Expertise
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Small Scale Biogas reactor

Biogas production feasibility in cold temperature

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Biogas is identified as one of the alternative fuels to the non-renewable fuels such as petrol, diesels and kerosene. Biogas production at both large and small scale is common in countries like Germany, United States and China. However, the concern has been about the production of biogas in developing countries facing cold climate. Biogas production is very much dependent on temperature; therefore, in cold climates, it is nearly impossible to produce biogas without the application of external heat.

The purpose of this thesis was to study the feasibility and viability of biogas production on small scale in cold temperatures. The thesis also focuses on the hazards that follow small scale biogas production. The protection measures for such hazards are also explored in the thesis.

The thesis also discusses the available technology to detect the leakages that might occur in a small-scale anaerobic digester. The study concludes that biogas production at colder climates require the biogas reactors to be externally heated, which is not cost-friendly. However, communal digester is suitable and feasible if heating is done.

Keywords	anaerobic digestion, biogas, hazards, sensors, mesophiles, psychrophiles, thermophiles, temperature, digestate

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Thank you!

April 2019
Bibek Shrestha and Sanju Shrestha

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List of abbreviations and symbols

AD	Anaerobic Digestion
CH_4	Methane
CO_2	Carbon Dioxide
UAS	University of applied science
EU	European Union
N	Nitrogen
P	Phosphorus
K	Potassium
kg/t	Kilograms per ton
kW	Kilowatt
C	Carbon
HRT	Hydraulic Retention Time
SRT	Solid Retention Time
OLR	Organic Loading Rate
mg/L	Milligrams per liter
VFA	Volatile Fatty Acids
LCFA	Long-chain Fatty Acids
TS	Total Solids
VS	Volatile Solids
$KgVSm^{-3}d^{-1}$	Kilograms of Volatile Solids per cubic meter per day
m^3/h	Cubic meter per hour
LEL	Lower Explosion Limit
UEL	Upper Explosion Limit
CNS	Central Nervous System
VOC	Volatile Organic Compound
PVC	Polymerizing Vinyl Chloride
IP65	Ingress Protection 65
OTAP	Over the Air Programming
mAh	Milli Ampere Hour
USB	Universal Serial Bus

RH	Relative Humidity
ppm	Parts per Million
mA	Milli Ampere
kPa	Kilopascal
ml	Milliliter
L	Liter
L gas d^{-1}	Liter of gas per day
BTU	British Thermal Unit
$kgVS/m^3$	Kilogram of Volatile Solid per cubic meter

1 Introduction

Anaerobic digestion is an oxygen-free natural decomposition process in the presence of bacteria. Biowastes such as animal manure, food wastes and straws. can be used as substrates. As a result of digestion, gaseous byproducts composed primarily of methane (CH_4) and carbon dioxide (CO_2) are released. Operation of typical anaerobic digesters are accomplished in mesophilic (20-45 °C) and thermophilic (45-65 °C) conditions. However, methanogenesis can also be achieved under 20 °C. Digestion is achieved in the presence of psychrophilic bacteria. [1]

There have been numerous researches done regarding biogas production in mid and high temperatures. However, for cooler temperatures, not enough studies and even fewer successful projects can be found. In this project, possibilities of biogas production in different temperatures will be studied along with successful-case studies. The success of a digester depends on the presence and production of methanogenic bacteria.[2]

Around one-third of the total food produced worldwide is wasted annually, which accounts to 1.3 billion tons of food. According to the European Environment Agency, around 40 % of the total municipal waste in Europe is biowaste. Municipal wastes in Europe are disposed of through landfilling (31 %), incineration (26 %) and recycling (43 %). Anaerobic digestion has the least impact on climate change followed by incineration and landfill respectively. [3]

2 Objectives

This thesis focuses on installing a functioning small-scale biogas reactor and a leakage detecting system to ensure the safety aspects of the project. The main objectives of this thesis are listed below:

- To design a small-scale biogas reactor
- To study biogas production potential at different temperatures
- To analyze biogas production feasibility and sustainability in cold climates
- To determine possible leakage detection system
- To identify possible usage of the digestate

3 Background

The initial plan for the thesis was to conduct an experiment with three digesters subjected to environments with different ambient temperatures: 0 °C, 21 °C and 35 °C. Because of the construction of the laboratory in Metropolia UAS during the period of thesis, the experiment was not possible. Therefore, looked at the different techniques used in production of biogas in cold climates were studied. The techniques were then compared to the practices in regions with warmer temperature throughout the year.

In Tongliang, China, a successful project in biogas production at different temperatures was conducted. However, at lower temperatures, gas production was insufficient. [1] The possibility of digestion with mesophilic-psychrophilic bacteria-mixture was also studied. According to Cordova report, at 15 °C, biogas production was achieved only in digester with psychrophilic bacteria. In digesters with mesophilic bacteria and mesophilic-psychrophilic bacteria mixture, no production was observed. At 25 °C, the psychrophilic digester had the highest production on average, followed by mixed and mesophilic digester respectively. [2]

Directive 2014/34/EU issued by European Parliament aims on minimizing potential risks at explosive atmosphere, by determining minimum requirements for revamping safety and health of workers. Gas hazards and their safety measures are also discussed in this thesis. To determine any possible leakages, a Waspmote Plug and Sense! - Smart Environment Pro node from Libelium is recommended. Such node is used for determining air quality in industrial, farming or environmental projects.

4 Literature Review

4.1 Anaerobic Digestion

Anaerobic digestion (AD) is a biological process where breakdown of organic materials forms biogas in absence of oxygen. Anaerobic digestion is possible due to the presence of bacteria that convert complex organic materials into acetate and hydrogen. Figure 1 below shows the phases of AD.

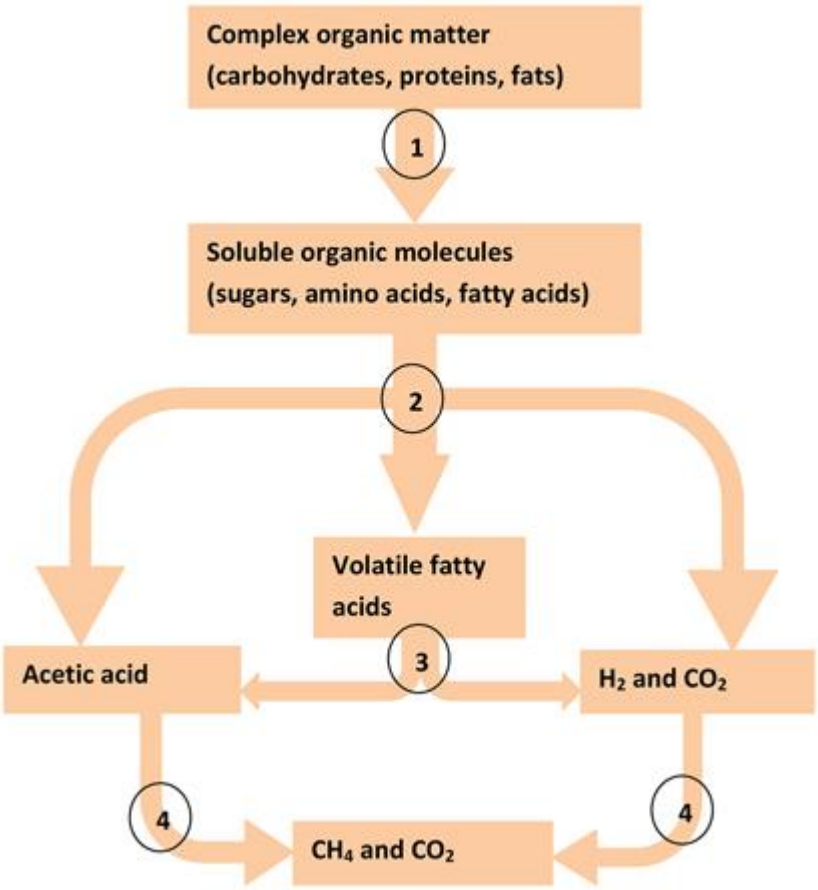

Figure 1. Phases of AD [5]

There are four basic phases of AD: hydrolysis, acidogenesis, acetogenesis and methanogenesis. [4]

4.1.1 Hydrolysis

Hydrolysis is a process of using water to split bonds of polymers [6]. Carbohydrates, fats and proteins, which are all polymers, are broken down into simple sugars, fatty acids and amino acids.

