilic batch tests than the ones in mesophilic batch test.

TABLE 23: Fermentation data for reject waste batch tests

		Fermentation test			abort	Mass different	Degradation rate
Temperature condition	Sample	Empty flask (g)	Inoculum (g)	Substrate (g)	Full flask after 35d	(g)	(%)
Mesophilic	Reactor 1	1632,0	3316,6	75,0	5007,6	16,0	85,56
	Reactor 2	2363,8	3425,0	74,2	5844,8	18,2	93,72
Thermophilic	Reactor 3	1522,6	3425,4	74,6	5000,8	21,8	70,82
	Reactor 4	1484,2	3424,8	74,6	4961,0	22,6	77,93

4.5 Result comparisons of specify methane production from municipal solid waste

In order to compare the results of specific methane production of municipal solid waste from different types of digesters, the results of each case were screened. Results of produced methane should be from stable processes, for example, the organic loading rate during the selected period should be constant. Below the methods of selecting the data from each fermenter is introduced in separated chapters.

4.5.1 Continuous Mesophilic Wet Digester

Continuous Mesophilic Wet Digester refers to the continuous reactor 3 and 4 operated by this thesis author. During day 36th to 56th, both reactors (reactor 3 and reactor 4) were under stable process, which means the organic loading rate was constant, and there was no gas leaks nor did other physical problems occur. Therefore, results of methane production from this period were selected for the comparison.

TABLE 24: Results of methane yield from mesophilic wet digester

Mesophilic wet digester	Reactor 3	Reactor 4
Produced methane (Vn l)	109,52	108,77
Used fresh mass (kg)	1,605	1,605
Total Methane (Vn l)	218,29	
Total fresh mass used (kg)	3,21	
Average CH4/FM (Vn[L/kg FM])	68,00	

TABLE 24 is the data used for the methane yield comparison. During the selected period of time, reactor 3 and 4 produced similar amount of methane with the same amount the inputted sorted municipal solid waste. By using total methane production from reactor 3 and 4 divides the total substrate used during the same period of time, there is average value of methane production per kg substrate. In mesophilic wet digester, 1 kg sorted municipal solid waste can produce 68 liter methane.

4.5.2 Mesophilic wet digester with enzyme addition

My team mate Patrick Niekamp was doing similar continuous tests using the same sorted municipal solid waste from Sweden, with enzyme (*T.reesei*) addition to see the influence of cellulose on the biogas potential. His thesis topic is "Einfluss von cellulasen von t. Reesei auf das biogaspotential von kommunalen haushaltsabfällen". There were two reactors as parallel experiments, however, one of them had gas pipe block for 3 days and led to gas leaks from the reactor water seal during the period of adding enzyme. Therefore for better comparison, only the other reactor's data is used here. The data below was from 11 days, on day 6th and 7th there was no substrate with enzyme fed nor gas measurement because of weekend. That is to say, the data in TABLE 25 below is from 9 days of substrate fed with enzyme. The weekday feeding amount was 150 g.

TABLE 25: Result of methane yield from thermophilic wet digester with enzyme addition

Thermophilic wet digester with enzyme	
Total methane production Vn l	103,29
Total fresh mass used(kg)	1,35
Average CH4/FM (Vn[L/kg FM])	76,51

As is shown in TABLE 25, 1 kg sorted municipal solid waste was able to produce 76, 51 liter methane with the adding enzyme.

4.5.3 Thermophilic Garage dry Fermenter

Another team mate Matthäus Barasinski investigated Swedish unsorted municipal waste on its methane production. There were two times of tests ran by the garage dry fermenter and each test ran for 18 days. In the first test, 9,05 kg of unsorted municipal solid waste was inputted to the garage fermenter at once on the first day of test, and the sum of produced methane was 589,67 liter. In the second test, 10,67 kg of unsorted municipal solid waste was inputted to the garage fermenter at once on the first day of test, and the sum of produced methane was 471,57 liter. The second test used more substrate but produced less methane. Below is the result of his experiment.

TABLE 26: Result from Garage fermenter

Thermophilic dry Garage Fermenter			
	SUM CH4	sum CH4	Input fresh mass
	(VN [L/kg FM])	Vn l	kg
1st test	65,19	589,67	9,05
2nd test	44,20	471,57	10,67
Average	53,83	1061,24	19,72

By using total methane production divides the total substrate used from 1st and 2nd test, there is average value of methane production per kg substrate from Thermophilic Garage dry Fermenter. As TABLE 26 shows, 1 kg unsorted municipal solid waste was able to produce 53, 83 liter methane.

4.5.4 Plug flow fermenter in Sweden

Data was chosen from day 25th and in total 12 days data was used, during these days, the organic loading rate was constant and the amount of daily fed substrate was 6, 27 kg. The sum of sorted municipal solid waste used during these 12 days was 75, 27 kg and the total methane production was 5615, 69 liter. By using total methane production divides the total substrate used from these 12 days, there is average value of methane production per kg substrate from Plug flow Fermenter.

TABLE 27: Results from Plug flow fermenter

Plug Flow Fermenter	
Sum CH4(Vn L)	5615,69
Sum Substrate(Kg)	75,24
Average CH4/FM (Vn L/kg FM)	74,64

As is shown in TABLE 27, in plug flow fermenter, 1 kg sorted municipal solid waste was able to produce 74, 64 liter of methane.

4.5.5 Results comparisons

TABLE 28 is the overall comparison of results of methane yield per kg fresh mass of municipal solid waste.

TABLE 28: Results of each fermenter for overall comparison

Fermenter Type	Substrate pre-treatment	Average CH4/fresh mass (Vn L/kg FM)
Mesophilic Wet Digester (Reactor 3 And Reactor 4)	Sorted, sanitation at 70ºC for 1 h	68,00
Mesophilic Wet Digester with Enzymes Addition	sorted, sanitation at 70ºC for 1 h, enzyme addition	76,51
Thermophilic Dry Garage Fermenter	Unsorted, no pre-sanitation	53,83
Thermophilic Plug Flow Fermenter	Sorted, no pre-sanitation	74,64

Mesophilic Wet Digester with enzyme addition shows the highest value of CH_4/FM, which is 76, 51 CH4/fresh mass (Vn L/kg FM). Thermophilic plug flow fermenter produced a little bit less methane, 74, 64 CH4/fresh mass (Vn L/kg FM), compared with the mesophilic wet digester with enzyme addition. Mesophilic wet digester (reactor 3 and 4) had a smaller value compared with the digester with enzyme addition, only 68 liter methane achieved from 1 kg sorted municipal solid waste. Thermophilic dry garage fermenter had the lowest value of CH_4/FM, that with 1 kg unsorted municipal solid waste, only 53, 83 liter methane produced.

4.6 Cash flow analysis

In order to find out factors that affect the profit of *Svensk Växtkraft AB* as well as to test the feasibility of cash flow calculation excel tool, cash flow excel tool is analyzed by comparing the results of inputting the financial data of previous years (2007 to 2013) from *Svensk Växtkraft AB* and theoretical data based on the market in Sweden.

4.6.1 Cash flow analysis using actual (historical) data from *Svensk Växtkraft AB*

Svensk Växtkraft AB had a total investment of 16, 9 million € for planning and construction of its biogas plant as well as gas upgrading plant and gas filling stations. The financial data used in the actual cash flow analysis excel tool is from the *Svensk Växtkraft AB*'s annual reports 2008 to 2013, which include cash flow information from year 2007 to 2013. However, there is no report nor data from startup year 2006, therefore in the actual data analysis, cost and revenue of year 2006 is empty. In the actual data cash flow analysis, the data in TABLE below was used.

TABLE 29: Raw Data from annual report 2008- 2013 [32]

Currency: Euro	2007	2008	2009	2010	2011	2012	2013
Net	2070200	3071530	3318370	4352700	4828340	6021400	7116340
Other Operating Income	100210	51700	58630	41470	26730	6050	17820
Operating And Capital Expenditure	-444620	-671770	-801350	-1216600	-1366970	-2124870	-2507670
Other External Expenses	-1080420	-1419660	-1648020	-1829520	-1489180	-1913670	-2082850
Labour Costs				-165440	-520410	-654940	-783530
Number Of Workers		6		2	8	10	11
Number On Board+ CEO	5	5	5	5			
Salary On Board And CEO	50050	44770	70840	74910	11550	7480	6490
Salary Per Person For Administrative	10010	8954	14168	14982	11550	7480	6490
Salary To Other Employee				110990	356290	460130	531190
Salary Per Person For Employee				4625	3711	3834	4024

Net and other operating income belong to the revenue, operating and capital expenditure, other external expenses and labor cost belong to the operating cost. In the annual report, the currency is Swedish crown, and the data presented in this thesis as well as cash flow excel tool are €, which has the currency exchange rate of 1 Swedish crown equal to 0, 11 €. TABLE 29 is the raw data, and after calculation, the cost and revenue from 2007 to 2013 is shown in TABLE 30. The data from TABLE is input to the cash flow excel tool to get the overview of the company's cash flow from 2007 to 2013.

TABLE 30: Data used in the actual cash flow excel tool [32]

Currency: Euro	2007	2008	2009	2010	2011	2012	2013
Operation Cost (Including Labour Cost)	-1525040	-2091430	-2449370	-3211560	-3376560	-4693480	-5374050
Revenue	2170410	3123230	3377000	4394170	4855070	6027450	7134160

By inputting the Cost and Revenue from 2007 to 2013 and total investment 16, 9 million €, the cash flow excel tool built up the graph (FIGURE 63).

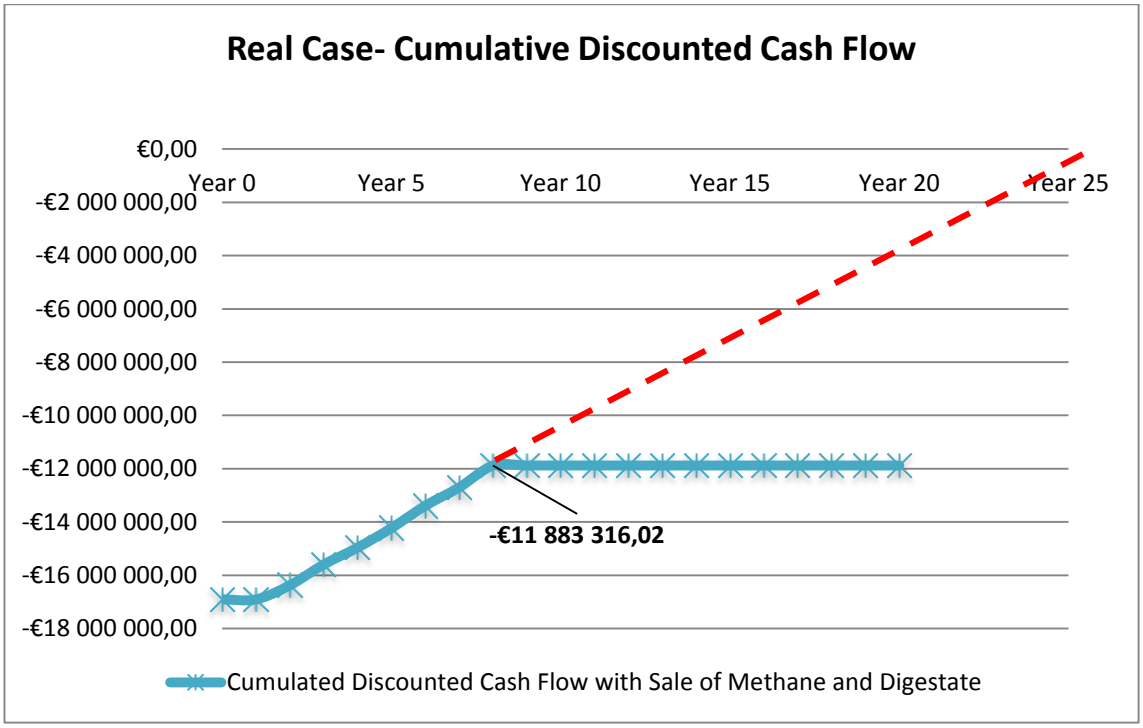

FIGURE 63: Real case- Cash flow using actual data from Svensk Växtkraft AB

As is show in the FIGURE 63, in year 0 the point is at the sample horizontal level like year 0, and in year 8th (2013) the line changes its trend, it is due to the fact that there is only data from year 2nd to year 8th inputted in the excel, thus the trend from year 8th to year 25th is not a remarkable reference. In order to see to possible trend of cumulative discounted cash flow line, a red dotted line is applied. As is show, the company can recover the cost and start get the payoff in year 25th. In year 8th, the plant have negative cash flow of -11883316 €.

4.6.2 Cash flow analysis using theoretical (hypothetic) data

The idea of this cash flow analysis using theoretical data is to test the feasibility of the cash flow excel tool, to see if the cash flow fits the reality or not, and to find out the important parameters which could affect the cash flow of *Svensk Växtkraft AB.*

In order to be close to reality, the amount of substrates used in *Svensk Växtkraft AB* from 2007 to 2013 is regarded as basic data for theoretical cash flow analysis. TABLE 31 shows the substrate types and amounts used for the biogas plant, and in the theoretical analysis, the average amount of each substrate is used. Source-separated biowaste, liquid waste (grease trap removal sludge) and ley crops are the substrates used in the *Svensk Växtkraft AB* biogas plant. Every year, an average value of 15328 tons of source-separated biowaste, 2338 tons of liquid waste and 2288 tons of ley crop are used in the biogas plant.

TABLE 31: Substrate list from Svensk Växtkraft AB [32]

Substrate List/ Year (Unit: ton)	2007	2008	2009	2010	2011	2012	2013	Average
Source-separated biowaste	13300	14300	15300	15000	15800	16600	16996	15328
Liquid waste (Grease trap removal sludge)	1500	2100	2100	2000	2100	3100	3468	2338
Ley crop	2100	4000	2900	2800	2400	1100	716	2288

TABLE 32 is the parameters of operational expenses used in the theoretical cash flow excel tool. There is no CHP unit in the biogas plant, but it is assumed there is CHP unit in the excel tool in order to get the produced electricity amount based on the produced biogas, for the purpose of getting the value of electricity used for the plant, which is 30% of the produced electricity from CHP unit generation.

TABLE 32: Parameters of operational expenses for theoretical cash flow analysis

Operational Expenses	Price	Literature Source/Database
Purchased Heat	0, 041€/kwh (2% increment rate) *exclusive of VAT*	Mälarenergi http://www.malarenergi.se/sv/foretag/varme-och-kyla/priser-fjarrvarme/vasteras/
Purchased Eletricity	0,06379€/kwh (6 % increment rate) *exclusive of VAT*	Mälarenergi http://www.malarenergi.se/sv/foretag/elnat/priser-elnat/sakringsabonnemang/
VAT	25%	Europa http://europa.eu/youreurope/business/vat-customs/buy-sell/index_en.htm#sweden_en_paying-taxes
Maintenance and repair	1,5cent/m³ Biogas (2% increment rate)	[Silvia] Own estimation, no stirring device
Operational labor costs	4049 €/month per person (2% increment rate)	[Annual report 2008- 2013 Svensk Växtkraft AB] Average value
Administrative labor	10519 €/month per person (2% increment rate)	[Annual report 2008- 2013 Svensk Växtkraft AB] Average value
Gas process cost	0,06 €/m3 (2% increment rate)	[Biogas-netzeinspeisung] http://www.biogas-netzeinspeisung.at/technische-planung/aufbereitung/aufbereitungsverfahren/druckwasserwaesche.html
Ley crop	40 €/t (2% increment rate)	[Silvia] Estimation
Insurance	0,50% * Total investment cost (2% increment rate)	[EMMA MOBERG, Economic analysis of biogas production by dry digestion of waste, pdf]
Transport costs (output digestate)	12,69 €/t (75 SEK/m3; 650 kg/m3; 1 SEK= 0,11€ (2% increment rate)	[EMMA MOBERG, Economic analysis of biogas production by dry digestion of waste, pdf]
Purchased services and goods	0,01 € * produced biogas [m3/a]	[Silvia] Estonian biogas plant model
Other operational costs (as service contracts)	0,03 € * produced biogas [m3/a]	[Silvia] Estonian biogas plant model
Other administrative costs	0,01 € * produced biogas [m3/a]	[Silvia] Estonian biogas plant model

The value of operational labor cost and administrative labor cost are the average value of the related actual data from Svensk *Växtkraft AB's* annual reports. Besides the expenses, there are also parameters of revenue, which are shown in TABLE 33.

TABLE 33: Parameters of revenue for theoretical cash flow analysis

Revenue	**Price**	**Literature Source/Database**
Source-separated Biowaste	54 €/t (2% increment rate)	[Svensk Växtkraft AB]
Liquid waste	60 €/t (2% increment rate)	[Silvia] Estimation
Gas sales (methane)	1,232 €/Nm3 (17,5 SEK/kg ; 0,8kg/Nm3; 1SEK= 0,11€; 20% VAT deducted) (2% increment rate)	[Gasbilen] http://www.gasbilen.se/Att-tanka-din-gasbil/Aktuella-priser
Digestate sales	2,12 €/t FM (12,5 SEK/m3; 650 kg/m3; 1 SEK= 0,11€) (2% increment rate)	[EMMA MOBERG, Economic analysis of biogas production by dry digestion of waste, pdf]

Based on the actual situation in *Svensk Växtkraft AB*, there are also some important factors considered in the theoretical cash flow analysis. There is no stirrer in the fermenter, instead, gas is pumped into the fermenter for sufficient mixing, which requires more electricity for operating. TABLE 34 is the factors and their specific value considered in the cash flow analysis.

TABLE 34: Factors considered in theoretical cash flow analysis

Other factors	Value
Discount rate for DCF	10 %
Electricity demand from theoretical CHP unit	30 %
Efficiency rate of biogas production	90 %
Gas lost for upgrading	2 %

4.6.2.1 Scenario 1- Hypothetic cash flow

All the parameters from the TABLE 31, 32, 33 and 34 in the chapter 4.6.2 were filled in the cash flow calculation tool, what was created by a student from Finland, Fenia Maria Niemitz. FIGURE 64 is the graph created by the excel tool.