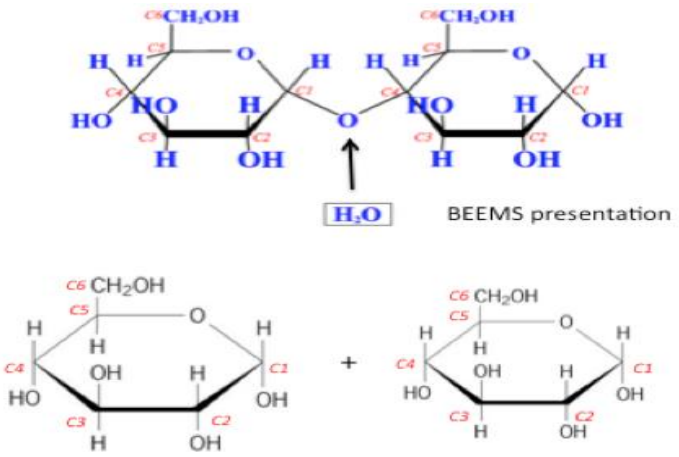

Figure 2. Reaction in Hydrolysis [4]

Exoenzymes (cellulosome and protease) from several bacteria, protozoa and fungi, along with water, are required for reaction. [4]

4.1.2 Acidogenesis

In acidogenesis, soluble monomers are further broken down into small organic compounds. There are two reactions in this phase as shown below.

$$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O$$

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2 \text{ [4]}$$

Ammonia, H_2, $C0_2$, H_2S, shorter volatile fatty acids, carbonic acids and alcohol are the products of acidogenesis. [5]

4.1.3 Acetogenesis

Acetogenesis is a phase in which the substrates of acidogenesis are broken down into acetate, H_2 and CO_2. Following reactions take place in acetogenesis.

$$CH_3CH_2COO^- + 3H_2O \rightarrow \ CH_3COO^- + H^+ + HCO_3- + 3H_2$$

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$$

$$CH_3CH_2OH + 2H_2O \rightarrow CH3COO^- + 2H_2 + H^+$$

$$2HCO_3^- + 4H_2 + H^+ \rightarrow CH_3COO^- + 4H_2O$$

There are various bacteria that contribute to acetogenesis. *Syntrophobacter wolinii* is propionate decomposer. *Syntrophomonos wolfei* is butyrate decomposer. *Clostridium spp*., *peptococcus anaerobes*, *lactobacillus*, and *actinomyces* form acids. [4]

4.1.4 Methanogenesis

Finally, methanogens create methane from the remains of acetogenesis and previous other phases. Acetic acid and carbon dioxide are the two main byproducts of the first three phases AD. [5] Following are the six reactions that occur during methanogenesis:

$$2CH_3CH_2OH + CO_2 \rightarrow 2CH_3COOH + CH_4$$

$$CH_3COOH \rightarrow CH_4 + CO_2$$

$$CH_3OH \rightarrow CH_4 + H_2O$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

$$CH_3COO^- + SO_4^{2-} + H^+ \ \rightarrow 2HCO_3 + H_2S$$

$$CH_3COO^- + NO^- + H_2O + H^+ \rightarrow 2HCO_3 + NH_4^+$$ [4]

Methanobacterium, methanobacillus, methanococcus, and methanosarcina, etc. are examplses of bacteria that contribute to methanogenesis [4].

4.2 Uses of digestate

Digestate is the nutrient-rich slurry byproduct of anaerobic digestion. It comprises of indigested feed and dead micro-organisms. Digestate, although having similar characteristic to, is not compost. Compost is formed under aerobic conditions. Nitrogen (N), Phosphorus (P) and Potassium (K) content of feedstock are retained in the digestate. Approximate concentration of N, P and K in the digestate is dependent of the nutrient concentration of the substrate. The typical range is, N: 2,3 - 4,2 kg/t, P: 0,2 – 1,5 kg/t, and K: 1,3 – 5,2 kg/t. [7] An anaerobic digestion plant with 500 kW capacity produces over 10000 tons of digestate annually with around 10% dry matter. [9]

Digestate has been primarily used as fertilizer and soil enhancers, but it has other uses as well.

4.2.1 Fertilizer

The C:N ratio of fibers separated form digestate can be optimized by mixing with woodchips, sawdust or straw and replace a peat-based compost, with additional P and k possibly required [7]. Solid fraction of the digestate separated from the solid-liquid slurry can be dried using different dryers. Pellets made from solid fraction of digestate can be used as biofertilizers [9].

4.2.2 Nutrient extraction and reuse

Nutrients are recovered from digestate using methods such as vacuum evaporation, struvite recovery, vacuum thermal stripping and combined evaporation and reverse osmosis. The extracted are usable in various sectors. A study has shown that the liquid fraction of digestate when filtered and fed at a controlled flow served as a nutrient supplement for mushroom cultivation. Recycled liquid digestate has also shown to have a positive impact in methane generation in a low mono-digestion of straw. [9]

4.2.3 Microalgal cultivation

Another viable method of nutrient recover is microalgal cultivation. Algal biomass can be cultivated in engineered ponds containing organic wastes. As a result, a high-grade protein is obtained that can be used as an animal feed or as a slow fertilizer. [8]

4.2.4 Construction materials

Fiberboards can be made from digestate using a wet-forming or a dry-forming process. Low density fiberboards are used for insulation. Medium density fiberboards are mainly for making furniture. High density fiberboards are used as an overlay on workbenches, floors and for siding. [10]

4.2.5 Bioethanol

Bioethanol is produced by sugar formation and can be used as an alternative for petrol. Digestate is a source of cellulose, hemicellulose and other organic materials usable as feedstock for enzymic hydrolysis, product of which is bioethanol by fermentation of produced sugar. [8]

5 Factors affecting biogas production

There are various factors that can affect the performance of an AD plant. There are environmental factors such as temperature, pH, nutrients and presence of toxic substances. Process factors such as hydraulic retention time (HRT) and organic loading rate (OLR) and operational factors such as mixing and characteristics of waste feed also have impacts on AD. The most important factors are discussed in the following sections. [11] [12] [13]

5.1 Temperature

Theoretically, temperature has a directly proportional effect on biogas yield. Biogas production can be seen at various temperatures: 1) psychrophilic: 0-15°C, 2) mesophilic: 15-45°C, and 3) thermophilic: 45-65°C. [11] The most significant effect of temperature is on the growth rate and activity of the methanogenic organisms [12].

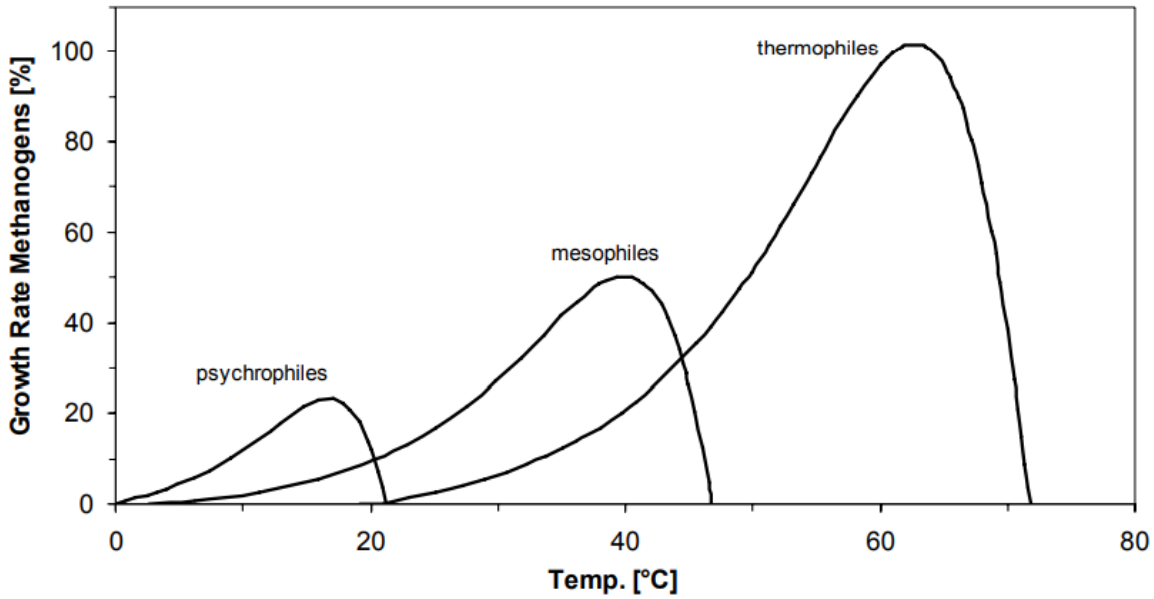

Figure 3. Relative growth rate of different methanogens [12]

The growth rate of each species in their respective temperature range follows the Arrhenius equation and increases exponentially until the peak at optimum temperature, after which the growth rate falls exponentially. Methanogenic activity follows the same trend since it is the sum of the

major catabolic reactions of methanogens. [12] The retention time also differed in different conditions. Table 1 shows the hydraulic retention time in different cases.

Table 1. Retention time in different fermentation [13]

	Retention time
Psychrophilic fermentation	100-300 days
Mesophilic fermentation	20-40 days
Thermophilic fermentation	Relatively shorter

Psychrophilic conditions have been far less studied. However, results were obtained at low loading rates. [13]

5.2 pH and buffering systems

pH is defined as the negative logarithm of the hydrogen-ion (H^+) concentration. PH affects enzyme activity in microorganisms, essential for their metabolism. Hence, pH affects the optimal growth of each of the microbial group. The optimal pH range for methanogens is 5.5-8.5, for acidogens it is 4.0-8.5 with an optimum around 6, and for acetogens it is about 7. Methanogenic growth plunges at pH under 6.6. pH should be maintained around neutral since methanogenesis is the most significant process, and other processes can function around neutrality. [12] A pH in the range of 6.6-8.0 is optimal [13].

Carbon dioxide produced in the digestion process acts a weak acid. CO_2 and water react to form carbonic acid:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3$$

Alkalinity is a measure of buffer capacity required to resist the drop in pH caused by the formation of acids. Alkalinity is expressed in terms of $CaCO_3$ as mg/L of $CaCO_3$. Concentrations are observed in the range of 3000 to 5000 mg/L of $CaCO_3$ during AD. When nitrogen-containing matter is destroyed, and the released ammonia reacts with carbon dioxide, bicarbonate alkalinity is produced:

$$NH_3 + H_2O + CO_2 \rightarrow + - NH^+_4 + HCO^-_3$$

When volatile fatty acids (VFAs) are produced in the digestion process, they are neutralized by bicarbonate alkalinity. The following equation represents the neutralization of acetic acid.

$$HCO^-_3 + HAc \rightleftharpoons H_2O + CO_2 + Ac^-$$

For a stable operation, bicarbonate alkalinity is maintained in high concentration to fight the VFAs with minimal effect to pH. [12]

5.3 Nutrients and toxic substances

Production of a digester highly depends upon of the type of substrate being fed and the nutrients contained. The feed must contain sources of energy and carbon for the synthesis of new cellular material and various nutrients such as nitrogen, phosphorus, sulphur, potassium, calcium and magnesium. Substrate composition also determines the resultant pH.