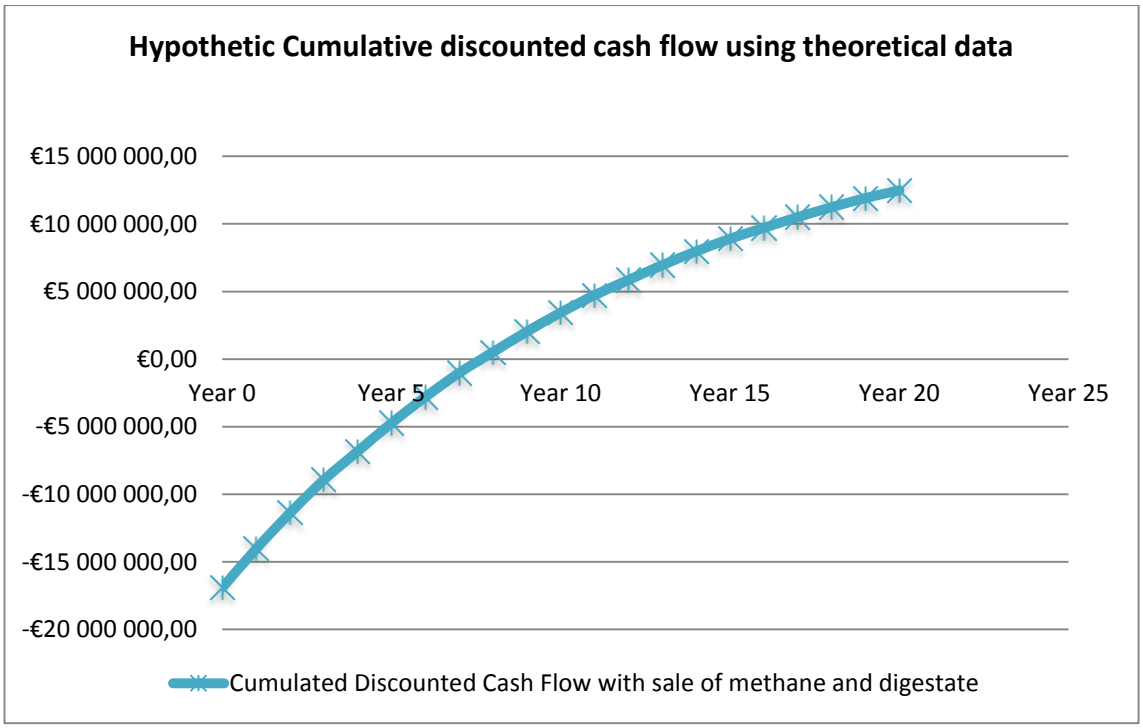

FIGURE 64: Hypothetic Cash flow using theoretical data

According to the excel tool, by using the theoretical data, the plant can earn profit around year 7th and 8th. The outcome of the theoretical cash flow is very different compared with the actual cash flow. In the actual cash flow analysis (FIGURE 63), the company will start to get the payoff in year 25th and in year 8th, the plant has negative cash flow of -11883316 €. But the hypothetic cash flow analysis (FIGURE 64), the plant would have started to get the payoff between year 7th and year 8th. In order to find out factors that affect the profit of *Svensk Växtkraft AB*, the Scenario 2, 3, 4, 5, 6 and 7 in the upcoming chapter was created by using one or more different parameters basing on same theoretical data background.

4.6.2.2 Scenario 2 More workers (6 to 11)

In the theoretical cash flow excel tool, the number of workers is calculated according to the annual capacity of CHP unit, and according to result from FIGURE 64 in chapter 4.6.2.1, only 6 workers should work for the plant. However, according to the annual report from *Svensk Växtkraft AB*, there was 11 workers in 2013, 10 workers in 2012, but only 2 in 2010(TABLE 29). In Scenario 2, it is assumed that there are 11 workers working for the plant.

TABLE 35: Different background between Scenario 1 and 2

	Different parameter- labour amount
Scenario 1	6
Scenario 2	11

TABLE 35 shows the specific different parameter inputted in the excel tool between Scenario 1 and 2. In Scenario 2, the labor amount is 11.

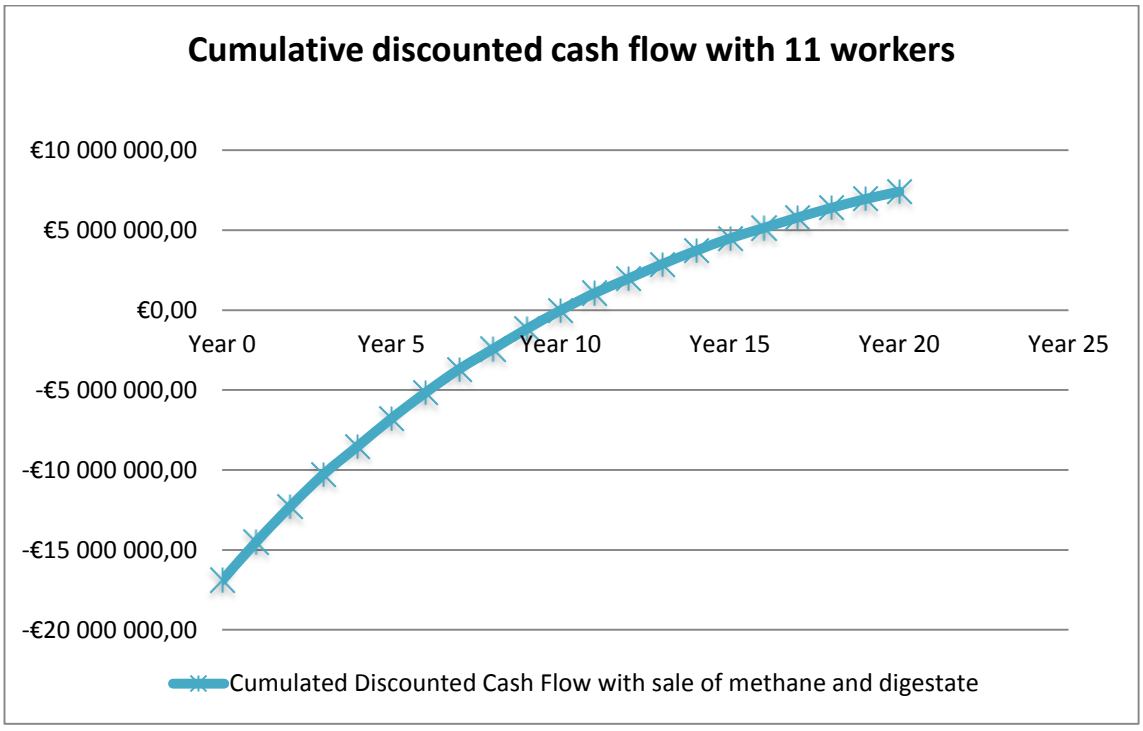

FIGURE 65: Theoretical cash flow with 11 workers

FIGURE 65 is the result of changing the worker number from 6 to 11. In year 10th the company can start earning profit in Scenario 2, while in Scenario 1 between year 7 and 8, the plant can start earning profit. That is so to say, 5 more workers costs can postpone 2 to 3 years for the plant to earn the profit.

4.6.2.3 Scenario 3 – total investment is 8 million Euro

Svensk Växtkraft AB has very high investment for planning and construction. There is no detail information about the actual investment items for this plant, but 16, 9 million € as total investment. In Scenario 3, the total investment is set to 8, 46 million €.

TABLE 36: Different background between Scenario 1 and 3

	Different parameters- total investment cost
Scenario 1	16, 9 million €
Scenario 3	8,46 million €

TABLE 36 shows the different parameters used in the excel tool between Scenario 1 and 3. The only different parameters used between Scenario 1 and 3 is the total investment cost.

After changing the total investment cost from 16,9 million € to 8,46 €, the plant is able to get profit after 3 years.(FIGURE 66) In Scenario 1, the plant can earn start earning profit between year 7^{th} and 8^{th} (FIGURE 64), that is to say, if the total investment is around 50% less, the plant can earn the profit 4 to 5 years earlier.

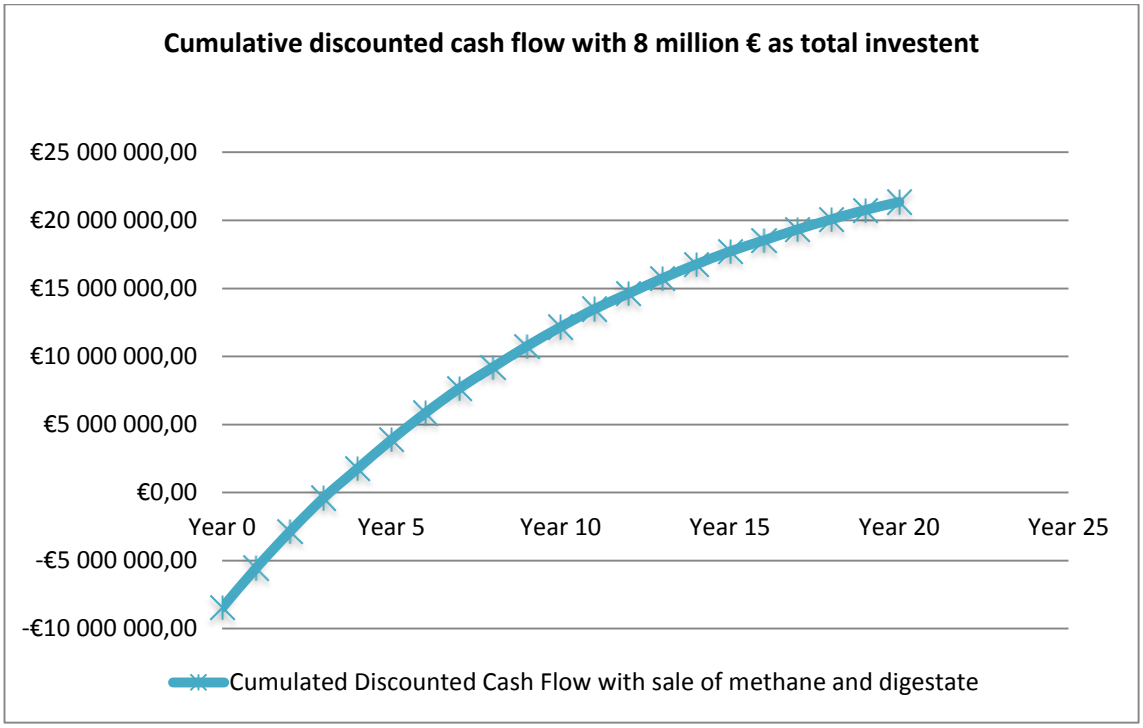

FIGURE 66: Theoretical cash flow with 8 million euro as total investment

4.6.2.4 Scenario 4 - Biogas price change from 1, 232 [€/m³] to 1, 176 [€/m³]

The biogas price changes yearly and varies from different region in Sweden. In order to see the influence of biogas price to the cash flow of plant, In Scenario 4 the biogas price is reduced 5%, from 1,232 to 1,176 [€/m³].

TABLE 37: Different background between Scenario 1 and 4

	Different parameters- biogas price
Scenario 1	1,232 [€/m³]
Scenario 4	1,176 [€/m³]

TABLE 37 shows the different parameters used in the excel tool between Scenario 1 and 4. The only different parameters used between Scenario 1 and 4 is the price of biogas (methane as car fuel). In Scenario 4, the price for biogas reduces to 1,176 [€/m³].

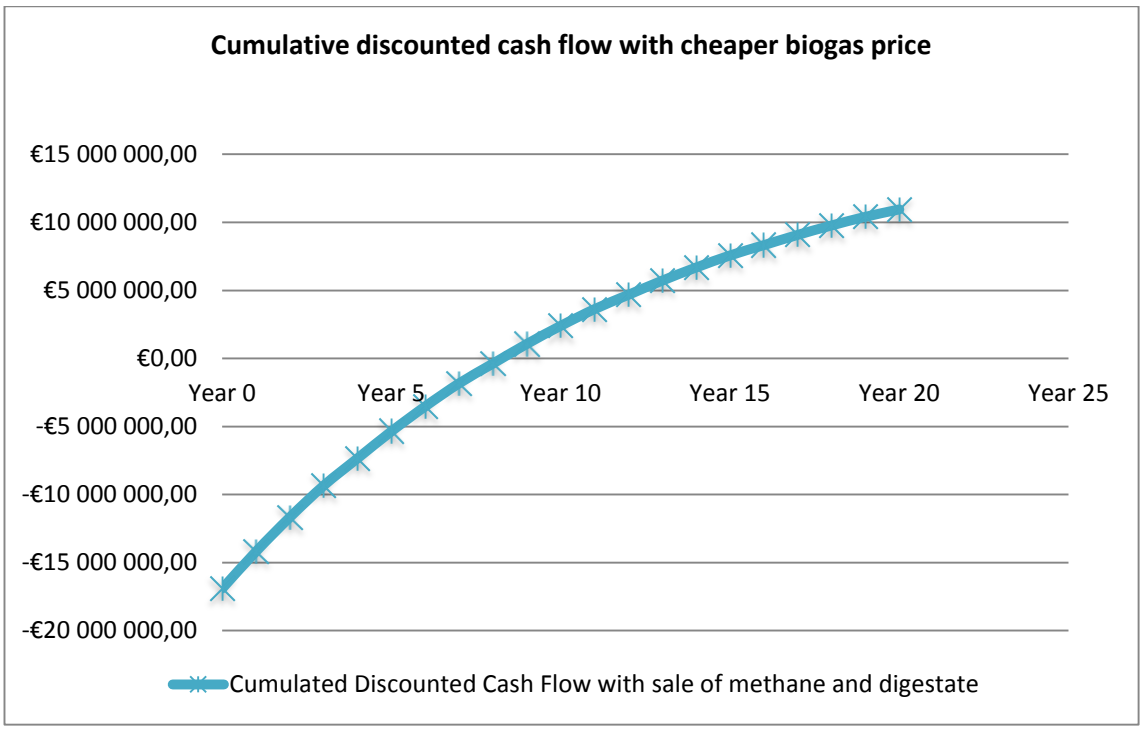

FIGURE 67: Cash flow analysis with cheaper biogas price

FIGURE 67 shows that if the biogas price is 1,176 [€/m³], the year of earning profit is 8th. In Scenario 1, the biogas price is 1,232 [€/m³], which means the plant can earn more money with the sale of biogas. Slight reduction of biogas price has small impact for the cash flow. Compared with FIGURE 64 in Scenario 1, the reduction of biogas price in Scenario 4 can postpone 1 year for the profit earning.

4.6.2.5 Scenario 5 - Add average reinvestment from actual data

There has been very high reinvestment in *Svensk Växtkraft AB*, TABLE 38 is the historical data of reinvestment from 2007 to 2013 in *Svensk Växtkraft AB*. There were investment grants in year 2007, 2008, 2010 and 2013, and in year 2007 the grants was quite large. The value of reinvestment cost is the investments in tangible assets minus the grants. In

TABLE 38, the value from the second row (Cash Flow from Investing Activities) is considered to be the reinvestment cost, therefore an average value form these data was applied for in the theoretical cash flow excel tool for the Scenario 5.

TABLE 38: Historical Reinvestment data from Svensk Växtkraft AB [32]

Currency: Euro	2007	2008	2009	2010	2011	2012	2013
Cash Flow From Investing Activities	1429340	-795630	-990330	-890230	-1239480	-2778490	-4312330
Investments In Tangible Assets	-897490	-756140	-1084380	-914870	-1239480	-2778490	-4365350
Yearly Investment Grant	2326830	134310	0	24640	0	0	53020
Yearly Average Reinvestment	-1368164						

In theoretical cash flow analysis excel tool, the cost of maintenance and repair belongs to the reinvestment cost. It varies according to the amount of produced biogas. As is presented in TABLE 32, every 1 cubic meter of biogas costs 1,5cent € for the maintenance and repair. In Scenario 1, the annual reinvestment cost of the biogas plant is 64074 € with 2% increment. In Scenario 5, the reinvestment cost value is based on the historical reinvestment data from the actual plant in TABLE 38.

TABLE 39: Different background between Scenario 1 and 5

	Different parameters- annual reinvestment cost
Scenario 1	- 64074 €
Scenario 5	-1368164 €

TABLE 39 shows the different parameters used in the excel tool between Scenario 1 and 5. The only different parameters used between Scenario 1 and 5 is the annual reinvestment cost. In Scenario 5, the annual reinvestment cost in 1368164 €, which is the double amount compared with the value used in Scenario 1.

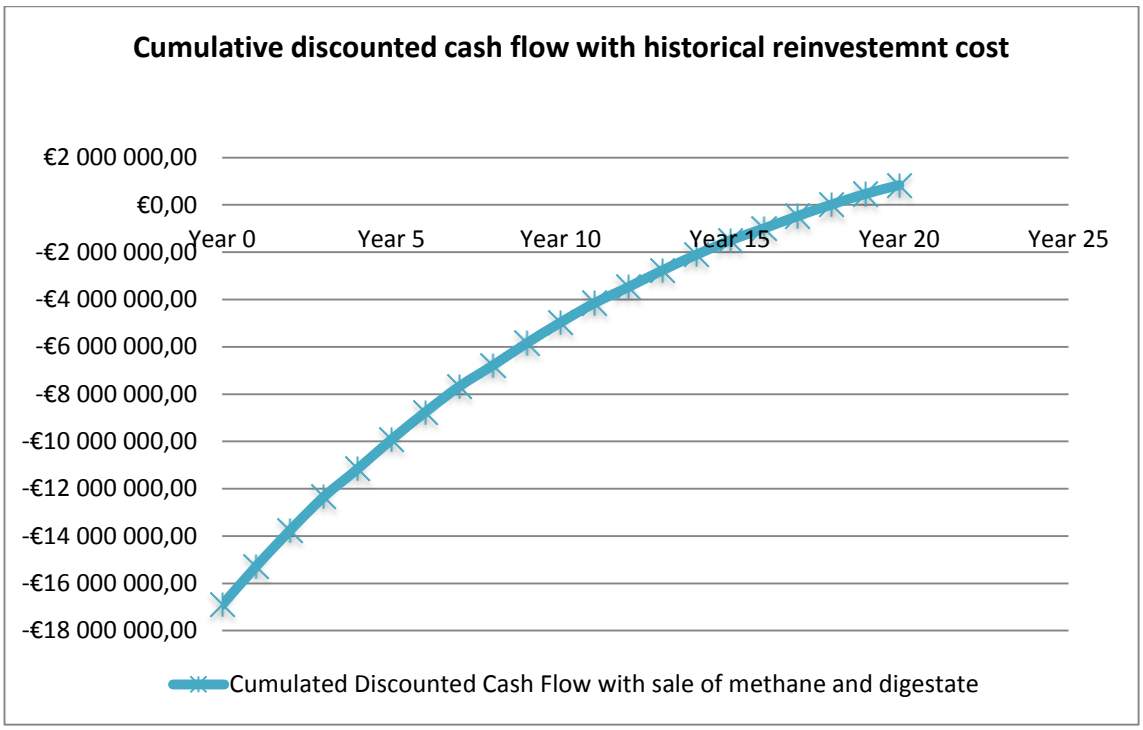

FIGURE 68: Theoretical cash flow with average reinvestment from actual (historical) data

FIGURE 68 shows that the plant is able earn money in year 18th after inputting historical average reinvestment cost in the theoretical cash flow excel tool. In Scenario 1, the plant can earn profit between year 7th and 8th (FIGURE 64). By inputting the historical average reinvestment cost in the excel tools, the time of earning profit for the plant is postponed to 10 years later (year 18th).

4.6.2.6 Scenario 6- Add average reinvestment cost from historical data and increase labour amount

For purpose of better comparisons, more than one parameters are applied in Scenario 6. In this Scenario, it is assumed that there are 11 workers working for the plant, and there is high reinvestment cost like the real case.

TABLE 40: Different background between Scenario 1 and 6

Different Parameters	Annual Reinvestment Cost	Labour Amount
Scenario 1	- 64074 €	6
Scenario 6	-1368164 €	11

TABLE 40 shows the different parameters used in the excel tool between Scenario 1 and 6. There are two different parameters used between Scenario 1 and 6. In Scenario 6, the annual reinvestment cost in 1368164 €, which is the double amount compared with the value used in Scenario 1. Also the labour amount in Scenario 6 is increased from 6 to 11.