Efficient digestion needs amounts of carbon and other nutrients in the substrate. Main factors to consider are nitrogen, phosphorus, C:N (10:1 to 30:1), N:P (5:1 to 7:1) and COD:N:P (420:7:1 to 1500:7:1). Trace elements are essential only in small concentrations. Elements such as fluorine, iodine, chromium, manganese, zinc, nickel, cobalt and copper are trace elements for the digestion process.

Inhibitory substances are either already present of formed during the process of degradation. The most common inhibitors are VFA, LCFA and ammonia. Sulphur compounds, heavy metals and antibiotics are the inhibitors preexisting in the substrate. Inhibitory effects are seen when the threshold concentrations are exceeded. The toxicity of NH_3 and VFAs are dependent on pH.

Heavy metals such as chromium, copper, nickel, cadmium, and zinc can also have inhibitory or toxic effects. [12]

5.4 Hydraulic Retention time

Hydraulic retention time is the average time that fermentable compounds stay in the digester in contact with biomass and decomposes into metabolic products such as monosaccharides, polysaccharides and amino acids [13] [14]. HRT can be calculated as:

$$HRT = V/\theta,$$

where V is the volume of the reactor in m^3 and θ is the rate of feeding in m^3/ h. [15]

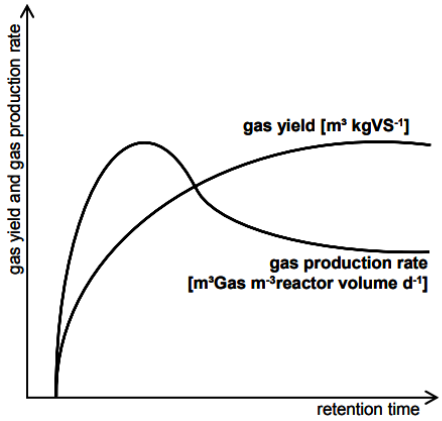

Figure 4. Gas yield and production rate vs. retention time [12]

HRT depends upon the climatic condition and location of the digester. Longer retention period needs larger digester and provides a more complete digestion of substrates. [14] HRT usually ranges from 30–50 days. For a country like Finland with a cooler climate, the process can take up to 100 days. [13]

5.5 Organic loading rate

The organic loading rate is the rate at which volatile solids in kilograms can be fed per m^3 of digester. In AD process, the organic matter to be degraded is often referred as Volatile Solid (VS) [13]. Organic Loading Rate (OLR) is related to retention time. It gives knowledge of the effectiveness of the reactor volume being utilized. OLR can be calculated as:

$$OLR = Q.C/V = C(Q/V) = C/HRT,$$

where OLR is the volumetric loading rate, Q is the influent rate, C is the concentration of volatile solids in the substrate and V is the bioreactor volume. OLR is represented in $kgVSm^{-3}d^{-1}$. [12] About 0.2 kg/m3 of digester capacity is recommended as the optimum loading rate. Loading should be done in a way that VS concentration in the digester will be constant. Underloading and overloading will negatively affect production. [14]

5.6 Total solid

Total solid is the amount of solid present in the crucible after the loss of water molecules. Total solid can be calculated as:

$$\%TS = (W_1 - W_2)/(W_3 - W_2) \times 100,$$

where $\%TS$ is the percentage total solid, W_1 is the weight of dried crucible and dried residue, W_2 is the weight of crucible and W_3 is the weight of wet sample (substrate) and crucible. [16]

6 Complications and Hazards related to Anerobic Digestor

While biogas brings a large opportunity, we also must be aware of the risks that come with it. Biogas produced via AD constitutes of main gases such as methane, carbon dioxide and hydrogen sulfide. Each of these gases is dangerous at certain conditions. Main hazards related to biogas are asphyxiation and fire or explosion potential. Presence of such hazardous gases and chances of leakages from the biogas reactor makes it necessary that the biogas reactor and its production process be monitored continuously.

6.1 Gas Hazards and Protective Measures

6.1.1 Asphyxiation

Asphyxiation is a condition when biogas production, transferring and flaring can lead to oxygen-deficient environment. Aggregation of biogas in a small space can decrease significant amount of oxygen in the atmosphere which can result in asphyxiation symptoms or even death. [24]

Biogas typically consist of following asphyxiants:

- simple asphyxiants – carbon dioxide and methane
- chemical asphyxiants – ammonia and hydrogen sulfide

6.1.2 Explosion potential

There is a certain range at which the Methane-air mixture can form an explosive fuel. Methane should be present at 4.8 % - 15.8 % range at 20°C for such a condition. [25] The lower limit of the range is called a Lower Explosion Limit (LEL), and the upper limit is called Upper Explosion Limit (UEL). Any mixture below LEL is considered too lean or weak to burn and above UEL the mixture is too strong to ignite. There are two ways for an explosion:

- auto-ignition
- spark or flame

Auto Ignition has been observed to have occurred at as low as 537°C. Under a normal room temperature, auto ignition is therefore impossible. Under the presence of spark or flame, the methane concentration in the air should be in between LEL and UEL.

6.1.3 Methane (CH_4)

Methane (CH_4) is one of the principal constituents of biogas produced via AD. Since methane is combustible and highly flammable, it can form detonating mixture with atmosphere and lead to rapid suffocation. Hazards of methane and the protective measures that should be followed to avoid any such hazards are discussed in more detail below.

Hazards

Methane is labelled as an asphyxiant which can cause headaches, drowsiness and dizziness. Lack of oxygen can even lead to death. The flammable characteristic of methane makes it dangerous as it can cause explosion as a result of mixture with air. [26]

Protective measures

In case of suffocation, artificial respiration should be given and if not, medical attention is necessary. The system should be kept in a well-ventilated environment to avoid any accumulation of such gases. In case of fire, all personnel should be evacuated from the danger area and the fire should be allowed to burn as there is a possibility of reignition. [26]

6.1.4 Carbon dioxide (CO_2)

Carbon dioxide (CO_2) is another main constituent of biogas, a colorless and odorless gas. Below are the hazards and protective measures related to carbon dioxide discussed in detail.

Hazards

CO_2 also acts as an asphyxiant by diluting the concentration of oxygen in the atmosphere. It is an inflammable gas and rather acts as an extinguishing media. [27]

Protective measures

The system should be kept in a well-ventilated place to avoid accumulation of such gases. In case of suffocation, artificial respiration should be given otherwise immediate medical attention is necessary. [27]

6.1.5 Hydrogen sulfide (H_2S)

Hydrogen sulfide (H_2S) is a colorless and a flammable gas with a smell of a “rotten egg”.

Hazards

- **Lower concentrations**: Irritation of eyes, nose, throat or respiratory system; effects can also be delayed
- **Moderate concentrations**: more severe eye and respiratory effects; headache, dizziness, nausea, soughing vomiting and difficulty in breathing\
- **High concentrations**: shock, unable to breathe, coma death: effects can be rapid
- Very toxic to aquatic life. [28]

Protective measures

Hydrogen sulfide is a combustible gas and can form explosion, use of an appropriate extinguishing media is recommended. The system should be kept in a well-ventilated place to avoid accumulation of such gases. [28]

6.1.6 Volatile organic compounds (VOCs)

Compounds that can easily change into vapors or gases are called VOCs. Such VOCs can be released from blazing fuel such as gasoline, wood, coal or natural gas (mostly containing methane). When VOCs fuse with nitrogen oxides in the atmosphere, they form smog. [29]

Hazards

Exposure to VOCs can cause irritation to eyes or respiratory tract, headaches, dizziness, optical disorders, memory complications. On a long term it can also cause damage to liver, kidney, central nervous system (CNS) and may even cause cancer. [29]

Protective Measures

Use of proper ventilation is recommended to avoid accumulation of such gases. Proper disposition of unused chemicals should be practiced. Health professional should be contacted if an individual feel affected by exposure to VOCs. [29]

6.2. Introduction of Oxygen in AD

As the anerobic digester itself is operated in aerobic open environment, it is virtually impossible to avoid the introduction of oxygen into the digester. It is generally anticipated that the oxygen operates as an inhibitory and noxious agent in AD due to engagement of rigorously anaerobic microorganism group of acetogens and methanogens. Due to these negative impressions, inoculums operated in AD are even de-oxygenated before starting the reactor and even some oxygen skulking chemicals such as sodium sulfide are annexed. [30]

However, there are studies that showed positive effects of oxygen in AD as its presence improved hydrolysis of particulate matter, such enhanced hydrolysis was found to be greatly beneficial to the overall process efficiency.

6.3. Change in pressure within Anerobic digestor

It is strictly advised that the negative pressure should not be allowed in the biogas system, as it pulls air within biogas system and the concoction of air and biogas can result in explosion. Negative pressure occurs in the structure when the force built by the density of gases outside the biogas system is higher than the force within the system. [31]

7 System Components

7.1 Anaerobic digester

The AD design was inspired by a small project conducted in Pakistan. The total capacity of the digester is 20l. Digesters are designed to replicate the environment inside an animal's stomach [19]. The working environment must be completely sealed to prevent airflow into the digester. Methanogens are strictly anaerobes [20]. The ends of overflow outlet and feed pipe are covered with standard caps to prevent any inflow of air.

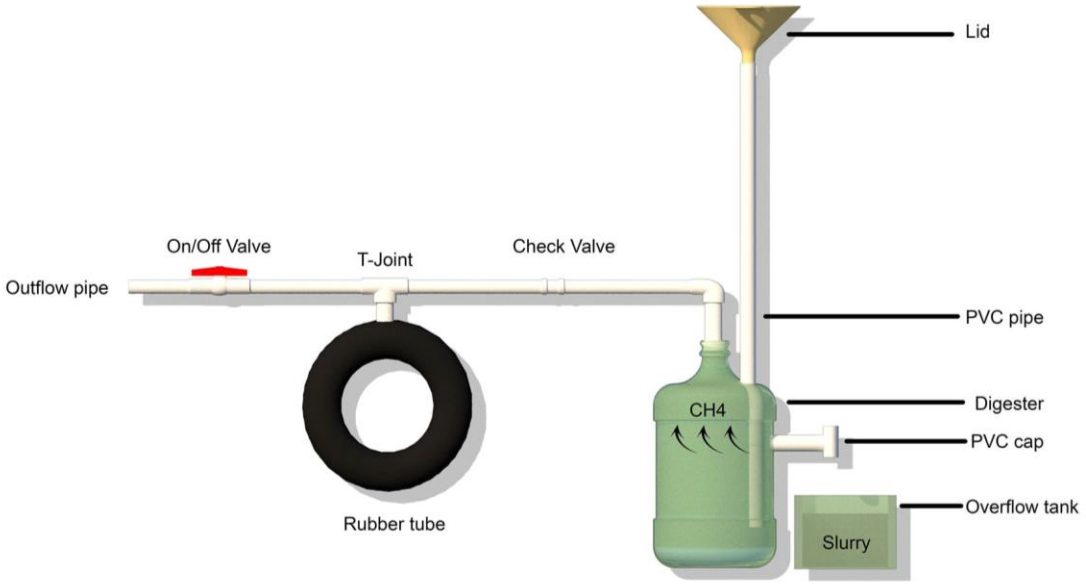

Figure 5. Gas yield and production rate vs. retention time [12]

The digester (jar) mentioned can be a transparent jar painted black or an opaque jar. There must be two to three coatings of paint in order to be sure that no sunlight can enter the jar. Sunlight encourages algal growth which in harmful for the production process. [17] All the components required for the project are tabulated.

Table 2. System components

Item	Image
20l Jar	
¼” gas pipe	
Vehicle Tube	
Tub	

¾" PVC pipe	
T-joint	
Flow control valve	
Waterproof Sealant (Liquid rubber)	
PVC plug	
½" Gas check valve	

	
Black Paint	

The characteristics and functions of components are briefly described below. Dimensions and specifications used are for a small-scale digestion plant.

7.1.1 Digester

A digester replicates the natural phenomenon that takes place inside an animal's stomach. The conditions must be anaerobic and opaque. For the purpose of the study, a plastic jar of 20-liter volume was selected. The digester must be fed with a water-biowaste mixture in a 1:1 ratio by weight. [17] [18]

7.1.2 Feeder

A PVC pipe of ¾" - 1" diameter would be suitable for a feeder. Biowaste is made finer and mixed properly with water before feeding. Hence, a larger diameter is needless. The pipe must be fixed to the digester in order to avoid leakage and stability. Length of the feeder is selected in respect to the size of digester. The pipe should not be touching the base of the digester, which will hamper the feeding process. A stirring rod must be used via feeder in order to ensure a properly mixed feed in the digester. [17]

7.1.3 Overflow outlet

Primary function of the overflow outlet is to excrete the slurry forming in the top of the digester and to clear out any oxygen accumulated in the tank. Outlet should be made at around two-third of the height of digester. Since, only around 70 % of the volume of digester should be used for optimum efficiency, outlet around the chosen height ensures the final level of the feed slightly higher than the outlet pipe. Consequently, when the outlet pipe is uncapped, slurry collected at the top will be excreted. The outlet pipe must be sealed with a standard fitting cap for preventing leakage. [17] [18]

7.1.4 Valves

There are different valves used for respective purposes. A gas check valve is used to prevent the flow of gas back to the digester. A t-joint is used to connect the collection tank, digester and outflow pipe. A flow control valve is used in the outflow pipe in order to control flow of biogas to the stove. [17]

7.1.5 Collection tank

Slurry formed in the digester is collected in the collection tank. Outlet pipe is uncapped every time the digester is fed. The collected slurry can be used as a fertilizer. [17] [18] For a small-scale project, a movable plastic bucket/container shall suffice.

7.2 Sensor

7.2.1 Libelium's Smart Environment PRO node

Smart Environment Pro is one of the models of Waspmote Plug and Sense, which allows users to analyze air quality, pollution required in industrial, environmental or farming projects. The figure 6 below demonstrates the smart environment pro model manufactured by Libelium.

Figure 6. Waspmote Plug and Sense! - Smart Environment Pro model [32]

This device is very useful for projects with immense requirements in terms of significant accuracy, reliability and measurement range as the sensors are calibrated in the factory.

Figure 7. Different front stickers to differentiate the various models of Waspmote Plug and Sense [32]

Figure 7 above demonstrates various other model of Waspmote's Plug and Sense. These different versions of the Waspmote Plug and Sense are manufactured to meet specific user demands. The sticker on the front of the enclosure gives the basic idea of what the product is used for.

7.2.1.1 Specifications

Waspmote Plug and Sense uses polycarbonate as the main material with robust waterproof IP65 coating. It is a heavy metal free design, weighing approximately 800 g which can be operated at an ambient temperature ranging from -20˚C (minimum) to 60˚C (maximum). [32]

Figure 8. Waspmote Plug and Sense! accessories: 1 enclosure, 2 sensor probes, 3 solar panel, 4 USB cable, 5 antennae, 6 cable ties, 7 mounting feet, 8 extension cord, 9 solar panel cable, 10 wall plugs and screws [32]

Figure 8 above demonstrates Waspmote Plug and Sense! and its components, a few of which are optional and might not be included.

Figure 9. Front and back view of the enclosure [32]

The front of the enclosure has a sticker that identifies the model and the back sticker has various details such as identification numbers and radio Mac addresses as shown in figure 9 above. Such information is needed for future maintenance.

Figure 10. Control side of the enclosure [32]

Depending on the user's demand, Wi-Fi and 4G models are also available for over the Air programming (OTAP).

Figure 11. Sensor probe socket side of the enclosure [32]

The enclosure contains six sensor probe sockets, each designed specifically for a separate sensor probe, meaning that only specific sensor probe should be attached to a specific socket otherwise it could be damaged. Having six sensor probe sockets allows users to make six different readings at the same time.

7.2.1.2 Sensor Probes

Sensor probes are simply attachable to the sockets present on the enclosure. These probes contain specific sensors for different parameters and are supposed to be attached to specific sockets.

Figure 12. Sensor probe with labels [32]

Sensor probes can be identified from the labels attached to it as shown in figure 12 above. These labels indicate the measured parameter and the sensor manufacturer reference.

Sensor Socket	Sensor probes allowed for each sensor socket	
	Parameter	Reference
A, B, C or F	Carbon Monoxide (CO) for high concentrations [Calibrated]	9371-P
	Carbon Monoxide (CO) for low concentrations [Calibrated]	9371-LC-P
	Carbon Dioxide (CO_2) [Calibrated]	9372-P
	Oxygen (O_2) [Calibrated]	9373-P
	Ozone (O_3) [Calibrated]	9374-P
	Nitric Oxide (NO) for low concentrations [Calibrated]	9375-LC-P
	Nitric Dioxide (NO_2) high accuracy [Calibrated]	9376-HA-P
	Sulfur Dioxide (SO_2) high accuracy [Calibrated]	9377-HA-P
	Ammonia (NH_3) for low concentrations [Calibrated]	9378-LC-P
	Ammonia (NH_3) for high concentrations [Calibrated]	9378-HC-P
	Methane (CH_4) and Combustible Gas [Calibrated]	9379-P
	Hydrogen (H_2) [Calibrated]	9380-P
	Hydrogen Sulfide (H_2S) [Calibrated]	9381-P
	Hydrogen Chloride (HCl) [Calibrated]	9382-P
	Hydrogen Cyanide (HCN) [Calibrated]	9383-P
	Phosphine (PH_3) [Calibrated]	9384-P
	Ethylene (ETO) [Calibrated]	9385-P
	Chlorine (Cl_2) [Calibrated]	9386-P
D	Particle Matter (PM1 / PM2.5 / PM10) - Dust	9387-P
E	Temperature, humidity and pressure	9370-P
	Luminosity (Luxes accuracy)	9325-P
	Ultrasound (distance measurement)	9246-P

Figure 13. Sensor sockets configuration for Smart Environment PRO (highlighted parameters for this project) [32]

Figure 13 above shows the different sensor designed to work with Waspmote Plug and Sense! model ‘Smart Environment PRO’ and designated socket for each sensor probe to assure the functionality of the device.

7.2.1.3 Battery and Power

The Waspmote Plug and Sense! contains a rechargeable battery with a capacity of 6600 mAh. This battery can be powered via a waterproof USB cable but can be recharged via solar panel as well. To ensure maximum performance, the solar panel should be mounted at an angle of 45˚.

Figure 14. Waspmote Plug and Sense! being powered by an external solar panel [32]

However, to extend its battery life, an external battery module is also available. The extension cycle varies from months to years based on its sleep cycle and radioactivity.

Figure 15. External Battery Module [32]

The diurnal charging time of the external battery module is between 5,15 and 30 minutes.

Figure 16. Waspmote Plug and Sense! with external battery Module and Solar Panel [32]

Furthermore, to extend the battery life even more, this external battery module can also be connected to the solar panel using the designated socket as shown in figure 16 above.