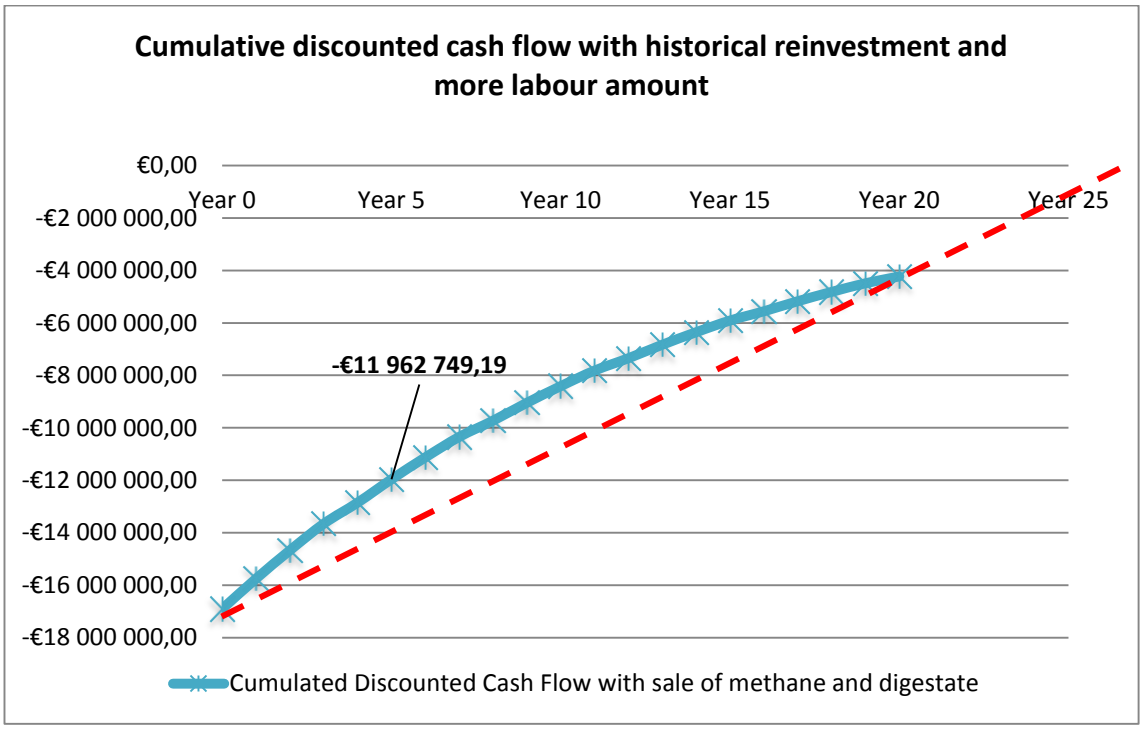

FIGURE 69: Cash flow with more workers and reinvestment cost

As is seen in FIGURE 69, in year 20, the plant is still not able to earn profit yet, only after year 26, it can cover all the cost and start earning profit. In year 5th, there is negative cash

flow of -11962749 €, the value is similar with the one indicated in FIGURE 63, which is from the actual historical data from the company. In the FIGURE 63, the plant have negative cash flow of -11883316 € in year 8th, instead of year 5th in FIGURE 69.

4.6.2.7 Scenario 7- Three parameters input (11 workers, reinvestment and biogas price 1,176 [€/m^3])

Scenario 7 has 3 different parameters applied in the excel tool compared with Scenario 1 and one more different parameter compared with Scenario 6. In this Scenario, it is assumed that there are 11 workers working for the plant, with average historical reinvestment and cheaper biogas price.

TABLE 41: Different background among Scenario 1, 6 and 7

Different Parameters	Annual Reinvestment Cost	Labour Amount	Biogas Price
Scenario 1	- 64074 €	6	1,232 [€/M³]
Scenario 6	-1368164 €	11	1,232 [€/M³]
Scenario 7	1368164 €	11	1,176 [€/M³]

TABLE 41 shows the different parameters used in the excel tool among Scenario 1, 6 and 7. There are three different parameters used between Scenario 1 and 7. In Scenario 7, the annual reinvestment cost is 1368164 €, labour amount is increased from 6 to 11 and biogas price is reduced to 1,176 [€/M³]. Compared with Scenario 6, Scenario 7 has one more different parameter, which is the price for biogas sale. The biogas price reduced from 1,232 [€/M³] to 1,176 [€/M³].

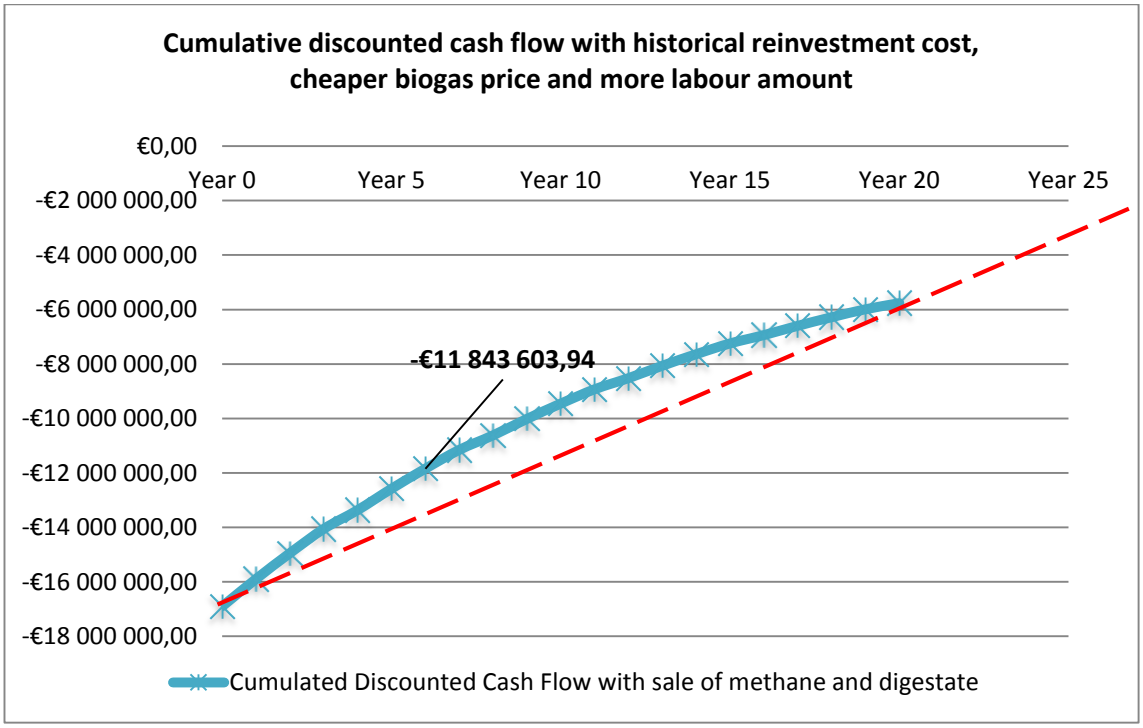

FIGURE 70: Three parameters input for theoretical cash flow

Regarding to three different parameters input based on the theoretical data: 11 workers working for the plant, high reinvestment every year and biogas price is reduced to 1,176 [€/m^3], the excel tools generates the trend line as is shown is FIGURE 70. It takes about 30 years for the plant to earn profit in this Scenario. In FIGURE 70, there is negative cash flow of -11843603 € in year 6th, the value is similar with the one indicated in year 8th in FIGURE 63(-11883316 €), which is from the actual historical data from the company. Compared with FIGURE 69 in Scenario 6, the FIGURE 70 shows a longer time for the plant to earn profit.

5. DISCUSSIONS

5.1 Presort Biowaste

5.1.1 Continuous reactors 1 and 2

On day 31st, the heating bath stopped working, causing the temperature change in reactor 1, temperature dropped from 42 ºC to 21ºC. The methane production and percentage in gas composition was lower compared with other days in both reactors. The FOS/TAC value of sample from reactor 1 was 0, 4, higher than the values measured on the other days under stable process, and the TAC value decreased, FOS value increased. In reactor 2, on day 29th and 30th, the stirrer did not work that the mixing in reactor 2 stopped. FOS/TAC value was 0, 66 on day 30th, which was a sign of overfed in the reactor 2, bacteria were not able to digest the substrate well. On day 31st, temperature changed as the same as in reactor 1, because the heating bath of reactor 1 and 2 was connected to each other. FOS/TAC value of samples from reactor 2 was 1, 04 on day 31st , which was an alarm of heavily overfed, at the same time, the pH value dropped to 6, 96. On the other hand, the produced methane percentage from reactor 2 on day 30th was only 52%, and CO_2 was 46%, and on day 31st CH_4% was 46% and CO_2% was 50%.

According to the literature review in chapter 2.2, if the substrate composition is stable, but the methane/ carbon dioxide ratio in the biogas falls, it is a sign of a higher rate of acid formation compared with methane formation, which means the equilibrium of mass flows in the degradation process is disrupted. The series changes were possibly due to the insufficient mixing in the reactor 2 and rapid temperature change in both reactors.

As is mentioned in chapter 2.4.6, there is density difference between bacterial mass and substrates. Most of the bacterial mass stays in the lower layer and substrates are collecting in the upper layers, thus mixing in the reactor can avoid the formation of layers. On day 29th and 30th, mixing stopped in reactor 2, it was most likely that bacteria were not able to contact with substrate intensively, leading to low level of biogas production and higher FOS/ TAC value.