7.2.1.4 Programming

Using the Waspmote IDE in an operating system (available for Linux, Mac OS X, and Windows), the Smart Environment Pro can be programmed. This IDE is accustomed for writing codes and transferring it to the Waspmote Plug and Sense! for its functionality. It is also operated to observe serial output and for debugging. The codes for nodes are written in Waspmote IDE software and programmed via USB connection. [34]

Another main component of the sensor system in Meshlium, a Linux router that acts as a gateway of Waspmote sensor networks. It can be enclosed of 6 different radio interfaces: WiFi 2.4GHz, WiFi 5GHz, 3G/GPRS, Bluetooth; XBee and LoRa. Meshlium uses a software called Manager system, an open source application that supports quick and easy control with the accessible radio interface configurations with the data base storage options of the sensor data received. This interface allows users to add new sensor, send data to different cloud platform and monitor the data collected by sensor. [35]

7.2.1.5 Methane Sensor

The methane sensor has the nominal range of 0 to 100 % LEL. This sensor is expected to last two years in air and works ideally at the temperature range of –40 °C to 55 °C. The accuracy of the sensor under ideal conditions is as good as ±0.15 % LEL. The response time of the sensor is less than 30 seconds.The CH_4 sensor and CO_2 sensor cannot operate in the same Gases PRO sensor board as both sensors have huge power requirements. [32]

```
#include <WaspSensorGas_Pro.h>

/*
 * Define object for sensor: gas_PRO_sensor
 * Input to choose board socket.
 * Waspmote OEM. Possibilities for this sensor:
 *      - SOCKET_1
 * P&S! Possibilities for this sensor:
 *      - SOCKET_A
 *      - SOCKET_B
 *      - SOCKET_C
 *      - SOCKET_F
 */
Gas gas_PRO_sensor(SOCKET_1);

float concentration;    // Stores the concentration level in ppm
float temperature;      // Stores the temperature in ºC
float humidity;         // Stores the realitve humidity in %RH
float pressure;         // Stores the pressure in Pa

void setup()
{
    USB.println(F("Pellistor CH4 example"));
}


void loop()
{
    ///////////////////////////////////////////
    // 1. Turn on the sensors
    ///////////////////////////////////////////

    // Power on the pellistor sensor.
    // If the gases PRO board is off, turn it on automatically.
    gas_PRO_sensor.ON();

    // The sensor needs time to warm up and get a response from gas
    // To reduce the battery consumption, use deepSleep instead delay
    // After 60 seconds, Waspmote wakes up thanks to the RTC Alarm
    PWR.deepSleep("00:00:01:00", RTC_OFFSET, RTC_ALM1_MODE1, ALL_ON);


    ///////////////////////////////////////////
    // 2. Read sensors
    ///////////////////////////////////////////

    // Read the pellistor sensor and compensate with the temperature internally
    concentration = gas_PRO_sensor.getConc();

    // Read enviromental variables
    temperature = gas_PRO_sensor.getTemp();
    humidity = gas_PRO_sensor.getHumidity();
    pressure = gas_PRO_sensor.getPressure();

    // And print the values via USB
    USB.println(F("***************************************"));
    USB.print(F("Gas concentration: "));
    USB.print(concentration);
    USB.println(F(" % LEL"));
    USB.print(F("Temperature: "));
    USB.print(temperature);
    USB.println(F(" Celsius degrees"));
    USB.print(F("RH: "));
    USB.print(humidity);
    USB.println(F(" %"));
    USB.print(F("Pressure: "));
    USB.print(pressure);
    USB.println(F(" Pa"));
```

```
///////////////////////////////////////////
// 3. Power off sensors
///////////////////////////////////////////

// Power off the pellistor sensor.
// If there aren't more gas sensor powered, turn off the board automatically
gas_PRO_sensor.OFF();


///////////////////////////////////////////
// 5. Sleep
///////////////////////////////////////////

// Go to deepsleep
// After 4 minutes, Waspmote wakes up thanks to the RTC Alarm
PWR.deepSleep("00:00:04:00", RTC_OFFSET, RTC_ALM1_MODE1, ALL_OFF);
```

Figure 17. Example of input codes to operate methane sensor [36]

Above is an example of codes that needs to be written in the manager system to obtain data from methane sensor. Similar codes can be written for different gases to get the data for other sensors. The codes are readily available in the library function of the manager system.

```
H#
Pellistor CH4 example
***************************************
Gas concentration: 3.9870300292 % LEL
Temperature: 23.8199996948 Celsius degrees
RH: 43.7714843750 %
Pressure: 99773.6250000000 Pa
***************************************
Gas concentration: 39299316406 % LEL
Temperature: 23.8299999237 Celsius degrees
RH: 43.8017578125 %
Pressure: 99769.9531250000 Pa
***************************************
Gas concentration: 3.9109802246 % LEL
Temperature: 23.8099994659 Celsius degrees
RH: 43.8007812500 %
Pressure: 99775.3281250000 Pa
***************************************
Gas concentration: 3.9679870605 % LEL
Temperature: 23.8600006103 Celsius degrees
RH: 43.7880859375 %
Pressure: 99768.2500000000 Pa
```

Figure 18. Example of output results shown by methane sensor [36]

Above is an example of the output given by the sensor which allows user to view parameters like gas concentration, temperature, RH and pressure.

7.2.1.6 Carbon dioxide sensor

CO_2 sensor needs warm up time of at least 60 seconds at 25°C. In ideal conditions, with accuracy of ±50 ppm (from 0 to 2500 ppm range) and ±200 ppm (from 2500 to 5000 ppm range), the sensor measures the changes in the concentration of CO_2 in the surrounding. [32]

The sensor functions ideally at the temperature range of -40 ºC to 60 ºC. The example of main codes to operate the sensor are given below [39]:

```
{

// Switch ON and configure the Gases Board

Gases.ON();

// Switch ON the CO2 Sensor SOCKET2

CO2Sensor.ON();

// PPM value of CO2

float co2Vol = CO2Sensor.readVoltage();

float co2ValPPM = CO2Sensor.readConcentration();

}
```

7.2.1.7 Hydrogen Sulfide Sensor

Hydrogen Sulfide sensor consumes an average of 1 mA. Although the presence of H_2S easily noticeable as it has the smell of rotten egg. It is important to have a sensor for collecting the data. This sensor ideally works at the temperature range of -20 ºC to 50 ºC and can handle the pressure of 90 to 110 kPa. [32] Example codes to operate the sensor are presented below [39]:

```
{

// Switch ON and configure the Gases Board

Gases.ON();

// Switch ON the H2S Sensor SOCKET3

H2SSensor.ON();

// PPM value of H2S

float h2sVol = H2SSensor.readVoltage();

float h2sValPPM = H2SSensor.readConcentration();

}
```

7.2.1.8 Volatile Organic Compound sensor

These compounds have unpleasant smell. VOC sensor accurately measures hydrocarbons, CO and VOCs. The measurement and temperature range of this sensor are 20 to 400ppm and -30 ºC to 85 ºC, respectively. [32]

7.2.1.9 Temperature, Humidity and Pressure sensor

Fluctuation in these specific parameters are very harmful to a biogas system, thus monitoring of these parameters is very important. Temperature, humidity and pressure sensor have an operational range of -40 ~ +85 ºC, 0 ~ 100% of Relative Humidity and 30 ~ 110 kPa, respectively. [32]

8. Case study

The initial plan was to subject three different digesters at 0° C, 21°C and 35°C. The general idea about temperature was based around mesophilic bacteria. However, results can also be achieved at extreme temperatures as shown by various projects around the globe. For the ease of understanding, the working temperature of mesophilic bacteria (20-45°C) will be called mid temperature. Similarly, for psychrophilic bacteria(<20°C), low and high for thermophilic bacteria(45-65°C). A few case studies conducted around the world are studied and discussed below.

8.1 Case studies at mid and high temperatures

There have been several studies for the temperature range of interest. However, only two of them are studied and discussed here. The temperature range of interest is 20°C to 65°C.

8.1.1 Case I

Batch anaerobic digestion of dairy manures were performed at three temperatures: 25°C, 37°C and 52.5°C. Temperatures 25°C and 37°C fall in the mid temperature range, where 25°C is towards the lower end of the range as compared to 37°C. The temperature 52.5°C is well within the thermophilic region. The experiment was conducted for 74, 40 and 29 days, respectively. [21]

The use of dairy manure to produce biogas as an energy source has been popular all around the world. Besides producing biogas which can be used for cooking, heating and various other purposes, AD also helps to reduce solid wastes. [21]

Figure 19. Water bath shaker [22]

Feedstock was made with 0.498 kg of fresh (24 hours old) manure 1.5 kg of distilled water and well mixed. Large solids and fibers were removed. 150 ml feedstock was then fed into each digester. 250 ml serum bottles were used as digesters. Digesters were then sealed with rubber septum and they were made anaerobic by removing air inside. Water bath shaker controlled the temperature of the digesters. Shaking speed was regulated at 150 rpm. Gas tight syringe collected biogas and liquids from digesters. Analyzation was done using standard methods. [21]

8.1.1.1 Result and discussion

The influence of temperature on biogas production in shown in the figure below. At 52.5 ºC, production started between 12 and 14 hours, and stopped on day 15. However, at 37 ºC production was not seen until the 25th day after which it continued until day 40. At 25 ºC, first production was recorded on day 61. There was not much production at 25 ºC, and slight production were seen on 61st and 62nd day. 541 ml of biogas was obtained at 52.5 ºC cumulatively, with a methane content of 70 % in 28 days of incubation period, which was 49 times the total production of 11 ml over 62 days at 25 ºC. At 37 ºC, a total of 193ml of biogas was cumulated and the methane content was 55 %. Methane content at 25 ºC was not calculated because of low production. Other researches have also seen high methane content during thermophilic digestion. [21]

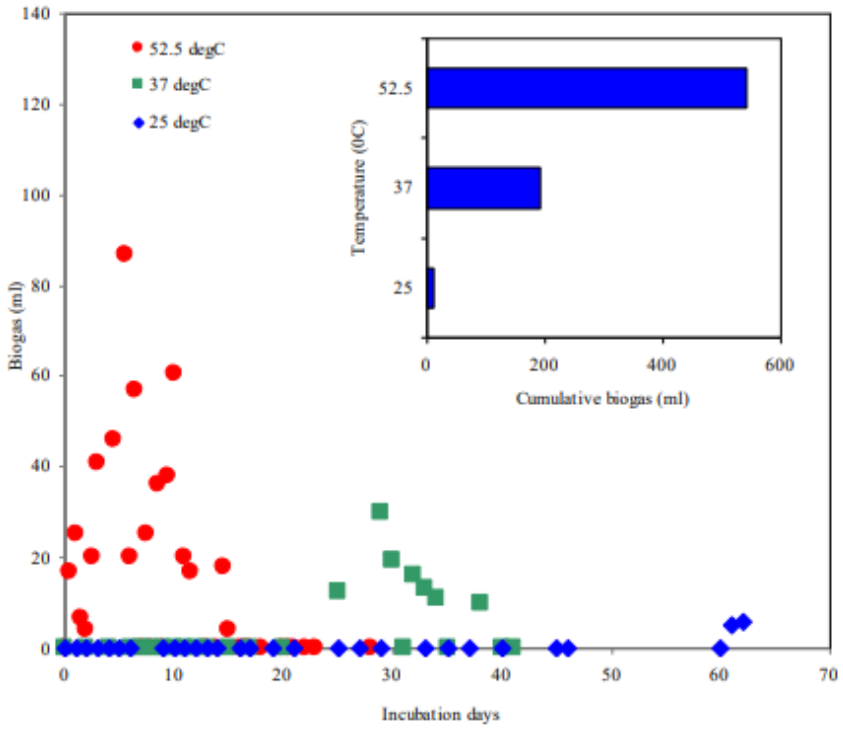

Figure 20. Biogas production at different temperatures [21]

The table below shows the effects of temperature on various parameters.

Table 3. Temperature influence in parameters [21]

Parameters	25ºC			37ºC			52.5ºC		
	Initial	Final	Reduc-tion (%)	Initial	Final	Reduc-tion (%)	Initial	Final	Reduc-tion (%)
pH	7.5	7.0	7.3	7.4	6.8	8.4	7.5	8.1	8.1
TS %	1.4	1.3	5.6	1.5	0.6	57.0	1.8	1.2	34
VS %	1.1	0.5	58.4	1.1	0.5	58.4	1.3	0.7	42.5

The results of pH were lsimilar to those of another study which reported that buffering capacity of reactors are better at mesophilic temperatures and pH values are maintained close to 7.0. At 52.5ºC, pH showed an upward trend throughout the digestion. [21]

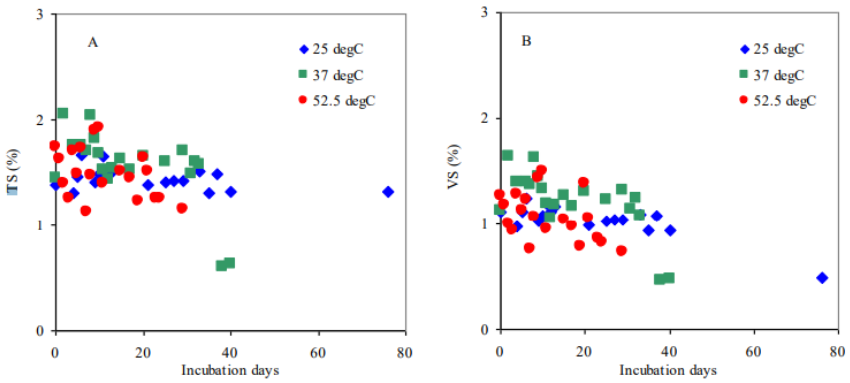

Figure 21. Total solid (A) and Volatile solid (B) reduction [21]

Total solid and volatile solid digestion is achieved the most efficiently at 37ºC. TS and VS at 52.5ºC varied between 1.13-1.9% and 0.73-1.5% respectively. At 37ºC and 25ºC, TS varied from 1.4 to 2.04% and 1.04 to 1.6% respectively. Similarly, VS varied from 1.3 to 1.7% and 0.48 to 1.24% respectively. [21]

8.1.2 Case Study II

In this study, the effect of temperature on biogas and methane production efficiency during AD of duckweed was studied and evaluated. Digesters were incubated at room temperature (23-28ºC), specific mesophilic (35ºC) and thermophilic (50ºC) for 45 days. [23]

Duckweed was collected from pond and used as a mono-substrate for the project. The duckweed collected was washed with tap water manually, dried at 60ºC and powdered for the experiment. The anaerobic inoculum used was collected from an operating digester at Energy research center in Maejo University. The inoculum had the following characteristics: [23]

Table 4. Characteristics of Inoculum [23]

Parameters	Value
TS	296.1 ± 0.05 mg/L
VS	158.5 ± 1.15 mg/L
COD	1241.6 ± 2.01 mg/L

Alkalinity	136.4 ± 0.04 mg/L of $CaCO_3$
VFA	136.4 ± 0.25 mgCH_3COOH/L
pH	6.66 ± 0.03

2 L Duran glass bottles were used as digesters having a working volume of 1 L. The batch digestion tests were triplicated under mesophilic conditions for 45 days. The bottles were flushed with Nitrogen to create anaerobic condition. Digesters were each filled with substrates containing 80 ml of inoculums, 400 g of powdered duckweed and remaining of 1 L with double distilled water. The substrate was prepared and mixed properly with a magnetic stirrer at the start of the experiment. The bottles were manually shaken twice a day. [23]

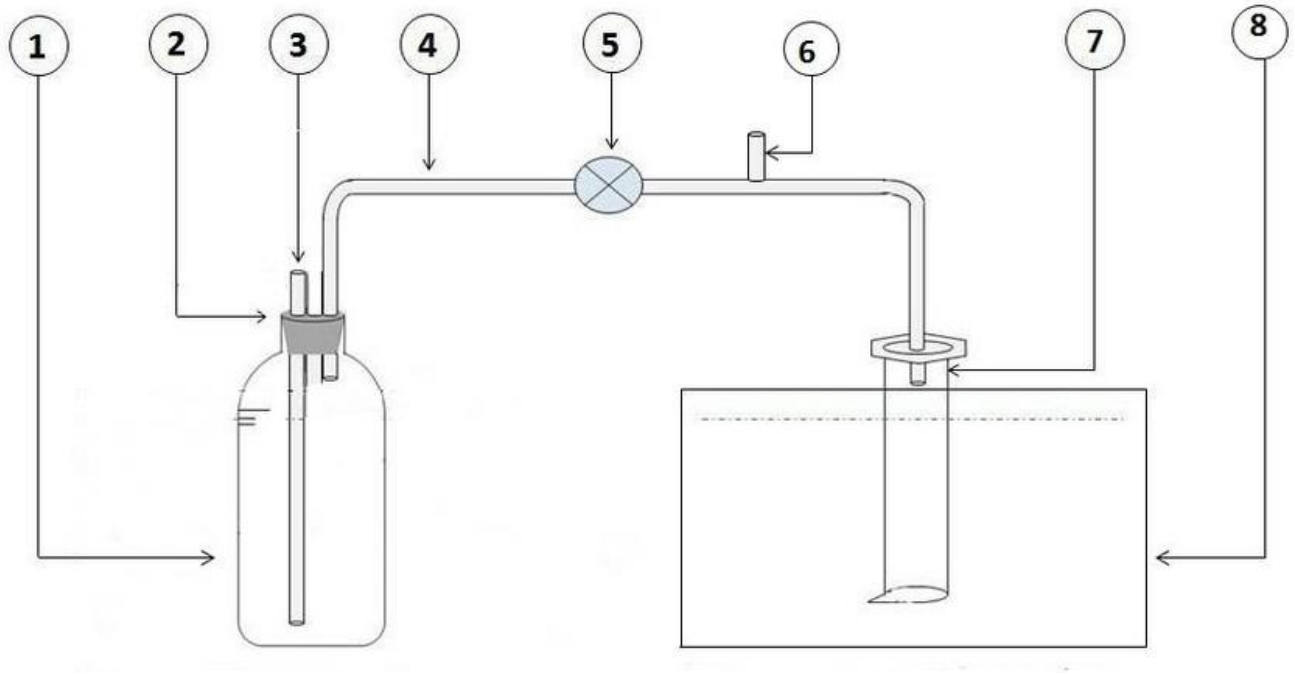

Figure 22. Schematic view of the experimental set up during anaerobic digestion of duckweed. 1: digester (2000 ml) 2: rubber stopper, 3: inlet of substrate and inoculums, 4: rubber septum, 5: valve 6: gas sampling port, 7: gas measuring cylinder, 8: water bath [23]

Duckweed is a small floating aquatic plant commonly found in different kinds of aquatic ecosystem. Duckweed can be found in high density in water bodies that are still or slightly moving. However, flourishing growth can be seen in still ponds, saline water, ditches rich in organic matter and near sewage outlets. They grow faster than most other plants and have doubling times of 48 h – 96 h depending on the species. [23]

Table 5. Characteristics of Duckweed (dry basis) [23]