Based on the literature review in chapter 2.4.1, mesophilic bacteria are able to tolerate ±3ºC differences without significant reductions of methane production, when the temperature had 21ºC difference on day 31st, there might have occurred inhibitions to the relevant microorganisms. The mesophilic bacteria seemed not active enough to digest the substrate effectively, causing increases in FOS/TAC value and less methane production in both reactors.

Apparently, insufficient mixing and instable temperature in the fermentation process could cause process inhibitory and lead to lower yield of methane.

After day 31st, the substrate feeding stopped for four days, and from day 35th, the feeding amount reduced 33%, from 120 g to 80g, in order to avoid overfed in reactor 1 and 2. After reduction of feeding amount, the CH_4% in the produced biogas composition was higher and stayed more constantly, and H_2S concentration decreased gradually. It seems that when biowaste is used as substrate, the organic load should be kept low in order to have a more stable fermentation process.

FIGURE 37 shows there was also slightly increases of FOS value in reactor 1, compared with FIGURE 43, the FOS value was increasing more significantly from beginning till day 31st, it means the volatile organic acids concentration was increasing in reactor 2. Compared TABLE 13 with TABLE 14, the acetic acid concentration was about 3 times higher in reactor 2 samples than reactor 1's, for example, on day 38th, there was 124,31 mg/l in reactor 1, while 396,17 mg/l in reactor 2. According to the index in TABLE 5, acetic acid under 1000mg/l is still stable process of fermentation. In chapter 1.2.4, it indicates that all acetic acid is converted into methane via acetic acid cleavage by acetoclastic methane-forming bacteria in methanogenic phase. It seems that the activity of methanogens in reactor 2 was weaker than the ones in reactor 1, from the parallel tests' view. Compared FIGURE 33 with FIGURE 39, it is obvious that the bacteria in reactor 1 were able to utilize the substrate more efficiently than the ones in reactor 2, because the sum methane line was closer to the sum substrate line in reactor 1. Despite of gas leaks affecting the layout of sum methane lines in FIGURE 33 and 39, the results from reactor 1 and 2 are adequate to draw a conclusion that the biocoenosis in reactor 2 was not as stable as the one in reactor 1. Such weak biocoenosis could have influenced the whole

operation in reactor 2, leading to lower methane yield. It should have added some active bacteria in reactor 2 to enhance the stability of biocoenosis. In reactor 1, the specific methane yield was 79,95 [(Vn) L/kg] CH_4/fresh mass, while in reactor 2 it was 63, 45 [(Vn) L/kg] CH_4/fresh mass. The degree of degradation of substrate in reactor one was the bacteria ware 74, 87%, while in reactor 2 it was 74,36%, which means the bacteria in reactor 1 were able to digest the presorted biowaste more efficiently. These results also prove that the reactor 2 was not able to utilize the substrate as sufficiently as reactor 1.

Reactor 2 had a bit higher ammonium concentration over the operation time. However, both reactors show similar ammonium concentration development. Both reactors show similar ammonium concentration development. The concentration rose steadily and also comparably for both reactors, except on day 31st and day 58th, the ammonium concentration was lower than the former result in reactor 1. According to the literature review in chapter 2.4.7, when pH value is over 8, ammonia (NH_3) concentration increases, which can inhibit the methanogens. As is showed in FIGURE 36 and 42, the pH values of samples from reactor 1 and 2 were relatively constant, only two data was more than pH 8. According to TABLE 6 in chapter 2.4.7, inhibition starts when the ammonium concentration exceeds 1500 mg/l. The highest concentration of ammonium in reactor 1 was 1208 mg/l and in reactor 2 was 1458 mg/l, that is to say, there was likely no ammonium nor ammonia inhibitory during the operational period of continuous reactor 1 and 2.

5.1.2 Result comparison between continuous test and batch test

The average methane yield per kg biowaste of continuous tests (reactor 1 and 2) was Vn 71,7 L/kg CH_4/FM. In mesophilic batch test, the average CH_4/FM was 68 Vn L/kg, and in thermophilic batch test, the average CH_4/FM was 47,10 Vn L/kg. In mesophilic batch test, one reactor was able to produce 81, 46 liter CH_4 per kg biowaste, while the other one only produced 55, 22 liter CH_4 per kg biowaste. The result differences is likely a hint that there was difference in the composition of biowaste samples. In spite of composition differences in the samples, it is obvious that the result of methane yield in mesophilic continuous wet reactor is similar with the one in mesophilic batch test. In thermophilic

batch test, the results from two reactor were more alike compared with mesophilic batch tests, but the average value was much lower. TABLE 17 presents the fermentation data of batch tests and tells that mesophilic batch tests had higher degradation rate of substrate than thermophilic ones. The average methane percentage was 55,6% in mesophilic batch test, 53,9% in thermophilic batch test, 56,5% in continuous reactor 1 and 59% in continues reactor 2. As conclusion, presorted biowaste from Västmanland region, Sweden, is likely to produce more biogas under mesophilic condition rather than thermophilic condition and its produced biogas consists of high methane concentration values which is perfect for biogas quality.

5.2 Municipal solid waste

The results of dry matter and organic dry matter content in three batches of municipal solid waste varied a lot, the result of DM and oDM content in the second batch waste indicated the highest values. The reason of oDM% in second batch waste was higher was probably due to the high content of plastic, since plastic is also organic, during the oDM test it could increase the weight of organic matter. However, the bacteria are not able to digest the plastic. Considering the municipal solid waste was quite inhomogeneous, it did not make much sense to use the specific value of dry matter and organic dry matter content from three batches waste for the calculation of organic loading. In other words, although the values of DM% and oDM% were different in three batches waste, in this thesis data analysis, only the first DM% and oDM% value was chosen.

5.2.1 Continuous reactor 3 and 4

Parallel tests in reactor 3 and 4 showed similar behaviors. Generally speaking, the data of tests for both reactors had similar characteristics. During the fermentation process, the average CH_4 concentration in produced biogas was 57, 32% in reactor 3 and 59,87% in reactor 4. pH values, FOS/TAC value, H_2S value were rather constant in both reactors, except the first 10 days there were variations, which was reasonable because the

microorganisms were not so stable at the beginning of the fermentation process and needed to get used to the environment.

First batch waste was used from day 1st till day 35th, and second batch waste was used from day 36th till day 50th, the third batch was used from day 51st till the end of the test. Compared the FIGURE 48 with 54, there was similar trend of weekly methane production in both FIGUREs, which showed that from week 6 to week 8, the weekly methane productions were lower compared with the previous weeks, and week 6 (day 36th) started the utilization of second batch waste. It seems that the second and third batches of municipal solid waste had less biogas potential. In FIGURE 49 and FIGURE 55, the CH_4% started to decrease since day 36th. This result is also a strong, convincing argument that the methane potential in second and third batches of municipal solid waste was lower and the results of organic dry matter content were not able to provide certain reference significance.

In FIGURE 47, the gap between the line of sum methane and the line of sum fresh mass was bigger on day 16th and day 17th, because there was gas leaks in reactor 3 on these two days. FIGURE 53 shows similar trend of both lines, which means in reactor 4, the microorganisms were able to digest the substrate well. The average methane potential of municipal solid waste in reactor 3 was 68, 78 Nm^3/ton fresh mass, while in reactor 4 was 73, 14 Nm^3/ton fresh mass. The results make sense, since there was gas leaks in reactor 3 but the reactor 4 did not have gas leaks. The degradation rate of substrate in reactor 3 was 57,39%, and in reactor 4 was 59,46%. Compared with the methane production, reactor 4 had higher yield of methane per ton fresh mass. It seems the bacteria in reactor 4 were able to digest more municipal solid waste and thus, more methane was produced. That is so to say, the higher methane yield in reactor is most likely due to the higher bacteria activity and fewer accidents occurring (gas leaks).

On day 31st, the heating bath stopped working, both reactor suffered dramatic temperature change, however, the test results from that day did not really show there was significant change in the reactors, although there was less biogas production on that day, but the values of pH, FOS/TAC, CH_4% stayed stable. In both reactors, H_2S concentrations in produced biogas were rather low that the highest measured data was only 246 ppm.

Ammonium concentrations of samples from reactor 3 and 4 were lower than 2000 mg/l, with an increasing trend along the fermentation process. As pH value in both reactors never reached to 8, there was likely no ammonium nor ammonia inhibitory during the operational period of continuous reactor 3 and 4. That is so to say, during the whole fermentation process, both reactors had relatively high stability.

5.2.2 Result comparison between continuous test and batch test

The average methane yield per kg municipal solid waste of continuous tests (reactor 3 and 4) was Vn 71 L/kg CH_4/FM, of which in mesophilic batch test was 68,24 1/kg CH4/FM and in thermophilic batch test was the average CH_4/FM was 68,71 1/kg CH4/FM. The average methane production in mesophilic and thermophilic batch tests was rather similar. However, the production of methane liter per kg fresh mass varied in the parallel tests. In mesophilic batch test, reactor 1 had a result of 94, 18 L/kg fresh mass, while reactor 2 had only 42, 30 L/kg fresh mass. Similar situation occurred in thermophilic batch test as well. On the other hand, mesophilic batch tests had higher average degradation rate of substrate than thermophilic ones. Reactor 2 (mesophilic) had the highest degradation rate (78, 77%) with lowest mass lost, but it produced least methane. Such result is likely a hint that the municipal solid waste is quite inhomogeneous.

Although the municipal solid waste is quite inhomogeneous, but the average cumulative methane amounts are relatively close. The produced biogas consists of high methane concentration values, which indicates that municipal solid waste is perfect for biogas quality.