Parameters	Results
Carbon %	44.19 ± 0.02
Hydrogen %	5.22 ± 0.06
Oxygen %	39.18 ± 0.02
Nitrogen %	0.44 ± 0.02
TS (ml/L)	55712 ± 0.49
VS (ml/L)	32229 ± 1.02
COD (ml/L)	10827 ± 1.44
VFA ($mgCH_3COOH/L$)	2152 ± 0.55
Alkalinity ($mgCACO_3/L$)	2592 ± 0.11
pH	7.2 ± 0.41

Apart from its use in the production of biogas, duckweeds can be used for various other purposes such as bio-oil, bioethanol, biochar, gas, electricity, bioleum etc. [23]

8.1.2.1 Results and Discussion

The results from the tests indicated that the digester at 35 ºC had the maximum biogas yield over the period as well as the highest methane content at 64.47 %. Total biogas yield in room temperature was 7863.69 ml/L, 10376.59 ml/L at 35 ºC and 9981.08 mL/L at 50 ºC. [23]

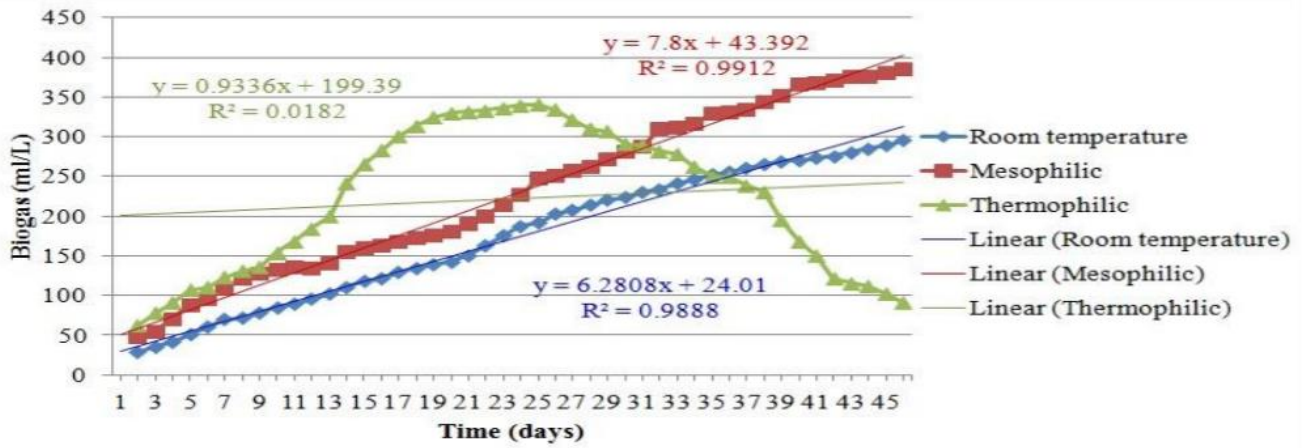

Figure 23. Biogas yield at different temperatures [23]

Results show that at thermophilic condition, production starts early, and peak is achieved relatively faster than at other temperatures. However, there are disadvantages of thermophilic anaerobic fermentation. Reduction in process stability, reduction in dewatering properties of sludge and high energy requirements are the major disadvantages of this process. The results indicated that duckweed can be successfully converted using AD. More research is required into the techno-economics in order to conclude on the scalability. The process under mesophilic conditions were expected to be economical and scalable.

R^2 values very close to 1 at room temperature and 35 ºC means that the production rate within the incubation period is almost perfectly linear. There are multiple data perfectly on the trendline. Low R^2 value also tells the trendline to be a good. Estimation of production of biogas can be made with about 99 % accuracy in relation with the incubation period in both the cases. In contrast, R^2 value of 0.0182 means that 18.2 % percent of the time the change in incubation period will correctly answer the change in biogas production. Peak production at thermophilic condition can be observed near the 25^{th} day. [23]

8.2 Case studies at cold temperatures

Typically, AD is operated in mesophilic or thermophilic conditions. However, AD is also possible under low temperature (<20 ºC) with the use of psychrophilic bacteria (cold temperature loving bacteria). AD in psychrophilic condition is not studied as much as anaerobic digestion in mesophilic or thermophilic conditions, likely due to less viability of its use and efficiency at low temperatures.

In developing countries where cold climates are an issue, development of well operating biogas digester would open doors to various benefits such as production of heat, light, and electricity. Below are few case studies related to biogas production conducted at cold temperatures.

8.2.1. Case I

In the first case study, primary objectives were to analyze the potential for psychrophiles (cold-adapted microbes) collected from an Alaskan thermokarst lake to enhance the biogas manufacture at cold climates at current biogas digesters. [35]

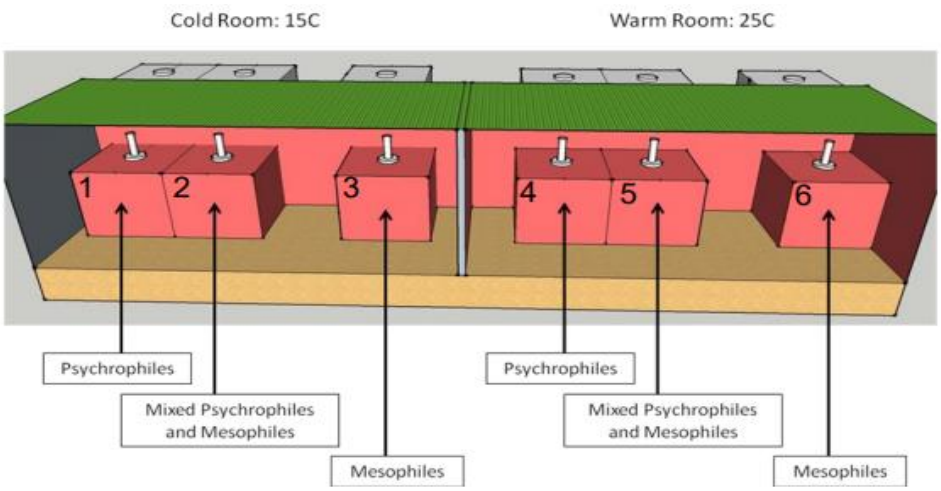

Figure 24. Experimental design to compare the biogas production involving different combinations of methanogen communities under two different temperature 15 ºC and 25 ºC [35]

Above figure 24 shows the experimental design of the Cordova anaerobic digester experiment. The containers were converted into single batch-type anaerobic digestion reactors and inoculated with methanogens, namely psychrophiles and mesophiles. Inside a 40-foot Conex the reactors were placed, that had a wall in built to separate two rooms. The room temperature was controlled using 1500 W radiator heaters with one room temperature being 15 ºC (cold) and the other being 25 ºC (tepid). Within the rooms each 3 tanks had different inoculations and were labeled as lake mud only (psychrophiles, 48 L mud per tank); manure only (mesophiles, 60 L manure per tank); and Mixture of lake mud and manure (48 L mud + 60 L manure). Tanks were filled 7/8 with warm water and crushed rock (~8 L per tank) was spread over the tank surface to make space for microbial production. [35]

8.2.1.2 Results and Discussion

From figure 25 below, it can be clearly observed that biogas production at mesophilic conditions are far more efficient than that of psychrophilic conditions. The maximum observed production rate of any operated 1000 L tank within a 24-hour period was 559 L d^{-1}. Average methane concentration of biogas collected was calculated to be near 67 % CH_4 by volume.

Gas Production Summary Data (L gas d^{-1} normalized to 1000-L of slurry)						
	15°C Room			25°C Room		
Date	Tank 1	Tank 2	Tank 3	Tank 4	Tank 5	Tank 6
12/11/2010	33	0	0	188	195	0.5
12/12/2010						
1/17/2011	23	0	0	308	187	28
1/18/2011	25	0	0	382	210	32
1/19/2011	37	0	0	300	254	49
1/20/2011	56	0	0	491	410	107
1/21/2011	32	0	0	246	247	104
1/22/2011	46	0	0	353	361	244
1/23/2011	68	0	0	514	413	310
1/24/2011	58	0	0	209	218	135
1/26/2011	53	0	0	532	559	390
1/29/2011	41	0	0	*260	236	170
1/30/2011	41	0	0	260	236	170
1/31/2011	73	0	0	230	*218	160
2/1/2011	55	0	0	270	277	201
2/2/2011	54	0	0	266	304	176
2/3/2011	49	0	0	*219	181	*120
2/4/2011	39	0	0	343	298	259
2/5/2011						
2/25/2011	32	0	0	135	191	133
2/26/2011	1	0	0	222	*215	184
2/27/2011	32	0	0	209	235	183
2/28/2011	59	0	0	209	246	191
3/1/2011	25	0	0	246	271	212
3/2/2011	47	0	0	231	241	198
3/3/2011	32	0	0	203	225	185
3/4/2011	28	0	0	*215	*211	192
3/5/2011	37	0	0	217	238	189
3/6/2011	21	0	0	226	254	194
3/7/2011	38	0	0	217	235	194
3/8/2011	45	0	0	241	262	*172
3/9/2011	43	0	0	247	256	185
3/10/2011	41	0	0	319	343	300
3/11/2011						
6/1/2011	47					
6/11/2011	105					
6/12/2011	116					
6/13/2011	86					
Average	**46**	**0**	**0**	**275**	**265**	**173**
Standard Dev.	**23**	**0**	**0**	**94**	**80**	**82**
Daily Max.	**116**	**0**	**0**	**532**	**559**	**390**

Figure 25. Daily biogas production values for winter 2011, normalized to 1000 L of slurry volume. The values represent average gas production within a 24 h period for each tank. [35]