5.3 Reject waste

In mesophilic and thermophilic batch tests, both parallel tests had very alike results. In mesophilic batch test, reject waste had an average methane potential of 65, 67 Nm^3/ton fresh mass and in thermophilic batch test, it had an average methane potential of 70, 41 Nm^3/ton fresh mass. However, mesophilic batch tests had higher average degradation rate

of substrate than thermophilic ones. Substrate in Reactor 2 (mesophilic) had the highest degradation rate (93, 72%), while substrate in reactor 3(thermophilic) had the lowest degradation rate than the other three reactors (70, 82%). Mass lost were larger in thermophilic batch tests than the ones in mesophilic batch test. The result indicates that reject waste under mesophilic condition is more easily digested, but methane produced during fermentation process is less. Considering the larger mass lost and higher methane yield in thermophilic batch tests, the results of lower degradation rate is doubtable. Besides, reactor 2 had a degradation rate of 93, 72%, which is much higher compared with the degradation rate from reactors. It seems there was operation error in the DM and oDM test, such as insufficient mixing during sample taking. It possibly led to the inaccuracy of the results of degradation rate of substrates.

5.4 Results comparison of different fermenters

According to the data in TABLE 28, mesophilic wet digester with enzymes could produce most methane (76, 51 liter under standard condition) with 1 kg municipal solid waste. The other mesophilic wet digesters (Reactor 3 and Reactor 4) without additive enzymes had a result of 68,00 CH_4/ fresh mass Vn L/kg FM. Things worth mentioning is that each person has his or her own method of sorting out the impurities, which may have affected the organic dry matter content in the same amount of waste. Besides, the organic loading rate was different, reactor 3 and 4 only received 107 g of sorted waste per weekdays, but the reactors ran my team mate Patrick received 150g of sorted waste per day. Compared with these two cases, a conclusion could be that with the help of enzymes, substrate can be digest more completely and more methane yield can be achieved, but the results differences might have been smaller if the waste was sorted out by the same person and the feeding amount was the same.

The pilot B- Plug Flow fermenter in Sweden had a specific methane yield of 74, 64 (Vn L/kg FM), which is slightly lower than the results of mesophilic wet digester with enzyme addition but a bit higher than the mesophilic wet reactor 3 and reactor 4. In this plug flow fermenter, much larger amount of waste was used for the experiment (6,27kg per day) , however, in reactor 3 and 4, during the 65 days measurement, in total 3965 g of fresh

mass per reactor. Due to the fact that there is a lot variations in the organic dry matter content of municipal solid waste, the more waste used in the experiment, the more accurate is the result. Besides, there was gas leaks in reactor 3, which brings the result down. At this point, the difference of results between pilot B and wet digester is sensible. Other things worth mentioning is that the operating temperature, the way of sorting out the impurities, the organic loading rate, the freshness of the waste, the retention time and also the limitation of selected data (small quantity) are influencing the output of methane. The plug flow fermenter received fresher waste compared with the other three fermenters, because of its location. The waste used in the other three fermenter in the school lab was not as fresh and had been frozen and unfrozen, which might have influenced the quality of the waste and reduced its organic content.

Thermophilic dry garage fermenter produced less methane per kg fresh mass. 1 kg municipal solid waste had capability to produce 53, 83 liter methane. If just compare the results from other reactors without further investigation, it seems like that the thermophilic dry garage fermenter is quite low-efficient. However, the waste was not sorted, impurities such as glass, metals contributed the share of waste weight. In other words, since thermophilic dry garage fermenter used unsorted waste, the results of methane yield per kg fresh mass did not really indicate the low efficiency of this fermenter.

It seems with enzyme addition, the municipal solid waste can be digested more completely and therefore a higher methane yield can be achieved. Plug flow fermenter also had high methane yield, and it might be because of the better quality of waste. The sorting method for the waste and the gas leaks might be the main reason of lower methane yield in continuous reactor 3 and 4. In the continuous reactor tests, the waste required pre-sanitation, but in the thermophilic plug flow fermenter and dry garage fermenter, the waste could have the sanitation effects because of the high temperature. Dry garage fermenter used unsorted waste, thus the lowest methane yield is reasonable. What's more, the dry garage fermenter does not need to sort out the impurities in the waste, which can save a lot of time and reduce the labor cost.

As conclusion, continuous reactor and plug flow reactors can ensure the stable gas production by the regular feeding, however, it required high energy consumption and

intensive labor work. Dry garage fermenter does not provide stable daily gas production, but it makes technically simpler, consumes less energy, less labor intensity, and no necessary requirements for waste sorting.

5.5 Cash flow analysis

FIGURE 63 is the cash flow layout with the use of actual data from *Svensk Växtkraft AB*, as is shown, if the plant continues to invest heavily in building filling stations, it will take about 25 years to get the payoff. Due to the fact that there is only data from year 2nd to year 8th inputted in the excel, and the future cash flow development is not known, the red dotted line is created for estimating the future cash flow development.

In theoretical cash flow analysis, Scenario 2, 3 and 4 do not show big similarity results with the results from actual data. However, compared them with the original theoretical cash flow FIGURE (FIGURE 64) in Scenario 1, it seems that the amount of workers, the price of biogas can influence the cash flow of the plant in a certain way. If the total investment cost is 8 million € instead of 16 million €, the plant can start the payoff 4 years earlier in the theoretical analysis.

In Scenario 5, the plant is able to earn money in year 18th after inputting average reinvestment cost in the theoretical cash flow excel tool. That is to say, by adding the reinvestment cost, 10 years more is needed until the plant start to earn profit. Reinvestment seems to be the main reason of enabling the earnings of profit.

Results of Scenario 6- Add average reinvestment and 11 workers has similar trend with the cash flow of actual data. As is seen in FIGURE 69, in year 20th, the plant is still not able to earn profit, only after 26 years, it can cover all the cost and start earning profit. In year 5th, there is negative cash flow of -11962749 €, the value is similar with the one indicated in FIGURE 63 of actual data cash flow analysis, which is -11883316 € in year 8th.

Results of Scenario 7- Three parameters input (11 workers, reinvestment and biogas price 1,176 [€/m3]), also shows similar trend with cash flow of actual data. As is shown in

FIGURE 70, in year 6th, there is negative cash flow -11843603 €, the value is similar with the one indicated in FIGURE 63. However, in this Scenario, about 30 years is needed for the plant to earn profit.

As Scenario 6 and 7 show parts of the similarities with the actual data cash flow and Scenario 5 shows the big influence of reinvestment cost, it is workable to conclude that the main factors of not being able to make up the cost in *Svensk Växtkraft AB* are mainly the high reinvestment cost, and the number of workers, the biogas price are also factors that could affect the cash flow in a certain extent.

5.6 Discussions of results under consideration of experimental mistakes

In continuous reactor 1, 2 and 3, there was gas leaks from gas bags and water seal, which led to the lower methane value in the results. Water bath stopped working for 20 hours, causing temperature reductions in the 4 continuous reactors and influenced the bacteria activity and methane production. The self-constructed stirrer did not work in some reactors and led to insufficient mixing of bacteria and substrate in the reactor 1 and 2, causing reduction of biogas production.

The batch reactors should have been shaken everyday manually to ensure a sufficient mixing. However, during weekends there was no mixing for the batch reactors, and during weekdays the mixing frequency is quite low compared with the continuous reactors, which might have influenced the biogas production from batch reactors.

The gas measuring device *SEWERIN SR2-DO* always showed higher CO_2 concentration and causing the sum of CH_4 and CO_2 percentage in the measured biogas was more than 100%. In the FOS/TAC titration test, it was hard to get the exact 5, 0 g liquid phase and reach to exact 20, 0 g mixture with milo pore water. This operational error could have influenced the value of FOS/TAC in a certain extent. In the DM and oDM test, the sample portion was small, which might not be able to reflect the real value of dry matter and organic dry matter content of the investigated waste. Especially for the municipal solid waste, it was not possible to sort out all the impurities, the remaining plastic might have increased the organic dry matter content value.

It is of great importance to eliminate or reduce the experimental errors for the higher accuracy of results. Gas leaks should be avoided by more careful check for the gas bags, gas pipes and other possible leakage spots. Temperature in the reactors should be kept constant to avoid inhibitions to the relevant microorganisms. Sufficient mixing in the reactor should be ensured for the stable biogas production. The experimental device is the foundation of accurate experiment results. It is of great importance to guarantee the accuracy in the experimental devices.

6. CONCLUSION

For the purpose of efficient fermentation, good contact of bacteria and substrate, stable temperature, and proper organic loading rate are the factors that should be ensured. When using biowaste as substrate, it is suggested to feed the reactor with lower organic loading rate. Although municipal solid waste is quite inhomogeneous, it has relatively high stability in the fermentation process. Biowaste and municipal solid waste are able to produce biogas consists of high methane concentration values, which is perfect for biogas quality.

The municipal solid waste could be digested more completely with enzyme addition. The better quality of waste might be the reason of higher methane from Plug flow fermenter. The sorting method for the waste and the gas leaks might be the main reason of lower methane yield in continuous reactor 3 and 4. The lowest methane yield from dry garage fermenter could be because of the unsorted waste.

Scenario 6 and 7 are similar with the historical data cash flow, it seems that the main factor of not being able to make up the cost in *Svensk Växtkraft AB* is the high reinvestment cost.

The aim of operating a biogas plant is to gain the maximum rate of methane production with lowest cost. Considering the type of fermenters for the plant, it is not enough to just compare the specific methane yield from each fermenter. The size of the fermenter, the installation and operation intensity of the fermenter, the labor intensity for substrate feeding, the time and labor intensity for substrate pretreatment such as sorting of impurities, the electricity consumption of fermenter operation and so on, are the other factors that should be carefully compared and considered.