Using the equation below, mean BTU production was 3,950-6,270 BTU d^{-1} per digester. It is necessary to remember that the obtained number is not static as the content of methane in biogas produced changes with time and BTU rating is important only to analyze the productivity of combustion. [35]

$$\frac{Production\ Rate \times Gas\ Composition\ \% \times Density\ of\ CH_4\ @\ 1bar}{100} = g\ CH_4$$

$$g\ CH_4 \times \frac{1\ mol}{16.042g} CH_4 = moles\ of\ CH_4\ per\ daily\ output$$

$$n\ Mols\ CH_4 \times \frac{891kJ}{mol} CH_4 = n\ kJ\ per\ day^*$$

$$1\ kJ \cong 0.95\ BTUs\ \therefore equivalent\ measure\ of\ gas\ energy\ content$$

After few days of initial setup of the biogas digester, biogas production was observed in all the tanks. Due to acidification as a result over-feeding in winter of 2010, methane content in the biogas depreciated. Nevertheless, by December 2010 ignitable biogas was manufactured in all the tanks except tanks 2 and 3. Over the whole time period of the project, biogas production was observed to be higher in warm conditions than in cold conditions. [35]

Table 6. Results of flammability tests [35]

Tank	First positive flame	Last confirmed flame
1	1/31/10	6/6/11
2	NA	NA
3	1/22/10	2/1/10
4	2/1/10	6/6/11
5	1/21/10	6/6/11
6	1/26/10	6/6/11

It was observed through the experiment that on average biogas production observed in psychrophilic-only digester in the tepid conditions (Tank 4) was 6 times the psychrophilic-only digester in the cold conditions (Tank 1). It was observed that psychrophilic only digester in the tepid condition had the highest average biogas production and generated around 60% more biogas per day than the mesophile-only digester at 25 ºC (Tank 6). Mixture of psychrophile-rich lake bottom mud and mesophile-rich manure at 25 ºC (Tank 5) yielded biogas at a similar average rate to tank 4 and was recorded to have highest diurnal production rate of 559 L gas d^{1}.[35]

This study concludes that even though addition of psychrophiles helps to improve the efficiency of bio digesters at low temperature, it is not economically viable to operate such operations as it requires supply of external heat and the biogas production without external heat supply is so less

that it cannot meet the daily demands of the user. Conversely, in elevated temperatures at other climatic zones the biogas production is enough to fuel the practical daily activities.

8.2.2 Case II

In the second case study, the main objective was to study the biogas production pattern of certain countries which faces cold climates as a challenge for biogas production. Biogas production at mesophilic and thermophilic conditions are well studied but the main concern is the development of technology that can operate in cold climates for biogas production. [38]

Singh et al. have studied the effect of HRT on production of biogas from night soil under psychrophilic conditions. At 20-day HRT, the propionate concentration was reported to be three times higher than that of acetate, whereas at higher HRT acetate and propionate were maintained at almost equal concentrations. They concluded that the anaerobic digestion could be conducted at 10 ºC using adapted inoculums. Meher et al., claimed that with added temperature adopted inoculums, methane production was observed below 20 ºC. Results of Zeeman showed a stable digestion process at digesting cow manure at a process temperature of 15 ºC and HRT of 100 and 150 days. However, even at 150 days HRT, the gas production was lower than that at 30 ºC and 20 days HRT. [38]

Safely and Westerman evaluated the performance of lagoon anaerobic digesters under low temperature, which shows digestion is feasible at a minimum digester temperature of 100 ºC with minimum hydraulic retention time of 50 days at the maximum loading rate of 0.12 kg VS/m^3/day and this could be adjusted upward for higher temperatures. Sutter and Wellinger indicate that the gross biogas production by a digester operating at 200 ºC and retention time of 40-50 days is comparable to a digester operating at mesophilic temperature but at half the retention time. [38]

The case of Tongliang in China is a success in biogas production at different temperature. The daily production rate of biogas during winter (6-100) ºC is 0.05 m3 /m3; in spring (16-220) ºC it is 0.1- 0.2 m3 /m3 and in summer (22-230) ºC it is 0.2-0.33 m3 /m3. The biodigester can therefore function all through the year, but winter gas production is insufficient.[38]

The Janata biogas plant in India lies in a hilly region; the digester temperature followed the same pattern as that of the ambient temperature. At a cold ambient temperature, the digester temperature also fell drastically, resulting in low gas production by 23-37 % in winter. [38]

Biogas production can occur at various temperatures ranging from (0- 97) ºC. In conclusion, there is very limited knowledge and experiments conducted on psychrophilic digestion, however, at lower temperature longer HRT is required to achieve a similar gas production. [38]

9. Interpretation and Discussions

In the first case study of mid and high temperatures, thermophilic condition clearly produced much more biogas in the incubation period specific for each digester. It also had better methane yield. At 25 ºC, the results were almost insignificant. [21] However, in the second study, the room temperature fluctuated around 23-28 ºC. This meant the result in production was much better. The production in the second study was the best at 35 ºC. Thermophilic conditions tend to provide better environment for bacteria to initiate production. Production were as early as 12 hours from the start. As compared to mid and low mesophilic temperatures, production starts significantly faster. However, over the period of 45 days, mesophilic digesters continue to produce significant amount of biogas, unlike thermophilic digesters, which peaked within 45 days and production began to fall. [23]

In the third case study, it was clear that mesophilic bacteria in tepid conditions (25 ºC) were far more efficient than that in cold conditions (15 ºC). It was also observed that psychrophiles also were more efficient in tepid conditions than in cold conditions. However, it was seen that the mixture of mesophiles and psychrophiles produced 60% more biogas than the mesophiles in tepid conditions. [35] Case IV suggested that low climate conditions have been an obstacle for biogas production especially in developing countries. However, few studies have been conducted to develop technology of such kind that would make it feasible for biogas production in a small-scale digester. [36]

High temperatures are not achieved in most places and certainly not consistently throughout the day. In places where it is achieved, the digester will produce at a rapid rate. HRT and SRT will be small. And consequently, OLR will be high since the parameters are inversely proportional. Consistent care is required for digesters. Meanwhile, at a mid-temperature, the production is optimal (only ~35-37 ºC) but slower than at a high temperature. Although, it takes longer to initiate production, methane content in biogas is better since TS and VS reduction is higher. Mid temperature range is easily achievable in most places and hence the most commonly researched. At a low temperature mesophilic and thermophilic methanogen do not operate. If appropriate measures are taken to create a suitable enough digester temperature (>25 ºC), production can be seen. Otherwise, researches have shown little to no success at low temperatures. Inversely, success has been seen at low temperature with the use of psychrophilic bodies. Places with long winters

are expected to give insignificant result if no care is given to make the ambient temperature higher.

In order to have better production, digesters must be either buried under the ground or kept inside a heated room. When kept under the ground, major portion of the digester must be inside the earth and the portion above the ground must be covered with straw or soil. In Finland, room is usually heated to 21 ºC. So, if the room is heated, keeping the digester inside will produce satisfactory result. It must also be kept in mind that better result at around 21 ºC were seen when mixture of psychrophilic and mesophilic bacteria was used.

10. Conclusion

The thesis has mainly focused in production on cold places like Finland. The feasibility of production and practices being conducted worldwide were assessed. Small scale biogas reactor in cold places must be externally heated in order to affect any production, which is not cost-friendly. In researches studies, it has been concluded that communal digester is suitable and feasible if heating is done.

Digester placement must be carefully chosen to have maximum sunlight possible. Care should also be given to the hazards posed by a biogas plant. A setup unmarked and too close to residential area can be harmful.

It can thus be concluded that biogas has potential to be globally accepted and not only in places with warm temperatures. More studies must be done to create an efficient plant and guidelines for communities to follow.

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Appendix 1. Structure of thesis

Under this subheading, the details of how the thesis is structured and the individual workloads are mentioned. The work has been divided into different headings and subheadings including the areas of individual interest and common areas. Figure 1 shows the responsible author for specific headings and subheadings.

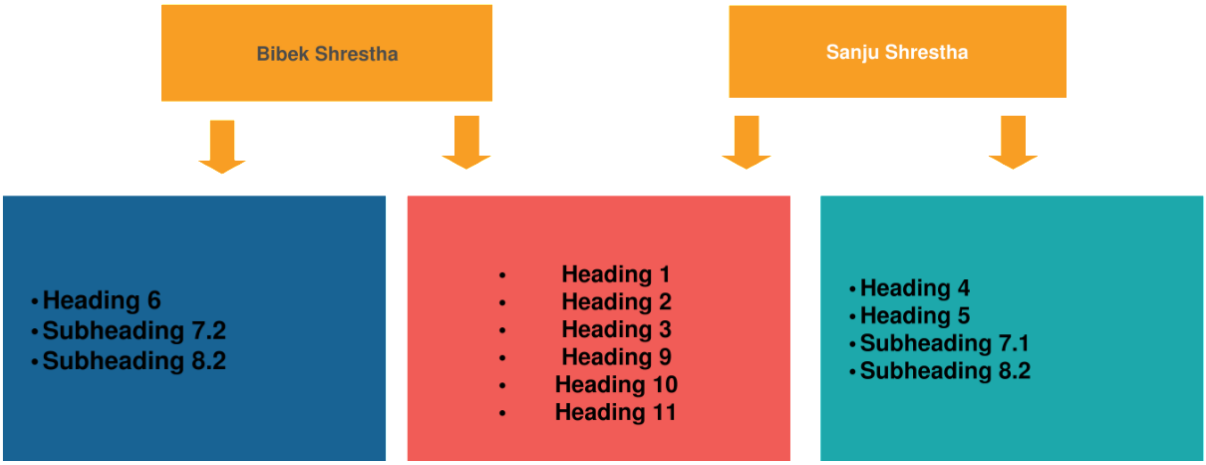

Figure 26. work division

The aim was to divide work equally among the authors. The middle section shows the mutual work done in headings.