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APPENDICES

Appendix 1. Data from continuous reactor 1

Day	Temperature(C)	Pressure(mbar)	Gas amount [l]	CH4 [%]	CO2 [%]	H2S [ppm]	Substrate(g)
1	20,5	1004	5,83	58	36	116	119,5
2	21,5	997	14,44	44	52	456	119,5
3			0				100
4	21,5	1007	24,13	54	44	238	0
5			0				0
6			0				0
7			0				0
8	24	1006	20,03	72	35	250	0
9							0
10			0				50
11	23	1008	12,66	60	41	256	80
12			0				119,5
13			0				0
14	22	1006	23,23	53	48	280	0
15			0				119,5
16	21,5	1005	19,15	51	51	352	119,5
17	21	1006	21,18	56	41	396	119,5
18	21	1003	18,43	57	45	494	119,5
19			0				119,5
20			0				0
21	20	1005	27,05	55	45	486	0
22	20,5	1004,5	16,69	59	42	478	119,5
23	20,5	1003	25,2	52	48	544	119,5
24	20	1003,5	24,05	58	43	426	119,5
25	20	1003	12,44	60	40	522	119,5
26			0				119,5
27			0				0
28	21	996	26,24	59	40	394	0
29	21	1001	14,3	59	42	342	119,5
30	21	1003	18,42	52	49	352	119,5
31	21	1005	12,57	52	46	272	119,5
32	22,5	1005	18,3	54	47	230	0
33			0				0
34			0				0
35	24	1005	15,16	66	33	190	0

36	23,5	995	6,72	61	38	230	80
37	23	992	12	58	42	320	80
38	22,5	992	14,14	56	46	250	80
39	23	995	11,11	57	45	210	80
40			0				80
41			0				0
42	22	994	11,41	61	42	250	0
43	23	1001	0,49	24	16	72	80
44	23,5	1003	1,28	41	31	48	80
45	24	1004	11,94	54	44	78	80
46	25	1004	4,46	60	38	66	80
47			0				80
48			0				0
49	27	995	20,43	61	37	172	0
50	25,5	999	8,7	61	36	168	80
51	26	1001	11,51	58	45	148	80
52	26	1001	12,68	57	39	176	80
53	25,5	1001	7,92	56	40	146	80
54			0				80
55			0				0
56	26	1001	21,74	59	47	104	0
57	25	994	9,18	61	37	34	80
58	24,5	994	13,44	55	45	100	80
59			0				0
60			0				0
61			0				0
62			0				0
63			0				0
64			0				0
65	22,5	1001	1,5	64	38	98	0

Appendix 2. Data from continuous reactor 2

Day	Temperature(C)	Pressure(mbar)	Gas amount [l]	CH4 [%]	CO2 [%]	H2S [ppm]	Substrate(g)
1	20,5	1004	2	21	28	60	119,5
2	21,5	997	9,44	33	48	324	119,5
3			0				100
4			0				0
5			0				0
6			0				0
7			0				0
8			0				0
9	24	1006	1,84	72	32	114	0
10			0				50
11	23	1008	1,46	63	40	166	80
12			0				119,5
13			0				0
14	22	1006	6,43	66	39	302	0
15			0				119,5
16	21,5	1005	3,87	55	49	216	119,5
17	21	1006	2,08	58	39	176	119,5
18	21	1003	22,57	54	46	502	119,5
19			0				119,5
20			0				0
21	20	1005	26,05	57	42	608	0
22	20,5	1004,5	16,65	62	39	666	119,5
23	20,5	1003	13,93	59	41	508	119,5
24	20	1003,5	18,7	52	47	450	119,5
25	20	1003	17,35	50	51	558	119,5
26			0				119,5
27			0				0
28	21	996	25,9	60	39	550	0
29	21	1001	11,89	65	38	506	119,5
30	21	1003	13,87	52	46	498	119,5
31	21	1005	7,58	46	50	488	119,5
32	22,5	1005	15	48	51	402	0
33			0				0
34			0				0
35	24	1005	17,46	69	31	384	0
36	23,5	995	6,95	69	30	332	80
37	23	992	9,2	61	38	336	80
38	22,5	992	11,18	54	45	274	80
39	23	995	10,68	53	45	222	80

40			0				80
41			0				0
42	22	994	17,08	61	41	294	0
43	23	1001	7,88	65	30	224	80
44	23,5	1003	8,7	59	41	186	80
45	24	1004	11,08	57	44	98	80
46	25	1004	11,3	58	42	124	80
47			0				80
48			0				0
49	27	995	14,91	61	38	216	0
50	25,5	999	7,02	61	36	192	80
51	26	1001	6,91	59	45	178	80
52	26	1001	10,55	50	45	182	80
53	25,5	1001	11,31	52	44	208	80
54			0				80
55			0				0
56	26	1001	18,26	62	45	160	0
57	25	994	7,05	62	34	66	80
58	24,5	994	9,65	57	43	154	80
59			0				0
60	23,5	998	12,62	61	41	188	0
61			0				0
62			0				0
63			0				0
64			0				0
65	22,5	1001	11,05	62	37	132	0

Appendix 3. Data from continuous reactor 3

Day	Temperature(C)	Pressure(mbar)	Gas amount [l]	CH4 [%]	CO2 [%]	H2S [ppm]	Substrate g/d
1	20,5	1004	7,8	47	35	6	119,5
2	21,5	997	10,26	49	49	214	119,5
3			0				87
4			0				
5			0				
6			0				
7			0				
8			0				
9	24	1006	8,54	54	34	18	
10			0				43
11	23	1008	0,6	18	22	4	65
12			0				107
13			0				
14	22	1006	9,1	59	40	170	
15			0				107
16	21,5	1005	17,42	55	41	122	107
17	21	1006	4,82	52	37	22	107
18	21	1003	14,42	57	41	100	107
19			0				107
20			0				
21	20	1005	23,65	64	37	132	
22	20,5	1004,5	12,29	65	37	102	107
23	20,5	1003	12,01	63	38	58	107
24	20	1003,5	17,01	62	41	46	107
25	20	1003	13,82	62	41	62	107
26			0				107
27			0				
28	21	996	25,38	62	39	64	
29	21	1001	14,18	60	39	32	107
30	21	1003	15,41	60	41	48	107
31	21	1005	10,95	63	38	22	107
32	22,5	1005	19,52	59	43	68	107
33			0				107
34			0				
35	24	999	26,29	60	48	46	
36	23,5	995	11,51	62	41	52	107
37	23	992	11,55	61	39	48	107
38	22,5	992	16,3	60	43	54	107
39	23	995	8	58	43	36	107

40			0				107
41			0				0
42	22	994	20,9	59	44	72	0
43	23	1001	10,84	58	39	74	107
44	23,5	1003	10,66	60	41	70	107
45	24	1004	13,2	60	41	42	107
46	25	1004	16,9	59	42	124	107
47			0				107
48			0				0
49	27	995	21,89	55	43	74	0
50	25,5	999	11	57	40	84	107
51	26	1001	10,14	60	43	86	107
52	26	1001	14,68	56	41	102	107
53	25,5	1001	15,55	54	43	102	107
54			0				107
55			0				0
56	26	1001	19,95	58	49	70	0
57	25	994	9,39	59	38	38	107
58	24,5	994	13	57	43	68	107
59			0				0
60	23,5	998	13,6	55	47	100	0
61			0				0
62			0				0
63			0				0
64			0				0
65	22,5	1001	11,45	59	44	30	0

Appendix 4. Data from continuous reactor 4

Day	Temperature(C)	Pressure(mbar)	Gas amount [l]	CH4 [%]	CO2 [%]	H2S [ppm]	Substrate g/d
1	20,5	1004	6,26	57	36	184	119,5
2	21,5	997	10,42	51	49	436	119,5
3			0				87
4			0				
5			0				
6			0				
7			0				
8	24	1006	15,53	69	37	276	
9			0				
10			0				43
11	23	1008	5,9	67	35	122	65
12			0				107
13			0				
14	22	1006	10,96	63	42	230	
15			0				107
16	21,5	1005	19,34	60	44	228	107
17	21	1006	15,61	60	39	104	107
18	21	1003	15,09	60	42	146	107
19			0				107
20			0				
21	20	1005	20,87	62	41	118	
22	20,5	1004,5	10,56	62	40	90	107
23	20,5	1003	13,96	61	40	80	107
24	20	1003,5	14,47	62	40	74	107
25	20	1003	12,62	62	40	52	107
26			0				107
27			0				
28	21	996	19,94	62	40	72	
29	21	1001	12,04	62	41	46	107
30	21	1003	13,56	60	42	76	107
31	21	1005	10,2	62	38	26	107
32	22,5	1005	19,56	59	45	58	107
33			0				107
34			0				
35	24	999	24,3	61	48	60	
36	23,5	995	13,22	61	39	48	107
37	23	992	11,04	62	39	58	107
38	22,5	992	14,12	61	43	70	107
39	23	995	17,18	60	42	60	107

40			0				107
41			0				0
42	22	994	23,91	60	42	64	0
43	23	1001	12,14	58	39	68	107
44	23,5	1003	11,34	60	42	72	107
45	24	1004	11,68	60	40	38	107
46	25	1004	16,24	59	41	50	107
47			0				107
48			0				0
49	27	995	21,89	56	42	82	0
50	25,5	999	7,96	59	38	82	107
51	26	1001	8,66	62	42	86	107
52	26	1001	16,17	57	40	108	107
53	25,5	1001	4,6	55	45	122	107
54			0				107
55			0				0
56	26	1001	22,6	54	43	100	0
57	25	994	13,51	58	39	40	107
58	24,5	994	18,51	56	46	104	107
59			0				0
60	23,5	998	17,86	56	44	100	0
61			0				0
62			0				0
63			0				0
64			0				0
65	22,5	1001	11	59	43	48	0